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Comparison of Nitrogen- and Proton-Induced Nuclear Reactions

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Excitation functions for $(p,2p)$, (p,α), and $(p,2\alpha)$ reactions on Mg^{25} were measured with the internal 22-Mev proton beam of the 86-inch cyclotron. The results are compared with the excitation functions obtained for the reactions produced by 29-Mev nitrogen ions on carbon in the 63-inch cyclotron. Both sets of reactions may proceed via the same compound nucleus, Al^{26}. After corrections for the barrier penetrations of the incident particles, the $(N,2p)$ and $(p,2p)$ results are quite comparable. The corrected (N,α) and $(N,2\alpha)$ cross sections are larger than those for the corresponding proton-induced reactions by factors of about two and four respectively, indicating that processes other than conventional compound nucleus formation are involved in these nitrogen-induced reactions. The shape of the excitation functions for the nitrogen-induced reactions indicates that the protons and alpha particles are emitted from nearly spherical nuclei with charge equal to that of the compound nucleus; direct interactions such as stripping are thus excluded.

IN order to study the nuclear reactions induced by energetic nitrogen ions on carbon reported in a preceding paper,[1] one can compare them with reactions induced by other particles forming the same compound nucleus, Al^{26}. Such a case is available in the bombardment of Mg^{25} with protons. The excitation functions involved, namely for (p,α), $(p,2\alpha)$, and $(p,2p)$, leading to Na^{22}, F^{18}, and Na^{24}, respectively, have been measured by Meadows and Holt[2] with 95-Mev protons, and the (p,α) excitation function has been measured by Batzel and Coleman[3] with 32-Mev protons. In each case, however, only a few points were obtained in the energy region below 30 Mev, and the accuracy is affected by straggling due to the energy degradation. Measurements of these cross sections were therefore undertaken with the 22-Mev protons in the internal beam of the 86-inch cyclotron at the Oak Ridge National Laboratory.

EXPERIMENTAL METHOD

The methods of measuring excitation functions and absolute cross sections have been described previously.[4] Natural magnesium metal foils approximately 25 mg/cm² thick were used as targets. The stopping power of magnesium relative to that of aluminum was measured, and no difference was found. In the beta counting of Na^{24} and F^{18} corrections for self absorption, backscattering, etc., were made by using the methods of Zumwalt.[5] The Na^{22} activity was counted on the 1.28-Mev gamma-ray peak with a scintillation spectrometer. The spectrometer efficiency relative to the beta counting efficiency of the Geiger counter was determined with a weightless Na^{22} source mounted on a thin backing. The Na^{24} and F^{18} activities were identified by their half lives and absorption characteristics. The Na^{22} activity was identified by its gamma-ray spectrum and by chemical means. However, since it was found that two weeks after the bombardment the Na^{22} activity was the only one of appreciable intensity for all incident proton energies, the chemical separations were not carried out routinely.

RESULTS

The excitation functions for the reactions $Mg^{25}(p,2p)Na^{24}$, $Mg^{25}(p,2\alpha)F^{18}$, and $Mg^{25}(p,\alpha)Na^{22}$ are shown in Figs. 1–3. The absolute cross sections were calculated by assuming that the activities are due to Mg^{25} only. In the first two reactions there is every indication that this is the case. For Na^{22}, however, the rise beginning at about 19 Mev is due to the $(p,\alpha n)$

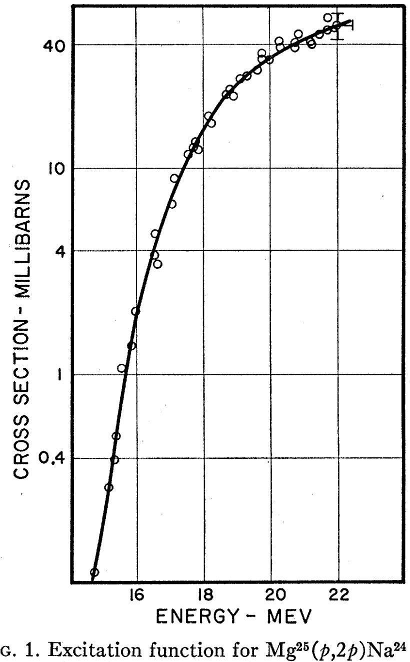

FIG. 1. Excitation function for $Mg^{25}(p,2p)Na^{24}$ as a function of incident beam energy.

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[1] H. L. Reynolds and A. Zucker, preceding paper [Phys. Rev. 96, 1615 (1954)].
[2] I. W. Meadows and R. B. Holt, Phys. Rev. 83, 1257 (1951).
[3] R. E. Batzel and G. H. Coleman, Phys. Rev. 93, 280 (1954).
[4] B. L. Cohen *et al.*, Phys. Rev. 94, 620 (1954); G. H. McCormick and B. L. Cohen, Phys. Rev. 96, 722 (1954).
[5] L. R. Zumwalt, U. S. Atomic Energy Commission Report MDDC-1346 (unpublished, 1947).

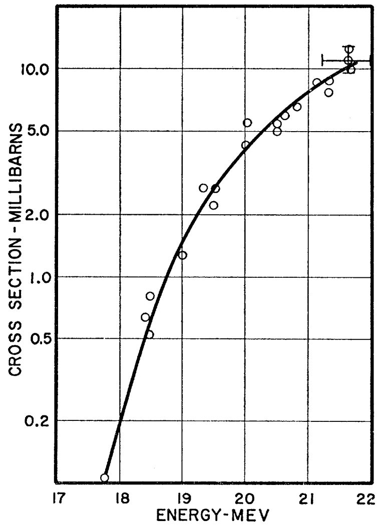

FIG. 2. Excitation function for $Mg^{25}(p,2\alpha)F^{18}$ as a function of incident beam energy.

reaction in Mg^{26} so that beyond that point this curve will not be used in the discussion to follow.

There is a serious discrepancy between the excitation function for $Mg^{25}(p,\alpha)Na^{22}$ and a similar measurement by Batzel and Coleman[3] whose excitation function, while similar in shape, is shifted to higher energy by approximately 3 Mev. It would be very difficult to explain this as being due to an error in the present measurements. The maximum energy of the cyclotron beam is limited by a probe placed at 180 degrees from the target so that the maximum orbit diameter, and thus the maximum energy on the target, is determined by 180 degree magnetic analysis. Since bombardments are carried out with approximately equal currents striking the target and the probe, the mean energy on the target (i.e., the energies used in plotting Figs. 1–3) is lower than this maximum energy by only about 0.3 Mev. The cyclotron magnetic field has been carefully measured as a function of magnet current, and its value is periodically checked to within about 0.2 percent by frequency measurements of the resonant system combined with calculations from cyclotron theory.[6] Measurements of the excitation function for the $Cu^{63}(p,n)$ reaction, which are essentially range measurements, because of the steep rise in the cross section at about 5 Mev,[7] agree with the calculated energy to within about 0.3 Mev.

DISCUSSION

A comparison of the data from Figs. 1–3 has been made with the predictions of the statistical theory of nuclear reactions.[8] The $(p,2p)$ cross sections were calculated by assuming the first proton to be emitted with the energy distribution for aluminum observed by Gugelot,[9] and by determining the total probabilities for emission of both the first and second protons (i.e., their probabilities relative to that of neutron or alpha emission) by the methods of Blatt and Weisskopf.[8] The (p,α) and $(p,2\alpha)$ cross sections were calculated by straightforward application of the formulas from Blatt and Weisskopf.[8]

In all cases the energy dependence of the experimental curves are in reasonable agreement with the theoretical predictions. The observed absolute values of the $(p,2p)$ cross sections are larger than the calculated values, by a factor of about three, but this discrepancy is perhaps understandable in view of the limitations of the theory for light elements. The maximum and the subsequent drop-off in the (p,α) excitation function are explained by the fact that proton emission following emission of alphas becomes energetically possible, so that the (p,α) reaction becomes a $(p,\alpha p)$ reaction. Theoretical calculations[4] indicate that the maximum should occur at about 15 Mev (quite independent of the nuclear temperatures assumed), which is in good agreement with the data from Fig. 3. The observed absolute values of the (p,α) cross section are smaller than the calculated values by a factor of three, but this again may be explained by the well known difficulties in the theory.

The $(p,2\alpha)$ cross section is at least ten times larger than predicted by statistical theory, but this is probably due to the fact that levels of very low excitation, for which the theory is inadequate, are of primary im-

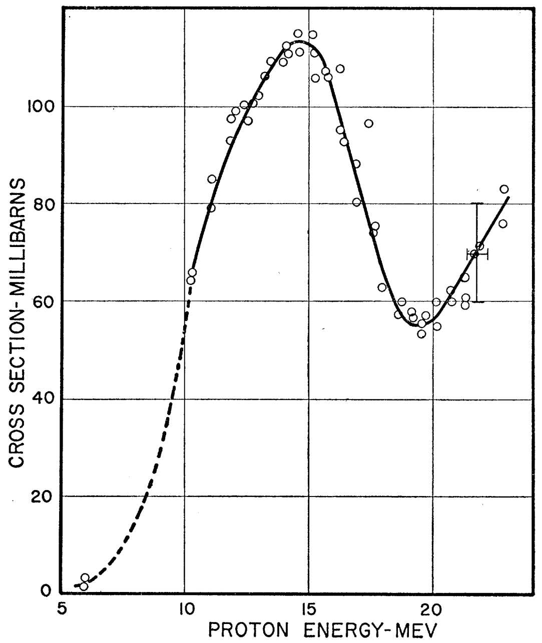

FIG. 3. Excitation function for $Mg^{25}(p,\alpha)Na^{22}$ as a function of incident beam energy.

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[6] B. L. Cohen, Rev. Sci. Instr. **24**, 589 (1953).

[7] Blaser, Boehm, Marmier, and Peaslee, Helv. Phys. Acta **24**, 3 (1951).

[8] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

[9] P. C. Gugelot, Phys. Rev. **93**, 420 (1954).

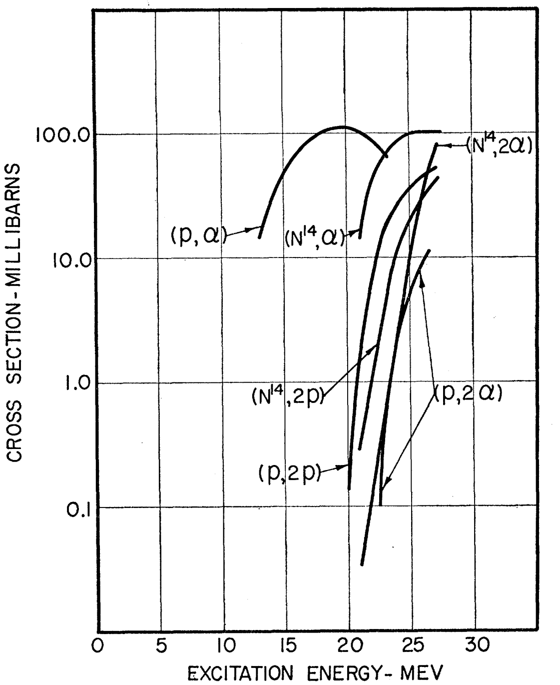

FIG. 4. Proton- and nitrogen-induced reaction cross sections as a function of the excitation energy of the compound nucleus.

portance in the calculation. From their very nature it seems natural to assume that (*p*,2*p*), (*p*,α), and (*p*,2α) reactions are compound nucleus reactions, and there is nothing in these measurements to indicate that such is not the case.

The reactions produced by nitrogen on carbon may lead to the same compound nucleus, Al^{26}, as the above described reaction. The compound nucleus is excited to about the same degree for 22-Mev protons as for the 29-Mev nitrogen ions.[10] A comparison of excitation functions for proton- and nitrogen-induced reactions should indicate whether they proceed by the same mechanism. The proton- and nitrogen-induced reaction cross sections are given in Fig. 4 as a function of the excitation energy of the compound nucleus. Since the Coulomb barriers for these two sets of reactions are different, entrance barrier penetration considerations have been eliminated in the comparison by plotting the ratios of the observed cross sections to the theoretical total reaction cross sections. The resulting ratio is the probability of the decay of the compound nucleus through a given type of reaction. These ratios are plotted as a function of the excitation energy of the compound nucleus, Fig. 5. The theoretical total reaction cross section has been calculated in the usual manner by assuming a sticking probability of unity and by using the tables of penetrability given by Feshbach *et al.*[11]

It is apparent from Fig. 5 that the percentage of total cross sections for the reactions (N,2*p*) and (*p*,2*p*) are identical within the accuracy of the experiment. This strongly suggests that this nitrogen-induced reaction proceeds by a compound nucleus interaction. In the case of the reactions yielding one or two alpha particles, there is a similarity between the shapes of the corresponding excitation functions in Fig. 5. The energy dependence of the curves given in Fig. 5 should be determined primarily by exit Coulomb barrier penetration factors. The close correspondence between the shapes of these curves for the nitrogen- and proton-induced reactions thus indicates that the exit Coulomb barriers are essentially identical in the two cases. It therefore seems that some sort of compound nucleus is formed in the nitrogen-induced reaction. If the particles were emitted from C^{12} or N^{14} nuclei, or from a dumbbell-shaped structure consisting of these two in grazing contact, the exit Coulomb barriers would be much lower. For example, the barrier height in the 2α-emission reaction—the "knee" in the excitation function occurs at about this energy above the energetic threshold—is about 6 Mev higher for an Al^{26} nucleus than for a C^{12} or N^{14} nucleus. For the 2*p*-emission

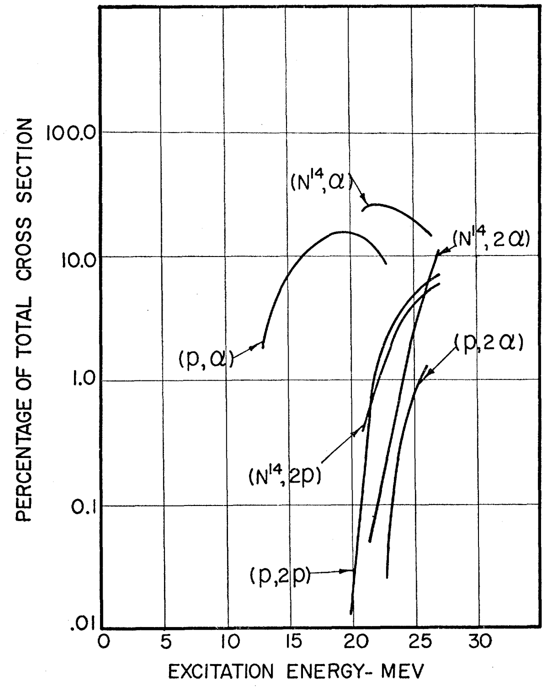

FIG. 5. Ratios of observed cross sections to theoretical total cross sections for proton- and nitrogen-induced reactions, plotted as a function of the excitation energy of the compound nucleus.

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[10] Actually, the orbital angular momenta in the incident nitrogen ion beam are somewhat higher than in the proton case, so that some states of the compound nucleus with very large spin ($J \gg 6$) can be formed by the nitrogen ions but not by the protons. However, it is conventional to assume that the energy dependence of level densities at high excitation energies is independent of spin [e.g., reference 8, and S. N. Ghoshal, Phys. Rev. **80**, 939 (1950)], in which case the competition among the various modes of decay is not affected by spin.

[11] Feshbach, Shapiro, and Weisskopf, U. S. Atomic Energy Commission Report NYO-3077, 1953 (unpublished).

reaction the difference is about 4 Mev. In both cases the correspondence between the curves for the proton- and nitrogen-induced reactions in Fig. 5 is much too close to allow such a difference in exit barrier heights. It therefore seems that these nitrogen-induced reactions do not proceed by direct interactions of the "stripping"[12] or "buckshot"[13] type. It would seem rather that the particles are emitted from a conglomerate nucleus which has proceeded toward thermodynamic equilibrium, at least to the point of being nearly spherical in shape. Alpha and two-alpha emission is more probable, however, in the case of nitrogen reactions by a factor of two and four, respectively, which, in an undoubtedly oversimplified classical picture, could indicate that complete thermodynamic equilibrium—that is, the compound nucleus assumed by Bohr[14]—is not always reached. Complete equilibrium would require that the relative probabilities of decay by α, 2α, and $2p$ emission be the same whether the compound nucleus was formed by an N^{14}-C^{12} or a p-Mg^{25} collision. This statement is contingent on the assumptions made in reference 10. In the reaction of nitrogen on carbon, the high cross sections for alpha emission may indicate a "memory" of the alpha-particle structure of the initial carbon nucleus.

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[12] J. R. Oppenheimer and M. Phillips, Phys. Rev. **48**, 500 (1935).

[13] Chackett, Fremlin, and Walker, Phil. Mag. **45**, 173 (1954).

[14] N. Bohr, Nature **137**, 344 (1936).

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Decay Characteristics of Some Short-Lived Nuclides of Low Atomic Number*

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The short-lived activities in Cl^{34}, K^{38}, Ca^{39}, Li^8, He^6, and O^{15} formed by high-energy bremsstrahlung irradiation have been examined, and some improved values for the half-lives of these nuclides are reported.

THE half-lives of the isomeric states in Cl^{34} and K^{38}, as well as the half-lives of Ca^{39}, Li^8, He^6, and O^{15} have been measured with an anthracene scintillation spectrometer using pulse-height discrimination and special timing equipment. These nuclides were formed by (γ,n) and (γ,p) reactions induced by bremsstrahlung whose maximum energy was kept below the thresholds of competing reactions.

Cl^{34} and K^{38} were of interest because of the recent report[1] of isomeric states in these nuclides. Ca^{39} was of interest because the "ft value" for this transition has recently been reported[2] to be somewhat higher than the ft values for some of the other "mirror transitions." A comparison with previously observed values for Li^8, O^{15} and He^6 was of general interest.

TABLE I. Summary of half-lives measured.

Nuclide[a]	Half-life (sec)	Maximum beam energy (Mev)	Possible interfering reaction	Threshold for interfering reaction[b] (Mev)
Li^8	0.841 ± 0.004	65	$\cdots$	$\cdots$
He^6	0.799 ± 0.003	65	$\cdots$	$\cdots$
O^{15}	$123.4\ \pm1.3$	25	$O^{16}(\gamma,2n)O^{14}$	26.8
Ca^{39}	$0.90\ \pm0.01$	19.5	$Ca^{40}(\gamma,d)K^{38}$	17.6
Cl^{34}	$1.53\ \pm0.02$	22.0	$Cl^{35}(\gamma,2n)Cl^{33}$	23.8
K^{38}	0.935 ± 0.025	22.0	$K^{39}(\gamma,2n)K^{37}$	24.0

[a] The first two nuclides listed were formed by (γ,p) reactions. The others were formed by (γ,n) reactions.

[b] All threshold calculations were based on semiempirical mass values given by N. Metropolis and G. Reitwiesner. Atomic Energy Commission Report NP-1980, 1950 (unpublished). The same thresholds calculated using semiempirical values given by W. H. Barkas, Phys. Rev. **55**, 691 (1939), give consistently higher values.

The target selected for each bombardment was a chemically pure element or compound. When it was necessary to use a compound, care was taken to choose one which would give no short-lived background. In all cases the activity was followed for more than six half-lives. Weighted-least-squares analyses were used to obtain the numerical values for half-lives and probable errors quoted. Care was taken to observe and correct for the small constant and decaying long-lived background in each case. Because of the short pulse duration from the scintillation counter, no "dead-time" corrections were necessary.

Since all the nuclides studied except O^{15} had half-lives of less than two seconds, a cyclic programming device which channeled the scintillation pulses into nine scalers in the time succession was used.[3] Bombardment and counting durations were adjustable and were controlled by a master clock operating cascaded stepping relays. The beam duration and counting periods were optimized for each measurement.

The essential results of this work are presented in Table I. In each case the accuracy is thought to be improved over previous measurements.

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* Work was performed in the Ames Laboratory of the U. S. Atomic Energy Commission.

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[1] P. Stähelin, Helv. Phys. Acta **26**, 691 (1953).

[2] Hunt, Kline, and Zaffarano, Phys. Rev. **95**, 611(A) (1954).

[3] The detailed experimental equipment and procedure are described in Atomic Energy Commission Report ISC-510 (unpublished).