Excitation Functions for Heavy-Ion-Induced Reactions on Aluminum-27*

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Excitation functions for a number of C^{12}-, N^{14}-, and O^{16}-induced reactions on aluminum-27 have been studied using stacked-foil techniques and the ion beams of the Yale Heavy Ion Accelerator. The yields of $Cl^{34,38}$, P^{32}, $Al^{28,29}$, Mg^{27}, Na^{24}, and F^{18} have been measured in the energy range from 10.5 to about 1 Mev per nucleon. The production of the radionuclides $Cl^{34,38}$, P^{32}, and in the case of C^{12} irradiation Al^{28}, are due to evaporation processes from a compound-nucleus system, while the production of F^{18}, Na^{24}, Al^{28}, Al^{29}, and Mg^{27} seems to occur by a direct-interaction mechanism. A comparison of the yields for specific radionuclei produced by different beams is given.

INTRODUCTION

HEAVY-ION-INDUCED reactions on Al^{27} have been reported by several groups.[1–5] However, these data have been in qualitative form, concentrated in particle detection or low or poorly defined heavy-ion beam energies. The intense beam currents and the well-defined ion beam from the Yale Heavy Ion Accelerator have facilitated a more quantitative investigation of the excitation function for the formation of several residual radio nuclides resulting from C^{12}, N^{14}, and O^{16} bombardments on Al^{27}.

The data presented make it possible to compare excitation functions for the various residual nuclei arising from direct interaction, reaction-intermediate, or compound-nucleus formation and decay in a particular projectile-target system, as well as demonstrating the relative effects of projectile structure on the different reaction mechanisms. Of particular interest are the excitation functions for radio nuclei produced by a pickup of nucleons by the target nucleus or charge exchange (exchange transfer reaction) and those in which the target nucleus is depleted by one or more nucleons or nucleon clusters.

This study has been carried out using C^{12}, N^{14}, and O^{16} heavy-ion beams ranging in energy from approximately one to 10.5 Mev per nucleon. Al^{27} was chosen as target material because of the availability of uniform thin foils of high purity, and the ease of identification of the residual nuclei anticipated from the heavy-ion-induced reactions (i.e., Cl^{34}, Cl^{38}, P^{32}, Al^{28}, Al^{29}, Mg^{27}, Na^{24}, and F^{18}). The cross sections were calculated from the data found by following the gamma-ray decay, gross beta decay, or both. The method of target preparation and irradiation was the usual stacked-foil technique.

EXPERIMENTAL

Foil stacks consisting of a number of Al^{27} foils (4.56 mg/cm^2 in superficial density), corresponding to the range of the incident heavy-ion beams in aluminum, were irradiated for periods ranging from 15 minutes to one hour. The incident beam energies were equivalent to 10.5 ± 0.2 Mev per nucleon for C^{12} (charge $+5$), N^{14} (charge $+6$), and O^{16} (charge $+6$), while the minimum energy observed represented energies of approximately 1 Mev per nucleon. The beam was integrated (charge integration) by use of a Faraday cup and a Cary electrometer.

At the end of each irradiation the foils were separated, mounted on aluminum disks and the gamma-ray or gross beta decay of the radionuclides formed was followed using the same methods and equipment described in an earlier paper.[6]

The cross sections were calculated from the corrected disintegration rates found by gamma-ray spectroscopy and/or gross beta-decay analysis in a manner similar to that previously reported by the authors.[6] The beam energies in a given foil were interpolated from the data of Northcliffe.[7]

Table I lists the observed and literature values of the gamma-ray energies and half-lives of the residual nuclei of interest. In Tables II–IV the calculated thin-target cross sections at the various heavy-ion beam energies are tabulated.

RESULTS

The activation cross sections listed in Tables II–IV and the corresponding excitation functions (Fig. 1–4) were determined to $\pm30\%$ in all cases except for the yields of Al^{29}, Mg^{27}, and the Cl^{34}-Cl^{38} yields resulting from O^{16} and N^{14} bombardments. The Al^{29} and Mg^{27} cross sections given in this paper represent the upper limit of these values, while the excitation functions for the O^{16} and N^{14} yields of Cl^{34}-Cl^{38} represent the total

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[1] K. F. Chackett, J. H. Fremlin, and D. Walker, Phil. Mag. **45**, 173 (1954).
[2] K. F. Chackett and J. H. Fremlin, Phil. Mag. **45**, 735 (1954).
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[4] W. H. Webb, H. L. Reynolds, and A. Zucker, Phys. Rev. **102**, 749 (1956).
[5] J. J. Pinajian, Nuclear Physics, **17**, 44 (1960).
[6] I. M. Ladenbauer, I. L. Preiss, and C. E. Anderson, Phys. Rev. **123**, 1368 (1961).
[7] L. Northcliffe, Phys. Rev. **120**, 1744 (1960).

yield of both nuclides, since no attempt was made to resolve either their gamma-ray spectra or gross beta-decay curves (similar gamma rays and half-lives) with respect to these two nuclides.

The uncertainty in beam energies in given foils is represented by the error bars plotted with the excitation function. These error bars represent the energy loss which the heavy ion undergoes in each given Al foil. This uncertainty in energy, and the fact that no correction for beam straggling was applied to the data, may produce a "shift" in the excitation function, corresponding to a few mg/cm² of Al, but should not affect the general shape of the excitation functions.

The shape of the excitation functions normally

TABLE I. List of residual nuclei observed formed by C^{12}, N^{14}, and O^{16} irradiations on aluminum-27.

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
Chlorine-38	β^-, 100%	...	...	37 min	...
Chlorine-34	β^+, 100%	...	...	32.4 min	35 min
Phosphorus-32	β^-, 100%	...	...	14.5 days	14.5 days
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-24	β^-, 100%	...	...	...	...
	γ, 100%	1.368, 100%	1.36	15 hr	15 hr
	... ...	2.75, 100%	2.7	...	...
Flourine-18	β^+, 100%	...	...	1.87 hr	1.85–1.9 hr

[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).

TABLE II. C^{12}-induced reaction on Al^{27}.

Foil No.	Energy (Mev)	Formation cross section (mb) Cl^{34}	P^{32}	Al^{28}	Al^{29}	Mg^{27}	Na^{24}	F^{18}
1	126.0–120.5	...	...	...	...	...	(13.0)[a]	(11.9)[a]
2	120.5–115.0	...	22.4	...	...	...	24.6	19.5
3	115.0–108.5	...	27.2	3.84	0.69	0.73_2	22.5	22.5
4	108.5–102.5	...	32.0	6.40	0.69	0.24_4	14.7	29.5
5	102.5– 94.8	...	41.6	...	...	...	11.2	27.2
6	94.8– 89.5	...	56.8	50.8	0.73	...	7.7_5	27.8
7	89.5– 82.4	6.0	75.3	...	...	...	4.6_3	19.8
8	82.4– 75.5	7.2	89.7	4.74	0.55	...	...	14.5
9	75.5– 66.2	5.6	99.3	...	...	...	...	14.5
10	66.2– 57.6	14.0	92.8	...	...	...	...	4.0
11	57.6– 47.5	19.0	56.0	...	...	...	...	...
12	47.5– 35.2	60.0	14.4	...	...	...	0.57	...
13	35.2– 20.4	76.0	...	...	...	...	0.38	...
14	20.4– 3.0	5.4	...	...	...	...	0.08	...
15	3.0 ...	...	...	...	...	...	0.06	...

[a] Values in parenthesis are not shown in the corresponding excitation functions.

TABLE III. N^{14}-induced reaction on Al^{27}.

Foil No.	Energy (Mev)	Formation cross section (mb) Cl^{34+38}	P^{32}	Al^{28}	Al^{29}	Mg^{27}	Na^{24}	F^{18}
1	147.0–140.0	(4.8)[a]	(10.4)[a]	...	...	...	(14.3)[a]	(8.9)[a]
2	140.0–132.0	11.2	37.4	15.3	10.2	2.09	24.6	17.9
3	132.0–123.0	10.1	45.8	...	...	...	22.2	20.7
4	123.0–114.0	12.7	54.8	15.3	15.3	<1.0	21.3	20.0
5	114.0–104.0	12.0	54.8	...	...	...	20.3	20.4
6	104.0– 95.7	12.4	54.8	19.2	<1.5	<0.1	15.3	21.6
7	95.7– 87.0	15.7	45.8	...	...	...	13.2	21.6
8	87.0– 75.0	28.4	45.8	19.2	...	...	7.9	24.4
9	75.0– 63.2	36.0	65.5	...	...	...	3.0	22.3
10	63.2– 48.5	34.4	87.3	9.0	...	...	...	16.0
11	48.5– 30.8	34.4	84.5	...	...	...	...	5.5
12	30.8– 8.0	25.5	10.4	...	...	...	...	0.65
13	8.0– ...	...	...	...	...	...	...	...

[a] Values in parenthesis are not shown in the corresponding excitation functions.

TABLE IV. O^{16}-induced reaction on Al^{27}.

Foil No.	Energy (Mev)	Formation cross section (mb) Cl^{34+38}	P^{32}	Al^{28}	Al^{29}	Mg^{27}	Na^{24}	F^{18}
1	168.0–161.0	(3.9)[a]	(8.9)[a]	...	...	...	(9.3)[a]	(11.7)[a]
2	161.0–150.0	8.9	45.3	8.82	present	0.59	16.2	21.7
3	150.0–140.0	8.9	58.3	6.78	in foils	0.44	15.6	27.0
4	140.0–129.0	9·6	66.5	8.14	1 to 4	...	13.4	28.1
5	129.0–114.2	9.6	81.0	5.28	...	0.15	6.7	33.9
6	114.2–104.5	10.0	93.5	...	...	...	4.7	32.8
7	104.5– 91.0	7.5	76.2	...	...	...	3.5_4	38.6
8	91.0– 75.5	11.4	31.2	...	...	...	2.0	43.3
9	75.5– 57.7	18.8	5.6_5	...	...	...	1.7_4	30.9
10	57.5– 35.5	10.3	...	...	...	...	0.47	12.0
11	35.5– 8.0	...	...	...	...	...	0.06	0.59
12	8.0 ...	...	...	...	...	...	...	...

[a] Values in parenthesis are not shown in the corresponding excitation functions.

expected for a compound-nucleus mechanism is distorted in the higher energy ranges principally because of the recoil range of the products (P^{32}, Cl^{34}, Cl^{38}). That is, the high-energy tail is probably due in part to a displacement of the peak anticipated for compound-nucleus formation and decay. However, consideration of range-energy relations[7] shows there can be little effect of recoil in the cases of the other nuclides observed in this study, since the available energy (for such products as Al^{28}, Na^{24}, and other light residual nuclei) is insufficient to produce recoil ranges greater than one or two target foil thicknesses.

The energy resolution of the detector system (a 3×3-inch NaI(Tl) crystal; 400-channel pulse-height analyzer) employed in this work was 7.3% at 1.78 Mev and 9.3% at 0.84 Mev facilitating the identification of the gamma rays of interest and permitting an accurate half-life assignment to the gamma peaks at given energies. For this reason and because the gross beta decay observed by using an end-window gas flow proportional counter could be resolved accurately into its components, no chemical separations were performed.

A contribution to the activity observed for given residual nuclei by neutron-induced reactions was eliminated. This was accomplished by determining that no activity was present in the Al^{27} foils beyond the range of the full energy heavy-ion beams (65 mg/cm² for C^{12}, 57.5 mg/cm² for N^{14}, and 50.5 mg/cm² for O^{16} at incident energies of 10.5±0.2 Mev/nucleon). If a neutron-induced contribution were significant, these activities would be observed in foils beyond this maximum range, as the range of fast neutrons is considerably greater than that of the heavy ions.

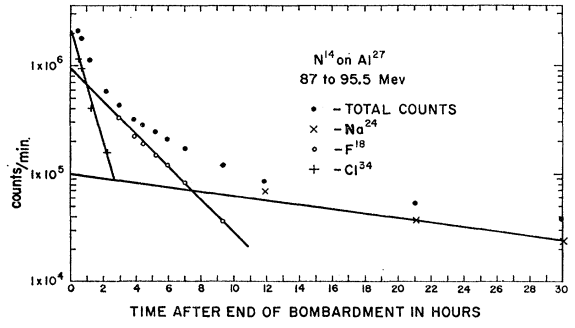


FIG. 1. Typical gross beta-decay curve observed in an Al foil after bombardment with 87- to 95.5-Mev N^{14} beam.

DISCUSSION

The criteria used in interpreting the excitation functions as to reaction mechanism are based on the general considerations employed in light-particle-induced reaction studies.

Hence, mechanisms are crudely related to the excitation function shape and more exactly to the apparent threshold energy for the process in question. The shape of the excitation function anticipated for compound-nucleus formation and subsequent decay by evaporation cascade will exhibit a peaking in cross section. The peak should correspond to the most probable energy distribution for the evaporated fragments. In this study, the high-energy tail exhibited by the curves for such products as P^{32} and Cl^{34} arise, then, not only from the effect of finite recoil range (see results), but also from the existence of various modes of decay of the compound system forming the same residual nuclide. For example, in the P^{32} yield from C^{12} on Al^{27}, the most energetically favored mode of formation is that of evaporation of an alpha particle, deuteron, and proton from the compound system. At higher energies single-nucleon evaporation becomes energetically possible (see Table V). Hence, the cross section for the formation of the residual nuclide is a composite of several modes of formation resulting from the energy dependence of the several possible evaporation processes giving rise to this nuclide. However, the significant characteristic of marked energy dependence (resulting in peaking of the excitation function) is evident for the most probable type of evaporation cascade.[8,9]

[8] R. Beringer and W. K. Knox, Phys. Rev. **121**, 1195 (1961).
[9] R. Beringer (private communication).

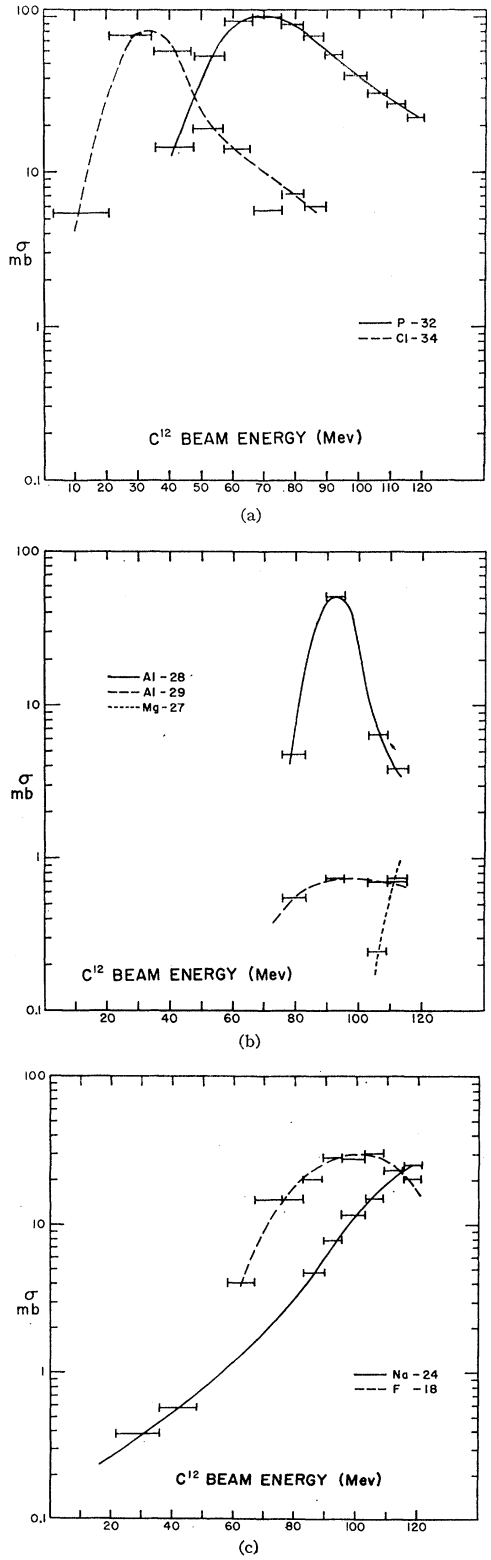


FIG. 2. Excitation functions for C^{12}-induced reactions on Al^{27}. The error bars represent the difference between beam energies on entering and leaving a given foil. (a) Excitation function for the formation of P^{32} and Cl^{34}. (b) Excitation function for the formation of Al^{28}, Al^{29}, and Mg^{27}. (c) Excitation function for the formation of Na^{24} and F^{18}.

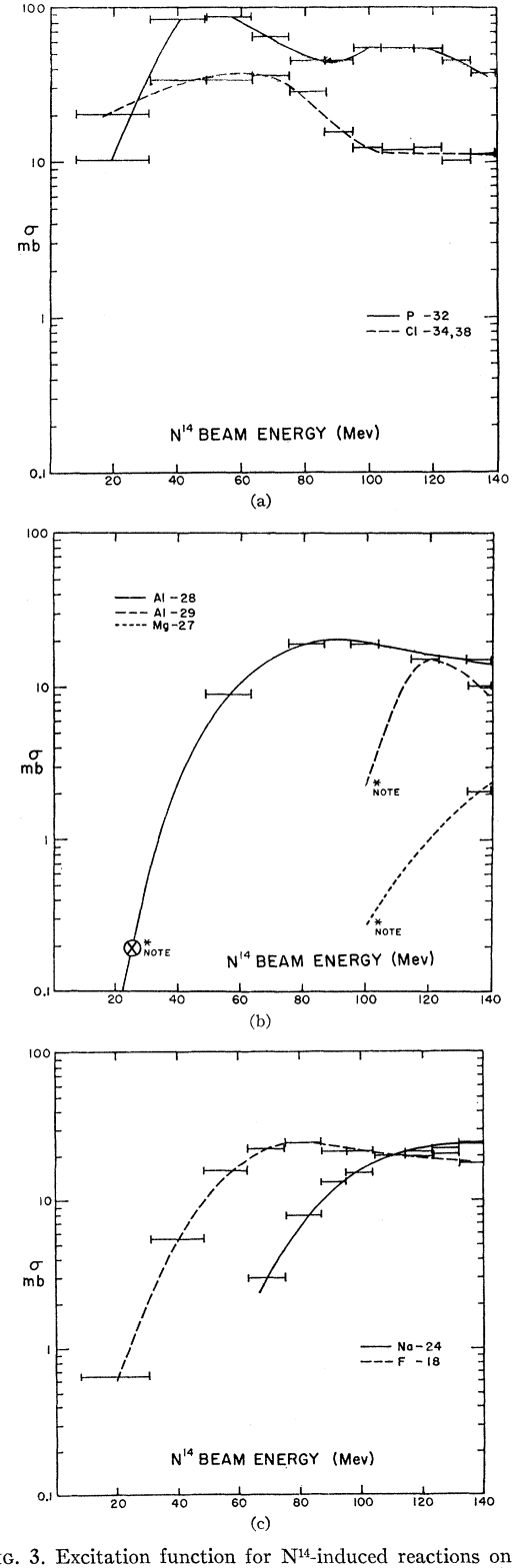
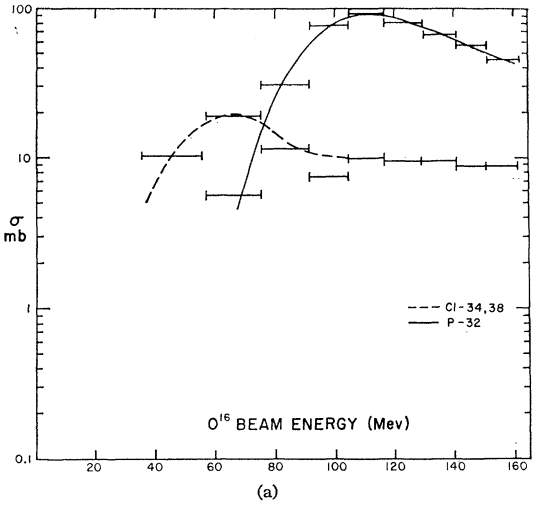
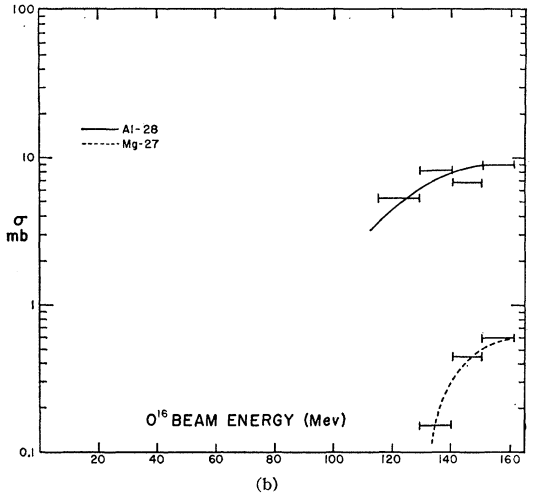


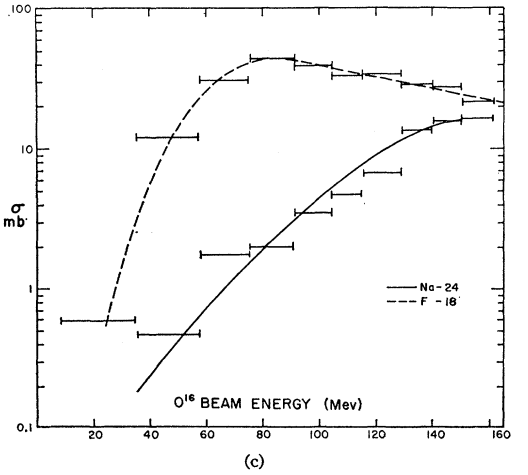
FIG. 3. Excitation function for N^{14}-induced reactions on Al^{27}. (a) Excitation function for the formation of P^{32} and $Cl^{34,38}$. (b) Excitation function for the formation of Al^{28}, Al^{29}, and Mg^{27}. [Note the point in the Al^{28} data is that due to Webb *et al.* (reference 2); for specific information on the Al^{29} and Mg^{27} cross section, see Table III.] (c) Excitation functions for the production of Na^{24} and F^{18}.



(a)



(b)



(c)

FIG. 4. Excitation functions for O^{16}-induced reactions on Al^{27}. (a) Excitation function for the production of $Cl^{34,38}$ and P^{32}. (b) Excitation function for the production of Al^{28} and Mg^{27}. (c) Excitation function for the production of Na^{24} and F^{18}.

The excitation functions for direct interaction products should exhibit little tendency toward the marked energy dependence (resulting in sharp peaking) found for the compound-nucleus mechanism. Recoil of the residual nuclides produced via the direct process and for nuclides of masses similar to, or less than, that of the target formed by either mechanism will be negligible. For example the absence of the high-energy tail for the Al^{28} yield from O^{16} on Al^{27}, and the yields of F^{18} and Na^{24} illustrate this point.

Tunneling[10–13] and grazing collision processes,[14] by definition are reactions proceeding below or just above the Coulomb barrier, and will be considered only in those cases where the low-energy limitations of this study permit.

C^{12}-Ion-Induced Reactions

The shape of the excitation function indicates that the formation of P^{32}, Cl^{34}, and Al^{28} are a result of compound-nucleus formation and decay. As noted above, at higher beam energies it is possible that several modes of production, and/or energy distribution of evaporated nucleons, result in the tail exhibited by the excitation functions found for P^{32} and Cl^{34}. Since the peaking in the Al^{28} yield occurs at relatively high beam energies with respect to the Coulomb barrier, such processes as tunneling or grazing collisions probably contribute little to the yield of this nuclide in the C^{12}-Al^{27} system.

The data indicate that probably both F^{18} and Al^{29} were formed with a marked contribution from the compound-nucleus process, although the broad peaking (as compared to that for Al^{28}) would suggest that a contribution from a direct-interaction mode of formation could be significant (e.g., 2-neutron pickup in the case of Al^{29}). The yield of Al^{29} from the compound system would be expected to be less than that of Al^{28} on the basis of level density considerations. However, the very large decrease in relative yield as compared to Al^{28} would not seem justifiable on this basis alone.

While sufficient data are not available to assign the production of Mg^{27} to any specific reaction mechanism, the apparent threshold energy would indicate that this residual nuclide is formed principally through a compound-nucleus process.

The yield of Na^{24} appears to exhibit the characteristics of a direct interaction mechanisms at the lower energies (energy below the threshold for the evaporation of nucleons from the compound system). At higher energies, the changes in slope of the excitation function would seem to indicate that the compound-nucleus process contributes to the yield to a marked

[10] J. A. McIntyre, T. L. Watts, F. C. Jobes, Phys. Rev. **119**, 1131 (1960).
[11] G. Breit, M. Hitlull, R. C. Gluckstern, Phys. Rev. **87**, 74 (1952).
[12] G. Breit, M. E. Ebel, Phys. Rev. **103**, 679 (1956).
[13] G. Breit, M. E. Ebel, Phys. Rev. **104**, 1030 (1956).
[14] R. Kaufman and R. Wolfgang, Phys. Rev. **121**, 206 (1961).

TABLE V. Q values[a] for the formation of the residual nuclei observed.

$N^{14}+Al^{27}$ Products	$-Q$(Mev)	$C^{12}+Al^{27}$ Products	$-Q$(Mev)	$O^{16}+Al^{27}$ Products	$-Q$(Mev)
$Cl^{38}+3p$	6.41	...	...	$Cl^{38}+4p+1n$	29.28
$Cl^{34}+1\alpha+1p+2n$	15.79	$Cl^{34}+1\alpha+1n$	3.30	$Cl^{34}+2\alpha+1n$	10.46
$Cl^{34}+3p+4n$	44.08	$Cl^{34}+2p+3n$	31.46	$Cl^{34}+4p+5n$	66.97
$P^{32}+2\alpha+1p$	2.17	$P^{32}+1\alpha+2p+1n$	17.59	$P^{32}+2\alpha+2p+1n$	25.10
$P^{32}+5p+4n$	58.75	$P^{32}+4p+3n$	46.26	$P^{32}+6p+5n$	81.62
$Al^{28}+3\alpha+1p$	12.05	$Al^{28}+2\alpha+2p+1n$	27.63	$Al^{28}+3\alpha+2p+1n$	34.96
$Al^{28}+7p+6n$	96.81	$Al^{28}+6p+5n$	79.78	$Al^{28}+8p+7n$	120.06
$Al^{29}+2\alpha+3p+1n$	30.94	$Al^{29}+2\alpha+2p$	18.45	$Al^{29}+3\alpha+2p$	25.61
$Al^{29}+7p+5n$	87.43	$Al^{29}+6p+4n$	74.95	$Al^{29}+8p+6n$	110.36
$Mg^{27}+3\alpha+2p$	21.60	$Mg^{27}+2\alpha+3p+1n$	37.39	$Mg^{27}+3\alpha+3p+1n$	44.55
$Mg^{27}+8p+6n$	106.45	$Mg^{27}+7p+5n$	93.68	$Mg^{27}+9p+7n$	120.21
$Na^{24}+N^{13}+p$	13.69	...	...	...	...
$Na^{24}+F^{17}$	7.88	...	...	...	...
$Na^{24}+4\alpha+1p$	22.92	$Na^{24}+3\alpha+2p+1n$	38.89	$Na^{24}+4\alpha+2p+1n$	45.86
$Na^{24}+9p+8n$	135.92	$Na^{24}+8p+7n$	123.44	$Na^{24}+10p+9n$	158.85
$F^{18}+Na^{23}$	5.70	...	...	...	...
$F^{18}+5\alpha+1p+2n$	41.47	$F^{18}+5\alpha+1n$	38.28	$F^{18}+6\alpha+1n$	45.44
$F^{18}+11p+12n$	191.92	$F^{18}+10p+11n$	179.53	$F^{18}+12p+13n$	214.95

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

degree over that of direct interaction. A more exact analysis is prohibited by the high-energy limitation of the experiment.

O^{16} Induced Reactions

Both the formation of P^{32} and the composite Cl^{34}-Cl^{38} can be attributed to compound-nucleus formation and decay based on the shapes of the excitation functions. The high-energy tail in the Cl^{34} and Cl^{38} yield is principally due to the inability to resolve the two Cl gamma or beta rays. The yields of both Cl^{34} and Cl^{38} should exhibit peaking characteristics of the compound-system mechanism. In addition the apparent threshold energies agree with the calculations shown in Table V.

Insufficient data are available in this study to determine the magnitude of the contributions from the various mechanisms that could give rise to Al^{28} and Mg^{27} formation resulting from O^{16} irradiations. However, the gradual slope of the Al^{28} excitation function seems to suggest a contribution by a direct neutron pickup process by the target nucleus. The magnitude of the cross section and nature of the gamma spectrum of this nuclide did not permit excitation function assignments at the lower beam energies.

The shape of the excitation function strongly infers that both F^{18} and Na^{24} are formed through a direct-interaction mechanism. The F^{18} yield (at energies below that required for the evaporation of particles from the compound nucleus) is suggestive of a deuteron pickup by the incident projectile, while the Na^{24} excitation function would seem to predict direct knockout, or pickup by the projectile, of a He^3 cluster associated with the target nucleus.

N^{14} Induced Reactions

The excitation function found for P^{32} and Cl^{34-38} composite in the N^{14} bombardments on Al^{27} indicates a compound-nucleus formation and decay mechanism. The two peaks observed for P^{32} yield may result from two independent modes of decay of the compound-nucleus system; one involves primarily particle emission and the other (at lower energies) involves α-particle evaporation from the compound nucleus. (See Table V.)

Although the data are limited to only a few points, the shape of the excitation functions indicates that at the higher energies the compound-nucleus mechanism is the major mode of the formation of Al^{29} and probably a large portion of the Mg^{27} production. However, Pinajian[5] has pointed out that the low-energy yield (thick target cross section at 27.6-Mev N^{14}—110 μb) seems to be characteristic of an exchange-transfer reaction, which is analogous to the Li^6-Al^{27} system.[6] The Al^{29} yield would most certainly have a reasonable contribution from a direct two-neutron pickup by the target. However the limitations of the experiment prohibit further conjecture on this point.

The excitation function for the yield of Al^{28} shows that a direct-interaction mode of production is predominant. A comparison with data previously reported[3,4] gives good agreement with the excitation function observed at low energies. However, at higher energies (above 5 Mev/nucleon) the N^{13} yield from the Al^{27}-N^{14} system reported by Volkov[3] is less than that of Al^{28} observed in the current experiment. This apparent disagreement may be explained on the basis of several mechanistic approaches. At low energies (below or at the barrier) the predominant reaction mechanism is that of a neutron tunneling,[9–12] giving rise to similar yields for both N^{13} and Al^{28}. However, at higher energies contributions to the Al^{28} yield by mechanisms not producing N^{13} may become significant (e.g., compound-nucleus formation and decay) in addition to the stripping process producing N^{13}. Furthermore, if a reaction-intermediate[6] mechanism

is envisioned, i.e.,

$$_{13}Al^{27}+{}_{7}N^{14} \rightarrow {}_{20}[Al^{27}:(C^{12},d)]^{41} \rightarrow {}_{13}Al^{28}+{}_{6}C^{12}+p \quad (\text{or } N^{13}),$$

both N^{13} and $C^{12}+p$ could be formed, contributing to the observed yield of Al^{28} while decreasing the cross section for the N^{13} formation as such.

Both the shape of the excitation functions and the apparent threshold energies (as compared to that needed for compound-nucleus decay, Table V) indicate the yield of both F^{18} and Na^{24} can be attributed almost entirely to a direct-interaction mechanism. This process would involve the pickup of He^4 by the projectile from the target material forming F^{18}, and either pickup by the N^{14} or direct knockout of a He^3 cluster in the case of Na^{24}. The formation of both these radio nuclides (as well as Al^{28}, Mg^{27}, and Al^{29}) would be enhanced by the formation of a reaction intermediate in which the exchange of several nucleons or nucleon clusters[15,16] would be possible, e.g.,

$$_{13}Al^{27}+{}_{7}N^{14} \rightarrow {}_{20}[Al^{27}:N^{14}]^{41} \begin{cases} \nearrow {}_{11}Na^{23}+{}_{9}F^{18} \quad (\text{or } {}_{11}Na^{23}+{}_{7}N^{14}+\alpha) \\ \searrow {}_{11}Na^{24}+{}_{9}F^{17} \quad (\text{or } {}_{11}Na^{24}+{}_{7}N^{14}+{}_{2}He^3) \end{cases}$$

[15] K. Wildenmuth and Th. Kanellopoulos, European Organization for Nuclear Research Report, Geneva, CERN-59-23, 1959 (unpublished).

[16] D. H. Wilkinson, Phil. Mag. 4, 215 (1959).

CONCLUSIONS

The over-all effect of the deuteron structure of N^{14} is evident from the shapes of the excitation functions as compared with those found for the alpha-particle nuclei O^{16} and C^{12}. In particular the direct-interaction mechanism suggested by the excitation function for the formation of Al^{28} by N^{14} (stripping mechanism) in contrast with the shapes found for Al^{28}, O^{16}, and C^{12}-induced production seems to be indicative of the deuteron-type cluster (with a weakly bound neutron) in N^{14}, similar to that observed by the authors for Li^6-induced reactions.[6]

The competition between the various reaction mechanisms proposed should exhibit marked energy dependence. The experiment as performed did not possess energy resolutions sufficient to permit observation of subtle variations in cross section over small energy increments.

Work is in progress at this laboratory which will permit the comparison between the activation excitation functions and those established by direct particles and heavy-fragment observation (e.g., de/dx vs E detections).[17,18]

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[17] D. A. Bromley (private communication).

[18] C. E. Anderson (private communication).