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Production of ^{7}Be, ^{22}Na, ^{24}Na and ^{28}Mg by Irradiation of ^{27}Al with 52 MeV Deuterons and 104 MeV Alpha Particles

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PRODUCTION OF ^{7}Be, ^{22}Na, ^{24}Na AND ^{28}Mg BY IRRADIATION OF ^{27}Al WITH 52 MeV DEUTERONS AND 104 MeV ALPHA PARTICLES

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Abstract

Excitation functions for the production of ^{7}Be, ^{22}Na, ^{24}Na and ^{28}Mg by irradiation of ^{27}Al with deuterons and alpha particles were measured for the energy range available with the Karlsruhe Isochronous Cyclotron. The error in the absolute cross section scale is estimated to be 2.5 %. The error in the energy scale is about 1 MeV in the threshold region and 0.5 MeV at the maximum energy.

1. Introduction

The isotopes with half lives larger than a few hours produced by irradiation of aluminium with deuterons are ^{7}Be, ^{22}Na and ^{24}Na. In alpha particle irradiations ^{28}Mg is produced, too. The two sodium isotopes are easily detected by their gamma rays using a NaJ(Tl) or a Ge(Li) detector. A Ge(Li) detector is needed to detect ^{7}Be and ^{28}Mg in the irradiated aluminium foils, but no radiochemical separation from the sodium isotopes is necessary.

A review of the published deuteron excitation functions shows that the production of ^{22}Na and ^{24}Na is known(1-7) with an error of 30 % for deuteron energies up to 190 MeV. We did not find published values for the production of ^{7}Be.

More is known about alpha particle irradiations of aluminium. The production of ^{7}Be, ^{22}Na and ^{24}Na was published(8,9) with quoted errors of 30 % for energies up to 120 MeV. The production of ^{24}Na was reported(4,10) for energies up to 380 MeV. The production of ^{7}Be and ^{24}Na near the threshold was published(11-13) several times. The production of ^{28}Mg is known(14) up to 42 MeV.

The reactions leading to the sodium isotopes are of interest because they may be used for monitoring beam intensities. The production of ^{7}Be was measured in order to obtain information about the reaction $^{27}Al(\alpha,{}^{7}Be)^{24}Na$.

It is the aim of this work to present accurate production cross sections of ^{7}Be, ^{22}Na, ^{24}Na and ^{28}Mg by irradiation of aluminium with deuterons and alpha particles within the energy range available with the Karlsruhe Isochronous Cyclotron.

2. Experimental Procedure

The production cross sections were measured by the stacked foils technique. Stacks of aluminium foils were irradiated with the full energy of the external+ beam of the Karlsruhe

+Troubles arose in previous measurements with the internal beam. The cross sections were not reproducible.

cyclotron. The contents of radionuclides with half lives larger than a few hours were determined by their gamma rays a few days after irradiation. Hence, the sum of radionuclides produced by nuclear reactions and by beta decays of short lived isobars was measured.

2.1. Targets

The targets were stacks of high purity aluminium foils++.

++Supplied by Schweizerische Aluminium AG, Zürich. 99.999 % bulk purity.

The foil thickness was chosen 100 μm and 200 μm for the deuteron irradiations and 50 μm and 100 μm for the alpha particle irradiations in order to obtain the excitation functions in steps of about 1 and 2 MeV, respectively.

The thickness of each foil was measured after the irradiation by weight and area determinations. For each thickness class the standard deviation from the mean thickness is about 0.6 %. That means that the foils are uniform in thickness to at least 0.6 % and the error in the thickness determination is of that order.

2.2. Beam current integration

The foil stacks were irradiated within a Faraday cup. In front of the cup was a diaphragm of 10 mm in diameter. The diameter of the foil surface exposed to the beam was 14 mm. The beam current was about 1 μA, the collected charge about 0.01 C. It was measured with an Elcor model A 309 B current integrator.

In order to establish the error in the beam current integration, following checks were performed:
The current on the diaphragm in front of the Faraday cup was measured to be less than 2% of the beam current. Therefore, slit scattering from the diaphragm is negligible.

The dark current due to the water cooling of the target and radio frequency pick up was measured introducing an internal target into the cyclotron. The rate of charge collection under these conditions was found to be the same immediately before and after the irradiation and to amount to 0.5 %. The collected charge was corrected for the dark current.

The amount of secondary electrons[15] emitted from the target was measured by isolating the target electrically from the Faraday cup and putting the cup at an electric potential. The difference of current on the target when the cup was grounded or put at -100 V amounted to 10 - 20 %. No change in current could be detected (< 2%) when increasing the potential to -350 V. In order to check the losses of secondary electrons from the normally operated cup we repeated the alpha particle irradiation with the isolated target and -350 V at the cup. The cross sections obtained differ by (0.15 ± 0.82) %.

The absolute scale of the current integrator was calibrated with a mercury cell and precision resistors to an accuracy of 0.2 %. Before each irradiation the current integrator was recalibrated with its internal calibration system.

The overall error in the current integration is less than 1%.

The losses of beam particles due to nuclear reactions in the target amount up to 5 %. The reaction products (neutrons, protons, etc.) produce the long lived isotopes as well as the beam particles do. No correction due to the beam particle losses was applied because of the lack of knowledge about the number of generated reaction products and their respective cross sections to produce the long lived isotopes.

2.3. Energy Determination

No absolute beam energy determination was performed in this experiment. Difference in the beam energy in different irradiations were found to amount up to 0.4 MeV for alpha particles by inspecting the threshold region. An energy correction of the form

$$\Delta E(E) = \Delta E(E_o) \cdot E_o/E \tag{1}$$

was applied, were E_o is the beam energy and $\Delta E(E_o)$ the difference from the mean of several beam energy determinations.

On the basis of other energy determinations of the external beam of the Karlsruhe cyclotron we assumed an energy of 52 MeV for deuterons and 104 MeV for alpha particles with an error of 0.5 %.

The tables of reference 16 were used to obtain the energy of the beam particles along the foils in the stack. The mean energy in the middle of each foil was used as abscissa of the excitation functions. Corrections for the energy spread in each foil, due to the foil thickness and the energy degradation in the preceding foils, were not applied. They are small in comparison to the energy uncertainty due to the error in the beam energy.

2.4 Activity Measurements

The contents of ^{7}Be, ^{22}Na, ^{24}Na and ^{28}Mg in the irradiated foils were measured counting the gamma rays emitted and using the values for half lives and gamma ray emission probabilities summarized in table 1.
The gamma rays were counted with a Ge(Li) detector of 33.7 cm^3 sensitive volume. The gamma rays of 1275 keV and 2754 keV from ^{22}Na and ^{24}Na, respectively, were also counted with a 4"x4" NaJ(Tl) detector.

The absolute detection efficiency of the Ge(Li) detector was determined with calibrated sources+ of ^{22}Na, ^{60}Co, ^{88}Y, ^{137}Cs and ^{203}Hg. Several efficiency determinations during four months agreed

+Supplied by IAEA, Vienna. The calibration error is quoted to be less than 1 %.

within the statistical error of 1 %.

The formula

$$(2) \qquad \varepsilon(E_\gamma) = \text{const.}/E_\gamma^{\,n}$$

was used to interpolate the efficiency $\varepsilon(E_\gamma)$ to other energies. The formula (2) was found to describe the results with an error less than 1 % for 511 keV $\leq E_\gamma \leq$ 2754 keV. The efficiencies for different detector-source distances were determined counting the gamma rays of several single foils at the smaller distances and the same foils together at the reference distance. This is the major source of error in the experiment. The error is estimated to be 2 %.

The detection efficiency of the NaJ(Tl) detector was obtained by comparison with the Ge(Li) detector.

The contents of ^{24}Na and ^{28}Mg in the foils were measured a few days after irradiation. The contents of ^{7}Be and ^{22}Na in the same foils were measured a few weeks later.

2.5. Neutron corrections

Neutrons produced in the foil stack induce(17) the reaction $^{27}Al(n,\alpha)^{24}Na$. In order to measure the amount of ^{24}Na produced by neutrons, we irradiated thick aluminium targets at different energies with the internal beam of the cyclotron. The amount of ^{24}Na produced beyond the range of the bombarding particles was used to compute an effective cross section as a function of the range of the bombarding particles. The amount of ^{24}Na produced by backscattered neutrons was measured by annular foils in front of the thick targets and was found to be negligible.

3. Results

The measured cross sections+ for the production of ^{7}Be, ^{22}Na and ^{24}Na by irradiation of ^{27}Al with deuterons are shown in figure 1. The solid curve labelled n is the neutron correction applied to the ^{24}Na data. The dashed curve at low energies was taken from reference 1.

+For numerical values see tables 3 and 4.

The error bars shown on the excitation functions of the sodium isotopes are standard deviations between cross sections obtained from different gamma rays (table 1). The error bars on the ^{7}Be excitation function show statistical errors;no standard deviation could be defined because ^{7}Be emits only one gamma energy, and it was measured with the Ge(Li) detector only. These errors are larger because of the large Compton background due to ^{22}Na.

The difference of 14 % between the excitation function of ^{24}Na published previously[5] at our laboratory and our result has been understood: a different efficiency of the NaJ(Tl) detector was used. This detector was now recalibrated with the gamma ray sources. Using the new efficiency, the difference reduces to (2.5$\pm$ 2)%.

The two alpha particle irradiations were performed with different set-ups for the beam charge collection (see section 2.2). The agreement is excellent. Figure 2 shows the results. The meaning of the error bars is the same as in figure 1. The error bars on the excitation function of ^{28}Mg show the difference in the cross sections obtained from the 400 keV and 1779 keV gamma ray peaks.

The two points at 103 MeV on the ^{7}Be excitation function were obtained from the first foil of each stack. Approximately 37 % of the ^{7}Be produced on a first foil is pushed into the next foils. The arrows indicate how far a ^{7}Be nuclei may recoil in the stack. No correction due to the recoil path was applied because of the unknown angular distribution.

The errors in the cross section scale are (see section 2) 0.6 % from the target thickness, 1 % from the current integration, 1 % from the gamma ray detection efficiency at the reference source-detector distance and 2 % from the change of the counting distance. Since these errors are uncorrelated the overall error in the cross section scale is 2.5 %.

The error in the energy scale is not linear. The quadratic increase of range with the particle energy leads to the formula (1). The error of the beam energy $\Delta E(E_0)$ is 0.25 MeV for deuterons and 0.5 MeV for alpha particles.

4. Discussion

Previously published excitation functions compared to ours are shown in table 2. The deviations were taken at the largest cross sections in the excitation functions.

The reactions leading to ^{22}Na are the most useful for monitoring beam intensities because a very small amount of ^{22}Na is produced by neutrons and because calibrated sources of ^{22}Na are available. The production cross sections of ^{7}Be and ^{24}Na with alpha particles are approximately equal at energies below 38 MeV, which is an indication[11,12] of the two body reaction $^{27}Al(\alpha,{}^{7}Be)^{24}Na$. It is not intended to clarify the reaction mechanisms for the presented excitation functions in the frame of this work.

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Table 1

Half lives $T_{1/2}$ and gamma ray emission probabilities ν for ^{7}Be, ^{22}Na, ^{24}Na and ^{28}Mg.

	^{7}Be	^{22}Na	^{24}Na		^{28}Mg	
$T_{1/2}$	53.4 d	2.602 a	15.05 h		21.3 h	
E [keV]	477	1275	1369	2754	1779	400
ν	0.103	0.9995	0.99994	0.9995	1.0	0.30

References: 18 and 19

Table 2

Comparison of published excitation functions with that of this work.

Reaction	Difference	Error quoted	Reference
$^{27}Al(d,x)^{22}Na$	10 %	30 %	7
$^{27}Al(d,x)^{24}Na$	-12 %	10 %	1
$^{27}Al(\alpha,x)^{7}Be$	-46 %	30 %	9
$^{27}Al(\alpha,x)^{22}Na$	20 %	20 %	7
$^{27}Al(\alpha,x)^{22}Na$	-43 %	25 %	8
$^{27}Al(\alpha,x)^{24}Na$	-25 %	30 %	8
$^{27}Al(\alpha,x)^{24}Na$	12 %	30 %	9

Table 3

Experimental cross sections in mb for the production of ^{7}Be, ^{22}Na and ^{24}Na by irradiation of ^{27}Al with deuterons. The errors listed are statistical errors for the ^{7}Be cross sections, and standard deviations between different measurements of the sodium isotopes cross sections. The error in the cross section scale is 2.5 %. The error in the energy scale is $\Delta E(E) = 12.5\ MeV^2/E$.

E_d [MeV]	^{7}Be σ	^{7}Be $\Delta\sigma$	^{22}Na σ	^{22}Na $\Delta\sigma$	^{24}Na σ	^{24}Na $\Delta\sigma$
17.2					26.82	0.78
18.3			0.0279	0.0215	34.10	0.61
19.3			0.0349	0.0035	42.25	0.78
20.3	0.0038	0.0010	0.0387	0.0050	47.80	0.11
21.3	0.0076	0.0016	0.0612	0.0054	53.65	1.20
22.4	0.0126	0.0160	0.0976	0.0042	55.80	0.62
23.3	0.0157	0.0025	0.135	0.006	58.03	0.45
24.2	0.0225	0.0025	0.202	0.009	58.25	0.25
25.0	0.0350	0.0037	0.272	0.022	57.64	0.37
25.9	0.0371	0.0042	0.406	0.007	57.68	1.15
27.1	0.0435	0.0053	0.586	0.010	54.79	0.61
28.3	0.0587	0.0055	0.915	0.026	51.61	0.21
29.5	0.0727	0.0075	1.233	0.037	48.78	0.51
30.7	0.106	0.008	1.580	0.044	45.66	0.68
31.9	0.111	0.010	1.980	0.053	42.25	0.52
33.0	0.123	0.011	2.480	0.024	39.66	0.25
34.1	0.159	0.015	3.08	0.02	37.39	0.22
35.1	0.192	0.019	3.79	0.06	35.48	0.58
36.1	0.177	0.018	4.66	0.10	33.13	0.40
37.1	0.227	0.019	5.79	0.31	31.18	0.39
38.1	0.225	0.021	7.24	0.34	30.60	0.27
39.1	0.274	0.030	8.80	0.31	28.88	0.81
40.0	0.370	0.044	10.51	0.16	28.06	0.31
40.9	0.300	0.050	12.44	0.45	27.49	0.27
41.8	0.408	0.052	14.47	0.12	26.65	0.22
42.7	0.433	0.055	16.23	0.22	25.85	0.37

Table 3 continued

E_d [MeV]	^{7}Be		^{22}Na		^{24}Na	
	σ	Δσ	σ	Δσ	σ	Δσ
43.6	0.400	0.060	18.96	0.04	24.81	0.14
44.5	0.416	0.062	20.80	0.27	24.15	0.27
45.3	0.483	0.064	22.72	0.34	23.57	0.44
46.1	0.506	0.067	24.49	0.08	23.76	0.64
47.0	0.356	0.060	25.10	1.06	22.61	0.41
47.8	0.389	0.064	27.52	0.17	22.78	0.20
48.6	0.490	0.067	28.75	0.09	22.70	0.47
49.3	0.371	0.063	29.85	0.12	21.95	0.26
50.1	0.469	0.062	30.80	0.28	21.96	0.27
50.9	0.516	0.125	32.57	0.83	22.20	0.27
51.7	0.540	0.125	32.24	0.30	21.64	0.23

Table 4

Experimental cross sections in mb for the production of ^{7}Be, ^{22}Na, ^{24}Na and ^{28}Mg by irradiation of ^{27}Al with alpha particles. The errors listed are statistical errors for the ^{7}Be and ^{22}Na cross sections and standard deviations between results from the various gammarays of ^{24}Na and ^{28}Mg. The error in the cross section scale is 2.5 %. The error in the energy scale is $\Delta E(E) = 50\ MeV^2/E$.

E_α [MeV]	^{7}Be		^{22}Na		^{24}Na		^{28}Mg	
	σ	$\Delta\sigma$	σ	$\Delta\sigma$	σ	$\Delta\sigma$	σ	$\Delta\sigma$
30.1			0.04	0.03				
31.3	0.005	0.002	0.07	0.01	0.041	0.014		
32.5			0.09	0.04	0.030	0.009		
33.5			0.21	0.06	0.056	0.012		
34.8	0.038	0.016	0.37	0.07	0.061	0.016		
35.7	0.046	0.018	0.74	0.07	0.106	0.010	0.022	0.002
36.8	0.073	0.036	1.87	0.17	0.102	0.035		
37.8	0.099	0.018	2.71	0.10	0.226	0.011	0.043	0.002
39.0	0.139	0.048	6.09	0.26	0.261	0.044		
39.9	0.119	0.041	7.61	0.21	0.444	0.005	0.088	0.005
40.9	0.123	0.060	10.35	0.35	0.483	0.068		
41.8	0.244	0.077	14.70	0.34	0.763	0.030	0.120	0.017
42.9	0.178	0.088	21.56	0.55	0.869	0.077		
43.8	0.328	0.087	23.81	0.55	1.28	0.005	0.201	0.032
44.8	0.358	0.100	31.13	0.60	1.48	0.14		
45.6	0.442	0.089	31.28	0.46	1.87	0.03	0.273	0.050
46.7	0.461	0.180	37.55	0.98	2.19	0.17		
47.4	0.536	0.097	39.40	0.54	2.91	0.04	0.376	0.040
48.4	0.615	0.200	45.15	1.10	3.38	0.28		
49.2	0.637	0.114	44.76	0.54	4.24	0.03	0.447	0.090
50.1	1.06	0.21	47.79	1.12	5.03	0.28		
50.8	0.68	0.08	49.94	0.62	6.23	0.095	0.513	0.006
51.8	0.95	0.23	49.33	1.18	7.05	0.43		
52.5	0.71	0.11	52.26	0.63	8.84	0.02	0.570	0.050
53.5	1.05	0.20	54.37	1.11	10.36	0.18		
54.2	0.87	0.11	50.38	0.64	11.70	0.02	0.502	0.120
55.0	1.20	0.19	52.32	1.17	13.71	0.27		

Table 4 continued

E_α [MeV]	^{7}Be σ	^{7}Be Δσ	^{22}Na σ	^{22}Na Δσ	^{24}Na σ	^{24}Na Δσ	^{28}Mg σ	^{28}Mg Δσ
55.6	0.96	0.10	48.93	0.63	15.11	0.05	0.46	0.04
56.8	1.32	0.19	48.60	1.08	17.25	0.40		
57.2	1.15	0.11	48.09	0.61	18.94	0.14	0.59	0.05
58.1	1.28	0.19	46.02	1.09	20.82	0.28		
58.8	1.32	0.10	46.20	0.58	22.56	0.28	0.60	0.01
59.6	1.33	0.19	44.63	1.03	24.49	0.34		
60.3	1.45	0.11	44.46	0.57	26.76	0.38	0.73	0.18
61.2	1.50	0.18	41.92	0.97	28.23	0.30		
61.8	1.35	0.07	41.44	0.53	29.81	0.27	0.51	0.12
62.6	1.41	0.18	40.79	0.90	31.40	0.79		
63.2	1.56	0.09	39.33	0.58	32.70	0.30	0.54	0.09
64.0	1.50	0.18	36.38	1.00	34.62	0.73		
64.6	1.67	0.10	37.38	0.57	35.12	0.16	0.59	0.10
65.4	1.93	0.17	34.46	0.88	36.51	0.78		
66.0	1.96	0.11	36.13	0.52	37.55	0.26	0.51	0.05
66.8	1.90	0.17	33.67	0.92	38.65	1.06		
67.9	1.98	0.08	33.38	0.42	38.10	0.81	0.50	0.08
68.7	2.15	0.12	31.36	0.61	40.30	0.30		
70.7	2.44	0.13	31.66	0.38	39.88	0.44	0.53	0.14
71.3	2.33	0.13	28.74	0.58	41.56	0.87		
73.4	2.68	0.09	30.00	0.35	40.74	0.74	0.42	0.05
74.0	2.44	0.13	28.96	0.61	42.06	0.39		
75.9	2.70	0.09	28.67	0.34	40.91	0.51	0.50	0.19
76.5	2.84	0.13	27.03	0.59	42.20	0.43		
78.4	2.93	0.10	29.06	0.36	40.51	0.03	0.35	0.03
78.9	3.13	0.13	28.05	0.58	40.74	0.38		
80.8	3.21	0.10	29.45	0.35	40.26	0.44	0.35	0.06
81.3	3.28	0.13	29.79	0.56	39.94	0.32		
83.1	3.44	0.10	29.91	0.35	39.41	0.24	0.35	0.09
83.7	3.39	0.14	28.63	0.58	39.96	0.89		
85.4	3.60	0.10	30.91	0.37	38.98	0.20	0.35	0.08
86.0	3.64	0.13	30.42	0.60	39.12	0.54		
87.6	3.65	0.11	32.26	0.40	37.98	0.02	0.40	0.01
88.2	3.83	0.14	31.78	0.60	38.29	0.64		
89.8	4.02	0.11	33.44	0.36	37.93	0.35	0.35	0.07
90.3	4.02	0.14	33.69	0.60	37.91	0.49		

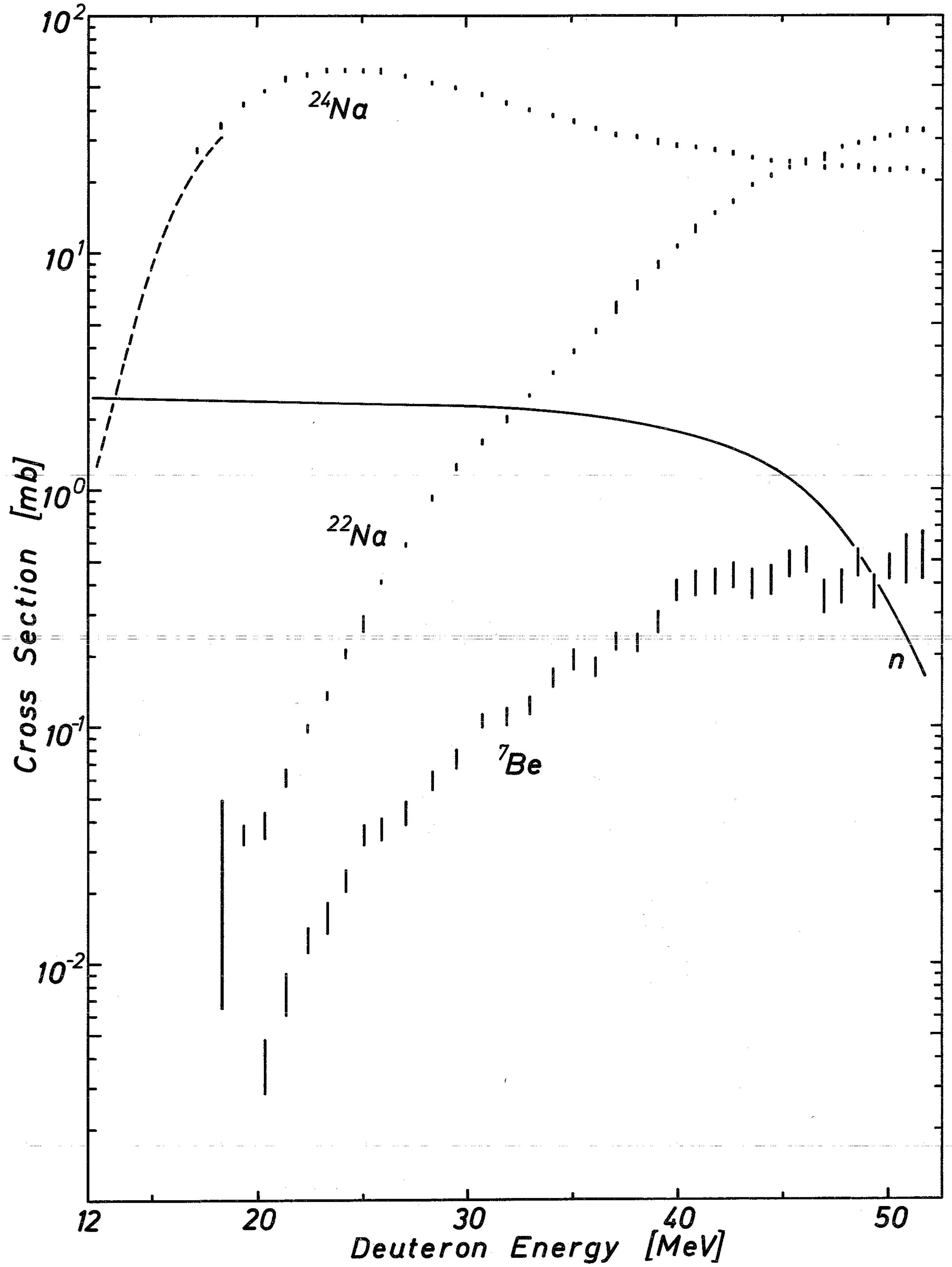
Table 4 continued

E_α [MeV]	^{7}Be		^{22}Na		^{24}Na		^{28}Mg	
	σ	Δσ	σ	Δσ	σ	Δσ	σ	Δσ
92.1	3.94	0.12	32.54	0.35	37.07	0.28	0.32	0.01
92.6	4.41	0.15	35.17	0.65	36.98	0.67		
94.3	3.94	0.11	35.62	0.40	37.11	0.26	0.26	0.05
94.6	4.15	0.15	35.27	0.61	37.00	0.40		
96.3	4.14	0.11	36.26	0.41	36.71	0.10	0.24	0.01
96.7	4.58	0.15	37.22	0.63	36.79	0.54		
98.3	4.60	0.12	38.10	0.43	37.05	0.15	0.21	0.07
98.6	4.66	0.16	37.40	0.68	36.22	0.36		
100.3	4.19	0.10	39.29	0.43	36.72	0.32	0.29	0.02
100.6	4.23	0.16	38.60	0.68	35.95	0.54		
102.3	2.94	0.11	38.78	0.42	34.44	0.12	0.28	0.02
102.7	2.81	0.14	39.39	0.66	35.29	0.45		

Figure Captions

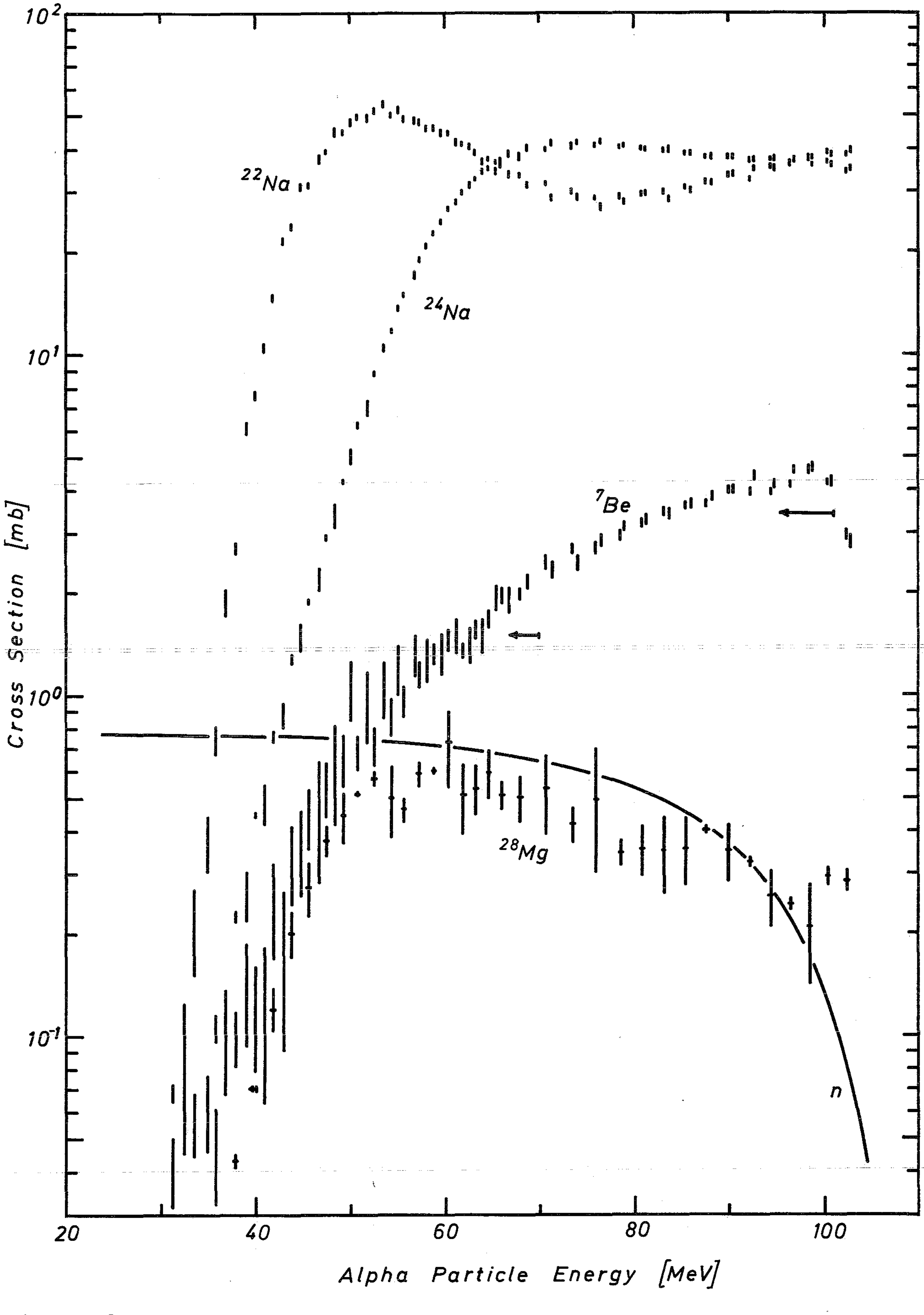
Figure 1 : Experimental cross sections for the production of ^{7}Be, ^{22}Na, and ^{24}Na by irradiation of ^{27}Al with deuterons. The curve labelled n shows the correction applied to the ^{24}Na cross section due to neutron produced ^{24}Na. The dashed curve was taken from reference 1. Only statistical errors are shown (see sect. 3). The error in the cross section scale is 2.5 %. The error in the energy scale is $\Delta E(E) = 12.5\ MeV^2/E$.

Figure 2 : Experimental cross sections for the production of ^{7}Be, ^{22}Na, ^{24}Na and ^{28}Mg by irradiation of ^{27}Al with alpha particles. The curve labelled n shows the correction applied to the ^{24}Na cross section due to neutron produced ^{24}Na. The arrows on the ^{7}Be excitation function show how far the ^{7}Be nuclei may recoil (see sect. 3). The error in the cross section scale is 2.5 %. The error in the energy scale is $\Delta E(E) = 50\ MeV^2/E$.



10^2
10^1
10^0
10^{-1}
10^{-2}
^{24}Na
^{22}Na
^{7}Be
n
Cross Section [mb]
12
20
30
40
50
Deuteron Energy [MeV]

Figure 1



10^2
10^1
10^0
10^{-1}
Cross Section [mb]
^{22}Na
^{24}Na
^{7}Be
^{28}Mg
n
20
40
60
80
100
Alpha Particle Energy [MeV]

Figure 2