markedly reduced from those at 14.7-Mev neutron energy.

CONCLUSION

The experimental results obtained in the present work support those findings previously reported[1] with the additional result that the 3.1-hr activity is associated with yttrium. Threshold considerations and the absence of a detectable beta particle associated with the 0.200- and 0.485-Mev gammas indicate an isomeric state of Y^{90}. The information on the decay of Y^{90m} is summarized in Fig. 4.

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Excitation Functions for Lithium-6 Induced Reactions on Aluminum-27†

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Excitation functions for a number of Li^6-induced reactions on Al^{27} have been studied using stacked foil techniques and the Li^6 ion beam from the Yale Heavy Ion Accelerator. Excitation functions corresponding to radioactive residual nuclei P^{32}, P^{30}, Si^{31}, Al^{29}, Al^{28}, Mg^{27}, Na^{24}, and Na^{22} have been measured in the Li^6 energy range from 1 to 63.3 Mev. The data strongly suggest that the P^{32}, P^{30}, and Si^{31} result from compound system processes and the Na^{22} and Na^{24} from a predominant direct knockout process. In the cases of Al^{28} and Al^{29} both compound system and direct pickup reaction amplitudes contribute to the reaction yield.

INTRODUCTION

SEVERAL laboratories[1–6] have reported results of the study of the interactions of accelerated Li^6 ions with various target materials. However, these data are limited either by very low Li^6 ion energies or by detection of the fragments resulting primarily from Li^6 ion breakup. The availability of a Li^6 ion beam of high intensity (3×10^{12} Li^6 ions/min) and energy (10.55 Mev/nucleon) from the Yale Heavy Ion Accelerator has facilitated more extensive studies, using activation methods, of excitation functions for several residual nuclei.

Reactions of particular interest are those, where the target nucleus—Li^6 ion interactions lead to products formed via nucleon pickup or charge exchange and those in which the target nucleus is depleted by one or more nucleons or nucleon-clusters as a result of a direct pickup or knockout reactions. In the present work Al^{27} foils were used as the target material because of the ease of identification of many of the residual nuclei in question (P^{32}, P^{30}, Si^{31}, Al^{28}, Al^{29}, Mg^{27}, Na^{22}, and Na^{24}) by observing either gamma-ray decay, beta decay, or both. In addition, the availability of very thin Al foils with uniform thickness and high purity permits the use of the normal stacked-foil technique.

EXPERIMENTAL

Foil stacks, each consisting of 27 foils of 99.9% Al^{27}, 4.65 mg/cm^2 in superficial density, were irradiated for periods ranging from 20 min to 1 hr with Li^6 ion beams having an incident energy of 10.55 ± 0.2 Mev per nucleon. In all bombardments the beam intensities were measured using a Faraday cup and a Cary electrometer. Following the bombardment the foils were separated, mounted on aluminum disks and the gamma-ray decay followed using a 3×3 in. NaI(Tl) crystal and a 400-channel pulse-height analyzer (Fig. 1; tables). The foils were counted with a gas-flow end-window beta proportional counter and the beta decay of P^{32}, Si^{31}, Na^{22}, and Na^{24} followed for times sufficient to establish accurate half lives.

The energy calibrations for the gamma-ray spectra were accomplished with several standard sources (i.e., Cs^{137}, Na^{22}, Mn^{54}, etc.). The gamma-ray spectra were normalized in the standard manner, corrections for background and efficiency[7] were applied, and the total disintegration rates established by observing the decay of the integrated areas of the gamma-ray peaks of interest. The gross beta-decay curves were resolved

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[3] E. Norbeck, *Proceedings of the Second Conference on Reactions between Complex Nuclei, Gatlinburg, Tennessee* (John Wiley & Sons, Inc., New York, 1960), p. 236.
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[6] E. Norbeck, J. M. Blair, L. Pinsouneault, and R. J. Gerbracht, Phys. Rev. **116**, 1560 (1959).
[7] R. L. Heath, Atomic Energy Commission Report, IDO-16408, 1957 (unpublished).

TABLE I. Assignment of activities observed.

Isotope	Mode of decay observed	γ-ray energy (Mev) Literature values[a]	γ-ray energy (Mev) Observed values	Half-life Literature values	Half-life Observed values
Phosphorus 32	β^-, 100%			14.5 days	14.5 days
Phosphorus 30	β^+, 100%			2.5 min	2.5–2.7 min
Silicon 31	β^-, 100%			2.62 hr	2.6 hr
Aluminum 28	γ	1.78, 100%	1.78	2.3 min	2.3 min
Aluminum 29	γ	1.28, 85%	1.28	6.6 min	6.6 min
Magnesium 27	γ	0.843, 70%	0.84	9.5 min	9.5 min
		1.015, 30%	1.0		
Sodium 22	β^+, 90%			2.6 yr	...
Sodium 24	β^-, γ, 100%	1.368, 100%	1.36	15 hr	15 hr
		2.75, 100%	2.7		

[a] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958): Nuclear Data Group, *Nuclear Data Sheets* (National Academy of Sciences, National Research Council, 1959).

into the half lives of the individual components, the counting rates corrected for counting efficiency, geometry, and window and air absorption. From these data the total disintegration rates at the end of bombardment were calculated.

Table I lists the observed and literature values for the gamma-ray energies and half-lives of the nuclides of interest in this study.

The activation cross sections for the radioactive nuclei formed were calculated using the thin-target equation and the corrected total disintegration rates found from gamma-ray spectra and/or gross beta counting. The excitation functions of the various products are listed in Table II. The Li^6 ion energy in a given Al foil was determined, using the range energy tables of Northcliffe.[8]

RESULTS

The activation cross sections at given energies for the formation of the radio-isotopes observed are tabulated in Table II, and the excitation functions shown in Figs. 2(a), 2(b), and 2(c). The cross sections were determined to within ±20%, except in the cases of Na^{22}, where the cross section values are the upper limits, and of Na^{24} [9] where the errors are listed in Table II and Fig. 2(c).

As the Li^6 ion beam energy is reduced in traversing the foil stacks the uncertainty in beam energy from the entrance into and exit from individual foils increases. This uncertainty is represented by the error bars at each value (Fig. 2). The excitation function was drawn through the mean energy point in each foil with no attempt to correct for range straggling. However, this error is relatively small since the aluminum foils used had a mean thickness of 4.65 mg/cm², which is less than 5% of the total range of the 10.55 Mev per nucleon Li^6 ion beam [total range 126.5 mg Al/cm² [8]]. Consequently the errors introduced by the Li^6 beam straggling were neglected in this study, since their magnitudes were small compared to the general error of ±20% encountered in the cross section determination.

The possibility of the production of nuclei by neutron induced reactions (e.g., Al^{28}, Na^{24}, and Mg^{27}) is eliminated by consideration of the activity found in the individual foils. If neutron induced reactions made an appreciable contribution to the intensity of a particular activity, then it would have been observed in foils beyond the range of the Li^6 ion beam. But no activities were found in these Al-foils and therefore it is concluded that all observed residual nuclei were produced by Li^6 ion induced reactions.

The shape of the excitation functions normally expected for the compound-nucleus-produced nuclides is distorted in the higher energy ranges due to the recoil range of the products (P^{32}, P^{30}, and Si^{31}). However, considerations of range-energy relations[8,10] show there

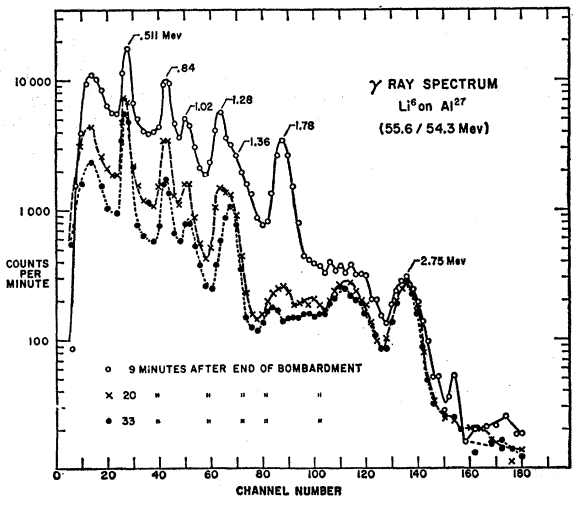

FIG. 1. Typical gamma-ray spectrum observed in an Al foil after irradiation with a beam corresponding to 55±0.6 Mev Li^6 ions.

[8] L. Northcliffe, Phys. Rev. **120**, 1744 (1960).
[9] Inge-Maria Ladenbauer, Nuclear Phys. **23**, (1961).
[10] J. B. J. Read (private communication).

TABLE II. Formation cross section (mb).[a]

Foil No.	Li^6 ion energy (Mev)	P^{32}	P^{30}	Si^{31}	Al^{28}	Al^{29}	Mg^{27}	Na^{24}	Na^{22}
1	63.3–61.6				(23.6)		(4.4)	(32.6±4.6)	(33.4)
2	61.6–60.0				28.4	5.7	5.9	43.0±8.0	37.6
3	60.0–58.7								37.6
4	58.7–57.0				37.8	5.4	6.4	40.3±4.4	30.2
5	57.0–55.6								26.7
6	55.6–54.3							40.7±4.0	24.7
7	54.3–52.8								20.6
8	52.8–51.0				39.2	6.5	6.7	41.1±4.6	18.9
9	51.0–49.4								20.6
10	49.4–47.9							44.0±3.2	18.7
11	47.9–46.2								17.7
12	46.2–44.4		13.8		50.5	5.4	8.0	43.3±1.0	14.6
13	44.4–42.6								13.1
14	42.6–40.5							43.8±0.9	12.4
15	40.5–38.7								
16	38.7–36.6		27.6		70.8	2.75	7.7	43.3±3.4	
17	36.6–34.7	0.37						34.3±0.7	
18	34.7–32.4	0.40						30.2±0.5	
19	32.4–30.4	0.44		3.81				21.2±1.7	
20	30.4–27.9	0.50	42.7	4.5	72.5		4.3	14.3±1.2	
21	27.9–25.0	0.58		7.35				7.6±0.2	
22	25.0–22.1	0.65	29.1	8.7	80.8		1.2	3.4±0.6	
23	22.1–18.9	1.2		11.9				0.9±0.1	
24	18.9–15.0	1.87	20.1	26.6	97.4				
25	15.0–10.5	3.2		24.4					
26	10.5– 6.0	6.0	7.3	4.9	76.5				
27	6.0– 0.0	1.64			0.69				

[a] With the exception of Na^{22} and Na^{24} all cross sections have an inherent uncertainty of ±20% (see text).

can be little effect of recoil in the cases of other nuclides observed, since the available energy is insufficient to produce recoils greater than the foil thicknesses employed.

The energy resolution of the gamma-ray spectra (e.g., 7.3% at 1.78 Mev and 9.3% at 0.84 Mev) permitted an accurate determination of the individual gamma-ray energies and intensities because of the negligible interference between adjacent gamma-ray peaks observed. In addition the accuracy of the half-life resolution found by following both gamma-ray decay and beta decay was enhanced by the magnitude of the half lives of the individual nuclides of interest (see Table I). Consequently, chemical separations of the radioisotopes produced by Li^6 irradiation were not necessary, thereby eliminating the inherent error in determining chemical yields.

CONCLUSION

From the shape of the excitation functions it is strongly suggested that the production of P^{30}, P^{32}, and Si^{31} [Fig. 2(a)] occurs through a compound system formation and decay. The broadening of the P^{30} excitation function may in part result from the difficulty experienced in resolving the decay of the 0.511-Mev annihilation peak from the contributions made by other positron emitters formed during the irradiation. Both the shape and the position of the peaks of these excitation functions agree with those which are generally anticipated for a compound nucleus mechanism.

The Al^{28} excitation function seems to suggest that possibly two or more modes of formation contribute to the yield observed. At the lower beam energies (25 Mev and below), the most probable reactions leading to Al^{28} from Al^{27} appears to have the characteristics of a compound nucleus, and/or a stripping mechanism. That is, the excitation function exhibits a sharp increase with increasing energy reaching a maximum cross section value at 20 Mev. The excitation function seems analogous to that observed in the above cases (P^{30}, P^{32}, Si^{31}) with a marked contribution from a direct stripping mechanism. Since the recoil range of Al^{28}

TABLE III. Q values for Li^6-induced reactions on Al^{27}.[a]

Reaction products	Q value (Mev)
$P^{32}+1p$	+13.9
$P^{30}+1p+2n$	−6.37
$Si^{31}+2p$	+5.27
$Al^{28}+1p+1\alpha$	+4.96
$Al^{28}+Li^5$	+2.23
$Al^{29}+3p+1n$	−14.87
$Al^{29}+2p+d$	−12.63
$Mg^{27}+1\alpha+2p$	−3.60
$Na^{22}+2\alpha+1p+2n$	−26.20
$Na^{22}+2\alpha+T^3$	−17.73
$Na^{22}+B^{11}$	−6.60
$Na^{24}+Li^6+2p+1n$	−31.32
$Na^{24}+Li^6+He^3$	−23.70
$Na^{24}+2\alpha+1p$	−6.83
$Na^{24}+B^9$	−7.02

[a] V. A. Kravtsov, Upsekhi Fiz. Nauk **65** (3), 451 (1958). Mass table used for the calculation of the Q values.

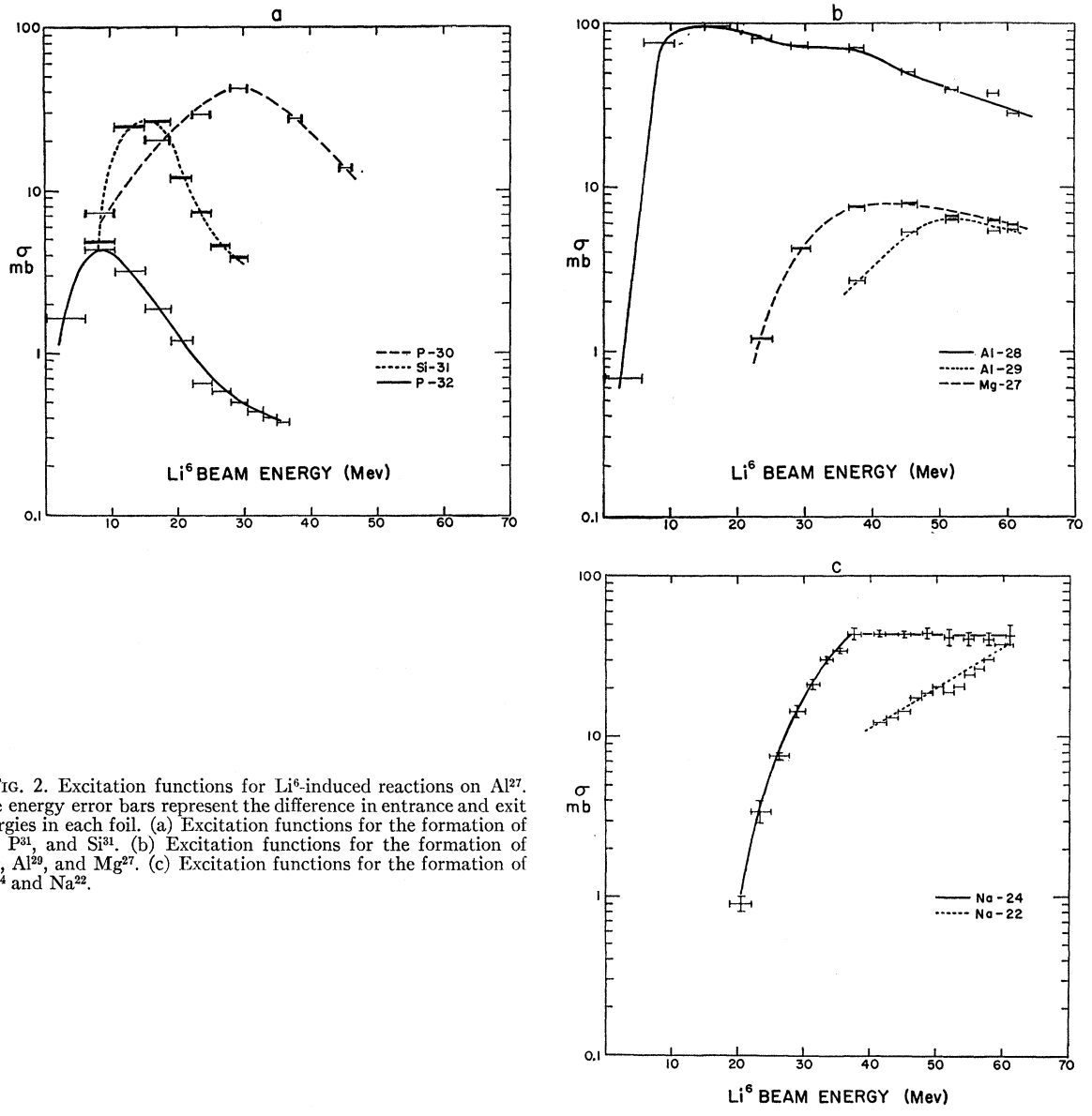

FIG. 2. Excitation functions for Li^6-induced reactions on Al^{27}. The energy error bars represent the difference in entrance and exit energies in each foil. (a) Excitation functions for the formation of P^{30}, P^{31}, and Si^{31}. (b) Excitation functions for the formation of Al^{28}, Al^{29}, and Mg^{27}. (c) Excitation functions for the formation of Na^{24} and Na^{22}.

resulting from Al^{27}-Li^6 compound system mechanism is small compared to the foil thicknesses employed, the part of the excitation function above 25 Mev can not be attributed to the recoil range of this nuclide. Apparently then, the predominant contribution to the cross section in the higher energy range is from one or more direct interaction processes. The most probable of these is a direct neutron pickup by the Al^{27} target nucleus.

Morrison,[1,5] Anderson,[4] and Gluckstern and Breit[11] have studied a mode of Li^6 breakup producing He^4 and a deuteron. The breakup of the projectile with its component nucleon clusters contains the inference that the Al^{28} formation may not only be due to the stripping of a neutron from Li^6 as such, but also to stripping from the individual clusters which make up the Li^6 nuclide. More specifically, the Li^6 interaction may be enhanced by the apparent He^4-d structure, in which the deuteron cluster is most probably the major contributor to the neutron stripping process. (e.g.,

$$Al^{27}+Li^6 \rightarrow [Al^{27}+(\alpha,d)] \rightarrow Al^{28}+\alpha+p).$$

This reaction mechanism would be most probable in a surface interaction similar to the contact process suggested by Kaufmann and Wolfgang[12,13] since the wave functions for the He^4-d system indicates the existence of the deuteron in the diffuse area outside the

[11] R. Gluckstern and G. Breit, *Proceeding of the Second Conference on Reactions between Complex Nuclei, Gatlinburg, Tennessee* (John Wiley & Sons, Inc., New York, 1960), p. 77.

[12] R. Kaufmann and R. Wolfgang, Phys. Rev. **121**, 192 (1961).
[13] R. Kaufmann and R. Wolfgang, Phys. Rev. **121**, 206 (1961).

He^4 core of Li^6.[11] The Q values in Table III for Al^{27} $(Li^6;\alpha,p)Al^{28}$ represent a magnitude attributed to a compound system formation with subsequent evaporation of particles. The value should not be much in excess of that anticipated for the reaction proceeding through the reaction intermediate. However, unlike the compound nucleus, the reaction intermediate would retain the basic structure of the nuclides forming it to a large degree.

The production of Al^{29} probably takes place via a two-neutron pickup by the target nucleus in a direct interaction mechanism, in addition to some contribution from the compound system production. However, the general shape of the excitation function is indicative of a direct interaction mode of production, most probably related to the contact stripping mechanism[12,13]. A significant contribution to the total yield of Al^{29} by the compound is decreased by consideration of the level densities of the residual nuclei. At these energies, the Q values indicate that the formation of Al^{28} by the evaporation of individual nucleons from the compound system would be favored over the formation of Al^{29} which would be formed near its ground state by a similar cascade (see Table III).

The formation of Mg^{27} via a compound nucleus mechanism is possible, but with only a small probability. As in the case of Al^{29}, level density consideration would not appear favorable for the compound system approach. The shape of the excitation function indicates the predominant mechanism is that of a direct interaction, since the peaking of the excitation functions appears to be negligible. In this case a reaction intermediate similar to that proposed for the Al^{27}-Al^{28} system seems to be appropriate (e.g.,

$$Al^{27}+Li^6 \rightarrow [Al^{27}+(\alpha,d)] \rightarrow Mg^{27}+\alpha+2p).$$

This mechanism is then analogous to the $(d,2p)$ or (n,p) direct interaction mechanism, with the deuteron cluster of Li^6 enhancing the yield of Mg^{27} over that anticipated from nucleon exchange produced by the Li^6 nuclide itself. The possibility of charge exchange between Li^6 or the nucleon clusters He^4-d and the target also presents itself. Again this mode of formation of Mg^{27} would be enhanced by the cluster structure of Li^6 and the surface interaction mechanism[12,13] discussed above.

The mechanism by which Na^{22} and Na^{24} are formed is almost certainly a direct interaction. This mechanism most probably involves either the evaporation, stripping or direct knock-on of nucleon clusters from the Al^{27} target. The excitation function indicates very little, if any, contribution from a compound system mechanism. As in the (d,p) instances previously discussed, a reaction intermediate may present considerable contribution to the over-all cross section found for these nuclides.

In general, it is highly probable that in all instances not clearly specified as compound system information and decay (i.e., all cases other than P^{30}, P^{32}, Si^{31}, and a portion of the low-energy Al^{28} formation), one or more direct interaction mechanisms predominate. The relative yields, apparent threshold energies and general shapes of the excitation function seem to indicate the importance of the contact process and subsequent reaction intermediate formation. A more precise conclusion as to the importance of the He^4-d structure of the Li^6 projectile and the nucleon cluster character of the target, as well as the relative merits of direct interaction, reaction intermediate, or compound nucleus formation, requires a careful analysis of excitation functions resulting from other heavy ion experiments and on a comparison of activation cross section data with those based on identification of the light fragments (He^3, He^4, Li^5, Be^7, etc.) resulting from a heavy ion-Al^{27} system.

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