Cross sections of α -induced reactions for targets with masses $A \approx 20 - 50$ at low energies

Peter Mohr^{1,2a}

¹ Diakonie-Klinikum, D-74523 Schwäbisch Hall, Germany

² Institute for Nuclear Research ATOMKI, H-4001 Debrecen, Hungary

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Abstract. A simple reduction scheme using so-called reduced energies $E_{\rm red}$ and reduced cross sections $\sigma_{\rm red}$ allows the comparison of heavy-ion induced reaction cross sections for a broad range of masses of projectile and target and over a wide energy range. A global behavior has been found for strongly bound projectiles whereas much larger reduced cross sections have been observed for weakly bound and halo projectiles. It has been shown that this simple reduction scheme works also well for α -particle induced reactions on heavy target nuclei, but very recently significant deviations have been seen for $\alpha + {}^{33}S$ and $\alpha + {}^{23}Na$. Motivated by these unexpected discrepancies, the present study analyses α -induced reaction cross sections for targets with masses $A \approx 20 - 50$. The study shows that the experimental data for α -induced reactions on nuclei with $A \approx 20 - 50$ deviate slightly from the global behavior of reduced cross sections. However, in general the deviations evolve smoothly towards lower masses. The only significant outliers are the recent data for 33 S and 23 Na which are far above the general systematics, and some very old data may indicate that 36 Ar and ⁴⁰Ar are below the general trend. As expected, also the doubly-magic ⁴⁰Ca nucleus lies slightly below the results for its neighboring nuclei. Overall, the experimental data are nicely reproduced by a statistical model calculation utilizing the simple α -nucleus potential by McFadden and Satchler. Simultaneously with the deviation of reduced cross sections $\sigma_{\rm red}$ from the general behavior, the outliers ²³Na, ³³S, ³⁶Ar, and ⁴⁰Ar also show significant disagreement between experiment and statistical model calculation.

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1 Introduction

The cross sections of α -induced reactions play an important role in nuclear astrophysics. Stellar evolution and nucleosynthesis depend on the Maxwellian-averaged cross sections or reaction rates $N_A \langle \sigma v \rangle$. Some prominent examples in the mass range under study are the ${}^{18}\text{Ne}(\alpha,p){}^{21}\text{Na}$ reaction which is important for the break-out from hot CNO-cycles to the so-called rapid proton capture process (*rp*-process) [1,2], the 22 Ne $(\alpha,n)^{25}$ Mg reaction which is an important neutron source in the slow neutron capture process (s-process) [3,4,5], the ${}^{23}Na(\alpha,p){}^{26}Mg$ reaction which affects the production of galactic ²⁶Al [6], and the ${}^{40}\text{Ca}(\alpha,\gamma){}^{44}\text{Ti}$ and ${}^{44}\text{Ti}(\alpha,p){}^{47}\text{V}$ reactions which govern the production and destruction of the tracer radionuclide 44 Ti in core-collapse supernovae [7,8]. Beyond stellar evolution and nucleosynthesis, α -induced reactions are also relevant for radionuclide production by energetic solar particles. It has been shown recently that α -induced reactions may significantly contribute to the production of positron emitters [9], and the abundance of the radionuclide ³⁶Cl may even be dominated by this scenario instead of stellar nucleosynthesis [10].

In addition to the astrophysical motivation, α -induced reactions can also be used for analytical purposes. The thin-layer activation analysis technique has been suggested for the measurement of vanadium and chromium contents by (α, X) reactions on ^{nat}V and ^{nat}Cr [11,12]. The concentration of sulfur which is an important element for material deterioration can be measured using the ${}^{32}S(\alpha,p){}^{35}Cl$ reaction [13]. At slightly higher energies α -induced reactions are used for the production of important tracer elements. For biological and medical studies ${}^{43}K$ can be produced by ${}^{40}Ar(\alpha,p){}^{43}K$ [14], and ${}^{30}P$ can be made from ${}^{27}Al(\alpha,n){}^{30}P$ [15]. The behavior of aluminum in bio- and eco-systems can be traced by ${}^{29}Al$ which is produced by the ${}^{26}Mg(\alpha,p){}^{29}Al$ reaction [16].

For heavy nuclei it has been found that the total reaction cross section $\sigma_{\rm reac}$ follows a general trend in the mass range around $A \approx 90 - 150$ [17,18]. This trend becomes nicely visible when so-called reduced cross sections $\sigma_{\rm red}$ are plotted versus the reduced energy $E_{\rm red}$ as suggested by [19]. However, very recently huge discrepancies have been found for the light nuclei ²³Na and ³³S where much larger values for $\sigma_{\rm red}$ have been observed; a detailed dis-

^a Email: WidmaierMohr@t-online.de; mohr@atomki.mta.hu

cussion of α -induced reactions of ³³S was provided recently in [20].

 $\mathbf{2}$

Cross sections for intermediate mass and heavy targets are usually calculated within the statistical model (StM). The basic prerequisite of the StM is a sufficiently high level density in the compound nucleus at the excitation energy $E^* = E_{\rm c.m.} + S_{\alpha}$ where $E_{\rm c.m.}$ is the energy in the center-of-mass system and S_{α} is the separation energy of the α -particle in the compound nucleus. This prerequisite is certainly fulfilled for heavy nuclei, but it will be shown that the experimental cross sections in the lower mass range under study can also be nicely reproduced by StM calculations.

For heavy nuclei α -induced cross sections are typically very well reproduced by StM calculations at energies above the Coulomb barrier. This finding is almost independent of the chosen parameterization of the underlying α -nucleus potential. At low energies the application of the widely used α -nucleus potential by McFadden and Satchler [21] typically overestimates the experimental cross sections. This general behavior of the McFadden/Satchler potential extends down to at least ⁶⁴Zn [22] and ⁵⁸Ni [23]. Much efforts have been done in the last decade to provide improved α -nucleus potentials (e.g., [18,24,25,26,27]).

Contrary to this general behavior for heavy nuclei, StM calculations underestimate the experimental results for ²³Na and ³³S. However, for the even lighter target ¹⁸Ne and the ¹⁸Ne $(\alpha, p)^{21}$ Na reaction it was found that StM calculations are – at least on average – in reasonable agreement with experimental results although the excitation function is governed by many resonances which cannot be reproduced by the StM [28]. It is the main scope of the present study to analyze the mass region around $A \approx 20 - 50$ and search for systematic trends for the cross sections of α -induced reactions. For this purpose all available reaction data in the EXFOR database [29] are reviewed and compared to StM calculations. It will be shown that there is a smooth trend of increasing reduced cross sections $\sigma_{\rm red}$ with decreasing mass A with two exceptionally large $\sigma_{\rm red}$ values for ²³Na and ³³S and perhaps exceptionally low $\sigma_{\rm red}$ values for ³⁶Ar and ⁴⁰Ar (based on very few data points from an experiment in the 1950s).

The paper is organized as follows. Sec. 2 provides general information on reduced energies $E_{\rm red}$ and reduced cross sections $\sigma_{\rm red}$ (Sec. 2.1), on the α -nucleus potential which is the essential ingredient for the StM (Sec. 2.2), and on the statistical model itself (Sec. 2.3). Sec. 3 briefly discusses experimental techniques for the determination of the relevant cross sections. Results for nuclei with A \approx 20 - 50 are presented in Sec. 4. For each nucleus under study the available experimental data are reviewed and compared to a theoretical prediction from the StM, and the reduced cross section is shown. The results are discussed in Sec. 5, and finally conclusions are drawn in Sec. 6. A list of all nuclei under study is provided in Table 1 which includes the residual nuclei and the reaction Q-values for the (α, γ) , (α, n) , and (α, p) reactions. The Q-value data are taken from nuclear masses in the latest AME2012 evaluation [30,31].

2 General considerations

2.1 Reduced energy $\mathit{E}_{\mathrm{red}}$ and reduced cross section σ_{red}

A simple reduction scheme for the comparison of heavyion induced reactions has been suggested by Gomes *et al.* [19]. The so-called reduced cross sections $\sigma_{\rm red}$ and reduced energies $E_{\rm red}$ are defined by:

$$E_{\rm red} = \frac{\left(A_P^{1/3} + A_T^{1/3}\right)E_{\rm c.m.}}{Z_P Z_T}$$
(1)

$$\sigma_{\rm red} = \frac{\sigma_{\rm reac}}{\left(A_P^{1/3} + A_T^{1/3}\right)^2}$$
(2)

The reduced energy $E_{\rm red}$ takes into account the different heights of the Coulomb barrier in the systems under consideration, whereas the reduced reaction cross section $\sigma_{\rm red}$ scales the measured total reaction cross section $\sigma_{\rm reac}$ according to the geometrical size of the projectile-plustarget system. It is found that the reduced cross sections $\sigma_{\rm red}$ show a very similar behavior for a broad range of projectiles and targets over a wide energy range. Significantly higher values of $\sigma_{\rm red}$ are found for weakly bound projectiles (like e.g. ^{6,7}Li) or halo projectiles (e.g. ⁶He), see [32, 33]. Results for α -induced reactions on heavy target nuclei fit into the systematics of heavy-ion induced reactions [17, 18]. Results are shown in Fig. 1.

The experimental $\sigma_{\rm red}$ data for ³⁴S and ⁵⁰Cr have been derived from the experimental angular distributions of Bredbecka *et al.* [34] by phase shift fits according to [35] (see Figs. 2 and 3). The data point for ⁴⁴Ti at $E_{\rm red} \approx 2.52 \,{\rm MeV}$ has been taken from the analysis of elastic ⁴⁴Ti(α, α)⁴⁴Ti scattering in [36]; it is hardly visible because it overlaps with a data point for ³⁴S. The low-energy data points for ⁴⁴Ti will be explained later (Sec. 4.7). As can be seen from Fig. 1, the $\sigma_{\rm red}$ values for lighter targets seem to be close above the general systematics with increasing differences towards lower energies and lower masses.

Interestingly, the relation between the reduced energy $E_{\rm red}$ and the most effective energy for the determination of astrophysical reaction rates (the so-called Gamow window) is practically independent of the target mass A_T and target charge number Z_T for α -induced reactions. In the mass range under study the Gamow window is found at $E_{\rm red} \approx 0.29 \,{\rm MeV}$ for $T_9 = 1$ (where T_9 is the temperature in Giga-Kelvin); the variation between ²¹Ne ($E_{\rm red}$ = 0.293 MeV) and ⁵¹V ($E_{\rm red} = 0.279 \,{\rm MeV}$) is practically negligible (and even for heavy nuclei like ²⁰⁸Pb a close value of $E_{\rm red} \approx 0.264 \,{\rm MeV}$ is found for $T_9 = 1$). $T_9 = 2$ corresponds to $E_{\rm red} \approx 0.45 \,{\rm MeV}$, and $T_9 = 3$ corresponds to $E_{\rm red} \approx 0.59 \,{\rm MeV}$ for all nuclei under study in this work. Further details on the relation between the Gamow window and the corresponding reduced energy $E_{\rm red}$ will be given in [37].

				(α,γ)		(α,n)		(α, p)	
Section	target	Z	N	residual	Q (MeV)	residual	\hat{Q} (MeV)	residual	\hat{Q} (MeV)
4.2	^{50}Cr	24	26	54 Fe	+8.417	⁵³ Fe	-4.961	⁵³ Mn	-0.437
4.3	^{51}V	23	28	^{55}Mn	+7.933	^{54}Mn	-2.294	^{54}Cr	-0.134
4.4	^{50}V	23	27	^{54}Mn	+8.758	^{53}Mn	-0.181	^{53}Cr	+1.198
4.5	48 Ti	22	26	^{52}Cr	+9.351	^{51}Cr	-2.687	^{51}V	-1.152
4.6	46 Ti	22	24	^{50}Cr	+8.560	^{49}Cr	-4.441	^{49}V	-1.030
4.7	$^{44}\mathrm{Ti}$	22	22	^{48}Cr	+7.698	$^{47}\mathrm{Cr}$	-8.634	$^{47}\mathrm{V}$	-0.407
4.8	^{45}Sc	21	24	^{49}V	+9.315	^{48}V	-2.241	^{48}Ti	+2.257
4.9	48 Ca	20	28	52 Ti	+7.669	51 Ti	-0.139	^{49}Sc	-5.860
4.10	^{42}Ca	20	22	^{46}Ti	+8.005	45 Ti	-5.185	^{45}Sc	-2.340
4.11	40 Ca	20	20	⁴⁴ Ti	+5.127	43 Ti	-11.172	^{43}Sc	-3.522
4.12	$^{41}\mathrm{K}$	19	22	^{45}Sc	+7.937	$^{44}\mathrm{Sc}$	-3.390	^{44}Ca	+1.045
4.13	40 K	19	21	$^{44}\mathrm{Sc}$	+6.705	$^{43}\mathrm{Sc}$	-2.994	^{43}Ca	+0.009
4.14	^{39}K	19	20	$^{43}\mathrm{Sc}$	+4.806	$^{42}\mathrm{Sc}$	-7.332	^{42}Ca	-0.124
4.15	$^{40}\mathrm{Ar}$	18	22	^{44}Ca	+8.854	^{43}Ca	-2.277	^{43}K	-3.329
4.16	$^{36}\mathrm{Ar}$	18	18	^{40}Ca	+7.040	39 Ca	-8.595	^{39}K	-1.288
4.17	^{37}Cl	17	20	^{41}K	+6.223	40 K	-3.872	$^{40}\mathrm{Ar}$	-1.586
4.18	^{35}Cl	17	18	^{39}K	+7.219	^{38}K	-5.859	^{38}Ar	+0.837
4.19	^{34}S	16	18	^{38}Ar	+7.208	$^{37}\mathrm{Ar}$	-4.630	^{37}Cl	-3.034
4.20	^{33}S	16	17	^{37}Ar	+6.787	^{36}Ar	-2.001	^{36}Cl	-1.928
4.21	^{32}S	16	16	^{36}Ar	+6.641	^{35}Ar	-8.615	^{35}Cl	-1.866
4.22	^{31}P	15	16	$^{35}\mathrm{Cl}$	+6.998	^{34}Cl	-5.647	^{34}S	+0.627
4.23	30 Si	14	16	^{34}S	+7.924	^{33}S	-3.494	^{33}P	-2.960
4.24	29 Si	14	15	^{33}S	+7.116	^{32}S	-1.526	^{32}P	-2.454
4.25	²⁸ Si	14	14	^{32}S	+6.948	^{31}S	-8.097	^{31}P	-1.916
4.26	^{27}Al	13	14	^{31}P	+9.669	^{30}P	-2.643	^{30}Si	+2.372
4.27	^{26}Mg	12	14	^{30}Si	+10.643	^{29}Si	+0.034	^{29}Al	-2.874
4.28	^{25}Mg	12	13	^{29}Si	+11.127	^{28}Si	+2.654	^{28}Al	-1.206
4.29	^{24}Mg	12	12	^{28}Si	+9.984	27 Si	-7.196	^{27}Al	-1.601
4.30	²³ Na	11	12	^{27}Al	+10.092	^{26}Al	-2.966	^{26}Mg	+1.821
4.31	22 Ne	10	12	^{26}Mg	+10.615	^{25}Mg	-0.478	25 Na	-3.531
4.32	$^{21}\mathrm{Ne}$	10	11	^{25}Mg	+9.886	^{24}Mg	+2.555	²⁴ Na	-2.178
4.33	20 Ne	10	10	^{24}Mg	+9.317	^{23}Mg	-7.215	²³ Na	-2.376
4.34	$^{18}\mathrm{Ne}$	10	8	^{22}Mg	+8.142	^{21}Mg	-11.242	21 Na	+2.638
4.35	^{19}F	9	10	^{23}Na	+10.467	22 Na	-1.952	^{22}Ne	+1.673

Table 1. Q-values of α -induced reactions (taken from AME2012 [30,31]). Stable residual nuclei are underlined.

2.2 α -nucleus potential

For heavy nuclei it has been found that total reaction cross sections $\sigma_{\rm reac}$ and thus reduced cross sections $\sigma_{\rm red}$ can be reproduced by almost any reasonable α -nucleus potential at energies above the Coulomb barrier. The reason for this universal behavior is discussed in detail in [38,39]. As an example the reduced cross sections for ¹⁴⁰Ce are calculated from three global α -nucleus potentials. The dashed green line in Fig. 1 shows the result from the ATOMKI-V1 potential which was derived from elastic scattering data in the mass range $A \approx 90 - 150$ [18]. The red dash-dotted line is calculated from the many-parameter potential by Avrigeanu *et al.* in the version of [26] which was derived from elastic scattering and reaction data in a similar mass range, and the blue dotted line corresponds to the old and very simple 4-parameter potential by McFadden and Satchler [21]. It is obvious that the results are very similar above $E_{\rm red} \approx 0.8 \,{\rm MeV}$, but at lower energies significant discrepancies appear. As a typical result for heavy nuclei it has been found that the McFadden/Satchler potential strongly overestimates experimental cross sections at low energies. This may be a consequence of the missing energy dependence of the imaginary part of the Mc-Fadden/Satchler potential, and noticeable improvements have been achieved by adding such an energy dependence (e.g., [40,41]). The ATOMKI-V1 potential has also a slight trend to overestimate experimental cross sections at low energies [18,39], and the Avrigeanu potential [26,27] typically slightly underestimates experimental data at very low energies.

As the ATOMKI-V1 potential and the Avrigeanu potential have not been optimized for the mass range under study in this work, reduced cross sections $\sigma_{\rm red}$ for the nuclei ⁵¹V, ³⁶Ar, and ²¹Ne have been calculated from the McFadden/Satchler potential (full black lines in Fig. 1). It will be shown later that the McFadden/Satchler potential gives excellent predictions in the whole mass range $A \approx 20 - 50$. The shown calculations for ⁵¹V, ³⁶Ar, and ²¹Ne indicate a slightly increased reduced cross section



Fig. 1. Reduced cross section $\sigma_{\rm red}$ versus reduced energy $E_{\rm red}$ for α -induced reactions on heavy nuclei. Data from elastic (α, α) scattering of heavy target nuclei have been taken from [17,18] and are shown as blue crosses. Slightly higher values for $\sigma_{\rm red}$ are found for 64 Zn and for the mass range of this work (50 Cr, 44 Ti and 34 S). The dashed, dash-dotted, and dotted lines show calculations for a heavy target nucleus (140 Ce) using three different α -nucleus potentials (data taken from [39]). The full lines show calculations for 21 Ne, 36 Ar, and 51 V, i.e. in the full mass range of this study, using the α -nucleus potential of Mc-Fadden and Satchler [21].

 $\sigma_{\rm red}$ at higher energies above $E_{\rm red} \approx 1.5$ MeV, as compared to the global systematics of heavy-ion induced reactions. At energies below $E_{\rm red} \approx 1.5$ MeV the $\sigma_{\rm red}$ for $A \approx 20-50$ are significantly increased, and this increase becomes more pronounced for lighter targets. In the detailed study of the available experimental data in the $A \approx 20-50$ mass range this trend will be confirmed for most nuclei under study (see Sec. 4).

2.3 Statistical model

Reaction cross sections of α -induced reactions for heavy nuclei can be calculated using the StM [42]. In particular, this model has been widely applied for the calculation of reaction cross sections and stellar reaction rates in nuclear astrophysics [43] using the TALYS [44] and NON-SMOKER [45] codes. The applicability of the StM to α induced reactions in the mass range $A \approx 20 - 50$ may be limited because the level density in the compound nucleus may be not sufficiently high. In such cases the cross section will be dominated by individual resonances instead of many overlapping resonances. Consequently, the StM model will not be able to predict the detailed shape of the excitation function, but nevertheless the StM should



Fig. 2. ${}^{34}S(\alpha,\alpha){}^{34}S$ elastic scattering: experimental data [34] and a phase shift fit to determine the total reaction cross section σ_{reac} using the method from [35].

be able to reproduce the general trend of the energy dependence of the cross section. E.g., such a behavior has been found for the ${}^{18}\text{Ne}(\alpha,p){}^{21}\text{Na}$ reaction, see [28] and Sec. 4.34. Further details on the applicability of the StM are given in [46] (see Fig. 8 of [46] for α -induced reactions).

In a schematic notation the reaction cross section in the StM is proportional to

$$\sigma(\alpha, X) \sim \frac{T_{\alpha,0} T_X}{\sum_i T_i} = T_{\alpha,0} \times b_X \tag{3}$$

with the transmission coefficients T_i into the *i*-th open channel and the branching ratio $b_X = T_X / \sum_i T_i$ for the decay into the channel X. The T_i are calculated from global optical potentials (particle channels) and from the gamma-ray strength function for the photon channel. For details of the definition of T_i , see [43]. $T_{\alpha,0}$ refers to the entrance channel where the target nucleus is in its ground state under laboratory conditions. The calculation of stellar reaction rates $N_A \langle \sigma v \rangle$ requires further modification of Eq. (3) [43].

It is typical for α -induced reactions on heavy nuclei that T_{α} (and thus $T_{\alpha,0}$) is much smaller than the other T_i . A simple qualitative explanation is the high Coulomb barrier in the α channel. In the neutron channel a Coulomb barrier is completely missing, and in the proton channel the barrier is much lower. As a consequence, the cross section in the StM in Eq. (3) factorizes into a production cross section of the compound nucleus which is proportional to $T_{\alpha,0}$, and a decay branching ratio $b_X = T_X / \sum_i T_i$ practi-



Fig. 3. 50 Cr(α, α) 50 Cr elastic scattering: experimental data [34] and a phase shift fit to determine the total reaction cross section σ_{reac} using the method from [35].

cally independent of T_{α} because T_{α} only marginally contributes to the sum $\sum_{i} T_{i}$ in the above nominator of b_{X} . The production cross section is thus entirely defined by the underlying α -nucleus potential whereas the branching ratio b_X does practically not depend on the chosen α potential but on all the other ingredients of the StM (optical potentials for the other channels, gamma-ray strength functions, level densities). Consequently, the cross sections of α -induced reactions are sensitive to the α -nucleus potential, but in addition each individual (α, p) , (α, n) , or (α, γ) reaction has further and sometimes complicated sensitivities to the other ingredients. A quantitative estimate whether a calculated reaction cross is sensitive to a particular ingredient, is the so-called sensitivity (as defined e.g. in [47]). As the α -nucleus potential affects directly the production cross section, the sensitivity on the α -nucleus potential is typically close to 1 for all (α, X) reactions at energies around or below the Coulomb barrier.

The present study focuses on the deviation of the $\sigma_{\rm red}$ values for α -induced reactions for $A \approx 20 - 50$ from the universal trend of heavy-ion induced reactions. This deviation mainly appears for reduced energies below $E_{\rm red}$ $\approx 1 \,{\rm MeV}$. At these energies typically at least one particle channel (proton or neutron channel) is open, and this open channel dominates the sum $\sum_i T_i$ because T_α is suppressed by the Coulomb barrier and T_γ is usually much smaller than T_X into particle channels. For particle channels this means that Eq. (3) simplifies to

$$\sigma(\alpha, X) \sim \frac{T_{\alpha,0} T_X}{\sum_i T_i} \approx T_{\alpha,0} \times \frac{T_X}{T_p + T_n}$$
(4)

Furthermore, because of the different Q-values of the (α, p) and (α, n) reactions, often one channel is strongly dominating. In such cases $b_X = T_X/(T_p + T_n) \approx 1$ for the dominating channel, and the (α, X) cross section is almost identical to the total reaction cross section σ_{reac} . Consequently, it is sufficient to measure the total reaction cross section of the dominating particle channel for these particular nuclei to determine the total reaction cross section σ_{reac} and the reduced cross section σ_{red} .

3 Experimental techniques

Total reaction cross sections σ_{reac} of α -induced reactions at higher energies far above the Coulomb barrier have been determined from transmission data, see e.g. [48]. At lower energies σ_{reac} can be derived from the analysis of elastic scattering angular distributions, and it has been shown recently that the result from elastic scattering is in agreement with the sum of the cross sections of all open channels [22]. As pointed out above, in many cases one particular open channel is dominating, and then it is sufficient to measure the total (α, p) or total (α, n) cross section to obtain an excellent estimate of the total reaction cross section σ_{reac} .

3.1 Activation

Activation is a reliable and widely used technique for the measurement of total (α, p) or (α, n) cross sections. A large fraction of the (α, p) and (α, n) data for targets with $A \approx$ 20-50 has been measured by activation. However, activation experiments are obviously limited to reactions with unstable residual nuclei. In a usual activation experiment many targets are irradiated at different energies, and the excitation function is derived from the activation yields. In several cases the so-called "stacked-foil" technique was applied which allows the determination of excitation functions within a very limited beamtime because many target foils are stacked behind each other and irradiated simultaneously. As will be shown below, this technique provides good results at energies close to the projectile energy before the stack of foils. However, the results for the lowest energies are often not reliable, probably because of uncertainties in foil thickness and resulting energy loss and straggling of the projectiles.

Various techniques can be used to determine the number of produced radioactive nuclei. The chosen technique depends on the half-life and the decay properties of the respective nucleus. In most cases γ -rays following the β^+ - or β^- -decay of the mother nuclide are detected using highresolution germanium detectors. In some cases without detectable γ -ray branch, X-rays can be measured (following e.g. electron capture from the K-shell). Also a direct detection of electrons from β^- -decay or positrons from β^+ -decay is possible. Finally, for long half-lives the accelerator mass spectrometry technique allows to count few nuclei with otherwise unrivaled sensitivity.

3.2 Direct neutron measurements

3.2.1 Neutron counting

As an alternative to activation, the total cross section of (α, n) reactions can be measured by neutron thermalization and counting. In practice, this technique is widely used, but experiments have to be done very carefully because minor build-up of carbon on the target may lead to a significant neutron yield from the ${}^{13}C(\alpha, n){}^{16}O$ background reaction. Highly enriched (and thus expensive) targets are required to avoid neutron yields from other (more neutron-rich) isotopes.

3.2.2 Time-of flight measurements

A direct neutron detection using the time-of-flight (TOF) technique is also possible. However, these experiments determine the differential cross section $d\sigma/d\Omega$ of a particular n_i channel at the detector angle ϑ (where n_0 stands for the ground state of the residual nucleus, n_1 for the first excited state, etc.). There are two basic problems to determine the total (α, n) cross section from such data. First, the integration of the differential cross section requires the knowledge of the full angular distribution (i.e., measurements at many angles), and second, all exit channels n_i have to be summed up properly. Here weak channels may be overlooked.

3.3 Direct proton measurements

Similar problems appear in direct measurements of (α, p) cross sections. Again, the angular distribution has to integrated correctly, and all channels p_i have to be summed up. This summation is even more critical for (α, p) reactions because relatively high-lying final states lead to small proton energies which may be difficult to detect (of course depending on the target thickness).

3.4 Target thickness

The target thickness is a very important experimental parameter. The experimental yield is given by the average cross section over the energy interval $[E_{\alpha}, E_{\alpha} - \varDelta E]$ where ΔE is the energy loss of the α projectile in the target. A precise determination of the cross section $\sigma(E)$ clearly asks for a thin target, i.e. a small energy loss ΔE . However, for the application of the StM a sufficient number of resonances must lie within the corresponding interval of excitation energies in the compound nucleus. There is no problem for heavy target nuclei which have high level densities, and any realistic target is sufficiently thick for the applicability of the StM. However, at the lower end of the mass range $A \approx 20 - 50$ the level density may be too low, in particular for very thin targets. As a consequence, the experimental data for a thin target will be governed by individual resonances, and the StM will not

be able to reproduce the details of the excitation function. Experimental data for a thick target will average over the individual resonances, leading to a smooth energy dependence of the excitation function. Such a behavior will be nicely illustrated e.g. for the target ²⁷Al (see Sec. 4.26).

3.5 (Infinitely) Thick-target yields

In principle, it is possible to derive reaction cross sections from thick-target yield curves by differentiation. However, in practice this leads to significant uncertainties. If the thick-target yield curve is measured with large energy steps (e.g., $E_2 \gg E_1$), the resulting cross section is averaged over a broad energy interval $E_2 - E_1$. Smaller energy steps reduce this uncertainty; but at the same time the yields $Y(E_2)$ and $Y(E_1)$ become more and more similar, and the cross section has to be derived from the difference $Y(E_2) - Y(E_1)$ which is a small number. The uncertainty in the difference of two quite similar numbers is further amplified if yield curves are not available numerically and have to be re-digitized from figures. Therefore, thick-target yield curves are not considered in this work.

One exception is made for the data by Roughton *et al.* [49] because these data allow to include the doubly-magic nucleus ⁴⁸Ca in this study. Roughton et al. have measured thick-target yield curves for 36 nuclear reactions in relatively small energy steps. The data are available numerically from Table II in [49], and the conversion from the given thick-target yield to cross sections is precisely defined in Eq. (3) of an earlier study of proton-induced reactions [50]; it is based on the energy-loss formulae given in [51]. The resulting cross sections are in reasonable agreement with other available data as long as the energy difference between two subsequent yields is sufficiently large. As expected, for very small energy differences the uncertainty of the derived average cross section increases dramatically. Surprisingly it turns out that practically all of these cross sections from small energy differences are much lower than other experimental data. Despite of these obvious inconsistencies, this allows at least to determine a good estimate of the 48 Ca $(\alpha, n)^{51}$ Ti cross section from Roughton *et* al. [49]. However, because of the above inconsistencies in the Roughton *et al.* data, in most cases the data are only shown in the cross section plots without further discussion in the text (with the same symbol "star" and same color "olive-green" in all figures), and the data are omitted in the plots of reduced cross sections (see Sec. 4.1).

3.6 Elastic scattering

The determination of total reaction cross sections σ_{reac} from elastic scattering can be done under two prerequisites. First, the deviation of the elastic scattering cross section from the Rutherford cross section of point-like charges has to exceed the experimental uncertainty. Thus, at energies below the Coulomb barrier experimental data with very small uncertainties are required. Second, full angular distributions must be available. Often total reaction cross sections are determined by fits of an optical potential; but it should be kept in mind that the choice of the parametrization of the optical potential already restricts the model space, and thus the derived σ_{reac} may become model-dependent. Such a model dependence should always be checked by a model-independent phase shift analysis. In the present work the formalism of Chiste *et al.* [35] was applied for this purpose.

For completeness it should also be noted that the parameters of optical potentials are not very well constrained from elastic scattering below the Coulomb barrier. Socalled continuous and discrete ambiguities are often found (see e.g. [52]). However, although the parameters of the optical potential may remain uncertain, the resulting angular distributions are more or less similar. It remains then possible to determine total cross sections σ_{reac} from elastic scattering even at low energies where it is impossible to determine the parameters of the optical potential [39].

3.7 Availability of experimental data

Fortunately, nowadays many experimental data are provided by the EXFOR database [29] which is a great facilitation for a literature overview. However, it has to be kept in mind that the quality of the data in EXFOR depends sensitively on the data source. Newer data are often provided by the authors of the experimental paper. For earlier papers the original data are only available if the data are listed in a table in the paper (or in an underlying thesis or laboratory report; however, the latter are often not easily accessible). If original data are not available, the EXFOR editors have often re-digitized experimental data from figures. In such cases significant uncertainties arise from the digitization procedure which may exceed the experimental uncertainties of the original data. This holds in particular for small figures in logarithmic scale.

The determination of total reaction cross sections σ_{reac} from elastic scattering is particularly sensitive to the available data quality because the experimental (α, α) angular distribution must be fitted in an optical model calculation or phase shift analysis. In many cases re-digitized data in EXFOR are listed without experimental error bars; then assumptions on the uncertainties have to be made for the fitting procedure. Fortunately, for the phase shift fits shown above in Figs. 2 and 3 the original data of Bredbecka *et al.* [34] could be restored, and these original data were sent to EXFOR to replace the previously available re-digitized data.

4 Results

4.1 General remarks on the presentation of results

The results for α -induced reactions for nuclei in the $A \approx 20 - 50$ mass range will be presented in the following way. For each nucleus the available data at EXFOR will be briefly described. A comparison is made between the

experimental (α, p) and (α, n) cross sections and predictions from the StM. Here I use the TALYS code [44] with standard parameters except the α -nucleus potential where the potential by McFadden/Satchler is selected. As the α -nucleus potential is the essential ingredient in most cases (see discussion above), NON-SMOKER [45] calculations lead to very similar results because the Mc-Fadden/Satchler potential is the default option in NON-SMOKER.

In practically all cases the (α, γ) cross section is much smaller than the (α, p) or (α, n) cross section. Thus, (α, γ) cross sections will be shown only in few cases; an explanation will be given in the respective sections for these special cases.

For some nuclei under study only very few or even no (α, p) or (α, n) data are available in literature. For these nuclei it was attempted to obtain further information on the total reaction cross section σ_{reac} from the analysis of elastic scattering angular distributions. In practice, this analysis can only be performed at energies around or above the Coulomb barrier whereas at very low energies below the Coulomb barrier the elastic scattering cross section approaches the Rutherford cross section of point-like charges.

For each nucleus under study the available data for the (α, p) and (α, n) reactions (and also the (α, γ) data and total reaction cross sections σ_{reac} from elastic scattering) will be shown in a first figure. In this figure also a comparison with a calculation in the StM will be made. The energy in all these figures is E_{α} in the laboratory system; for experiments in inverse kinematics, the corresponding energy E_{α} is calculated from the given energy of the heavy projectile.

In addition to the comparison of reaction cross sections, reduced cross sections $\sigma_{\rm red}$ are shown versus the reduced energy $E_{\rm red}$ in a second figure for each nucleus under study. In these $\sigma_{\rm red}$ figures the experimental data are shown together with the three calculations of $\sigma_{\rm red}$ from the total reaction cross section $\sigma_{\rm reac}$ for ²¹Ne, ³⁶Ar, and ⁵¹V (these calculations have already been shown as full lines in Fig. 1). The purpose of this presentation is to show how the experimental data for nuclei with $A \approx 20 - 50$ move smoothly with decreasing A from the calculation for ${}^{51}V$ to the calculation for ^{21}Ne with the few noticeable exceptions of ⁴⁰Ar, ³⁶Ar, ³³S, and ²³Na (as already mentioned in the introduction). For this purpose the scale of all graphs with $\sigma_{\rm red}$ versus $E_{\rm red}$ is exactly the same to guide the eye, and the systematics for α -induced reaction cross sections for heavy targets (see Fig. 1) is repeated in each graph with small blue crosses.

In general, experimental data for (α, n) reactions will be shown as open symbols, and (α, p) reactions will be shown as full symbols. Exceptions will be indicated in the figure captions.

For several nuclei under study, data in the book of Levkovskij [53] are referenced in EXFOR. Often significant deviations to other available data sets are found for the Levkovskij data. As the book [53] is not available to the author of this study, it is not possible to trace back to the origin of these discrepancies. The data of [53] are omitted in the following graphs.

4.2 ⁵⁰Cr

The ${}^{50}\mathrm{Cr}(\alpha,n){}^{53}\mathrm{Fe}$ and ${}^{50}\mathrm{Cr}(\alpha,p){}^{53}\mathrm{Mn}$ reactions can both be measured by activation. However, the half-life of ${}^{53}\mathrm{Mn}$ is extremely long $(T_{1/2} = 3.74 \times 10^6 \text{ years})$, and no activation data are available for the proton channel. Because of the strongly negative Q-value of the (α,n) reaction and $Q \approx -0.44 \text{ MeV}$ for the (α,p) reaction, the (α,p) channel is dominating at low energies, but at energies above about 6 - 7 MeV the (α,n) cross section also contributes significantly to the total reaction cross section σ_{reac} .

A detailed study of both α -induced reactions on ⁵⁰Cr has been done by Morton *el al.* [54]. The excitation function of the ⁵⁰Cr(α ,p)⁵³Mn reaction has been measured using a silicon detector at the angle of $\vartheta = 125^{\circ}$. The measured protons have been grouped into p_0 , p_1 , p_{2-4} , p_{5-7} , p_{8-15} , and p_{16-28} . Corrections for the angular distributions have been taken from StM calculations; however, these corrections remain relatively small because of the chosen angle. The total (α ,p) cross section is determined by the sum over the above proton groups. The result is shown in Fig. 4. default parameters and the α -nucleus potential by Mc-Fadden and Satchler [21] (dashed line in Fig. 4). It can be seen that the agreement is excellent at low energies whereas above about 8 MeV the calculation is higher than the experimental data. As the StM calculations are typically very stable and reliable at higher energies, this deviation may indicate that the summation over the proton groups (p_{0-28}) is insufficient at the highest energies. Alternatively, the uncertainty of the correction on the angular distribution of the proton groups increases with energy [54]; this uncertainty may be larger than estimated by the authors.

The ${}^{50}Cr(\alpha,n){}^{53}Fe$ reaction has been measured by Morton et al. using two independent techniques. Neutrons were counted directly with ³He-filled proportional counters, and activation was observed with a germanium detector by detection of the $378 \text{ keV} \gamma$ -ray in the decay of ${}^{53}\text{Fe} \rightarrow {}^{53}\text{Mn}$. Both data sets show the same energy dependence, but unfortunately the two data sets deviate by about 20% in their absolute scale. The reason for this discrepancy remains unclear. An earlier experiment by Vlieks *el al.* [55] has measured the induced activity by positron counting. These earlier data are in better agreement with the direct neutron data by Morton et al. [54]. As a similar experiment has been done by the same authors on ${}^{51}V(\alpha,n){}^{54}Mn$ (see next Sec. 4.3) where direct neutron counting and activation are in excellent agreement, the discrepancy observed for the ${}^{50}Cr(\alpha,n){}^{53}Fe$ re-



Fig. 4. Cross sections of the ${}^{50}\text{Cr}(\alpha,n){}^{53}\text{Fe}$ and ${}^{50}\text{Cr}(\alpha,p){}^{53}\text{Mn}$ reactions. The (α,n) data are shown with open symbols and dotted line, the (α,p) data are shown with full symbols and dashed line. (The same style will be used in all following figures except explicitly noted.) The experimental data have been taken from [54, 55, 49]. Further discussion see text.

The experimental ${}^{50}Cr(\alpha,p){}^{53}Mn$ cross section is compared to a StM calculation using the code TALYS with



Fig. 5. Reduced cross section $\sigma_{\rm red}$ versus reduced energy $E_{\rm red}$ for α -induced reactions on ${}^{50}{\rm Cr}$. The experimental data have been taken from [54]. In addition, the result of a reanalysis of the elastic scattering data of [34] is shown. Data points from elastic scattering on heavy (A > 60) target nuclei are repeated from Fig. 1 (blue crosses). As a guide to the eye, the calculations for ${}^{21}{\rm Ne}$, ${}^{36}{\rm Ar}$, and ${}^{51}{\rm V}$ are also repeated from Fig. 1 (full black lines). Further discussion see text.

action is probably the consequence of an incorrect decay branching of the analyzed 378 keV γ -ray. Morton *et al.* have used $42 \pm 8\%$; the present ENSDF evaluation recommends $42 \pm 3\%$ [56], and good agreement between direct neutron counting and activation would be obtained for a branching of about 34%.

It is obvious from Fig. 4 that the StM calculations reproduce the experimental data of both reactions very well. In particular at low energies the agreement is excellent, and a possible explanation for the deviation at higher energies in the ${}^{50}\text{Cr}(\alpha,p){}^{53}\text{Mn}$ channel has already been given above.

For the determination of the total reaction cross section $\sigma_{\rm reac}$ and the reduced cross section $\sigma_{\rm red}$, the (α, p) and (α, n) data of Morton *et al.* [54] were summed. The result is shown in Fig. 5. In addition, the data from elastic ${}^{50}{\rm Cr}(\alpha,\alpha){}^{50}{\rm Cr}$ scattering (see Fig. 3) are shown. The $\sigma_{\rm red}$ data are slightly higher than the general trend which was derived from elastic (α, α) scattering of heavy target nuclei. Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for ${}^{50}{\rm Cr}$ do not show a peculiar behavior.

$\textbf{4.3}~{}^{51}\textbf{V}$

Many experimental data are available at EXFOR for the ${}^{51}V(\alpha,n){}^{54}Mn$ reaction which can be measured by activation. Contrary, only one data set is available for the ${}^{51}V(\alpha,p){}^{54}Cr$ reaction which was measured using the same technique as for ${}^{50}Cr(\alpha,p){}^{53}Mn$ (see previous Sec. 4.2).

The ${}^{51}V(\alpha, n){}^{54}Mn$ data are shown in Fig. 6. The precision data by Vonach *et al.* [57] were measured by activation and are in excellent agreement with the activation data and the direct neutron counting data by Hansper *et al.* [58]. Earlier data by Vlieks *et al.* [55] are slightly higher especially at energies above 9 MeV. Recent stackedfoil data by Peng *et al.* [11] and Chowdhury *et al.* [12] are in good agreement with the other data whereas earlier stacked-foil data [59,60,61,62,63,64] deviate significantly at the lowest energies. The agreement of the experimental data with the StM calculation is excellent over the full shown energy range.

The ${}^{51}V(\alpha,p){}^{54}Cr$ data by Hansper *et al.* [58] are not shown in Fig. 6 for several reasons. It is impossible to derive the total (α, p) cross section from the information in the paper. Proton groups $(p_0, p_1, p_2, p_{3-4}, and p_{5-7})$ are shown in the spectrum (Fig. 3 of [58]) but in the following cross section plots the strong group p_{5-7} is missing. In addition, the data at EXFOR are re-digitized from the figures in [58] which makes a point-by-point addition of the proton groups practically impossible. Fortunately, the ${}^{51}V(\alpha,p){}^{54}Cr$ reaction contributes only very minor to the total reaction cross section σ_{reac} of ⁵¹V which is dominated by the ${}^{51}V(\alpha,n){}^{54}Mn$ reaction (see the shown calculations in Fig. 6). Only at the lowest energies below about 5 MeV the (α, p) cross section becomes comparable to the (α, n) cross section whereas at higher energies the (α, p) reaction contributes by less than 20% [57]. The data points at the lowest energies for the (α, p) reaction in [58] are about



Fig. 6. Cross sections of the ${}^{51}V(\alpha,n){}^{54}Mn$ and ${}^{51}V(\alpha,p){}^{54}Cr$ reactions. The experimental data have been taken from [57, 58, 55, 11, 12, 59, 60, 61, 62, 63, 64, 49]. The lowest data points of several stack-foil experiments [59, 60, 61, 62, 63, 64] (shown as small dots in different colors) are in disagreement with the other data. Further discussion see text.

 10^{-2} mb at ≈ 5 MeV with huge error bars, i.e. close to the theoretically expected values (dashed line in Fig. 6).



Fig. 7. Same as Fig. 5, but for α -induced reactions on ⁵¹V. The experimental data have been taken from [55,57,58,11,12]. Further discussion see text.

Fig. 7 shows the reduced cross section $\sigma_{\rm red}$ for ⁵¹V. For better readability only the (α, n) data of [55, 57, 58, 11, 12]are shown. The agreement between the experimental (α, n) data and the calculated total reaction cross section σ_{reac} and reduced cross section $\sigma_{\rm red}$ is excellent up to $E_{\rm red} \approx$ 1.5 MeV. At these energies other reaction channels open, and thus the (α, n) cross section does not represent the total cross section σ_{reac} anymore. At even higher energies (above the range shown in Fig. 7) the analysis of elastic ${}^{51}V(\alpha,\alpha){}^{51}V$ scattering leads to data points of $\sigma_{red} = 55 \pm$ 2 mb at $E_{\rm red} = 2.90 \,\text{MeV} \,[65]$ and $\sigma_{\rm red} = 46 \pm 4 \,\text{mb}$ at $E_{\rm red}$ $= 2.49 \,\mathrm{MeV}$ [33], again in reasonable agreement with the theoretical expectations of 46.4 mb and 43.8 mb. Finally, it is interesting to note that the reduced cross sections $\sigma_{\rm red}$ for the semi-magic (N = 28) nucleus ⁵¹V are very similar to the non-magic neighboring nuclei ⁵⁰Cr (see previous Sec. 4.2) and 48 Ti (see following Sec. 4.5). Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for ⁵¹V do not show a peculiar behavior.

4.4 ⁵⁰V

10

The odd-odd (Z = 23, N = 27) nucleus ⁵⁰V has a very low natural abundance. Unfortunately, no data for α -induced reactions are available below 10 MeV. The only available data set by Peng *et al.* [11] covers the ⁵⁰V(α ,2n)⁵²Mn reaction from close above threshold around ≈ 13 MeV to about 26 MeV. The data have been measured using the stacked-foil activation technique. The experimental data are well reproduced by the StM calculation. However, the data do not restrict the total reaction cross section σ_{reac} of α -induced reactions on ⁵⁰V, and thus no figure for cross sections or reduced cross sections σ_{red} is shown here. Nevertheless, from the nice agreement between the experimental ⁵⁰V(α ,2n)⁵²Mn data and the StM calculation it can be concluded that there is at least no evidence for a peculiar behavior of the odd-odd nucleus ⁵⁰V.

4.5 ⁴⁸Ti

Five data sets for the ${}^{48}\text{Ti}(\alpha,n){}^{51}\text{Cr}$ reaction are available from EXFOR. All experiments have applied activation techniques. The precision data for the ${}^{\overline{48}}\overline{\mathrm{Ti}}(\alpha,n)^{51}\mathrm{Cr}$ reaction by Vonach et al. [57] have been obtained by measuring the induced activity by γ -spectroscopy. The same technique was used by Morton et al. [67] and Baglin et al. [68] whereas Chang el al. [66] used X-ray spectroscopy of the 4.95 keV X-ray which is emitted in ⁵¹V after the electron capture decay of 51 Cr. Iguchi *et al.* [60] used the stacked-foils technique and γ -spectroscopy. It can be seen from Fig. 8 that in general the data are in good agreement. Exceptions are the lowest energy points of the stackedfoil experiment [60] and also the lowest data point of the X-ray experiment [66]; here the analysis at the lowest energy may be hampered by the relatively thick target $(485\,\mu g/cm^2)$. The agreement with the StM calculation is excellent over the full energy range.



Fig. 8. Cross sections of the ${}^{48}\text{Ti}(\alpha,n){}^{51}\text{Cr}$ and ${}^{48}\text{Ti}(\alpha,p){}^{51}\text{V}$ reactions. The experimental data have been taken from [60,66, 57,67,68,49]. Further discussion see text.

The ⁴⁸Ti(α, p)⁵¹V reaction has been measured by Morton *et al.* [67]. Cross sections for the proton groups p_0 to p_5 are shown in Fig. 4 of [67]; the sum of these cross sections is shown as (α, p) cross section in Fig. 8. The proton groups p_{6-8} could not be resolved from background reactions, but should have only a minor contribution to the



Fig. 9. Same as Fig. 5, but for α -induced reactions on ⁴⁸Ti. The experimental data have been taken from [60,66,57,67,68]. Further discussion see text.

⁴⁶Ti

5 6 7 8 9

Δ

 10^{2}

10

1

10⁻¹

10⁻²

10⁻⁴

0.0

(mb)

total (α, p) cross section (see the spectrum in Fig. 3 of [67]). The agreement with the StM calculation is good for the ${}^{48}\text{Ti}(\alpha,p){}^{51}\text{V}$ reaction although the experimental results are slightly overestimated at the upper and lower end of the measured energy interval. It is interesting to note that the NON-SMOKER calculation for the ${}^{48}\mathrm{Ti}(\alpha,p){}^{51}\mathrm{Cr}$ reaction deviates from the TALYS calculation, leading to better agreement at higher and lower energies, but underestimation in the middle.

Because the (α, n) cross section for ⁴⁸Ti is much larger than the (α, p) cross section, the total reaction cross section $\sigma_{\rm reac}$ and the reduced cross section $\sigma_{\rm red}$ are taken from the (α, n) data. A contribution of less than 20 % was estimated in [57] for the (α, p) reaction. At higher energies the low $\sigma_{\rm red}$ values from [60] can be explained by additional open channels. At even higher energies the analysis of elastic scattering angular distributions in [65] leads to $\sigma_{\rm red} = 54.6 \,\mathrm{mb}$ at $E_{\rm red} = 2.98 \,\mathrm{MeV}$ (not shown in Fig. 9). Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for ⁴⁸Ti do not show a peculiar behavior.

4.6 ⁴⁶Ti

Only few data sets are available for ⁴⁶Ti. The cross section of the ${}^{46}\text{Ti}(\alpha,n){}^{49}\text{Cr}$ reaction has been measured by activation and annihilation spectroscopy by Vlieks et al. [55] and by Howard et al. [69]. The data by Vlieks et al. are significantly lower than the data by Howard et al. (see Fig. 10). The Vlieks *et al.* data are confirmed by the thick-target yield measured by Roughton et al. [49]. As the experimental data from Vlieks *et al.* [55] for 50 Cr (see Sec. 4.2), 51 V (see Sec. 4.3), and 45 Sc (see Sec. 4.8) agree with other experimental data, the data of Vlieks et al. should be adopted. In addition, the data by Vlieks et al. are available from a table in [55] whereas the data by Howard *et al.* had to be re-digitized from Fig. 3 of [69] (see also comment in Sec. 3.7). Furthermore, also for ${}^{40}Ca$ and 35 Cl the data by Howard *et al.* [69] are slightly higher than other available data (see Sec. 4.11 and 4.18).

The agreement between the data of Vlieks *et al.* [55]and the StM calculation (dotted line in Fig. 10) is again excellent. However, the total reaction cross section σ_{reac} and the reduced cross section $\sigma_{\rm red}$ are dominated by the ${}^{46}\mathrm{Ti}(\alpha,p){}^{49}\mathrm{V}$ reaction (dashed line in Fig. 10) where no data are available from EXFOR. As a consequence, the $\sigma_{\rm red}$ data from the ${}^{46}{\rm Ti}(\alpha,n){}^{49}{\rm Cr}$ reaction are significantly lower than the expectation for the total reaction cross section (see Fig. 11).

4.7 ⁴⁴Ti

It is not surprising that only very few data are available for the radioactive nucleus $^{44}{\rm Ti.}$ Nevertheless, a determination of the total reaction cross section at low energies is possible from the dominating ${}^{44}\text{Ti}(\alpha,p){}^{47}\text{V}$ reaction. The $^{44}\text{Ti}(\alpha,n)^{47}\text{Cr}$ reaction has a strongly negative Q-value and does not contribute to σ_{reac} at low energies.

Fig. 10. Cross section of the ${}^{46}\text{Ti}(\alpha,n){}^{49}\text{Cr}$ reaction. The experimental data have been taken from [55,69,49]. Further discussion see text.

 E_{α} (MeV)

 (α,n) :

• Vlieks 1974

Howard 1974

Roughton 1983

10 11 12 13 14

Howard 197

1.5

2.0

determined by Sonzogni et al. [70] using a radioactive ⁴⁴Ti

 $E_{\rm red}$ (MeV) Fig. 11. Same as Fig. 5, but for α -induced reactions on ⁴⁶Ti. The experimental data have been taken from [69,55]. According to StM calculations, the shown ${}^{46}\text{Ti}(\alpha,n){}^{49}\text{Cr}$ cross section is about a factor of two smaller than the dominating ${}^{46}\mathrm{Ti}(\alpha,p){}^{49}\mathrm{V}$ cross section. Consequently, the total reaction cross section σ_{reac} should be about a factor of three larger than the shown (α, n) cross sections. Further discussion see text.

0.5

1.0





Fig. 12. Cross section of the ${}^{44}\text{Ti}(\alpha,p){}^{47}\text{V}$ reaction. The experimental data have been taken from [70,71]. Further discussion see text.

beam in combination with a ⁴He gas cell and the Argonne fragment mass analyzer. Very recently, at lower energies an upper limit was obtained by Margerin *et al.* [71] at CERN using also a ⁴⁴Ti beam. Further suggestions for experiments have been made in [72] very recently. The two data sets [70,71] are shown in Fig. 12 and are compared to a StM calculation. Again very good agreement between experiment and theory is found.

As the total reaction cross section σ_{reac} is essentially defined by the ⁴⁴Ti(α, p)⁴⁷V cross section, reduced cross sections σ_{red} can be determined from the available (α, p) data [70,71]. The result is shown in Fig. 13. An additional data point from ⁴⁴Ti(α, α)⁴⁴Ti elastic scattering ($\sigma_{\text{red}} =$ 55.8 mb at $E_{\text{red}} = 2.53$ MeV; not shown in Fig. 13) has already been presented above in Sec. 2.1. Similar to most nuclei under study in this work, the σ_{red} data for ⁴⁴Ti do not show a peculiar behavior.

4.8 45Sc

 α -induced reactions on ⁴⁵Sc have been studied by Chen *et al.* [73], Vlieks *et al.* [55], and Hansper *et al.* [74]. Chen *et al.* have used the stacked-foil activation technique in combination with β -proportional counters, Vlieks *et al.* used activation and annihilation spectroscopy, and Hansper *et al.* applied both direct neutron counting and activation in combination with γ -ray spectroscopy. The different techniques provide results which are in excellent agreement with each other (see Fig. 14). The StM calculation reproduces the experimental cross sections of the ⁴⁵Sc(α , n)⁴⁸V reaction very nicely.

The ${}^{45}Sc(\alpha,p){}^{48}Ti$ reaction cannot be measured by activation because the residual ${}^{48}Ti$ is stable. Only one



Fig. 13. Same as Fig. 5, but for α -induced reactions on ⁴⁴Ti. The experimental data have been taken from [70,71]. Further discussion see text.

data set is available by Hansper *et al.* [74]. However, the shown data cover only the p_0 , p_1 , and p_{2-3} groups whereas the spectrum in Fig. 2 of [74] shows additional proton groups at higher excitation energies which cannot be fully resolved from background. A rough estimate from that Fig. 2 shows that about twice the strength of the shown



Fig. 14. Cross sections of the ${}^{45}Sc(\alpha,n){}^{48}V$ and ${}^{45}Sc(\alpha,p){}^{48}Ti$ reactions. The experimental data have been taken from [73, 55, 74]. Further discussion see text.



Fig. 15. Same as Fig. 5, but for α -induced reactions on ⁴⁵Sc. The experimental data have been taken from [73, 55, 74]. Further discussion see text.

 p_{0-3} groups is found in higher-lying proton groups up to p_{48} at $E_{\alpha} = 6.8$ MeV. As expected, the StM calculation for the total (α, p) cross section is far above the experimental partial p_0 , p_1 , and p_{2-3} cross sections. This is consistent with the finding from the spectrum shown in Fig. 2 of [74]. The determination of the total (α, p) cross section is further hampered by the fact that only re-digitized data are available for the (α, p) cross sections.

The calculated total (α, n) and (α, p) cross sections for ⁴⁵Sc in Fig. 14 show that the total reaction cross section $\sigma_{\rm reac}$ and the reduced cross section $\sigma_{\rm red}$ are dominated by the (α, n) contribution at energies above ≈ 7 MeV. However, at the lowest energies the (α, n) and (α, p) cross sections are of comparable strength. The reduced cross sections $\sigma_{\rm red}$ in Fig. 15 are thus well-defined around $E_{\rm red} \approx$ 1 MeV by the (α, n) cross section whereas at the lowest energies in Fig. 15 around $E_{\rm red} \approx 0.5$ MeV $\sigma_{\rm red}$ will be underestimated by about a factor of two. At higher energies one further data point is obtained from elastic ${}^{45}{\rm Sc}(\alpha, \alpha){}^{45}{\rm Sc}$ scattering: $\sigma_{\rm red} = 52.1$ mb at $E_{\rm red} = 3.06$ MeV [65]. Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for ${}^{45}{\rm Sc}$ do not show a peculiar behavior.

4.9 ⁴⁸Ca

⁴⁸Ca is a doubly-magic (Z = 20, N = 28) nucleus with a significant neutron excess (N/Z = 1.4). As a consequence, the ⁴⁸Ca(α, p)⁵¹Sc reaction is strongly suppressed, and the total reaction cross section σ_{reac} at low energies is well-defined by its dominant ⁴⁸Ca(α, n)⁵¹Ti contribution. Unfortunately, no data for this reaction are available a EX-FOR. The thick-target yield curve of Roughton *et al.* [49]

has been differentiated to extract the ${}^{48}\text{Ca}(\alpha, n){}^{51}\text{Ti}$ cross section (see Sect. 3.4). The result is shown in Fig. 16.



Fig. 16. Cross sections of the ${}^{48}\text{Ca}(\alpha,n){}^{51}\text{Ti}$ and ${}^{48}\text{Ca}(\alpha,p){}^{51}\text{Sc}$ reactions. The experimental data have been taken from [49]. Further discussion see text.

Because of the few available reaction data for 48 Ca, in addition the elastic 48 Ca (α, α) 48 Ca scattering data of



Fig. 17. Same as Fig. 5, but for α -induced reactions on ⁴⁸Ca. The experimental data have been taken from [49]. Further discussion see text.

Gaul *et al.* [75] at 18 to 29 MeV were analyzed. Total cross sections σ_{reac} between 1365 and 1771 mb were obtained for the four angular distributions at 18.0, 22.0, 24.1, and 29.0 MeV, corresponding to reduced cross sections σ_{red} of 50.0, 58.5, 64.9, and 59.3 mb at $E_{\text{red}} = 2.17, 2.65, 2.90$, and 3.49 MeV (above the shown range in Fig. 17). Although the experimental data are quite limited, it can be concluded that there is no evidence for a peculiar behavior of the reduced cross sections σ_{red} for the doubly-magic nucleus ⁴⁸Ca.

4.10 ⁴²Ca

The semi-magic ⁴²Ca nucleus is characterized by relatively large negative *Q*-values for the (α, n) (-5.18 MeV) and (α, p) (-2.34 MeV) reactions. Therefore, at very low energies the ⁴²Ca $(\alpha, \gamma)^{46}$ Ti reaction plays also an important role in the determination of the total reaction cross section.



Fig. 18. Cross sections of the ${}^{42}\text{Ca}(\alpha,n){}^{45}\text{Ti}$, ${}^{42}\text{Ca}(\alpha,p){}^{45}\text{Sc}$, and ${}^{42}\text{Ca}(\alpha,\gamma){}^{46}\text{Ti}$ reactions. The experimental data have been taken from [76,77,78]. The additional dash-dotted line shows the StM calculation for the (α,γ) reaction. Further discussion see text.

The ${}^{42}\text{Ca}(\alpha, n){}^{45}\text{Ti}$ cross section has been determined by Cheng *et al.* [76] using activation in combination with annihilation spectroscopy. The energy range starts close above the (α, n) threshold. A comparison with a StM calculation shows excellent agreement (see Fig. 18).

Buckby *et al.* [77] have measured excitation functions for the ${}^{42}\text{Ca}(\alpha, p){}^{45}\text{Sc}$ reaction at five different angles. Unfortunately, no spectrum is shown in [77], but total cross sections for the (α, p) reaction are reported, and it is stated



Fig. 19. Same as Fig. 5, but for α -induced reactions on 42 Ca. The experimental data have been taken from [76,77,78]. At energies above the (α,n) threshold, the cross sections of the 42 Ca (α,n) 45 Ti and 42 Ca (α,p) 45 Sc reactions are very similar. Below the (α,p) threshold, the total cross section σ_{reac} is dominated by the 42 Ca (α,γ) 46 Ti reaction. Further discussion see text.

that "sufficient counts were obtained for the smallest proton peaks in the spectrum" and "The contribution of any remaining missed proton groups was then estimated by reference to their percentage contribution to the total yield at higher energies." At energies above the (α,n) threshold the (α,p) and (α,n) cross sections are of comparable strength whereas at energies below the (α,n) threshold (and obviously above the (α,p) threshold) the total reaction cross section is dominated by the (α,p) cross section.

The (α, p) data by Buckby *et al.* are extended towards lower energy by Mitchell *et al.* [78]. Here two techniques were applied. The ${}^{42}\text{Ca}(\alpha, p_{0,1})^{45}\text{Sc}$ cross section was measured by a proton detector at $\vartheta = 145^{\circ}$, and isotropy of the angular distributions was checked at few energies with a five-detector array. The ${}^{42}\text{Ca}(\alpha, p_{>1})^{45}\text{Sc}$ reaction was measured by the γ -ray yield of de-exciting ${}^{45}\text{Sc}$ residual nuclei. The total ${}^{42}\text{Ca}(\alpha, p)^{45}\text{Sc}$ cross section is then obtained from the sum of the measured $(\alpha, p_{0,1})$ and $(\alpha, p_{>1})$ cross sections. Figs. 18 and 19 show the individual $(\alpha, p_{0,1})$ and $(\alpha, p_{>1})$ cross sections. As both contributions are almost equal, the total (α, p) cross section should be about a factor of 2 higher than the two individual cross sections. However, this sum is slightly higher than the result of Buckby *et al.* [77].

At energies below about $E_{\alpha} \approx 4 \text{ MeV}$, the (α, p) cross section approaches its threshold (Q = -2.34 MeV), and thus the cross section is further suppressed by the Coulomb barrier in the exit channel. As a consequence, the (α, γ) cross section exceeds the (α, p) cross section. Experimental data for the ${}^{42}\text{Ca}(\alpha,\gamma){}^{46}\text{Ti}$ cross section have also been measured by Mitchell *et al.* [78] by summing the intensities of the γ -rays to the ground state and the γ -ray from the first excited 2^+ state to the 0^+ ground state in ${}^{46}\text{Ti}$.

The total reaction cross section σ_{reac} and the reduced cross section σ_{red} for ⁴²Ca are essentially given by the (α, γ) cross section at very low energies, by the (α, p) cross section between about 5 and 6.5 MeV, and the sum of (α, p) and (α, n) cross sections at energies above the neutron threshold. The individual (α, n) , (α, p) , and (α, γ) cross sections are shown as reduced cross sections σ_{red} in Fig. 19. Similar to most nuclei under study in this work, the σ_{red} data for ⁴²Ca do not show a peculiar behavior.

4.11 ⁴⁰Ca

Similar to the semi-magic ⁴²Ca, the doubly-magic ⁴⁰Ca nucleus is also characterized by strongly negative Q-values for the (α, p) (-3.52 MeV) and the (α, n) (-11.17 MeV) reactions. As both residual nuclei of the (α, p) and (α, n) reaction are unstable, and ⁴³Ti has a very short half-life of less than 1 second, the activation technique can be applied to measure the sum of the (α, p) and (α, n) cross sections by detection of the induced ⁴³Sc activity. Annihilation spectroscopy was used by Howard *et al.* [69] for this purpose. The result is shown in Fig. 20. The agreement with the StM calculation is excellent for lower energies. At higher energies the experimental data are slightly underestimated. As the StM calculation shows, the (α, n) cross section is practically negligible for ⁴⁰Ca.



Fig. 20. Cross sections of the 40 Ca $(\alpha,n)^{43}$ Ti, 40 Ca $(\alpha,p)^{43}$ Sc, and 40 Ca $(\alpha,\gamma)^{44}$ Ti reactions. The experimental data have been taken from [69,81,49]. The additional dash-dotted line shows the StM calculation for the (α,γ) reaction. Further discussion see text.



Fig. 21. Same as Fig. 5, but for α -induced reactions on ⁴⁰Ca. The experimental data have been taken from [69,81]. Further discussion see text.

Again similar to ⁴²Ca, at very low energies close above the (α, p) threshold, the (α, p) reaction is further suppressed by the Coulomb barrier in the exit channel, and consequently the total reaction cross section is significantly affected by the (α, γ) cross section. However, average cross sections for the ${}^{40}Ca(\alpha,\gamma){}^{44}Ti$ reaction are very rare in literature, and the focus of recent (α, γ) experiments was the astrophysically very important resonance triplet around 4.5 MeV and the properties of resonances [79,80,81,82, 83,84,85]. The thick-target data point of Nassar et al. [81] leads to an average cross section of $8.0 \pm 1.1 \,\mu b$ for the broad energy range from about 2.1 to 4.2 MeV in the center-of-mass system. Using the calculated average energy dependence of the (α, γ) cross section, the effective energy is $E_{\rm c.m.} \approx 3.45 \,{\rm MeV}$. This data point is shown in Figs. 20 and 21.

As pointed out above, the total reaction cross section $\sigma_{\rm reac}$ and the reduced cross section $\sigma_{\rm red}$ are well-defined by the (α, p) cross section over a wide energy range. The reduced cross section for ⁴⁰Ca is shown in Fig. 21. At higher energies above $E_{\rm red} \approx 1 \,{\rm MeV}$, the obtained $\sigma_{\rm red}$ is close to the other nuclei in the $A \approx 20 - 50$ mass range. However, at lower energies below $E_{\rm red} \approx 1 \,{\rm MeV}$, the reduced cross section $\sigma_{\rm red}$ for ⁴⁰Ca is slightly lower than for neighboring nuclei. This reflects the doubly-magic nature of ⁴⁰Ca.

4.12 41 K

Whereas the previously studied nuclei are located completely in the fp-shell, ⁴¹K with Z = 19 and N = 22enters the transition region between the sd-shell and the fp-shell. Several experimental data sets are available for the 41 K(α, n) 44 Sc reaction. Scott *et al.* [88] have measured the (α, n) cross section by neutron counting and by activation in combination with γ -ray detection of the 1157 keV γ -ray in the decay 44 Sc $\rightarrow {}^{44}$ Ca. Both experimental techniques provide consistent results in the energy range under study by Scott *et al.*; a small correction of a few per cent was applied to the activation data to take into account a long-living $J^{\pi} = 6^+$ isomer with $T_{1/2} = 2.44$ days.

16



Fig. 22. Cross sections of the 41 K $(\alpha,n)^{44}$ Sc and 41 K $(\alpha,p)^{44}$ Ca reactions. The experimental data have been taken from [86,87, 88,89] and are the sum of the ground state and isomer cross sections in the (α,n) channel. Further discussion see text.

At higher energies yields for the ground state and isomeric state have been measured separately. Keedy *et al.* [87] used activation in combination with annihilation spectroscopy whereas Riley *et al.* [86] and Matsuo *et al.* [89] used also activation, but in combination with γ -ray spectroscopy. All experimental data sets are in reasonable agreement within the experimental uncertainties, with about 10-25% lower cross sections in [87] and [89]. The results are shown in Fig. 22; the ground state cross section and the isomeric cross section. The agreement between the experimental data and a StM calculation is again excellent.

Scott *et al.* [88] also provide cross sections for the 41 K $(\alpha,p){}^{44}$ Ca reaction from an excitation function measurement at one angle $\vartheta = 125^{\circ}$. Fig. 4 of [88] shows only the cross sections of the lowest p_0 , p_1 , p_2 , p_3 , p_4 , and p_5 proton groups. However, the spectrum in Fig. 3 of [88] shows a dominating peak for p_{6-9} , another strong peak for p_{10-14} , and further peaks for p_{15-35} . The results for the low-lying proton groups are shown in Fig. 22; as expected, they are significantly lower than the StM calculation for the total (α, p) cross section. A point-by-point summing



Fig. 23. Same as Fig. 5, but for α -induced reactions on ⁴¹K. The experimental data have been taken from [86,87,88,89] and include the ground state and isomer contributions of the ⁴¹K(α ,n)⁴⁴Sc reaction. Further discussion see text.

of the p_i channels is again hampered by the fact that the EXFOR data had to be re-digitized from Fig. 4 of [88].

The total reaction cross section $\sigma_{\rm reac}$ and the reduced cross section $\sigma_{\rm red}$ are dominated by the ${}^{41}{\rm K}(\alpha,n){}^{44}{\rm Sc}$ reaction for energies above 5 MeV, i.e., over almost the entire energy range under study. The results for $\sigma_{\rm red}$ from the (α,n) channel are shown in Fig. 23. Only at the lowest energies a significant contribution of the (α,p) channel is found. Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for ${}^{41}{\rm K}$ do not show a peculiar behavior.

4.13 40 K

The odd-odd (Z = 19, N = 21) nucleus ⁴⁰K has a very low natural abundance, and in addition it is unstable. The 1461 keV γ -ray of the ⁴⁰K \rightarrow ⁴⁰Ar decay is a prominent background line in almost any γ -ray spectrum. Therefore, only very few experimental data are available for ⁴⁰K. Elastic ⁴⁰K(α, α)⁴⁰K scattering has been measured by Oeschler *et al.* [90] at 24 MeV. Unfortunately, the experimental data are only presented as a line in Fig. 1 of [90] which had to be re-digitized for EXFOR. As this is the only data set for ⁴⁰K, a phase shift fit was made to the angular distribution (as provided by EXFOR). The result of $\sigma_{\rm red}$ 67.5 mb at $E_{\rm red} = 2.88$ MeV is within the expected range. Because of the lack of experimental data, no figure is shown for $\sigma_{\rm red}$ of ⁴⁰K. But from the only available data set it can be concluded that there is at least no evidence for a peculiar behavior of $\sigma_{\rm red}$ for the odd-odd ⁴⁰K.

4.14 ³⁹K

Contrary to ⁴¹K with the dominating (α, n) cross section, the semi-magic $(N = 20)^{39}$ K has a much larger (α, p) cross section. The ³⁹K $(\alpha, n)^{42}$ Sc reaction has a strongly negative Q-value (Q = -7.33 MeV). Only two data points are available by Nelson *et al.* [91], one for the ground state and one for the $(7)^+$ isomer in ⁴²Sc which decays to a 6⁺ state in ⁴²Ca. The two data points are shown in Fig. 24; both experimental (α, n) data are far below the theoretical expectation from the StM model. As the (α, n) cross section is by far more than one order of magnitude below the (α, p) cross section, this deviation does fortunately not affect the determination of the total reaction cross section σ_{reac} which is close to the (α, p) cross section.



Fig. 24. Cross sections of the 39 K $(\alpha,n){}^{42}$ Sc and 39 K $(\alpha,p){}^{42}$ Ca reactions. The experimental data have been taken from [77,92, 91]; the (α,n) of [91] data are separated for the ground state and the isomer in 42 Sc. Further discussion see text.

The ${}^{39}K(\alpha,p){}^{42}Ca$ reaction has been studied by Buckby et al. [77] and Scott et al. [92]. Buckby et al. have measured five-point angular distributions (for a discussion of the experimental procedure, see Sec. 4.10). Scott et al. have measured excitation functions at one angle $\vartheta = 125^{\circ}$, and results are reported for the proton groups p_0, p_1, p_2 , p_3 , and p_4 . However, it can be seen from the spectrum in Fig. 1 of [92], that significant contributions to the total (α, p) cross section come also from the p_{5-9} and p_{10} proton groups, and it is stated in the text that additional proton groups p_{11-18} , p_{19-28} , and p_{29-32} have been observed at higher energies. In addition, the EXFOR data of Scott etal. had to be re-digitized. Thus, it is impossible to determine the total (α, p) cross section from these data. But it can be seen in Fig. 24 that the Scott et al. data for each proton group are – as expected – below the total (α, p)



Fig. 25. Same as Fig. 5, but for α -induced reactions on ³⁹K. The experimental data have been taken from [77]. Further discussion see text.

cross section reported by Buckby *et al.* in their Table 1 of [77].

For the determination of the total reaction cross section $\sigma_{\rm reac}$ and the reduced cross section $\sigma_{\rm red}$ only the data by Buckby *et al.* [77] are used. The results are shown in Fig. 25. Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for ³⁹K do not show a peculiar behavior.

4.15 40 Ar

For the neutron-rich ⁴⁰Ar it is obvious that the (α, n) cross section dominates whereas the (α, p) cross section is much smaller. Unfortunately, only few experimental data for ⁴⁰Ar are available at EXFOR. The ⁴⁰Ar(α, n)⁴³Ca cross section was determined by Schwartz *et al.* [93] at E_{α} = 7.4 MeV using a argon-filled gas target. The emitted particles were detected by nuclear track counting at one angle $(\vartheta = 90^{\circ})$, and isotropy was assumed. The result of 33 mb has an uncertainty of a factor of two and is much lower than the prediction from the StM (see Fig. 26). It should be noted that the energy loss of the beam in the entrance window of the gas target and in the gas cell was not taken into account in [93]. This energy loss should be of the order of 500 keV for the entrance window. The target thickness in [93] is given with 130 keV leading to an effective energy which is about 65 keV lower. These corrections of more than 500 keV bring the data point closer to the StM prediction.

In addition to the Schwartz *et al.* [93] experiment at 7.4 MeV, the ${}^{40}\text{Ar}(\alpha,p){}^{43}\text{K}$ reaction was also measured at higher energies by Tanaka *et al.* [94] and Fenyvesi *et al.* [14]. Both experiments used a stacked-target technique



Fig. 26. Cross sections of the ${}^{40}\text{Ar}(\alpha,n){}^{43}\text{Ca}$ and ${}^{40}\text{Ar}(\alpha,p){}^{43}\text{K}$ reactions. The experimental data have been taken from [93,94,14]. The energy of the data points by Schwartz *et al.* [93] at $E_{\alpha} = 7.4$ MeV should be corrected by about 500 keV because of the energy loss of the beam in the entrance window of the gas target and in the gas cell. Further discussion see text.

and 4π - β -counting in [94] and γ -spectroscopy in [14] for the detection of the decay of the residual ⁴³K nucleus. The results of the experiments of [94,14] are in good agreement, and also the 7.4 MeV data point of Schwartz *et al.* [93] seems roughly to follow the expected energy dependence (in particular, if the energy of this data point is corrected by about 500 keV as discussed above). Similar to the ⁴⁰Ar(α ,n)⁴³Ca cross section, also the ⁴⁰Ar(α ,p)⁴³K cross section is overestimated by the StM calculation at low energies. For completeness it should be noted that the StM calculations using either TALYS or NON-SMOKER are almost identical for ⁴⁰Ar.

The total reaction cross section $\sigma_{\rm reac}$ and the reduced cross section $\sigma_{\rm red}$ can be derived from the ${}^{40}{\rm Ar}(\alpha,n){}^{43}{\rm Ca}$ cross section. However, there is only one data point with large uncertainties [93] which may need a correction of the energy. The results for $\sigma_{\rm red}$ are shown in Fig. 27. Based on the one data point by Schwartz *et al.* [93] with its large error bars, the reduced cross section of ${}^{40}{\rm Ar}$ seems to be smaller than for most neighboring nuclei in the $A \approx 20-50$ mass region. Improved data for ${}^{40}{\rm Ar}$ are highly desirable.

Because of the noticeable behavior of $\sigma_{\rm red}$ of 40 Ar at low energies, $\sigma_{\rm red}$ of 40 Ar was additionally studied at higher energies using 40 Ar(α, α) 40 Ar elastic scattering. Data at relatively low energies are available in [95,96], and data above 20 MeV have also been measured in [75,90]. Only the 18 MeV data by Seidlitz *et al.* [96] are available numerically from Table I of [96]; the other data had to be redigitized from small figures with logarithmic scale in [95,



Fig. 27. Same as Fig. 5, but for α -induced reactions on ⁴⁰Ar. The experimental data have been taken from [93,94, 14]. The energy of the data points by Schwartz *et al.* [93] at $E_{\alpha} = 7.4$ MeV should be corrected by about 500 keV because of the energy loss of the beam in the entrance window of the gas target and in the gas cell. Only one data point is available for the dominating ⁴⁰Ar(α, n)⁴³Ca reaction. The ⁴⁰Ar(α, p)⁴³K reaction contributes only minor to the total reaction cross section σ_{reac} . Further discussion see text.

75,90], and no error bars are available in the EXFOR data. Therefore the following study is restricted to the data by Seidlitz *et al.* [96] and the data at the lowest energies by Bucurescu et al. [95]. It turns out that the limited angular range of the angular distributions by Bucurescu et al. [95] is not sufficient to derive the total reaction cross section $\sigma_{\rm reac}$ from these data. The angular distribution of Seidlitz et al. [96] covers the full angular range; however, at forward angles the measured cross section is almost twice the Rutherford cross section of pointlike charges. Therefore, Gaul et al. [75] have suggested to scale the angular distribution by Seidlitz *et al.* by a factor of 0.55; a similar scaling factor of 0.57 is suggested from the best fit obtained in this work. The total reaction cross section is $\sigma_{\rm reac} = 1468$ mb at $E_{\alpha} = 17.98 \,\mathrm{MeV}$, corresponding to a reduced cross section $\sigma_{\rm red} = 58.5 \,{\rm mb}$ at $E_{\rm red} = 2.27 \,{\rm MeV}$. This value fits nicely into the general systematics of reduced cross sections at higher energies around $E_{\rm red} \approx 2 \,{\rm MeV}$ (see Fig. 1). Thus, the behavior of $\sigma_{\rm red}$ for ${}^{40}{\rm Ar}$ is extraordinary only at low energies.

4.16 ³⁶Ar

Contrary to the neutron-rich nucleus ⁴⁰Ar, the dominating channel for ³⁶Ar is the ³⁶Ar(α, p)³⁹K reaction. The ³⁶Ar(α, n)³⁹Ca reaction has a strongly negative *Q*-value (Q = -8.60 MeV) and thus cannot contribute to the total cross section σ_{reac} for ³⁶Ar at low energies. There is only one data point for the ³⁶Ar(α, p)³⁹K reaction at 7.4 MeV by Schwartz *et al.* [93] with large uncertainties. The energy of this data point should be corrected by about 500 keV because of the energy loss of the beam in the entrance window of the gas target and in the gas cell (see discussion in the previous Sec. 4.15). Even with the correction of the energy, the experimental data point of [93] is significantly below the StM calculation (see Fig. 28).



Fig. 28. Cross sections of the ${}^{36}\text{Ar}(\alpha,n){}^{39}\text{Ca}$ and ${}^{36}\text{Ar}(\alpha,p){}^{39}\text{K}$ reactions. The experimental data point has been taken from [93]. The energy of the data point by Schwartz *et al.* [93] at $E_{\alpha} = 7.4$ MeV should be corrected by about 500 keV because of the energy loss of the beam in the entrance window of the gas target and in the gas cell. Further discussion see text.

The determination of the total reaction cross section $\sigma_{\rm reac}$ and reduced cross section $\sigma_{\rm red}$ for ³⁶Ar is possible from the dominating ³⁶Ar(α, p)³⁹K cross section. However, this determination is obviously hampered by the availability of experimental data, and improved data for the ³⁶Ar(α, p)³⁹K reaction are highly desirable. Similar to ⁴⁰Ar, the noticeable behavior of $\sigma_{\rm red}$ for

Similar to ⁴⁰Ar, the noticeable behavior of $\sigma_{\rm red}$ for ³⁶Ar at low energies requires further studies. Elastic scattering data are available by Gaul *et al.* [75], Oeschler *et al.* [90], and at higher energies by Kocher *et al.* [97]. A reasonable description of the 18 MeV data by Gaul *et al.* [75] was only obtained in the later analysis by Kocher *et al.* [97]. Therefore, the total reaction cross section $\sigma_{\rm reac}$ at 18 MeV was obtained by repeating the optical model calculation in [97]. This leads to $\sigma_{\rm reac} = 1241 \,\mathrm{mb}$ or $\sigma_{\rm red}$ $= 51.9 \,\mathrm{mb}$ at $E_{\rm red} = 2.20 \,\mathrm{MeV}$. Also this value fits nicely into the general systematics of reduced cross sections at higher energies around $E_{\rm red} \approx 2 \,\mathrm{MeV}$ (see Fig. 1). Thus,



Fig. 29. Same as Fig. 5, but for α -induced reactions on ³⁶Ar. The experimental data have been taken from [93]. The energy of the data point by Schwartz *et al.* [93] at $E_{\alpha} = 7.4 \text{ MeV}$ should be corrected by about 500 keV because of the energy loss of the beam in the entrance window of the gas target and in the gas cell. Further discussion see text.

also the behavior of $\sigma_{\rm red}$ for $^{36}{\rm Ar}$ is extraordinary only at low energies.

4.17 ³⁷Cl

Surprisingly, no experimental data are available in EX-FOR for the ${}^{37}\text{Cl}(\alpha,n){}^{40}\text{K}$ and ${}^{37}\text{Cl}(\alpha,p){}^{40}\text{Ar}$ reactions. This may be related to the fact that both experiments cannot be done by activation because ${}^{40}\text{K}$ is quasi-stable with its half-life of more than 1 billion years and ${}^{40}\text{Ar}$ is stable. An excitation function for the ${}^{37}\text{Cl}(\alpha,\gamma){}^{41}\text{K}$ reaction is available by Zyskind *et al.* [98]; therefore, the presentation of results for ${}^{37}\text{Cl}$ deviates from the usual restriction of this work on (α, p) and (α, n) cross sections.

Zyskind *et al.* [98] used a Ge(Li) detector to measure excitation functions for five strong γ -transitions at the angle of $\vartheta = 55^{\circ}$, i.e. at a zero of the $P_2(\cos \vartheta)$ Legendre polynomial. The total cross section of the ${}^{37}\text{Cl}(\alpha,\gamma)^{41}\text{K}$ reaction was derived from the sum of the five strong transitions. Additionally, careful corrections were made for weak transitions which were measured in special very long runs; these corrections were of the order of about 25 %. The data are compared to a StM calculation in Fig. 30. At low energies below the (α, n) threshold, good agreement is found. It has to be noted that the shown data by Zyskind *et al.* from the EXFOR database are taken from a table in the underlying Ph.D. thesis; the three data points at the highest energies which deviate from the expected energy dependence are not shown in the paper [98].



Fig. 30. Cross sections of the ${}^{37}\text{Cl}(\alpha,n){}^{40}\text{K}$, ${}^{37}\text{Cl}(\alpha,p){}^{40}\text{Ar}$, and ${}^{37}\text{Cl}(\alpha,\gamma){}^{41}\text{K}$ reactions. The experimental data for the ${}^{37}\text{Cl}(\alpha,\gamma){}^{41}\text{K}$ reaction have been taken from [98]. No data are available in EXFOR for the ${}^{37}\text{Cl}(\alpha,n){}^{40}\text{K}$ and ${}^{37}\text{Cl}(\alpha,p){}^{40}\text{Ar}$ reactions. The additional dash-dotted line shows the StM calculation for the (α,γ) reaction. Further discussion see text.

According to the StM calculations, at very low energies below about 3 MeV the (α, γ) reaction is dominating. However, above 3 MeV up to the (α, n) threshold, the (α, p) cross section is comparable or even larger than the (α, γ) cross section, and above the (α, n) threshold the (α, n) reaction becomes dominant. Due to the lack of other experimental data, the reduced cross section $\sigma_{\rm red}$ is taken from the ${}^{37}\text{Cl}(\alpha,\gamma)^{41}\text{K}$ cross section (see Fig. 31). At the lowest energies the real $\sigma_{\rm red}$ should be only slightly larger than the shown data points from the (α, γ) reaction. Around $E_{\rm red} \approx 0.5 \,{\rm MeV}$ one can see a weak kink in the excitation function, indicating that a contribution of the (α, p) cross section is missing here. At energies above $E_{\rm red} \approx 0.6 \,{\rm MeV}$ there is a strong cusp indicating the (α, n) threshold. Although the limited availability of experimental data somewhat hampers the analysis for ³⁷Cl, it can nevertheless be stated that similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for ³⁷Cl do not show a peculiar behavior.

4.18 ³⁵Cl

Three data sets are available for α -induced reactions on ³⁵Cl, but the experimental data cover the ³⁵Cl(α ,n)³⁸K reaction only. Because of the negative *Q*-value of the (α ,n) reaction (Q = -5.86 MeV), the (α ,n) data cannot restrict the total reaction cross section σ_{reac} and the reduced cross section σ_{red} at low energies.

Howard $et \ al.$ [69] used the activation technique in combination with annihilation spectroscopy to measure



Fig. 31. Same as Fig. 5, but for α -induced reactions on ³⁷Cl. The experimental data have been taken from [98] for the ³⁷Cl(α, γ)⁴¹K reaction. No data are available at EXFOR for the ³⁷Cl(α, n)⁴⁰K and ³⁷Cl(α, p)⁴⁰Ar reactions. Further discussion see text.

the ${}^{35}\text{Cl}(\alpha,n){}^{38}\text{K}$ cross section from about 7 to 11 MeV. At higher energies the stacked-foil activation technique has been used by Qaim *et al.* [99] and by Tárkányi *et al.* [100]; the activity of the residual ${}^{38}\text{K}$ nucleus was observed



Fig. 32. Cross sections of the ${}^{35}\text{Cl}(\alpha,n){}^{38}\text{K}$ and ${}^{35}\text{Cl}(\alpha,p){}^{38}\text{Ar}$ reactions. The experimental data have been taken from [69,99, 100]. Further discussion see text.

in both cases by γ -spectroscopy. The agreement between the different data sets is not very good; deviations are of the order of at least a factor of two (see Fig. 32).

As already stated above, a determination of the total reaction cross section $\sigma_{\rm reac}$ and reduced cross section $\sigma_{\rm red}$ is not possible from the available ${}^{35}{\rm Cl}(\alpha,n){}^{38}{\rm K}$ data because the ${}^{35}{\rm Cl}(\alpha,p){}^{38}{\rm Ar}$ reaction is dominating. Taking into account the factor of about 5 – 7 from the StM calculation in Fig. 32, the estimated reduced cross section $\sigma_{\rm red}$ is close to the expected values. The ${}^{35}{\rm Cl}(\alpha,n){}^{38}{\rm K}$ data thus do not show evidence for a peculiar behavior of $\sigma_{\rm red}$ for ${}^{35}{\rm Cl}$.



Fig. 33. Same as Fig. 5, but for α -induced reactions on ³⁵Cl. The experimental data have been taken from [69,99,100] for the ³⁵Cl(α ,n)³⁸K reaction. The ³⁵Cl(α ,n)³⁸K reaction is only a small ($\approx 10 - 15\%$) contribution to the total reaction cross section σ_{reac} which is dominated by the ³⁵Cl(α ,p)³⁸Ar reaction. Further discussion see text.

4.19 ³⁴S

The ³⁴S(α,n)³⁷Ar, ³⁴S(α,p)³⁷Cl, and ³⁴S(α,γ)³⁸Ar reactions have been measured simultaneously by Scott *et*. [101]. These data should allow to determine the total reaction cross section $\sigma_{\rm reac}$ and the reduced cross section $\sigma_{\rm red}$ with small uncertainties.

The ${}^{34}S(\alpha,n){}^{37}Ar$ reaction has been measured in [101] by direct neutron counting from the (α,n) threshold (Q = -4.63 MeV) up to about 10 MeV. Although minor problems with background from the ${}^{13}C(\alpha,n){}^{16}O$ reaction are reported in [101], an overall uncertainty of about 16% is estimated in [101]. The data are shown in Fig. 34. The comparison with the StM calculation shows that the energy dependence is nicely reproduced; however, the abso-



Fig. 34. Cross sections of the ${}^{34}S(\alpha,n){}^{37}Ar$, ${}^{34}S(\alpha,p){}^{37}Cl$, and ${}^{34}S(\alpha,\gamma){}^{38}Ar$ reactions. The experimental data have been taken from [101]. The additional dash-dotted line shows the StM calculation for the (α,γ) reaction. Further discussion see text.



Fig. 35. Same as Fig. 5, but for α -induced reactions on ³⁴S. The experimental data have been taken from [101,34]. Above the (α,n) threshold, the total reaction cross section is dominated by the ³⁴S $(\alpha,n)^{37}$ Ar reaction. For completeness, the ³⁴S $(\alpha,p)^{37}$ Cl and ³⁴S $(\alpha,\gamma)^{38}$ Ar cross sections and data points from ³⁴S $(\alpha,\alpha)^{34}$ S elastic scattering (see also Figs. 1 and 2) are also shown. Further discussion see text.

lute values of the cross section are slightly overestimated by the StM. It is obvious that the total reaction cross section σ_{reac} is dominated by the (α, n) cross section as soon as the energy is a few hundred keV above the threshold. It is interesting to note that the scatter in the experimental data points is probably related to the appearance of individual resonances. The target in the experiment of Scott *et al.* [101] is not thick enough to average over a sufficient number of resonances because of the relatively low level density in the semi-magic $(N = 20)^{-38}$ Ar compound nucleus.

Below the (α, n) threshold, the ${}^{34}S(\alpha, p){}^{37}Cl$ reaction dominates. The total (α, p) cross section was derived from the excitation function of the ${}^{34}S(\alpha, p_0){}^{37}Cl_{g.s.}$ reaction which was measured at one particular angle $(\vartheta = 125^{\circ})$. Corrections for the angular distribution of the emitted protons and for proton groups $p_{i>0}$ were estimated to be small in [101]. The shown data in Fig. 34 represent the p_0 channel only which contributes to about 90% to the total (α, p) cross section [101]. Similar to the ${}^{34}S(\alpha, n){}^{37}Ar$ cross section, also the ${}^{34}S(\alpha, p){}^{37}Cl$ cross section is slightly overestimated by the StM.

At energies below about 4 MeV the ${}^{34}S(\alpha,p){}^{37}Cl$ cross section approaches its threshold (Q = -3.03 MeV), and consequently the total reaction cross section σ_{reac} is essentially given by the ${}^{34}S(\alpha,\gamma){}^{38}Ar$ reaction. The experimental data in [101] are restricted to the analysis of the 2168 keV γ -ray from the decay of the first excited state in ${}^{38}Ar$ to the ground state. Corrections for capture events which bypass the first 2⁺ in ${}^{38}Ar$ were estimated to be of the order of about 20%. Excellent agreement with the StM calculation is found for the low-energy region below the (α,n) and (α,p) thresholds.

The reduced cross section of ³⁴S has been extracted from the available data of Scott *et al.* [101]. Additional data points have been obtained from the analysis of the ³⁴S(α, α)³⁴S elastic scattering data (see also Figs. 1 and 2). Whereas the elastic scattering data are in the expected range, the data of Scott *et al.* [101] are somewhat lower than expected. This holds in particular at the highest energies of the Scott *et al.* experiment where unobserved contributions of higher proton groups $p_{>0}$ in the ³⁴S(α, p)³⁷Ar reaction may be relevant. Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for ³⁴S do not show a peculiar behavior.

4.20 ³³S

22

Recently, the cross section of the ${}^{33}S(\alpha,p){}^{36}Cl$ reaction was measured by Bowers *et al.* [102]. A ⁴He gas target was irradiated with a ³³S beam in inverse kinematics, and the residual ³⁶Cl nuclei were captured in an aluminum catcher foil. The number of produced ³⁶Cl nuclei was determined using accelerator mass spectrometry. The result is shown in Fig. 36; here the cross section is presented as a function of E_{α} (i.e., in forward kinematics). The observed cross section shows a smooth energy dependence; no individual resonances are visible. Compared to ³⁴S in the previous



Fig. 36. Cross section of the ${}^{33}S(\alpha,n){}^{36}Ar$ and ${}^{33}S(\alpha,p){}^{36}Cl$ reactions. The experimental data for the (α,p) reaction have been taken from [102]; the (α,n) cross section was calculated from the experimental (α,p) cross section and theoretical ratios between the (α,n) and (α,p) cross section [20]. Further discussion see text.

Sec. 4.19, the level density in the odd-even compound nucleus 37 Ar is higher, and the target thickness is larger in the 33 S experiment. Thus, the experimental results are average cross sections, averaged over a sufficient number of resonances within the energy spread of the experimental data points, and the StM should provide excellent results.

The experimental data of [102] are compared to a StM calculation in Fig. 36. At the upper end of the energy range of [102] close to 10 MeV, the StM calculation slightly underestimates the experimental data. However, towards lower energies the discrepancy increases significantly.

The Q-values of the (α, p) and (α, n) reactions on ³³S are similar $(Q = -1.93 \,\mathrm{MeV} \text{ and } -2.00 \,\mathrm{MeV})$. Thus, at low energies very close above the almost common threshold, the (α, n) cross section dominates. But at somewhat higher energies around 6 MeV the (α, p) cross section becomes dominant because of the larger number of states in the exit channel towards the odd-odd nucleus ³⁶Cl. The ${}^{33}S(\alpha,n){}^{36}Ar$ cross section was estimated in [20] from the experimental ${}^{33}S(\alpha,p){}^{36}Cl$ cross section [102] and the theoretical ratio between the (α, n) and (α, p) cross section (for details see [20]). Finally, the total reaction cross section σ_{reac} is determined from the sum of (α, p) and (α, n) cross sections. Because the ratio between the (α, n) and (α, p) cross sections is well constrained by theory [20], the uncertainties for the (α, n) cross section and the total reaction cross section σ_{reac} remain acceptable.

The reduced cross section $\sigma_{\rm red}$ was derived from the total reaction cross section $\sigma_{\rm reac}$. The result is shown in Fig. 37. At the highest energies the results for ³³S lie



Fig. 37. Same as Fig. 5, but for α -induced reactions on ³³S. The experimental data have been taken from [102] for the ³³S(α , p)³⁶Cl reaction. In addition, the ³³S(α , n)³⁶Ar cross section has been estimated using a theoretical branching ratio from the StM [20], and the total reaction cross section is calculated from the sum of the (α , p) and (α , n) contributions. Further discussion see text and [20].

within the typical range which is indicated by the reduced cross sections for ²¹Ne and ⁵¹V in Fig. 37. However, at lower energies the $\sigma_{\rm red}$ values are significantly above the typical range. This means that the reduced cross section $\sigma_{\rm red}$ of ³³S behaves significantly different compared to most other nuclei in the $A \approx 20-50$ mass range under study, and also the energy dependence is unusually flat for ³³S. A detailed discussion of this unexpected behavior is given in [20].

4.21 ³²S

Individual resonances shape the energy dependence of α induced cross sections for ³²S at low energies. Because of the strongly negative *Q*-value of the (α, n) reaction (Q = -8.61 MeV), the total reaction cross section σ_{reac} is governed by the ³²S $(\alpha, p)^{35}$ Cl reaction wich was measured by Soltani-Farshi *et al.* [13]. The proton groups p_0 , p_1 , p_2 , p_3 , p_4 , p_5 , and p_6 are nicely resolved in the spectrum at $E_{\alpha} = 12 \text{ MeV}$ (Fig. 2 of [13]), and excitation functions have been measured from about 6 to 12 MeV at six angles. Unfortunately, only the p_0 cross section data are shown in Fig. 3 of [13]. The EXFOR database provides this minor part by re-digitization and states that it was impossible to obtain data tables from the authors.

Some estimates can nevertheless be made from available information of Soltani-Farshi *et al.* [13]. The average differential cross section at 12 MeV is about $(d\sigma/d\Omega) \approx$ 2.5 mb/sr. This leads to an angle-integrated cross section of 31.4 mb with an uncertainty below a factor of two. In the shown spectrum (Fig. 2 of [13]) the p_0 group has a about the same intensity as the p_3 , p_4 , p_5 , and p_6 groups; the p_1 and p_2 groups are much weaker. This leads to a total (α, p) cross section of about $5.5 \times 31.4 \,\mathrm{mb} \approx 173 \,\mathrm{mb}$ (assuming that higher-lying proton groups do not contribute). In addition, at this energy the (α, n) channel is already open; i.e., the value at 12 MeV should be considered as a lower limit. This value corresponds to a reduced cross section $\sigma_{\rm red}$ $> 7.6\,{\rm mb}$ at $E_{\rm red}$ = 1.59 MeV. At the lowest energy of 6 MeV $(d\sigma/d\Omega) \approx 1 \text{ mb/sr}$, leading to $\sigma(p_0) \approx 12.6 \text{ mb}$. Higher-lying proton groups should be much weaker, leading to a total (α, p) cross section of about a factor of two larger than the p_0 cross section: $\sigma(\alpha, p) \approx 25 \,\mathrm{mb}$. This corresponds to $\sigma_{\rm red} \approx 1.1 \,\mathrm{mb}$ at $E_{\rm red} = 0.79 \,\mathrm{MeV}$. These roughly estimated data points are shown in Fig. 38. The StM calculation is slightly above the estimated experimental data. Although only roughly estimated, it can be seen that the data are at least not far above the expectations.

Because of the few available reaction data for ³²S, in addition ³²S(α, α)³²S elastic scattering data were analyzed. Low-energy angular distributions are available from Coban *et al.* [103] and Aldridge *et al.* [104]. Unfortunately, both data had to be re-digitized from figures in [103, 104],



Fig. 38. Cross section of the ${}^{32}S(\alpha,p){}^{35}Cl$ reaction and total reaction cross sections from ${}^{32}S(\alpha,\alpha){}^{32}S$ elastic scattering. The experimental data have been taken from [13] for the ${}^{32}S(\alpha,p_0){}^{35}Cl$ reaction with the additional estimates for ${}^{32}S(\alpha,p_0){}^{35}Cl$ as discussed in the text; the upper data point should be considered as a lower limit only. Elastic ${}^{32}S(\alpha,\alpha){}^{32}S$ data from [103,104] have been re-analyzed in this study to determine the total reaction cross section $\sigma_{\rm red}$ and should be compared to the corresponding calculation (dash-dotted line) which is shown in addition to the (α,p) and (α,n) cross sections.

and the EXFOR data are provided without the original error bars. Because the angular distributions have to be fitted for the determination of the total reaction cross section σ_{reac} , the resulting numbers have significant uncertainties from the digitizing error and from the missing original uncertainties (for the fitting procedure a fixed uncertainty of 5% was used for all data points).



Fig. 39. Same as Fig. 5, but for α -induced reactions on ³²S. The experimental data have been taken from [13, 103, 104]. Further discussion see text.

Resonant structures in the excitation function of the ${}^{32}S(\alpha,\alpha){}^{32}S$ elastic scattering were analyzed in the study of Coban *et al.* [103]. At resonance energies detailed angular distribution measurements were carried out for a J^{π} assignment. Therefore, the total cross sections σ_{reac} from these detailed angular distributions around 7 MeV in [103] (corresponding to reduced energies $E_{\text{red}} \approx 0.9 - 1$ MeV, shown as data points in Fig. 39) should be considered as resonance-based upper limits. At the same energies the resonance properties were confirmed by an enhanced yield in the (α, p_0) cross section which was observed in [103].

Angular distributions in 100 keV steps were measured by Aldridge *et al.* [104] at about 30 angles. A phase shift fit of these angular distributions is at the limits of numerical stability because the number of adjustable parameters (two parameters per partial wave: reflexion coefficient η_L and phase shift δ_L) is not much lower than the number of experimental data points. Nevertheless, the general trend of the reduced cross sections $\sigma_{\rm red}$ is close to the expected values, and at least in the overlap region with [13] the outliers are correlated with maxima in the excitation function of the (α , p_0) cross section of [13]. The resulting $\sigma_{\rm red}$ values for ³²S are shown in Fig. 39. Concluding the analysis of 32 S, it can be said that the $\sigma_{\rm red}$ data for 32 S do not show evidence for unusual behavior. Thus, for the even-even sulfur isotopes 32,34 S the $\sigma_{\rm red}$ values behave regularly or even low, whereas $\sigma_{\rm red}$ for 33 S is significantly enhanced in particular at low energies.

4.22 ³¹P

The present study focuses on low-energy cross sections of α -induced energies around $E_{\rm red} \approx 0.5 - 1 \,{\rm MeV}$. The corresponding energies E_{α} decrease towards lighter nuclei. Simultaneously, the level density decreases towards lighter nuclei. Whereas for heavier nuclei a smooth energy depencende of the α -induced reaction cross sections was found, for lighter nuclei individual resonances become more and more important. Calculations in the StM model cannot reproduce these individual resonances; nevertheless, the general trend of the data should be reproduced.



Fig. 40. Cross section of the ³¹P(α,n)³⁴Cl and ³¹P(α,p)³⁴S reactions. The experimental data have been taken from the (α,n) data of [107] and from the (α,p_0) and (α,α) data of [105]. Further discussion see text.

Experimental data for the ³¹P(α, p_0)³⁴S reaction have been measured by Schier *el al.* [105]. Two excitation functions at $\vartheta = 105^{\circ}$ and 155° are shown in their Fig. 2. As no spectrum is shown in [105], it is not possible to determine the contributions of higher-lying proton groups from this experiment. However, at low energies close above the threshold the p_0 channel should be dominating. The experimental data are shown in Fig. 40 together with a StM calculation. As expected, at higher energies the (α, p_0) data of [105] are below the theoretical estimate whereas at low energies there is – on average – reasonable agreement between theory and experiment. At lower energies resonance



Fig. 41. Same as Fig. 5, but for α -induced reactions on ³¹P. The experimental data have been taken from [105,107]: the differential cross sections $(d\sigma/d\Omega)$ at $\vartheta = 105^{\circ}$ and 155° of the dominating ³¹P $(\alpha, p_0)^{34}$ S reaction has been converted to the total cross section assuming isotropy. Further discussion see text.

parameters of the ${}^{31}P(\alpha,p){}^{34}S$ reaction were determined by McMurray *et al.* [106].

Because of the relatively high (α, n) threshold (Q = $-5.65 \,\mathrm{MeV}$), the ³¹P(α, n)³⁴Cl reaction does practically not contribute to the total reaction cross section $\sigma_{\rm reac}$ and the reduced cross section $\sigma_{\rm red}$. The (α, n) data by Umbarger et al. [107] are also shown in Figs. 40 and 41. In addition, five data points from a re-analysis of the elastic scattering data of Schier et al. [105] are shown which have been measured simultaneously with the (α, p_0) cross section. However, this re-analysis is hampered by the limited number of data points in the angular distributions which had to be re-digitized from Fig. 1 of [105]. As four of the five angular distributions in Fig. 1 of [105] are measured in resonances (see the corresponding yield maxima in the (α, p_0) excitation functions in Fig. 2 of [105]), the resulting σ_{reac} and σ_{red} should again be considered as resonance-based upper limits. The off-resonance point at $E_{\alpha} = 4.75 \,\mathrm{MeV}$ corresponds to $E_{\mathrm{red}} = 0.70 \,\mathrm{MeV}$ and σ_{red} $= 2.77 \,\mathrm{mb}$. Although the eve may be mislead by the many resonant data points of the (α, p_0) cross section in Fig. 41, the $\sigma_{\rm red}$ data for ³¹P behave on average similar to most nuclei under study in the $A \approx 20 - 50$ mass region.

4.23 ³⁰Si

The ${}^{30}\text{Si}(\alpha,n){}^{33}\text{S}$ cross section was measured by Flynn *et al.* [108] by direct neutron counting. Because a very thin target was used in this experiment, the measured



Fig. 42. Cross section of the ${}^{30}\text{Si}(\alpha,n){}^{33}\text{S}$ and ${}^{30}\text{Si}(\alpha,p){}^{33}\text{P}$ reactions. The experimental data have been taken from [108]. Further discussion see text.

cross section is governed by many resonances. It has been shown already in [108] that the average cross section is well reproduced by a StM calculation, and a similar result is obtained in this study. The experimental data of [108] and the present StM calculation are shown in Fig. 42.



Fig. 43. Same as Fig. 5, but for α -induced reactions on ³⁰Si. The experimental data have been taken from [108]. Further discussion see text.

It is obvious from Fig. 42 that the ${}^{30}\text{Si}(\alpha,n)^{33}\text{S}$ reaction dominates the total reaction cross section σ_{reac} and the reduced cross section σ_{red} . The ${}^{30}\text{Si}(\alpha,p)^{33}\text{P}$ reaction has a cross section which is about one order of magnitude smaller over the entire measured energy range of the experiment in [108]. Hence, the reduced cross section σ_{red} of ${}^{30}\text{Si}$ is well-defined by the experimental data of [108].

Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for $^{30}{\rm Si}$ – on average – do not show a peculiar behavior. This is also confirmed by the analysis of $^{30}{\rm Si}(\alpha,\alpha)^{30}{\rm Si}$ elastic scattering at 15.7 MeV [109]. The analysis of the EXFOR data leads to a relatively high $\sigma_{\rm red} = 68.7 \,{\rm mb}$ at $E_{\rm red} = 2.32 \,{\rm MeV}$. However, the χ^2/F of the phase shift fit can be reduced by about a factor of three if the experimental data of [109] are scaled by a factor of ≈ 0.6 , leading to a lower value of $\sigma_{\rm red} = 61.2 \,{\rm mb}$.

4.24 ²⁹Si

26

Three experimental data sets are available at EXFOR for the ²⁹Si(α, n)³²S reaction. The main focus of these experiments was the determination of resonance properties from the measured neutron yield, and thus relatively thin targets were used. Gibbons and Macklin [110] provide data from about 2 to 4.5 MeV, obtained with a 43 µg/cm² target. Balakrishnan *et al.* [111] identify 134 resonances for $E_{\alpha} = 2.15 - 5.25$ MeV using a very thin target ($\Delta E \approx$ 5 keV, corresponding to less than 5 µg/cm²), and Flynn *et al.* [108] show data for $E_{\alpha} \approx 2.75 - 7$ MeV using a 9 µg/cm² target. In addition, for the measurements close above the threshold, a thicker target with 113 µg/cm² was used in [108]. At energies around 4 MeV the newer data



Fig. 44. Cross section of the ²⁹Si $(\alpha,n)^{32}$ S and ²⁹Si $(\alpha,p)^{32}$ P reactions. The experimental data have been taken from [110, 111,108]. Further discussion see text.

by Flynn et al. and Balakrishnan et al. are in good agreement. However, at lower energies the data by Balakrishnan et al. are much higher. Flynn et al. [108] state in their discussion that the data by Balakrishnan et al. show structures which are also visible in the ${}^{13}C(\alpha,n){}^{16}O$ reaction, and thus the Balakrishnan et al. data are contaminated by background. The early data by Gibbons et al. [110] are about a factor of two below the later Flynn et al. data around 4 MeV where the cross section of the ${}^{13}C(\alpha,n){}^{16}O$ reaction is small. At lower energies the agreement between the Flynn et al. data and the Gibbons and Macklin data may be considered as accidental because also the Gibbons and Macklin experiment seems to suffer from ¹³C background at lower energies (as discussed in [108]). In a further experiment McMurray et al. [106] have determined resonance properties of the ${}^{29}\text{Si}(\alpha, n){}^{32}\text{S}$ reaction.



Fig. 45. Same as Fig. 5, but for α -induced reactions on ²⁹Si. The experimental data have been taken from [110,111,108]. Further discussion see text.

The experimental data of [110,111,108] are shown in Fig. 44. The data are – on average – in reasonable agreement with the StM calculation. According to the StM calculation, the cross section of the ${}^{29}\text{Si}(\alpha,p){}^{32}\text{P}$ reaction is much lower in the entire energy range under study. Unfortunately, no data for the ${}^{29}\text{Si}(\alpha,p){}^{32}\text{P}$ reaction are available at EXFOR.

The $^{29}{\rm Si}(\alpha,n)^{32}{\rm S}$ data are shown as reduced cross sections $\sigma_{\rm red}$ in Fig. 45. An additional data point can be taken from the analysis of $^{29}{\rm Si}(\alpha,\alpha)^{29}{\rm Si}$ elastic scattering. The fit to the angular distribution at $E_{\alpha}=26.6\,{\rm MeV}$ in [112] leads to $\sigma_{\rm red}\approx55\,{\rm mb}$ at the relatively high reduced energy $E_{\rm red}\approx3.89\,{\rm MeV}$. Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for $^{29}{\rm Si}$ do not show a peculiar behavior.

4.25 ²⁸Si

Data for the ²⁸Si(α, p)³¹P and ²⁸Si(α, n)³¹S reactions are available at EXFOR. Because of the relatively high negative *Q*-value of the (α, n) reaction (Q = -9.10 MeV), at low energies the (α, p) reaction is dominating. At very low energies also the (α, p) channel is closed, and the only open reaction channel is ²⁸Si(α, γ)³²S. However, only resonance strengths are available for the (α, γ) reaction [113, 114, 115, 116].



Fig. 46. Cross section of the ²⁸Si(α,n)³¹S and ²⁸Si(α,p)³¹P reactions. Three additional data points have been derived from a phase shift analysis of ²⁸Si(α,α)²⁸Si elastic scattering. The experimental data have been taken from [117,118,119]. Further discussion see text.

The ${}^{28}\text{Si}(\alpha,p){}^{31}\text{P}$ reaction was measured by Buckby *et al.* [117]. The total (α,p) cross section was derived from proton angular distributions (further discussion see also Sec. 4.10, 4.14, and [77]). The results are shown in Fig. 46. The StM calculation slightly overestimates the experimental data, in particular at the lowest energies.

Contrary to the finding for the (α, p) reaction, the ${}^{28}\text{Si}(\alpha, n)^{31}\text{S}$ data by Cheng *et al.* [118] are nicely reproduced by the StM. Here the (α, n) cross section was determined by activation in combination with annihilation spectroscopy.

Because of the deviation between the experimental (α, p) data and the StM model calculation, additionally ²⁸Si $(\alpha, \alpha)^{28}$ Si elastic scattering data are studied. The angular distributions measured by Coban *et al.* [119] around $E_{\alpha} \approx 6-7$ MeV can be nicely fitted by a phase shift analysis. The result at 5.96 MeV is in almost perfect agreement with the StM calculation; at this energy the excitation functions in [119] do not show strong resonances. At the higher energies (6.80 and 6.85 MeV) a broad resonance

(perhaps a dublet of resonances) can be seen in the excitation functions; the existence of this resonance is confirmed by the excitation function at backward angles measured by Källman *et al.* [120]. Therefore it is not surprising that the total reaction cross sections σ_{reac} from elastic scattering at resonant energies are significantly above the StM prediction.



Fig. 47. Same as Fig. 5, but for α -induced reactions on ²⁸Si. The experimental data have been taken from [117,118,119]. Further discussion see text.

Around 6 MeV a discrepancy of about a factor of two is found between the (α, p) cross section by Buckby *et al.* [117] and the total reaction cross section σ_{reac} from the analysis of elastic scattering data by Coban *et al.* [119]. Unfortunately, there is no simple explanation for this discrepancy.

The available α -induced cross sections are converted to reduced cross sections. Fig. 47 shows that the $\sigma_{\rm red}$ values for ²⁸Si are smaller than for neighboring nuclei. Obviously, this effect is more pronounced when one considers the lower (α, p) cross sections of Buckby *et al.* [117] compared to the higher results from the analysis of elastic scattering data by Coban *et al.* [119].

4.26 ²⁷AI

Although the EXFOR database contains a lot of data for α -induced reactions on ²⁷Al, there are practically no data for the ²⁷Al(α , p)³⁰Si reaction which dominates the total reaction cross section σ_{reac} at low energies. Barros *et al.* [121] have measured angular distributions for a relatively thick (70 μ g/cm²) ²⁷Al target using nuclear track detection. From the measured angular distributions of the resolved p_0 , p_1 , p_2 , p_3 , and p_4 proton groups a total (α , p)

cross section for ²⁷Al can be roughly estimated to about 54 mb. This result is very close to the StM calculation (see Fig. 48). Unfortunately, only resonance parameters were exracted from the experimental low-energy data by Kuperus [122].



Fig. 48. Cross section of the ${}^{27}\text{Al}(\alpha,n){}^{30}\text{P}$ and ${}^{27}\text{Al}(\alpha,p){}^{30}\text{Si}$ reactions. The experimental data have been taken from [121, 108, 125, 126, 49]. Further discussion see text.

The ${}^{27}\text{Al}(\alpha,n){}^{30}\text{P}$ reaction was already reviewed recently in the first NACRE compilation of astrophysical reaction rates [123] (the later NACRE-II compilation [124] is restricted to lower masses up to A < 16). The following discussion is thus shortened and focuses on information which is particularly relevant for this study.

The ²⁷Al(α, n)³⁰P reaction was measured by Flynn *et al.* [108] by direct neutron counting from about 3.5 to 6 MeV with two different targets. Whereas the thin-target (thickness 27 µg/cm²) measurement shows resonant structures, the thick-target (442 µg/cm²) measurement averages over the resonances, and the resulting excitation function shows a smooth energy dependence. The smooth thick-target measurement is in good agreement with a StM calculation.

Earlier data by Stelson *et al.* [125] extend the data by Flynn *et al.* [108] towards higher energies. Stelson *et al.* have used a similar experimental technique and also thick targets. In the overlap region, the Flynn *et al.* data are slightly lower but roughly compatible within the experimental uncertainties.

At even higher energies (only shown in Fig. 49) Sahakandu *et al.* [15] have used activation and the stackedfoil technique. As often, the lowest data points of the stacked-foil experiment deviate significantly from the other



Fig. 49. Same as Fig. 5, but for α -induced reactions on ²⁷Al. The experimental data have been taken from [121] for the dominating ²⁷Al(α , p)³⁰Si reaction and from [108, 125, 15, 126] for the ²⁷Al(α , n)³⁰P reaction. Further discussion see text.

available data whereas at higher energies the agreement becomes much better.

A similar energy range as in Flynn *et al.* [108] and in Stelson *et al.* [125] was investigated by Howard *et al.* [69]. The data are in good agreement with the other experiments but show larger uncertainties. Following the NACRE recommendations, these data are disregarded because of their larger uncertainties [123].

The above data are extended towards lower energies by Holmqvist and Ramström [126]. An infinitely thick ²⁷Al target was irradiated in small energy steps, and the observed neutron yield as a function of energy was differentiated to obtain the cross section of the ²⁷Al(α,n)³⁰P reaction. The experimental data by Holmqvist and Ramström agree nicely with the other available data sets.

An attempt was made to add further data points at low energies from the analysis of ${}^{27}\text{Al}(\alpha,\alpha){}^{27}\text{Al}$ elastic scattering data. Unfortunately, the available low-energy angular distribution by Dyachkov *et al.* [127] does not provide a sufficient number of experimental data points for a stable phase shift fit or optical model analysis. The phase shift analysis of the angular distribution by Gailar *et al.* [128] at $E_{\alpha} = 18.82 \text{ MeV}$ leads to $\sigma_{\text{reac}} = 1278 \text{ mb}$, corresponding to $E_{\text{red}} = 2.89 \text{ MeV}$ and $\sigma_{\text{red}} = 60.7 \text{ mb}$, i.e. a result in the expected range.

The reduced cross section $\sigma_{\rm red}$ from the ${}^{27}{\rm Al}(\alpha,n){}^{30}{\rm P}$ data (see Fig. 49) is obviously below the typical range of $\sigma_{\rm red}$ values for $A \approx 20-50$ nuclei because the ${}^{27}{\rm Al}(\alpha,p){}^{30}{\rm Si}$ reaction is the dominating channel. But from the ratio of the (α,n) and (α,p) cross sections in the StM calculation it can be concluded that the $\sigma_{\rm red}$ values for ${}^{27}{\rm Al}$ do not show an unusual behavior.

4.27 ²⁶Mg

Because ²⁶Mg is a relatively neutron-rich nucleus, the lowenergy cross section is dominated by the ${}^{26}Mg(\alpha,n){}^{29}Si$ reaction. Data for the ${}^{26}Mg(\alpha,p){}^{29}Al$ reaction are available at higher energies. Minai *et al.* [16] cover the energy range between 6 and 34 MeV, and the data of Probst et al. [129] are restricted to energies above 10 MeV (i.e., above the range shown in Fig. 50). Both experiments used the stacked-foil activation technique in combination with γ ray spectroscopy for the detection of the residual ²⁹Al nuclei. Surprisingly, the experimental (α, p) data are almost one order of magnitude lower than the StM calculation. This holds for both TALYS and NON-SMOKER. However, the (α, p) cross sections from the thick-target yield of Roughton et al. [49] are in reasonable agreement with the StM calculation. Fortunately, this discrepancy does not affect the conclusions on the total reaction cross section σ_{reac} which is dominated by the (α, n) channel.



Fig. 50. Cross section of the ${}^{26}Mg(\alpha,n){}^{29}Si$ and ${}^{26}Mg(\alpha,p){}^{29}Al$ reactions. The experimental data have been taken from [130, 131, 16, 49]. Further discussion see text.

The ²⁶Mg(α, n)²⁹Si reaction is included in the NACRE compilation [123]. At low energies the data by Anderson *et al.* [130] and the unpublished data by Wieland [131] are recommended. Both experiments used direct neutron counting. According to NACRE, at very low energies the Wieland data should be preferred because special care was taken to minimize background from the ¹³C(α, n)¹⁶O reaction. In the overlap region there is reasonable agreement between both data sets. As the (α, n) cross section at low energies is dominated by resonances, the StM calculation is only able to reproduce the average trend of the data (see Fig. 50). For completeness it has to be noted that recently much lower data for the ${}^{26}Mg(\alpha,n){}^{29}Si$ reaction have been reported in an unpublished PhD thesis by Falahat [132].



Fig. 51. Same as Fig. 5, but for α -induced reactions on ²⁶Mg. The experimental data have been taken from [130, 131]. Further discussion see text.

The total reaction cross section $\sigma_{\rm reac}$ for ²⁶Mg is welldefined from the available ²⁶Mg(α, n)²⁹Si data. The derived reduced cross sections $\sigma_{\rm red}$ are shown in Fig. 51. Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for ²⁶Mg do not show a peculiar behavior.

4.28 ²⁵Mg

Similar to ²⁶Mg in the previous section 4.27, at low energies the ²⁵Mg(α, n)²⁸Si cross section is much larger than the ²⁵Mg(α, p)²⁸Al cross section. The NACRE compilation [123] recommends the experimental data by Anderson *et al.* [130], Wieland [131], and an additional data set which is available from van der Zwan *et al.* [133]. The present status of the ²⁵Mg(α, n)²⁸Si reaction is also reviewed in [6]. It is concluded in [6] that all data sets agree well, in particular if the ($\alpha, n\gamma$) data of [130] are considered which are less sensitive to background than the (α, n) data. The average trend of the data is nicely reproduced by the StM calculation (see Fig. 52). Similar to ²⁶Mg, the recent PhD thesis by Falahat [132] reports lower results, and because of these discrepancies new experimental efforts have been started by Caciolli *et al.* [134].

The determination of the total reaction cross section $\sigma_{\rm reac}$ for 25 Mg is well defined by the above (α, n) data. But because of the huge deviation between the StM calculation and experimental data for the 26 Mg $(\alpha, p)^{29}$ Al reaction in the previous section, the 25 Mg $(\alpha, p)^{28}$ Al reaction is



Fig. 52. Cross section of the ${}^{25}Mg(\alpha,n){}^{28}Si$ and ${}^{25}Mg(\alpha,p){}^{28}Al$ reactions. The experimental data have been taken from [130, 131, 133, 135, 49]. Further discussion see text.



Fig. 53. Same as Fig. 5, but for α -induced reactions on ²⁵Mg. The experimental data have been taken from [130, 131, 133]. Further discussion see text.

also analyzed here. Unfortunately, data are available only for a partial (α, p) cross section. Recently, Negret *et al.* [135] have measured the γ -ray yields after bombardment of ²⁵Mg by α -particles. The yield of the 1779 keV γ -ray from the first excited 2⁺ state in ²⁸Si to the 0⁺ ground state corresponds to almost the total ²⁵Mg $(\alpha, n)^{28}$ Si cross section because practically all excited states in ²⁸Si decay through

the first 2^+ state. Fig. 52 shows that the partial (α, n) cross section from the $1779 \text{ keV} \gamma$ -ray yield is even slightly above the (α, n) cross sections from direct neutron counting. In a similar way, a partial (α, p) cross section can be derived from the yield of the 942 keV γ -ray in the ${}^{25}Mg(\alpha,p){}^{28}Al$ reaction. This γ -ray corresponds to the transition from the second exited state $(J^{\pi} = 0^+, E^* = 972.4 \text{ keV})$ to the first excited state $(J^{\pi} = 2^+, E^* = 30.6 \text{ keV})$; the ground state of ²⁸Al has $J^{\pi} = 3^+$. This γ -ray transition should also represent a considerable amount of the total (α, p) cross section at energies sufficiently far above the (α, p) threshold. Surprisingly, similar to the ²⁶Mg case, the experimental ${}^{25}Mg(\alpha,p){}^{28}Al$ data are overestimated by the StM by about one order of magnitude. Again, this statement holds for TALYS and NON-SMOKER calculations. However, again similar to ²⁶Mg, the estimated (α, p) cross sections from the thick-target yield of Roughton et al. [49] show reasonable agreement with the StM calculation.

The total reaction cross section $\sigma_{\rm reac}$ of ²⁵Mg is well defined by the dominating ²⁵Mg(α,n)²⁸Si data, leading to the reduced cross sections $\sigma_{\rm red}$ shown in Fig. 53. Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for ²⁵Mg do not show a peculiar behavior.

4.29 ²⁴Mg

It is difficult to determine the total reaction cross section $\sigma_{\rm reac}$ of $^{24}{\rm Mg}$ at low energies. The $^{24}{\rm Mg}(\alpha,n)^{27}{\rm Si}$ reaction has a strongly negative Q-value ($Q = -7.20 \,{\rm MeV}$) and thus does not contribute at low energies. Also the $^{24}{\rm Mg}(\alpha,p)^{27}{\rm Al}$ reaction has a slightly negative Q-value ($Q = -1.60 \,{\rm MeV}$), and practically no experimental data



Fig. 54. Cross section of the ${}^{24}Mg(\alpha,n){}^{27}Si$ and ${}^{24}Mg(\alpha,p){}^{27}Al$ reactions. The experimental data have been taken from [118, 136, 137, 138]. Further discussion see text.

can be found in EXFOR at low energies. At very low energies individual resonances of the $^{24}{\rm Mg}(\alpha,\gamma)^{28}{\rm Si}$ reaction dominate.

expectation. Therefore, there is no evidence that the $\sigma_{\rm red}$ values for ²⁴Mg behave extraordinary.

10^{2} Μg 10 1 $\sigma_{\rm red}~({\rm mb})$ 10⁻¹ (α,n) : 10⁻² • Cheng 1980 Blyth 1977 10⁻³ Gruhle 1977 (α, α) , based on Ikossi 197 10^{-4} 0.5 1.0 0.0 2.01.5 $E_{\rm red}$ (MeV)

Fig. 55. Same as Fig. 5, but for α -induced reactions on ²⁴Mg. The experimental data have been taken from [118,136,137, 138]. Further discussion see text.

The ²⁴Mg(α, n)²⁷Si reaction has been studied by Cheng et al. [118], by Blyth et al. [136], and by Gruhle et al. [137]. The data are shown in Fig. 54. All experiments used the activation technique in combination with annihilation spectroscopy. Unfortunately, there is a disagreement of about a factor of two between the three data sets. Note that the EXFOR data are based on a numerical table ([118]) and have been provided by the authors in numerical form ([136]), and only the data set of [137] had to be re-digitized from a figure; thus, the above discrepancy cannot be explained by simple digitization errors. Excellent agreement is found between the StM calculation and the data by Cheng et al. whereas the data by Blyth et el. and Gruhle et al. are overestimated.

Angular distributions of ²⁴Mg(α, α)²⁴Mg elastic scattering have been measured by Ikossi *et al.* [138] at low energies. For one particular angular distribution at $E_{\alpha} = 6.055$ MeV a relatively thick target (33 µg/cm²) was used; this angular distribution is appropriate for the determination of an average cross section because in addition the excitation function shows a smooth behavior around this energy. A phase shift fit leads to $\sigma_{\rm reac} = 222$ mb, corresponding to $\sigma_{\rm red} = 11.1$ mb at $E_{\rm red} = 0.97$ MeV.

As the (α, n) cross section contributes only minor to the total reaction cross section σ_{reac} of ²⁴Mg, the experimental (α, n) data are far below the expectations for σ_{red} as shown in Fig. 55. However, the data point from ²⁴Mg $(\alpha, \alpha)^{24}$ Mg elastic scattering is close to the general

4.30 ²³Na

The ²³Na(α ,n)²⁶Al reaction has significant astrophysical relevance because it affects the production of the longlived ²⁶Al nucleus. The observation of γ -rays from the ²⁶Al decay in our galaxy confirms ongoing nucleosynthesis [139]. Very recently, an updated galactic emission map was derived from the SPI spectrometer data aboard the INTEGRAL mission [140]. Because of a low-lying 0⁺ isomer in ²⁶Al which decays directly to ²⁶Mg and bypasses the 5⁺ ground state of ²⁶Al, much efforts have been made to distinguish the ²³Na(α ,n)²⁶Al_{g.s.} and ²³Na(α ,n)^{26m}Al reactions.



Fig. 56. Cross section of the 23 Na $(\alpha,n)^{26}$ Al and 23 Na $(\alpha,p)^{26}$ Mg reactions. The experimental data have been taken from [142, 143, 146]. Further discussion see text.

The $^{23}\mathrm{Na}(\alpha,n)^{26}\mathrm{Al}$ reaction has been reviewed in the NACRE compilation [123], and the role of the isomer is discussed e.g. in [141]. Because of its negative Q-value $(Q=-2.97\,\mathrm{MeV})$, this reaction does not affect the total reaction cross section σ_{reac} of $^{23}\mathrm{Na}$ at low energies. Therefore, only the total cross section of the $^{23}\mathrm{Na}(\alpha,n)^{26}\mathrm{Al}$ is studied here.

The NACRE compilation [123] recommends three data sets for the ²³Na(α,n)²⁶Al reaction: Skelton *et al.* [142] and Norman *et al.* [143] have measured the total yield which can be directly converted to the total (α,n) cross section. Doukellis and Rapaport [144] used the time-offlight technique to resolve the n_0 , n_1 , and n_2 neutron groups at six laboratory angles. The data by Doukellis and Rapaport are not available at EXFOR, and the numerical data at the NACRE web site seem to be re-digitized because the given energies are discrepant for the n_0 , n_1 , and n_2 groups. Consequently, it is practically impossible to derive the total (α, n) cross section from the data by Doukellis and Rapaport. Such a determination is further hampered at higher energies by contributions of higher neutron groups $n_{>2}$. The recommendation of NACRE that "The DO87 time of flight experiment is indeed considered to be more reliable than the NO82 thick target measurements" is not well traceable, and the resulting recommendation to scale the Norman *et al.* data by a factor of 1/3to adjust to the Doukellis and Rapaport data is not taken into account in this work. Here the original data of Norman *et al.* [143] and the data by Skelton *et al.* [142] are shown in Fig. 56. As thin-target measurements of [142] show many resonances, the StM calculation is only able to reproduce the average behavior of the excitation function. Furthermore, it can be seen from the StM calculations in Fig. 56 that the cross section of the 23 Na $(\alpha, p)^{26}$ Mg reaction exceeds the 23 Na (α, n) ²⁶Al cross section significantly for energies below about 6 MeV.



Fig. 57. Same as Fig. 5, but for α -induced reactions on ²³Na. The experimental data have been taken from [143,146]. The lowest data point of Almarez-Calderon *et al.* [146] represents an upper limit only. For better visibility the data of Skelton *et al.* [142] are omitted. Further discussion see text.

In a detailed sensitivity study of the production of ²⁶Al [6] it has been shown that the ²³Na(α,p)²⁶Mg reaction also plays an essential role in the production of ²⁶Al. Lowenergy data for the ²³Na(α,p)²⁶Mg reaction are available from Whitmire and Davids [145]. However, only resonance strengths have been determined in [145]. Some criticisms to this work have been reported in [6], and it was concluded in [6] that StM calculations should be preferred and that the 23 Na $(\alpha, p)^{26}$ Mg reaction is a prime target for future measurements.

In a very recent study new experimental data for the $^{23}\mathrm{Na}(\alpha,p)^{26}\mathrm{Mg}$ reaction at low energies became available. Almarez-Calderon *et al.* [146] used a 23 Na beam in inverse kinematics to irradiate a cryogenic ⁴He gas target, and a silicon strip detector was placed $20\,\mathrm{cm}$ downstream from the target to detect protons in an angular range from $\vartheta_{\text{lab}} = 6.8^{\circ} - 13.5^{\circ}$. From the observed proton groups p_0 and p_1 average cross sections (averaged over the energy distribution of the beam which is caused by energy loss and straggling in the entrance window and in the target gas cell itself) were determined. However, the measured differential (α, p) cross sections constrain the angular distribution of the (α, p) cross section only in a very limited angular range. The determination of angle-integrated cross sections in [146] had to use angular distributions of the ${}^{27}\text{Al}(\alpha,p){}^{30}\text{Si}$ reaction where similar J^{π} of the nuclei under study are found. The resulting cross section of the p_0 and p_1 groups are finally summed to provide the total 23 Na (α, p) 26 Mg cross sections. It can be seen from Fig. 56 that the experimental results are dramatically underestimated by the StM calculation. The total reaction cross section of 23 Na is well defined by the 23 Na $(\alpha, p)^{26}$ Mg reaction already below about 6 MeV, and below the (α, n) threshold the total reaction cross section $\sigma_{\rm reac}$ is almost entirely given by the only open particle channel. The results for the reduced cross section $\sigma_{\rm red}$ are shown in Fig. 57. It is obvious from Fig. 57 that the recent data by Almarez-Calderon et al. [146] deviate dramatically from the general behavior which is otherwise found for nuclei in the $A \approx 20 - 50$ mass region. The new data lead not only to significantly higher $\sigma_{\rm red}$ values, but also to a steeper energy dependence than for other nuclei in the $A \approx 20 - 50$ mass range.

4.31 ²²Ne

Because of the negative Q-value of the ${}^{22}\text{Ne}(\alpha, p){}^{25}\text{Na}$ reaction $(Q = -3.53 \,\mathrm{MeV})$, at astrophytically relevant energies the ${}^{22}\text{Ne}(\alpha,n){}^{25}\text{Mg}$ reaction dominates the total re-action cross section of ${}^{22}\text{Ne}$. This reaction plays a major role as neutron source for the astrophysical s-process. It is included in the NACRE compilation [123] where the data of Haas et al. [147] and Drotleff et al. [148,149] are recommended. These data are shown in Fig. 58 and compared to a StM calculation. As the cross section is dominated by resonances at low energies, the StM calculation is only able to reproduce the average properties of the excitation function. Later data by Jaeger et al. [150] extend the measurements of Drotleff et al. towards lower energies. The cross section at these very low energies is essentially given by resonant contributions, and only an experimental yield (but not the cross section) is presented in [150]. Therefore, the data by Jaeger et al. [150] are not shown in Fig. 58 because there is no straightforward conversion from the experimental yield to the (α, n) reaction cross section for extended gas target measurements (see e.g. [151]).



Fig. 58. Cross section of the ${}^{22}\text{Ne}(\alpha,n){}^{25}\text{Mg}$ and ${}^{22}\text{Ne}(\alpha,p){}^{25}\text{Na}$ reactions. The experimental data have been taken from [147,149]. Further discussion see text.

A full discussion of this reaction and the derived astrophysical reaction rate $N_A \langle \sigma v \rangle$ has to include further indirect information (e.g., properties of levels in the compound ²⁶Mg nucleus). This is beyond the scope of the present paper. New results for the ²²Ne(α, n)²⁵Mg reaction after publication of the first NACRE compilation [123] are



Fig. 59. Same as Fig. 5, but for α -induced reactions on ²²Ne. The experimental data have been taken from [147,149]. Further discussion see text.

e.g. summarized in [152], and further information is given in [153, 154, 155].

No data for the ²²Ne(α, p)²⁵Na reaction are listed in the EXFOR database. Fortunately, this does not affect the determination of the total reaction cross section σ_{reac} of ²²Ne because of the dominating ²²Ne(α, n)²⁵Mg reaction. The (α, n) cross section is presented as reduced cross section σ_{red} in Fig. 59. Similar to most nuclei under study in this work, the σ_{red} data for ²²Ne do not show a peculiar behavior.

4.32 ²¹Ne

Similar to the results for ²²Ne in the previous section, the ²¹Ne(α, n)²⁴Mg cross section is much larger than the ²¹Ne(α, p)²⁴Na cross section. Because of the low natural abundance of ²¹Ne, only very few data exist for this nucleus. The NACRE compilation [123] recommends the data by Haas *et al.* [147] and Denker [156]. Surprisingly, the data of Mak *et al.* [157] are not taken into account in NACRE. Mak *et al.* report average cross sections (averaged over a about 100 keV thick neon gas target) which are in good agreement with the other data which are recommended in NACRE. In Fig. 60 the experimental data are compared to a StM calculation which is able to reproduce the average properties of the ²¹Ne(α, n)²⁴Mg cross section. No data are available at EXFOR for the ²¹Ne(α, p)²⁴Na reaction which has a negative *Q*-value of Q = -2.18 MeV.



Fig. 60. Cross section of the ${}^{21}\text{Ne}(\alpha,n){}^{24}\text{Mg}$ and ${}^{21}\text{Ne}(\alpha,p){}^{24}\text{Na}$ reactions. The experimental data have been taken from [147, 156, 157]. Further discussion see text.

The reduced cross sections $\sigma_{\rm red}$ for ²¹Ne from the experimental ²¹Ne(α,n)²⁴Mg data of [147,156,157] are shown



Fig. 61. Same as Fig. 5, but for α -induced reactions on ²¹Ne. The experimental data have been taken from [147, 156, 157]. Further discussion see text.

in Fig. 61. Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for ²¹Ne do not show a peculiar behavior.

4.33 ²⁰Ne

Because of the negative Q-values of the ${}^{20}\text{Ne}(\alpha,n){}^{23}\text{Mg}$ (Q = -7.22 MeV) and ${}^{20}\text{Ne}(\alpha,p){}^{23}\text{Na}$ (Q = -2.38 MeV) reactions, it is not possible to determine the total cross section of ${}^{20}\text{Ne}$ at low energies from (α,p) and (α,n) data. The ${}^{20}\text{Ne}(\alpha,\gamma){}^{24}\text{Mg}$ reaction at low energies is dominated by isolated resonances (e.g., [159, 151]), and the experimental yield in these gas target measurements is dominated over broad energy ranges by the tails of strong resonances.

Fig. 62 shows the available ${}^{20}\text{Ne}(\alpha,n){}^{23}\text{Mg}$ data at higher energies, i.e. above the (α,n) threshold, in comparison to a StM calculation. As the cross section of the ${}^{20}\text{Ne}(\alpha,n){}^{23}\text{Mg}$ reaction is much smaller than the cross section of the ${}^{20}\text{Ne}(\alpha,p){}^{23}\text{Na}$ reaction, an attempt was made to estimate the total reaction cross section σ_{reac} from ${}^{20}\text{Ne}(\alpha,\alpha){}^{20}\text{Ne}$ elastic scattering at low energies. However, a phase shift analysis to the data of [95] at 13.1 MeV is only able to constrain σ_{reac} in a relatively wide range of $\sigma_{\text{reac}} = 600 \pm 300 \,\text{mb}$ because of the limited number of data points in [95]; this corresponds to $\sigma_{\text{red}} = 32 \,\text{mb}$ at $E_{\text{red}} = 2.35 \,\text{MeV}$. Somewhat higher σ_{red} values between 58 and 78 mb were found from the analysis of full angular distributions from [160] at slightly higher energies from 15.8 to 17.8 MeV, corresponding to E_{red} between 2.83 and 3.19 MeV.

Unfortunately, no data for the ²⁰Ne(α, p)²³Na reaction can be found in the EXFOR database. γ -ray yields after bombardment of ²⁰Ne with α -particles have been reported in [161]. In principle, these yields should allow to



Fig. 62. Cross section of the ${}^{20}\text{Ne}(\alpha,n){}^{23}\text{Mg}$ and ${}^{20}\text{Ne}(\alpha,p){}^{23}\text{Na}$ reactions. The experimental data have been taken from [158,95]. Further discussion see text.

constrain the ²⁰Ne(α, p)²³Na cross section. However, the strong γ transition in ²³Na at 1637 keV (7/2⁺; 2076 keV $\rightarrow 5/2^+$; 440 keV) almost coincides with the first 2⁺ in ²⁰Ne at 1634 keV which is excited by inelastic scattering, and therefore it was not possible to distinguish between the (α, p) reaction and inelastic scattering in [161]. No in-



Fig. 63. Same as Fig. 5, but for α -induced reactions on ²⁰Ne. The experimental data have been taken from [158]. Further discussion see text.

formation is given in [161] on the 440 keV transition from the first excited state in $^{23}\rm Na$ to the ground state.

It is clear that the $^{20}{\rm Ne}(\alpha,n)^{23}{\rm Mg}$ data are much lower than the expected values for reduced cross sections $\sigma_{\rm red}$ (see Fig. 63) because of the dominating $^{20}{\rm Ne}(\alpha,p)^{23}{\rm Na}$ reaction. Nevertheless, together with the additional data from $^{20}{\rm Ne}(\alpha,\alpha)^{20}{\rm Ne}$ elastic scattering at higher energies (above the shown range in Fig. 63) it can be concluded that there is at least no evidence for an unexpected behavior of $\sigma_{\rm red}$ of $^{20}{\rm Ne}$.

4.34 ¹⁸Ne

The experimental situation for the unstable ¹⁸Ne nucleus is completely different from all above examples. Only indirect data are available to constrain the ¹⁸Ne(α,p)²¹Na cross section, and the ¹⁸Ne(α,n)²¹Mg reaction does not contribute to the total reaction cross section σ_{reac} at low energies because of the strongly negative *Q*-value (Q =-11.24 MeV). The available experimental information for the ¹⁸Ne(α,p)²¹Na reaction has been summarized recently in [28,162]. Although the ¹⁸Ne(α,p)²¹Na cross section is dominated by individual resonances, it has been shown in [28] that a StM calculation is roughly able to reproduce the average properties of the excitation function.

The latest result of [28] for the ${}^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$ cross section has been converted to the reduced cross section $\sigma_{\rm red}$; the result is shown in Fig. 64. Similar to most nuclei under study in this work, the $\sigma_{\rm red}$ data for ${}^{18}\text{Ne}$ do not show a peculiar behavior.



Fig. 64. Same as Fig. 5, but for α -induced reactions on ¹⁸Ne. The estimate for the experimental cross section is taken from [28]. Further discussion see text.

4.35 19 F

Because of its positive Q-value, the ${}^{19}\mathrm{F}(\alpha,p)^{22}\mathrm{Ne}$ reaction dominates at low energies. Unfortunately, no total cross section data are available at EXFOR. The differential cross sections measured by Ugalde *et al.* [163] are fitted by an R-matrix calculation, and the R-matrix result is directly converted to the stellar reaction rate in [163]. The adopted rate of [163] is well reproduced by StM calculations using the α -nucleus potential by McFadden and Satchler [21] (see Fig. 9 of [163]).



Fig. 65. Cross section of the ${}^{19}\text{F}(\alpha,n){}^{22}\text{Na}$ and ${}^{19}\text{F}(\alpha,p){}^{22}\text{Ne}$ reactions. The experimental data have been taken from [164, 165, 166]. Further discussion see text.

Several data sets are available for the ${}^{19}F(\alpha,n)^{22}Na$ reaction. Wrean and Kavanagh [164] have used thin targets and direct neutron detection for their measurement at low energies below about 3.5 MeV. At higher energies Norman et al. [165] have measured thick-target neutron yields which were converted to cross sections by differentiation. The earlier data by Gladun and Chursin [166] have huge uncertainties in energy and deviate from the other experimental results [164, 165]. The thick-target data at higher energies [165] are well reproduced by the StM, and as expected, at lower energies the StM is only able to reproduce the average energy dependence of the experimental data of [164]. Earlier data by Balakrishnan et al. [167] are omitted because of problems with background from ^{13}C (see discussion in [164] and similar problems of these authors for 29 Si, see Sec. 4.24).

As the ${}^{19}\text{F}(\alpha,p){}^{22}\text{Ne}$ reaction dominates at low energies, it is not surprising that the reduced cross sections σ_{red} from the ${}^{19}\text{F}(\alpha,n){}^{22}\text{Na}$ data [164,165,166] are somewhat lower than the general trend of reduced cross



Fig. 66. Same as Fig. 5, but for α -induced reactions on ¹⁹F. The experimental data have been taken from [164, 165, 166]. Further discussion see text.

sections. Nevertheless, from the excellent agreement of the experimental data and the StM calculations for the ${}^{19}F(\alpha,p)^{22}Ne$ and ${}^{19}F(\alpha,n)^{22}Na$ reactions it can be concluded that there is no evidence for a peculiar behavior of ${}^{19}F$.

5 Discussion

A first finding of the above presentation is that many experimental data for α -induced reactions in the $A \approx 20-50$ mass range show reasonable agreement. Major discrepancies between individual data sets have been discussed in the corresponding sections above. Nevertheless it should be kept in mind that in several cases absolute normalizations of the experimental data are stated with additional uncertainties of 10 - 20% which are not included in the shown error bars. New experimental data should provide absolute cross sections with small uncertainties, as has been done e.g. by Vonach *et al.* [57]. Additionally, for some reactions only one or even no data set is available. Here of course new data should provide excitation functions in small energy steps.

The general agreement between the experimental data and calculations in the StM is very good. The basic ingredient for the StM calculations is the α -nucleus potential which essentially defines the total reaction cross section σ_{reac} for α -induced reactions. As long as either the (α, p) or (α, n) cross section is the dominant (say greater than about 70 - 80%) contribution to σ_{reac} , the StM calculation is practically insensitive to all other ingredients of the StM. Fortunately, this is the case for many nuclei under study in the $A \approx 20 - 50$ mass region which allows are careful test of the α -nucleus potential.

In the present study the simple energy-independent 4parameter potential by McFadden and Satchler [21] has been chosen. As this potential leads to overestimation of α -induced cross sections for a wide range of heavy target nuclei (above $A \approx 60$) at low energies, the very good agreement between the experimental data and the StM calculation in the $A \approx 20 - 50$ mass region is somewhat surprising. For heavy nuclei it has been suggested to add an energy dependence to the imaginary part of the McFadden/Satchler potential to avoid this typical overestimation of cross sections (e.g., [40,41]). Such an energy dependence is also expected from theoretical side, and various parametrizations have been suggested like a Fermi-type function [40,41], the Brown-Rho parametrization [168], or a resonance-like parametrization [18]. All these parameterizations have two features in common: (i) They start from very small imaginary parts at very low energies and end at a saturation value at higher energies significantly above the Coulomb barrier; (ii) the increase is characterized by an energy where e.g. half of the saturation value is reached, and by a slope parameter. Such an energy dependence of the imaginary part reduces the total reaction cross section $\sigma_{\rm reac}$ towards lower energies, compared to the original McFadden/Satchler potential.

Obviously, such a reduction is not needed for the nuclei in the $A \approx 20 - 50$ mass range. Following the discussion in McFadden and Sachler [21], it is stated that "There is a tendency for the heavier nuclei to favour smaller r_0 , and for the lighter ones to favor larger r_0 ". A larger radius parameter r_0 leads to increased total reaction cross sections σ_{reac} . Thus, strictly speaking, the 4-parameter Mc-Fadden/Satchler potential with the fixed radius parameter $r_0 = 1.4 \,\mathrm{fm}$ has two shortcomings. First, the calculations should overestimate the experimental reaction cross sections σ_{reac} towards lower energies because of the missing energy dependence of the imaginary part. Second, the calculations should underestimate σ_{reac} because the adjustment of the potential to elastic scattering data in [21] requires a larger radius parameter than the fixed average value of $r_0 = 1.4 \,\mathrm{fm}$ which is adopted by McFadden and Satchler. Therefore, the very good agreement between experimental data and the StM calculation using the McFadden/Satchler potential may even be considered as somewhat accidental because the missing energy dependence of the imaginary part may partly compensate the missing A dependence of the radius parameter r_0 .

For some nuclei under study a good agreement between the StM calculation and the experimental data is found for the dominating channel whereas the StM calculation deviates strongly from the experimental data for the weak channel. The most prominent example for such a behavior is ²⁶Mg where the dominating ²⁶Mg(α ,n)²⁹Si cross section is well reproduced by the StM, but the ²⁶Mg(α ,p)²⁹Al cross section is overestimated by about one order of magnitude. Such a behavior points to a deficiency in the theoretical treatment of the ²⁹Al + p channel, as the α -nucleus potential is confirmed by the reproduction of the (α ,n) channel. However, although two independent data sets [16,129] are available for the ${}^{26}Mg(\alpha,p){}^{29}Al$ reaction (see Sec. 4.27), both data sets have been obtained from the stacked-foil activation technique which has turned out to be not very reliable for low energies (see e.g. the huge scatter of such data for 51 V in Fig. 6 in Sec. 4.3). A quite similar deviation for the (α, p) channel can be seen for the neighboring ²⁵Mg nucleus; however, here the experimental data represent only a partial cross section of the (α, p) reaction (see Fig. 52 in Sec. 4.28). Interestingly, for both cases ²⁵Mg and ²⁶Mg the estimated (α, p) cross sections from the thick-target yields in [49] show much better agreement with the StM calculations. Thus, it is not fully clear whether there is really a deficient in the StM calculations or an experimental problem in the (α, p) data of [16, 129].

The agreement between experimental data and the StM calculation is limited to cases where the experimental cross section is averaged over a sufficient number of resonances in the compound nucleus. This sufficiently high level density is achieved for nuclei at the upper end of the mass range $A \approx 20 - 50$ under study. For the lighter nuclei individual resonances become more and more visible. This obviously depends crucially on the experimental conditions like the energy spread of the beam and in particular on the target thickness. A nice example has been given for ²⁷Al where thin-target data show many individual resonances whereas thick-target data from the same experiment show a smooth (i.e., non-resonant) energy dependence (see data from [108] in Fig. 48 in Sec. 4.26). As soon as the level density in the compound nucleus is not high enough, the StM calculation is only able to reproduce the general trend of the energy dependence of the excitation function, but not all the individual resonances.

The present study attempts to provide a comparison of reaction cross sections for various target nuclei at energies below and above the Coulomb barrier. For this purpose the method of reduced energies $E_{\rm red}$ and reduced cross sections $\sigma_{\rm red}$ was used [19]. It is found that the data for α -induced cross sections in the $A \approx 20-50$ mass range are slightly higher than the general results for α -induced reactions on heavy (above $A \approx 90$) targets [17,18]. The $\sigma_{\rm red}$ values increase relatively smoothly with decreasing target mass A. The expected range of $\sigma_{\rm red}$ values is indicated by three lines in all figures with reduced cross sections $\sigma_{\rm red}$; these lines correspond to the theoretical predictions for ⁵¹V, ³⁶Ar, and ²¹Ne (i.e., covering the mass range under study). An expected exception is the doubly-magic $(Z = N = 20)^{40}$ Ca nucleus which shows slightly smaller $\sigma_{\rm red}$ compared to its neighboring nuclei (see Fig. 21 in Sec. 4.11). Surprisingly, not much differences are seen for even-even, even-odd, odd-even, and odd-odd nuclei. Unfortunately, experimental data for odd-odd nuclei are only scarcely available.

Four more significant exceptions from this generally smooth behavior of $\sigma_{\rm red}$ have been found. The results for ⁴⁰Ar and ³⁶Ar are far below the expected range of $\sigma_{\rm red}$ values. However, there are only very few data points which are based on one particular very old experiment [93]. New data for ⁴⁰Ar and ³⁶Ar are highly desirable to illustrate this behavior. The recent results from the ${}^{33}S(\alpha,p){}^{36}Cl$ reaction [102] are slightly above the expected range; this discrepancy sharpens dramatically as soon as the additional cross section of the ${}^{33}S(\alpha,n){}^{36}Ar$ reaction (estimated from the theoretical ratio between (α, p) and (α, n) channel, see [20]) is taken into account. The summed (α, p) and (α, n) cross sections are far above the expected range for $\sigma_{\rm red}$, and the energy dependence is much flatter than expected (see Fig. 37 in Sec. 4.20 and detailed discussion in [20]). Finally, the recent 23 Na $(\alpha, p){}^{26}$ Mg data [146] are very far above the expected range, and they show a much steeper energy dependence than expected (see Fig. 57 in Sec. 4.30). As for both ³³S and ²³Na only one data set is available in the relevant energy range, new experimental data would be very helpful to confirm the unexpected behavior of these two nuclei.

The $\sigma_{\rm red}$ vs. $E_{\rm red}$ reduction scheme is very simple, and also other reduction schemes have been suggested. For ³³S it was stated [20] that also the reduction scheme from [169] leads to similar conclusions.

The strong deviation between expected reduced cross sections $\sigma_{\rm red}$ and experimental results for 40 Ar, 36 Ar, 33 S, and 23 Na is correlated with a poor agreement between the experimental data and the StM calculations. From the otherwise smooth behavior of $\sigma_{\rm red}$ values for nuclei with $A \approx 20 - 50$ it is obvious that it is not possible to find an α -nucleus potential with smoothly varying parameters which is able to reproduce the general trend of $\sigma_{\rm red}$ and the lower outliers 40 Ar and 36 Ar and the upper outliers 33 S and 23 Na simultaneously.

6 Summary and conclusions

Reduced cross sections $\sigma_{\rm red}$ were derived for α -induced reactions on nuclei in the $A \approx 20 - 50$ mass range. This simple reduction scheme (reduced cross section $\sigma_{\rm red}$ versus reduced energy $E_{\rm red}$ as suggested in [19]) shows a very similar behavior for heavy-ion induced reactions in a broad energy range. It has been found earlier [17,18] that this reduction scheme works also well for α -induced reactions on heavy nuclei. The present study shows that α -induced reactions in the $A \approx 20 - 50$ mass range show a trend of slightly larger reduced cross sections at low energies (below $E_{\rm red} \approx 1 \,{\rm MeV}$) with decreasing target mass. However, this trend is weak and relatively smooth. Four outliers are identified: ³⁶Ar and ⁴⁰Ar with smaller $\sigma_{\rm red}$ values (based on early experimental data of [93]) and ²³Na (based on [146]) and ³³S (based on [102]) with significantly increased $\sigma_{\rm red}$ values.

In general, the calculation of $E_{\rm red}$ and $\sigma_{\rm red}$ allows for a quick and simple test whether the cross section of an α induced reaction for a particular nucleus behaves regularly or extraordinary. The present study provides the basis for such a comparison. From my point of view, such a test is strongly recommended for any new data on α -induced reactions.

As a byproduct of the present study it was found that the reduced energy $E_{\rm red}$ has a simple approximate relation to the most effective energy for astrophysical reaction rates (the so-called Gamow window): e.g., for $T_9 = 2$ the Gamow window appears around $E_{\rm red} \approx 0.45 \,{\rm MeV}$ for all nuclei under study in this work.

The experimental cross sections of α -induced reactions in the $A \approx 20 - 50$ mass range are compared to calculations in the statistical model. Here the cross section factorizes into a production cross section of the compound nucleus which depends on the chosen α -nucleus potential, and into a decay branching of the compound state which depends on the other ingredients of the statistical model, but is almost independent of the α -nucleus potential. Fortunately, for most of the nuclei under study, one particular reaction channel – (α, p) or (α, n) – is dominating which allows a strict test of the chosen α -nucleus potential by comparing only the cross section of the dominating (α, p) or (α, n) channel; this test is only weakly affected by the other ingredients of the statistical model. Surprisingly it is found that the old and very simple 4-parameter potential by McFadden and Satchler [21] leads to very good agreement with most of the experimental data; i.e., the smooth energy dependence of excitation functions for nuclei in the upper half of the mass range $A \approx 20 - 50$ is reproduced, and for the lighter nuclei under study the statistical model reproduces only the average energy dependence of the experimental excitation function which is governed by individual resonances. For the four outliers in the $\sigma_{\rm red}$ reduction scheme (⁴⁰Ar, ³⁶Ar, ³³S, ²³Na) it is found that these nuclei also show poor agreement between the experimental data and the statistical model calculations for α -induced reactions.

Acknowledgments

38

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Note added in Proof:

According to a private communcation with Alison Laird, new experiments on the ²³Na(α, p)²⁶Mg reaction have been done very recently. She points out that the "cross sections agree with NON-SMOKER, apart from at the lowest energies (below $E_{\rm c.m.} = 1.4 \,\text{MeV}$)" where the new data are even lower than the theoretical prediction. As the calculated ²³Na(α, p)²⁶Mg cross section in the StM depends essentially only on the chosen α -nucleus potential, the agreement between the latest experimental data and theory also holds for the TALYS calculations in Fig. 56 (see Sec. 4.30). Thus, the status of ²³Na may change from "outlier" to "regular behavior".

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Peter Mohr: Cross sections of α -induced reactions for targets with masses $A \approx 20 - 50$ at low energies

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