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INVESTIGATION OF THE REACTION $^{6}Li + {}^{40}Ca$ AT 156 MeV IN A COINCIDENCE EXPERIMENT

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ABSTRACT

The cross sections for inelastic break up have been studied for the $^{6}Li + ^{40}Ca$ reaction at $E_{Li} = 156$ MeV. For this, gamma ray spectra from the heavy residual nuclei were measured in coincidence with beam velocity projectile fragments. The cross sections were found to be: $34 ^{+14}_{-9}$ mb for protons, $30 ^{+12}_{-7}$ mb for deuterons, and $78 ^{+142}_{-41}$ mb for α-particles, respectively. These values are small when compared to total break up cross sections.

A comparison of the cross section sum of all known reaction paths induced by $^{6}Li + ^{40}Ca$ at 156 MeV with total reaction cross section indicates a missing cross section of the order of a few hundred millibarns. It is discussed whether this cross section may be attributed to pick up reactions.

UNTERSUCHUNG DER REAKTIONEN $^{6}Li + ^{40}Ca$ BEI 156 MeV IN EINEM KOINZIDENZEXPERIMENT

ZUSAMMENFASSUNG

Die Wirkungsquerschnitte für inelastischen Projektilaufbruch in der Reaktion $^{6}Li + ^{40}Ca$ bei $E_{Li} = 156$ MeV wurden gemessen. Dazu wurden die von den schweren Restkernen emittierten γ-Quanten in Koinzidenz mit den Projektilfragmenten nachgewiesen. Folgende Werte für die Koinzidenz-Wirkungsquerschnitte wurden gefunden: $34 ^{+14}_{-9}$ mb für Protonen, $30 ^{+12}_{-7}$ mb für Deuteronen und $78 ^{+142}_{-41}$ mb für α-Teilchen. Diese Werte sind klein im Vergleich zum gesamten Aufbruchs-Wirkungsquerschnitt.

Ein Vergleich der Summe aller für die $^{6}Li + ^{40}Ca$ Reaktion bekannten partiellen Wirkungsquerschnitte mit dem gesamten Reaktionsquerschnitt ergibt eine Differenz von einigen hundert Millibarn. Eine mögliche Erklärung dieser Differenz in den Wirkungsquerschnitten durch "pick up"-Reaktionen wird diskutiert.

1. INTRODUCTION

It was found recently that for the $^{6}Li + ^{40}Ca$ reaction at 156 MeV (LAB) complete fusion exhausts only 3 - 4 % of the total reaction cross section [1], while ^{6}Li break up channels provide a much larger cross section [2]. Large yields of light particles with energy spectra peaking near the beam velocity dominate the spectra at forward angles. These high energy particles originate from the projectile break up where in principle each of the fragments can interact elastically or inelastically with the target nucleus. The inelastic break up of the projectile, where one of the components fuses with the target nucleus has been shown to play an important role when bombarding ^{208}Pb with 156 MeV ^{6}Li ions [3]. This inelastic break up mode appears to be strongly related to the incomplete fusion reactions of complex nuclei which have been shown to contribute increasingly with increasing incident bombarding energy. One can suspect that at least part of the cross section attributed to complete fusion in a number of experiments belongs in fact to partial fusion since the distinction between evaporation residues originating from these two reaction mechanism is not easy.

The present work studies the inelastic break up modes more in detail by measuring the γ-ray spectra from the heavy residual nuclei in coincidence with light ejectiles (in particular beam-velocity break up fragments) when bombarding ^{40}Ca with 156 MeV ^{6}Li ions. The measurements aimed at a determination of the ($^{6}Li,p\gamma$), ($^{6}Li,d\gamma$), ($^{6}Li,t\gamma$) and ($^{6}Li,\alpha\gamma$) contributions clarifying more details of the reaction mechanism for the emission of light particles. The choice of ^{6}Li as a bombarding particle is motivated by the interesting possibility of observation of some transitional features of the reaction mechanism when going from light ion to heavy ion reactions. The well pronounced cluster structure of the ^{6}Li projectile promises observation of break up and transfer phenomena in few a priori expected channels.

2. EXPERIMENTS

The 156 MeV ^{6}Li beam of the Karlsruhe Isochronous Cyclotron was focused onto a 18.1 mg/cm² thick Ca target. The beam current was measured by a shielded Faraday cup situated 6 m behind a 70 cm diameter scattering chamber wherein the target and the particle detector were mounted. Between the scattering chamber and the Faraday cup additional focussing magnets were installed. The current actually available for the experiment did scarcely exceed 1 nA.

The light charged particles were detected by a semiconductor detector telescope consisting of a 300 μm thick Si detector (ΔE) and a 15 mm thick high purity Ge detector (E) which has been cooled to the temperature of liquid nitrogen. The solid angle for particle detection defined by a tantalum diaphragm was 0.95 msr. The measurements were done with the particle telescope positioned at $\theta_L = 12°$. An additional measurement aiming only at α-particle emission was performed at $\theta_L = 9°$.

The γ-ray spectra were measured with a Ge(Li) detector (resolution: 1.8 keV, efficiency: 14 % for the 1332 keV γ-rays from

^{60}Co) placed at 135° to the beam direction and supplied with a Cu-Cd-Pb filter in order to reduce the low-energy X-ray and γ-ray intensity. The energy and absolute efficiency calibration of the γ-branch were determined using a set of calibrated sources.

The particle-γ coincidences were registered on magnetic tape in an event-by-event mode using an on-line Nova-2 computer. Two time to amplitude converters (TAC) measured the delay time between E_γ and ΔE and between E_γ and the cyclotron high frequency (H.F.) pulses. A coincidence of the four signals (ΔE, E, $TAC_{E\gamma-\Delta E}$, $TAC_{E\gamma-H.F.}$) enabled recording of the four signals: ΔE, E, E_γ, $TAC_{E\gamma-\Delta E}$. Fig. 1 shows a $TAC_{E\gamma-\Delta E}$ spectrum. The time distance of 33 nsec between the two peaks corresponds to the frequency of the cyclotron pulses. The second peak contains only random coincidences which have been minimized by choosing proper counter-target distances in order to get nearly the same counting rates in both detector branches. The recorded list-mode data have been analysed using a sorting and particle identification program.

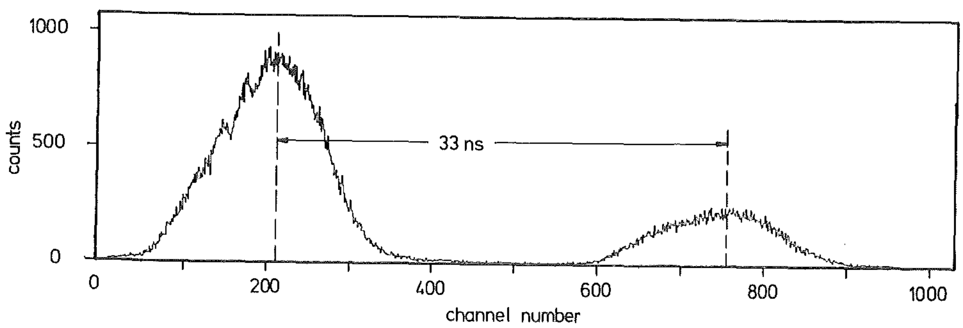


Fig. 1 Example of a $TAC_{E\gamma-\Delta E}$ spectrum.

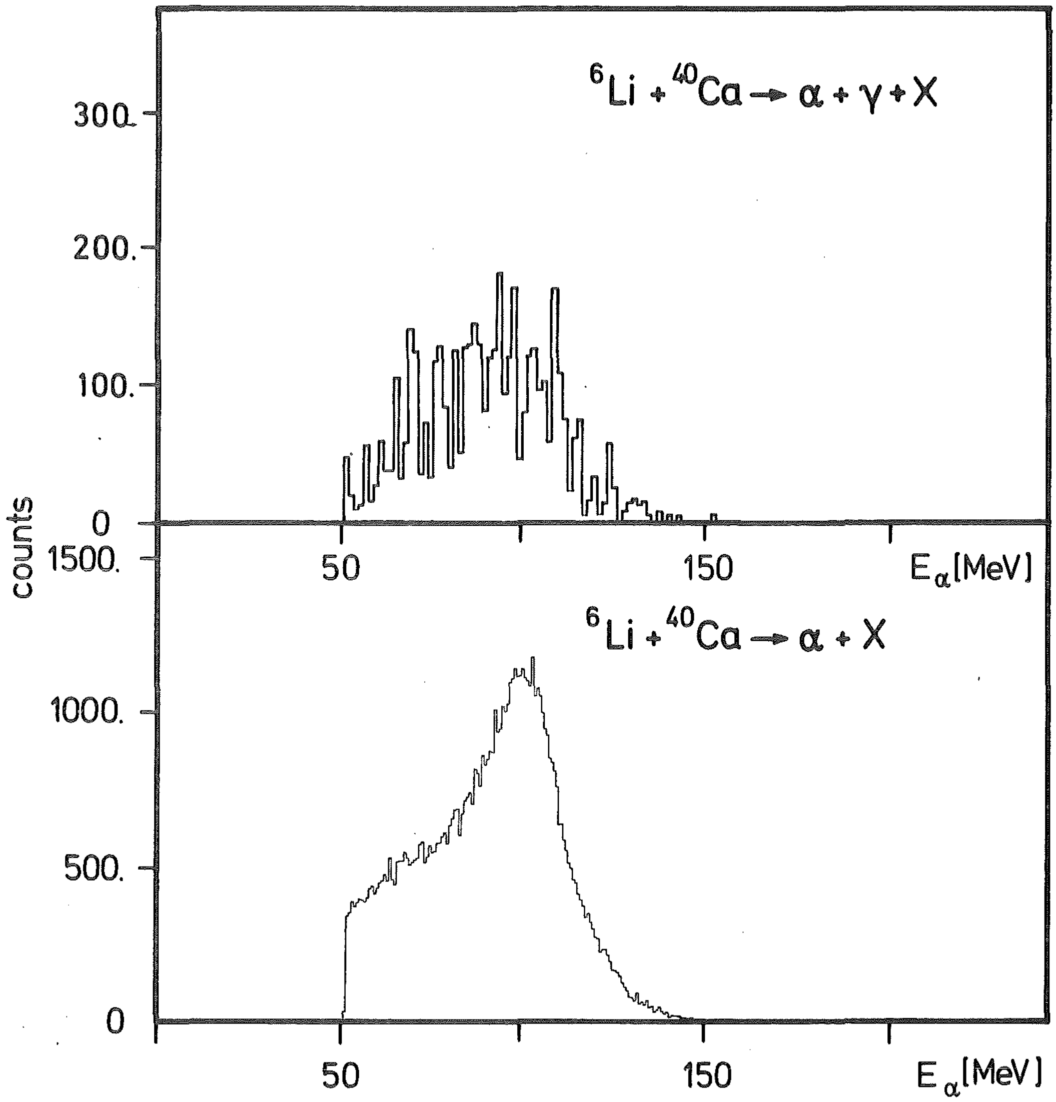
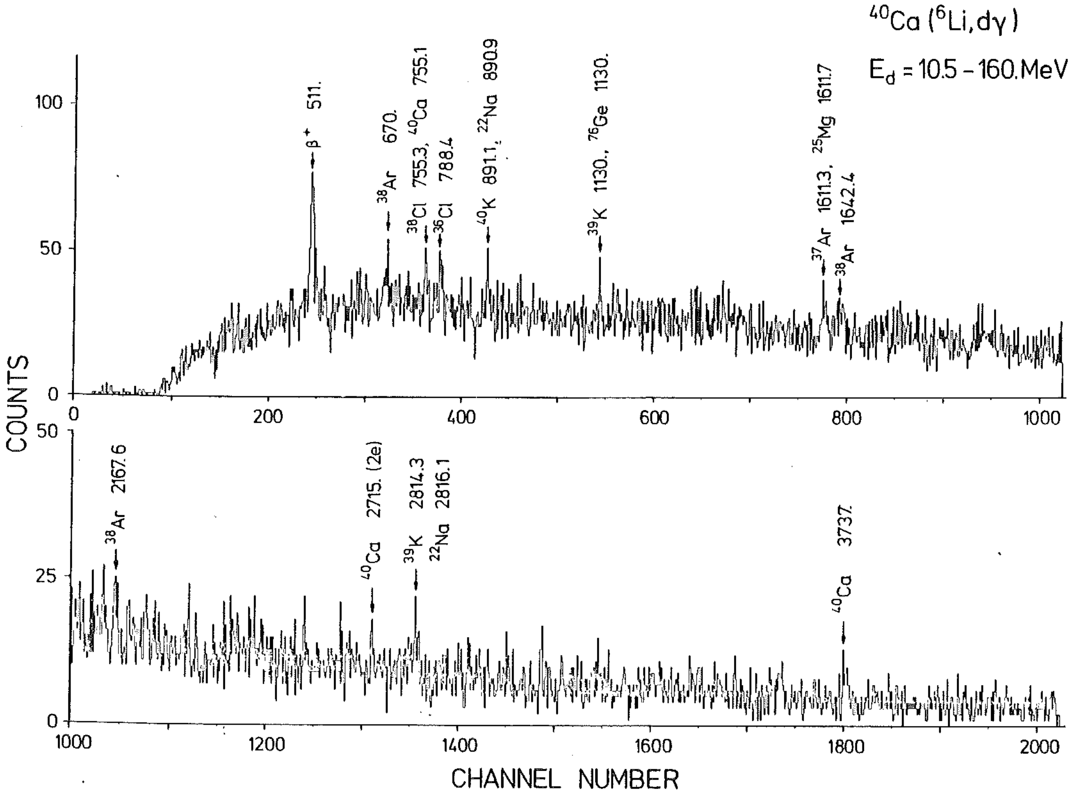
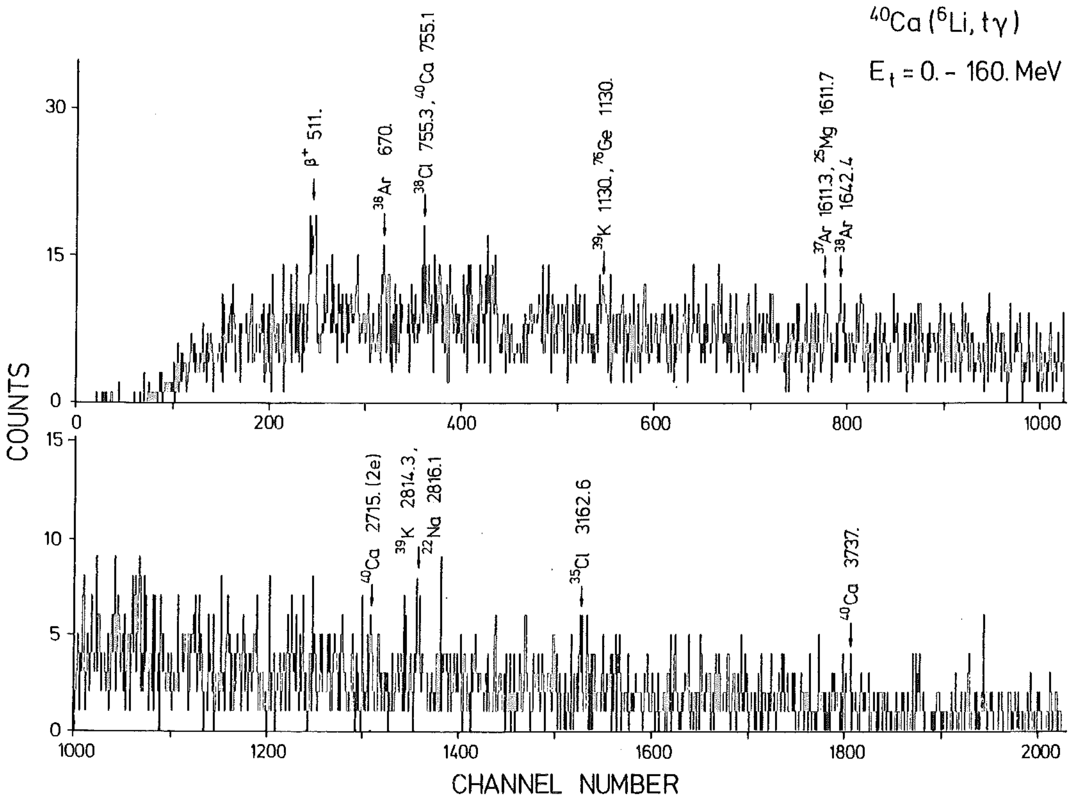


Fig. 2 Energy spectra of α particles emitted when bombarding ^{40}Ca with 156 MeV ^{6}Li ions. Lower part: inclusive spectrum; upper part: in coincidence with all visible γ-lines after correction for the efficiency of the Ge(Li) detector.

Fig. 2 compares the inclusive energy spectrum of α-particles at θ_{Li} = 12° with that obtained in coincidence with all visible γ-lines after correction for the efficiency of the Ge(Li) detector. The α-particle spectrum in coincidence with only one γ-line (e.g. ^{38}Ar) does not remarkably deviate from spectrum shown in fig. 2. As one can see both spectra in fig. 2 have a similar shape. The maximum of the coincidence spectrum is shifted towards lower energies by about 10 MeV.

Examples of γ-ray spectra correlated with the emission of deuterons, tritons and α-particles are displayed in figs. 3. The energy windows set in the charged particle spectra preferred the correlation with beam velocity ^{6}Li fragments.





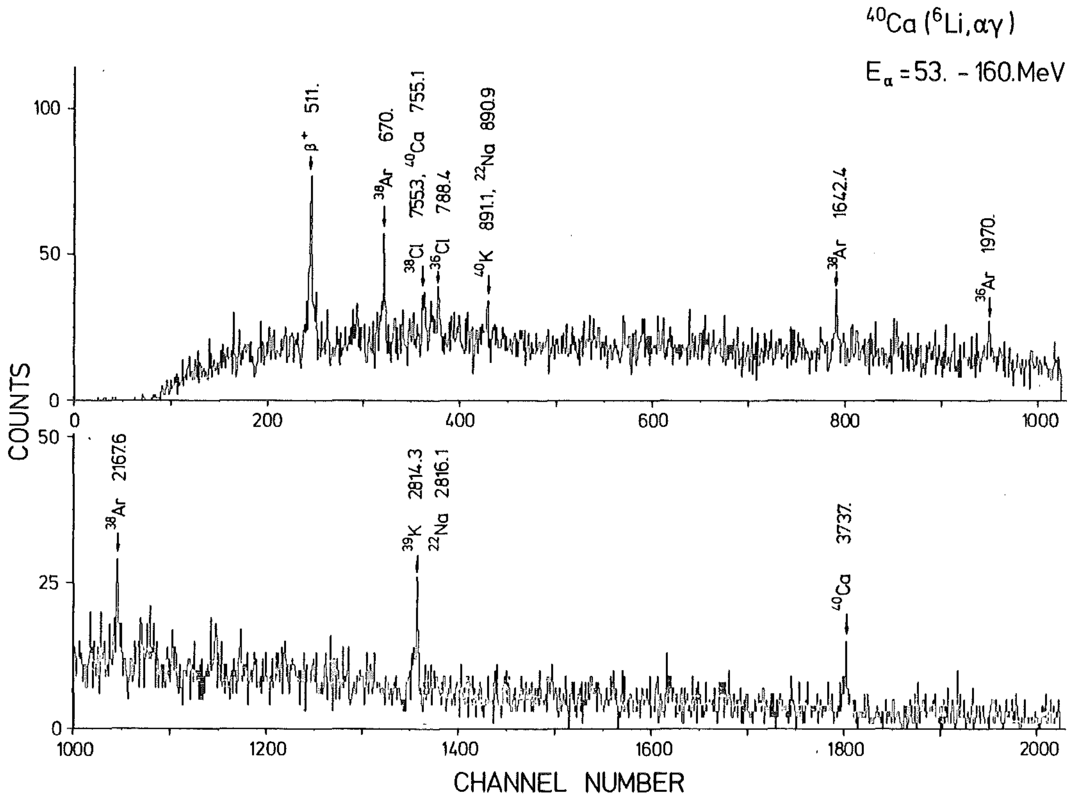


Fig. 3a-c γ-ray spectra emitted in coincidence with light ejectiles detected at θ_L = 12° when bombarding ^{40}Ca with 156 MeV ^{6}Li ions. The energy windows set for light particles are indicated in the figures.

From a comparison of the spectra presented in figs. 3 to the inclusive γ-ray spectrum from ref. [1)] it follows that all intense lines from the inclusive spectrum are seen also in the coincidence spectra. Weaker lines are not visible in the background of the coincidence spectra due to the much larger statistical error.

3. ANALYSIS OF THE SPECTRA AND CROSS SECTION EVALUATION

After energy calibration and evaluation of the peak areas of all visible γ-lines with background subtraction the γ-lines have been assigned to known nuclear transitions [4] using the standard γ-transition tables [5]. In the coincidence spectra 15 γ-lines were found and all of them were identified.

The evaluation of cross sections needs a correction for the random coincidences which was derived in two independent ways:

(i) the γ-spectrum measured in coincidence with the "random" TAC peak (second peak in fig. 1) has been subtracted from the γ-spectrum in coincidence with the "true plus random" TAC peak, assuming that the random component is the same in both peaks. From this procedure we obtained a random coincidences correction equal to 19 %;

ii) a second alternative method was based on the four most intensive γ-lines from different energy regions of the γ-spectrum. For each line the peak area has been determined using all γ-events in coincidence with the total TAC spectrum, N_2, and with that, N_1, including only the coincidences with the TAC peak comprising the sum of random and true coincidences. Evidently, we have the relations:

$$N_{rand} = N_2 - N_1 \tag{1}$$

$$N_{true} = 2N_1 - N_2 \tag{2}$$

by which $N_{rand}/N_1 \approx 0,25$ could be estimated.

Thus both methods give approximately equal results. The average value of the random coincidence correction equals to 22 %.

Following the procedure used in ref. 1 for the cross section evaluation from the inclusive γ-spectra we have multiplied all γ intensities by a factor of 1.5. This factor (1.5 $\pm$ 0.2) has been found by comparing the experimental total reaction cross section with the optical model predictions. The origin of this factor is twofold:

(i) It takes into account side feeding of γ-transitions to the ground state parallel to the main (Yrast) band, whose transition intensities are used to determine the cross sections.

(ii) Another contribution to this factor is probably due to the angular dependence of γ-ray intensities. In this experiment all γ-ray spectra were measured at an angle of 135° with respect to the beam axis. At this angle all relevant γ-multipolarities lead to similar cross sections. Since an exact accounting for the different angular distributions was not possible, we assumed isotropy and a possible scaling factor independent on the multipolarity to be contained in the experimental scaling factor of (1.5 $\pm$ 0.2). This procedure is justified by an previous study of cross sections measured in the same nuclidic region and based on anisotopic γ-ray intensities [6)]. There it was shown that the error induced by the above assumption is on the average less than 10 %.

Differential cross sections for production of the residual nuclei in coincidence with beam velocity fragments emitted at 9° and 12°, respectively, are presented in table 1. Table 2 shows

Table 1 Coincidence cross section values for different Z-values

Z	$\frac{d\sigma_{coinc}}{d\Omega}$ [mb/sr]				
	$\theta_L = 9°$	$\theta_L = 12°$			
	α	α	t	d	p
21	$1.6^{+3.2}_{-1.6}$	$1.5^{+3.0}_{-1.5}$	-	$1.9^{+3.8}_{-1.9}$	$1.4^{+2.8}_{-1.4}$
20	$4.0^{+4.5}_{-4.0}$	$3.8^{+3.9}_{-3.8}$	0.2 ± 0.2	4.3 ± 2.2	$2.1^{+2.1}_{-2.1}$
19	$24.3^{+17.0}_{-16.7}$	$19.0^{+7.2}_{-6.7}$	2.9 ± 1.4	$19.1^{+11.4}_{-9.1}$	$15.5^{+8.6}_{-5.9}$
18	$56.1^{+23.2}_{-22.8}$	$6.3^{+4.9}_{-4.9}$	$0.6^{+1.2}_{-0.8}$	$7.6^{+10.9}_{-5.6}$	$5.1^{+7.0}_{-3.9}$
17	15.0 ± 10.8	$8.0^{+6.6}_{-5.3}$	3.8 ± 1.8	$9.3^{+6.4}_{-4.8}$	6.0 ± 4.6
16	$9.2^{+9.4}_{-9.2}$	-	-	-	-
15	$33.0^{+15.2}_{-14.6}$	$1.5^{+1.5}_{-1.5}$	-	-	$1.7^{+1.7}_{-1.7}$
14	11.4 ± 10.4	$5.9^{+6.3}_{-4.9}$	-	$5.8^{+9.7}_{-4.7}$	$3.3^{+6.7}_{-3.3}$
13	$10.6^{+8.0}_{-7.8}$	$0.5^{+1.0}_{-0.5}$	$0.6^{+1.2}_{-0.6}$	$3.4^{+6.8}_{-3.4}$	-
12	-	$0.5^{+1.0}_{-0.5}$	$0.6^{+1.2}_{-0.6}$	$3.4^{+6.8}_{-3.4}$	-

Table 2 Inclusive and exclusive cross sections for emission of beam velocity particles in the $^{6}Li + {}^{40}Ca$ reaction

	$\theta_L = 9°$	$\theta_L = 12°$		
	α	α	d	p
$\frac{d\sigma_{incl}}{d\Omega}$ [mb/sr]	1750 ± 262	720 ± 108	540 ± 81	410 ± 61
$\frac{d\sigma_{coinc}}{d\Omega}$ [mb/sr]	165^{+38}_{-37}	47^{+14}_{-12}	55^{+22}_{-13}	35^{+14}_{-10}
$\frac{d\sigma_{incl}}{d\Omega} / \frac{d\sigma_{coinc}}{d\Omega}$	10.6	15.3	9.8	11.7

differential cross sections summed up for a residual nuclei in coincidence with beam velocity fragments. The quoted errors reflect:

(i) the error in the peak integration;

(ii) the error due to the ambiguity in the identification procedure (see ref. 4);

(iii) the errors of target thickness and beam current measurements;

(iv) the error of the random coincidence correction;

(v) the error of the experimental scaling factor mentioned above.

In order to compare our coincidence results with inclusive data for the production of light particles and for fusion it was necessary to integrate the differential cross sections over the emission angle θ_L of the charged ejectile. For this purpose we had to know the angular dependence of the cross sections measured for coincident events. It has been shown that the inclusive differential cross section for producing break up fragments decreases exponentially with the emission angle [2,7]. It was asumed [8] that the angular distribution for the light ejectiles measured in coincidence with γ-emission follows this angular dependence. As far as this could be checked by the α-yields for θ_L = 9° and 12°, this assumption appeared to be reasonable. Using this approximation angle integrated cross sections for the (^{6}Li,Xγ) channels (X = p,d,α) are derived and presented in table 3. The corresponding errors include additional uncertainties due to the integration procedure. For the forward discussion we exclude the triton data since the inclusive spectra show a complex structure indicating additional reaction path.

Table 3 Integrated experimental cross sections available for the $^{6}Li + ^{40}Ca$ reaction at 156 MeV

Reaction channel	Cross section (mb)	Ref.
Total reaction cross section	1981 ± 200	9)
Complete fusion	67 ± 20	1)
$(^{6}Li,\alpha\gamma)$	78^{+142}_{-41}	This work
$(^{6}Li,d\gamma)$	30^{+12}_{-7}	
$(^{6}Li,p\gamma)$	34^{+14}_{-9}	
Quasi symmetric binary splitting of compound system	10 ± 3	10)
Inclusive emission of light particles		2)
α	440 ± 88	
d	360 ± 72	
p	320 ± 64	
^{3}He	80 ± 16	

Tables 2 and 3 compare data of this work with other ones available for the $^{6}Li + {}^{40}Ca$ reaction at 156 MeV. The inclusive break up cross sections at 12° given in table 2 result from an interpolation of the results obtained in ref. 2 for $\theta_L = 10°$ and $\theta_L = 15°$. In fig. 4 we compare the Z distribution resulting from complete fusion [1] and ($^{6}Li,X\gamma$) channels (X = p,d,α) to that found by observation of inclusive γ-rays [1].

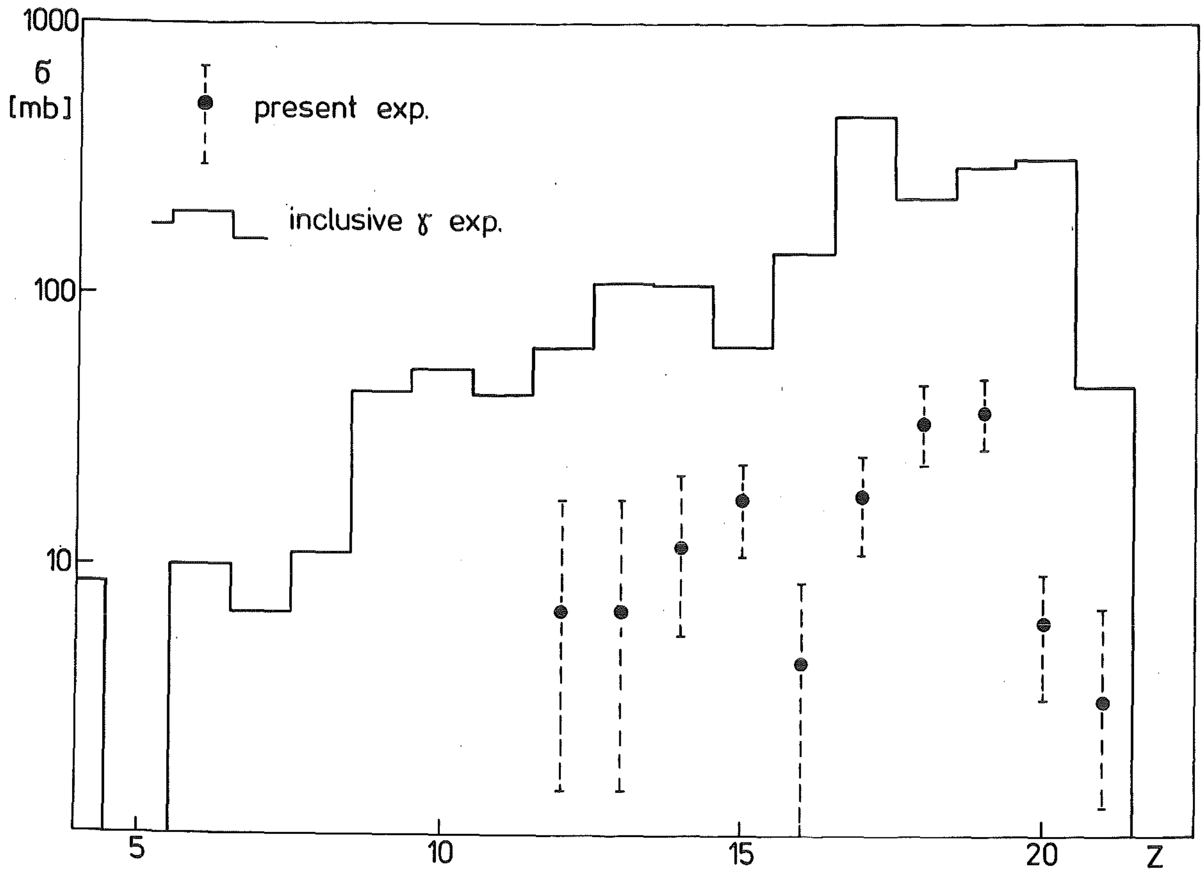


Fig. 4 Z distribution for the present experiment resulting from summing up cross sections for complete fusion [1] and ($^{6}Li,X\gamma$) channels (X=p,d,α) as compared to distribution found by observation of the inclusive γ-rays emitted in the $^{6}Li + {}^{40}Ca$ reaction at 156 MeV [1].

Inspection of table 2 shows that the interaction of the non-observed projectile fragment with the target nucleus is unexpectedly small. The most conspicuous result seen in table 3 and fig.4 is the following: (^{6}Li,Xγ) channels which have been previously expected to be the dominant ones in ^{6}Li break up reactions [2), contribute to a rather small extend to the total reaction cross section, σ_R.

In order to estimate the total ^{6}Li break up cross section the elastic contribution must be known. To derive this contribution from inclusive measurements is difficult since correlations between the emitted light particles are disregarded. An upper limit however for the total break up cross section is given by summing up the inclusive fragment cross sections given in table 3. From this we estimated that the ^{6}Li break up contributes with not more than 1280 mb to the total reaction cross section. Comparing the sum of cross sections for all reaction channels listed in table 3 to the total reaction cross section it follows that a few hundred millibarns are missing.

4. COMPARISON WITH THE "SUM-RULE" MODEL

In order to elucidate the origin of this missing cross section we have compared our data to a model which in principle should take into account all two-body reaction channels. This is the "sum-rule" of Wilczyński et al. [8)].

The model is based on the assumption that for each binary channel "i" the reaction probability p(i) is proportional to an exponential factor:

$$p(i) \sim \exp\{[Q_{gg}(i) - Q_c(i)]/T\} \tag{3}$$

where Q_{gg} is the ground state to ground state reaction Q value, T is an adjustable parameter sometimes interpreted as a temperature of a partial statistical equilibrium of a strongly interacting dinuclear system, and Q_c is the change of the Coloumb interaction energy of the system between the entrance and exit channels. Q_c depends on another adjustable parameter, R_c, which denotes an effective relative distance where the transfer of charge takes place. The final formula for calculating the cross-section in a channel "i" is:

$$\sigma(i) = \Pi \lambda\!\!\!^{-2} \sum_{l=o}^{l_{max}} (2l+1) \frac{T_l(i)\ p(i)}{\sum_j T_l(j)\ p(j)} \tag{4}$$

where p(i) and p(j) are given by eq. (3), $\lambda\!\!\!^{-}$ is the reduced wave length for the entrance channel, and the transmission coefficient $T_l(i)$ is given by:

$$T_l(i) = [1+\exp \frac{l-l_{lim}(i)}{\Delta}]^{-1} \tag{5}$$

Here Δ is an adjustable smooth cut-off parameter and l_{lim} is the critical angular momentum l_{cr} transformed to the channel "i" for fusion of a transferred fragment of mass m_c and a target nucleus (m_a). It is given as:

$$l_{lim}(i) = \frac{m_a}{m_c(i)} l_{cr}(i) \tag{6}$$

The main formula (4) is based on the unitarity condition, requiring that for each partial wave the sum of probabilities for all binary channels plus complete fusion is equal unity.

Table 4 Comparison of experimental cross sections with the prediction of the "sum-rule" model.

Exit channel	σ_{exp} [mb]	σ_{calc} [mb]
^{46}V complete fusion	67 ± 20	89.9
$^{45}Ti + p$	34^{+14}_{-9}	19.0
$^{44}Ti + d$	30^{+12}_{-7}	23.2
$^{42}Sc + \alpha$	78^{+142}_{-41}	281.0
$^{43}Ti + t$		3.5
$^{43}Sc + {}^{3}He$		11.8
$^{39}Ca + {}^{7}Li$		18.8
$^{37}K + {}^{9}Be$		104.2
$^{36}Ar + {}^{10}B$		50.3
$^{35}Ar + {}^{11}B$		2.7
$^{34}Cl + {}^{12}C$		9.2
$^{32}S + {}^{14}N$		4.6
$^{30}P + {}^{16}O$		7.3
$^{27}Si + {}^{19}F$		0.3

In our "sum-rule" model calculations we have included the 14 most probable channels. Table 4 presents results of a search performed in the T, R_C, Δ space. The optimum values: T = 4.5 MeV, $R_C/(A_1^{1/3} + A_2^{1/3}) = 2.01$ fm, $\Delta = 0.5\ \hbar$ were found by minimizing the differences between measured values of complete and incomplete fusion cross sections and corresponding values obtained from eq.(4). The "best fit" values of the adjustable parameters T, R_C and Δ are reasonable and not much different from those obtained in other cases [8]. A reasonable agreement between experimental data and predictions of the "sum-rule" model supports the two body character of the incomplete fusion channels. In table 4 we see also some pick up channels predicted by the "sum-rule" with a quite large cross sections. Heavy ejectiles probably due to such reactions have already been observed in the former inclusive experiments [1,11]. If one assumes that kinetic energy of relative motion in such reactions is provided mainly by the Coulomb repulsion [12], the remaining energy of the system is spent for excitation of the reaction products. Usually the excitation energy is distributed proportionally to the fragment mass and most of it has to be accumulated in the heavier target-like fragment. Evaporation residues of these target-like nuclei may be found in Z spectra measured recently in the inclusive γ-experiment [1] and consequently it can explain partly the difference between the two Z distributions shown in fig. 4.

5. SUMMARY

In the presented work we have measured contributions from the (^{6}Li,pγ), (^{6}Li,dγ) and (^{6}Li,$\alpha\gamma$) channels to the total reaction cross section for the ^{6}Li + ^{40}Ca reaction at 156 MeV. They are found to be: $34 {}^{+14}_{-9}$ mb, $30 {}^{+12}_{-7}$ mb, and $78 {}^{+142}_{-41}$ mb, respectively. A reasonable agreement of these data with predictions of the Wilczyński "sum-rule" model suggests a binary character of the investigated reactions. The p,d, and α particle channels together with the complete fusion channel exhaust an unexpectedly small part of the total reaction cross section. Consequently, the measured cross section for coincidences between γ-rays and beam velocity fragments of ^{6}Li projectiles reveals a surprisingly weak interaction of non observed break up partners with the target nuclei. This experimental fact contradicts trends observed for some other systems [13)].

A comparison of all known reactions induced by the ^{6}Li + ^{40}Ca collision at 156 MeV, presented in tab. 3, indicates a missing cross section of the order of a few hundred millibarns. The prediction of the "sum-rule" model suggests that at least part of this cross section can be attributed to pick up reactions.

An experimental proof of this pick up reaction branch will be highly desirable in order to support the proposed explanation for the missing cross section.

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