and Halperin,[28] Grundl *et al.*,[29] Tewes *et al.*,[30] and the present experiment have been plotted. The solid curve of Fig. 6 was calculated with $a=4.0$ MeV^{-1} and $\delta=4.1$ MeV while the dashed curve corresponds to $a=1.7$ MeV^{-1} and $\delta=2.6$ MeV. The notable feature of both curves is that they fall well below the data for neutron energies near the threshold for the (n,α) reaction. This result is consistent with the assumption that the transmission of the potential barrier for charged particles is too small for energies near the Coulomb barrier height. Since the sharp-cutoff potential used by Shapiro[19] is known to give just this effect for alpha particles,[31] the use of a more realistic diffuse well such as a Woods-Saxon or similar potential for calculation of the reaction cross sections should remove this discrepancy. Schmitt and Halperin[28] were, in fact, successful in fitting the gross features of their $Al^{27}(n,\alpha)Na^{24}$ data using alpha-particle reaction cross-section calculations by Igo[31] based on a diffuse-edge potential.

The achievement of consistency in the statistical model parameters in regions where the model is applicable will require elimination of some of the variable parameters from the model. A first step in this direction will be to use the more accurate diffuse-well values[31,32] for the reaction cross sections σ_c. More independent information about level densities is needed. The data presently available for studying the statistical assumption are not sufficiently sensitive to the joint variation of so many parameters to give detailed information about the "correct" form for the energy-dependent quantities.

ACKNOWLEDGMENTS

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[28] H. W. Schmitt and J. Halperin, Phys. Rev. **121**, 827 (1961).
[29] Reference f, Table I.
[30] *Reports to the AEC Nuclear Cross Sections Advisory Group*, WASH—1028 (Office of Technical Services, Department of Commerce, Washington 25, D. C., 1960), p. 66-67.
[31] G. Igo, Phys. Rev. **115**, 1665 (1959).
[32] F. G. J. Perey and B. Buck (to be published); R. D. Albert and L. F. Hansen, University of California Radiation Laboratory Report UCRL-6427 (unpublished); F. Bjorklund and S. Fernbach, Phys. Rev. **109**, 1295 (1950); J. S. Nodvik and D. S. Saxon, Phys. Rev. **117**, 1939 (1960); D. S. Saxon, *Proceedings of the International Conference on Nuclear Structure, Kingston* (University of Toronto Press, Toronto, 1960), p. 197.

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Excitation Functions of Some Reactions of 6- to 24-MeV He^3 Ions with Carbon and Aluminum*

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Excitation functions of the reactions $C^{12}(He^3,\alpha)C^{11}$, $C^{12}(He^3,pn)N^{13}$, $C^{12}(He^3,2\alpha)Be^7$, $Al^{27}(He^3,\alpha 2p)Na^{24}$, $Al^{27}(He^3,2\alpha)Na^{22}$, and $Al^{27}(He^3,3\alpha)F^{18}$ have been measured for He^3 energies from 6 to 24 MeV by the stacked-foil technique. The cross section for production of C^{11} reaches a maximum of 340 mb at 8.9 MeV, with smaller maxima at 10.6 and 15.5 MeV. The cross section for N^{13} reaches a broad maximum of 140 mb in the vicinity of 14 MeV, with evidence of a secondary maximum at 10.9 MeV. The cross section for Be^7, measured with somewhat poorer resolution, reaches a broad maximum of about 100 mb in the vicinity of 17.5 MeV. The cross section for production of Be^7 by 24-MeV He^3 bombardment of aluminum is about 0.1 mb.

INTRODUCTION

THE present work was undertaken to measure the total cross sections for formation of three of the products of the reactions of 6- to 24-MeV He^3 ions with carbon. The primary motive was to explore the energy dependence of cross sections of the reactions as a partial guide and supplement to more detailed energy-angular distribution experiments. A secondary motive was to obtain information on the type and magnitude of contamination to be expected from carbon compounds encountered in vacuum systems and targets.

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EXPERIMENTAL

Apparatus and Materials

The measurements of all products except Be^7 were made by the stacked-foil technique. Stacks of foils of measured thickness were bombarded with He^3 ions at selected incident energies from 10 to 24 MeV at the Los Alamos variable-energy cyclotron and the quantities of radioactive products were determined by absolute beta and gamma counting. The use of aluminum catcher foils in the stacks provided the need and the opportunity to measure also the excitation functions of the reactions in aluminum leading to the longer-lived radioactive species. Since Be^7 was produced in amounts too small

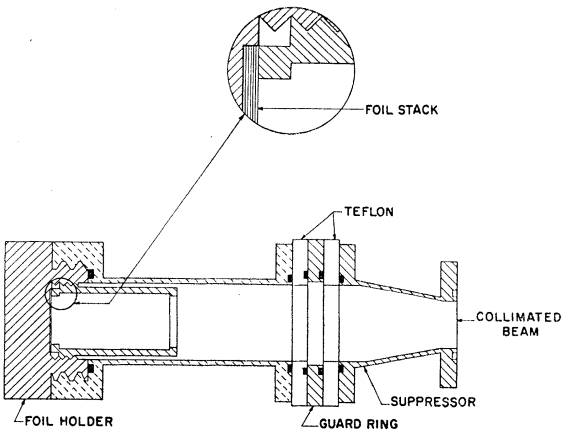

FIG. 1. Target holder-Faraday cup assembly.

to be measured reliably in the stacked foils, the excitation function for this product was obtained from a series of thick-target bombardments on heavy graphite disks.

The "carbon foils" consisted of polyethylene, $(CH_2)_x$, die cut from nominally 0.0005-in. sheet stock to disks 1.000±0.003 in. in diam. All foils were washed with petroleum ether, acetone, and water, and then were dried and weighed; weighing of sample foils before and after the cleaning treatment showed that the wash liquids were effectively removed by a few hours of drying. The carbon content of the foils, as shown by chemical analysis, was within 0.1% of the theoretical value for the empirical composition CH_2. The most serious source of error in the physical description of the polyethylene foils was irregularity in thickness. Groups of foils cut from the same general area of the sheet stock exhibited weight variations averaging about 1.5%. Variations of thickness within a given foil may have been larger, but the effects were largely averaged out by the diffuseness of the beam on the target.

The aluminum foils were cut to 1.000±0.001-in. diam from nominally 0.00022-, 0.0005-, and 0.001-in. rolled 2S aluminum sheet, and were individually cleaned and weighed by the technique described above. Variations in thickness of foils from adjacent cuts were of the order of 0.8%. Spectroscopic analysis showed that there was less than 0.1% of iron and manganese, the only bothersome impurities.

The graphite targets were cylinders 1 in. in diam and 0.1 in. thick machined from reactor-grade graphite rod, which had no significant impurities.

The foil stacks were held in a combination target holder and Faraday cup (Fig. 1) mounted at the end of a 24-ft tube extending from the beam-extraction port of the Los Alamos variable-energy cyclotron. The He^3 ion beam was magnetically and electrostatically focused and collimated so as to strike more or less uniformly an area $\frac{1}{2}$ in. in diam on the foil stack. A precision current source was used for beam-integrator calibration.

For most of this work the energy of the He^3 ions was measured before and after each bombardment with 200-μ Ilford L2 plates of known emulsion density. The plate calibration was based on the work of Wilkins,[1] and the energy uncertainty associated with calibration and individual plate readings amounted to 0.25 MeV. Variation in beam energy due to drifts in tuning during the course of a run was estimated to be about 0.1 MeV. In the last few experiments, the particle energy was determined also by scattering a portion of the beam by means of a thin gold foil into an energy monitor. The monitor assembly consisted of a set of aluminum energy degrading foils, a solid-state detector, and an energy reference standard of Pu^{239} alphas. The original energy was inferred from the amount of aluminum required to degrade the beam energy to correspond to the alpha standard. The energy difference corrections were based on the proton work of Bichsel *et al.*[2,3] with proton-helium ion range differences corrected according to Northcliffe.[4] Beam energies as determined with the monitor system agreed with those determined from nuclear emulsions to within 0.1 MeV.

In addition to the references quoted for aluminum,[2,3,4] the work of Schambra *et al.*[5] provided a direct comparison of the energy loss in polyethylene to that of aluminum. These data were needed to develop range energy expressions applicable to the calculation of energy loss in each foil of a stack. For carbon, as graphite, the data of Sternheimer[6] were used with minor corrections for multiple scattering and straggling.

After bombardment, the polyethylene and aluminum foils were individually mounted on aluminum sample plates and counted on a set of intercalibrated beta proportional counters. Counting efficiencies of the C^{11} and N^{13} were established by a separate experiment in which two typical polyethylene foils were counted alternately with the proportional counters and, suitably covered to stop the positrons, with a calibrated gamma scintillation counter. Beta counting efficiencies of the F^{18} and Na^{22} were also established by annihilation radiation measurements. The ratios of positron decays to total disintegrations for C^{11}, N^{13}, F^{18}, and Na^{22} were taken as 1.00, 1.00, 0.97, and 0.90, respectively. The beta counting efficiency of Na^{24} was based on 4π calibrations. All counting efficiencies are estimated to have an absolute uncertainty of ±5%.

The Be^7 in the graphite targets was measured with a calibrated scintillator unit and a 100-channel pulse-height analyzer, and calculations were based on the assumption of a 52.9-day half-life and 0.11 gamma rays per disintegration. Over-all uncertainty in number of

[1] J. J. Wilkins, Atomic Energy Research Establishment Report *G/R* 664, 1951 (unpublished).
[2] H. Bichsel, Phys. Rev. **112**, 1089 (1958).
[3] H. Bichsel, R. F. Mozley and W. A. Aron, Phys. Rev. **105**, 1788 (1957).
[4] L. C. Northcliffe, Phys. Rev. **120**, 1744 (1960).
[5] P. E. Schambra, A. M. Rauth, and L. C. Northcliffe, Phys. Rev. **120**, 1758 (1960).
R. M. Sternheimer, Phys. Rev. **115**, 137 (1959).

Be^7 atoms is mainly that in the gamma ray/total disintegration ratio, and is estimated to be ±15%.

All multicomponent decay data were resolved by least-squares analysis and corrected for finite length of bombardment on an IBM 704 computer.

Bombardment and Measurement Techniques

On the basis of half-lives, radiations, and cross section range, the reaction products were measured in four groups, each group with a characteristic target type, bombardment intensity, and counting technique.

For the first group, comprising C^{11} and N^{13} from carbon, the target stacks were generally made up of six aluminum foils interleaved with five polyethylene foils. The first aluminum foil served as a shield against possible radioactive debris coming down the beam tube; the remaining five served as "catchers" for C^{11} and N^{13} recoiling out of the polyethylene foils. The He^3 energy decrements in the individual polyethylene foils ranged from about 0.5 MeV at 24 MeV to about 0.8 MeV at 5 MeV; the range of energy decrements in the aluminum foils was about the same.

In general, two bombardments were conducted at each beam energy setting, the first with a foil stack as described and the second with an additional aluminum foil as an energy degrader; the degrader thickness was chosen so as to give an energy displacement about half the spacing between the energy values of like foils. Each bombardment was run for 10 to 50 sec at about 0.02 μA, and the two five-foil sets from it were counted by turns on a set of five simultaneously-operated counters.

The dominant decay components in both the polyethylene and aluminum foils were those of C^{11} and N^{13}, with average measured half-lives of 20.4 and 10.1 min. In addition to the weaker components representing F^{18}(111 min) and Na^{24}(15.0 h), the decay data showed the presence of a shorter-lived component due to Al^{28}(2.30 min). Most of the Al^{28}, from $Al^{27}(He^3,2p)$, and virtually all of the shorter-lived products died away in the interval between end of bombardment and start of counting. The remaining Al^{28}, plus possible traces of O^{15}, was taken into account by inclusion of a 2.30-min period in the analysis code. Possible contributions from neutron-induced reactions in aluminum were checked by counting foils that had been added to the end of one of the stacks and behind sufficient absorber to put them beyond the He^3 range. The activity of Mg^{27}, which could interfere with measurement of N^{13}, was found to be about 0.4% of the activity of the N^{13} contained in a typical catcher, and was neglected.

The loss of C^{11} by backward recoil into the catcher foil preceding the foil in which it was produced was checked in separate experiments at He^3 energies 13 and 24 MeV. At both energies this loss was found to be approximately 0.7% for typical polyethylene foils. The effect should have been nearly self-compensating for the first four target-catcher couples in a stack. The N^{13} was kinematically constrained to the forward hemisphere in the laboratory system for all incident He^3 energies.

The uncertainty in the individual C^{11} and N^{13} cross-section values (apart from the 5% uncertainty in counting efficiency) was estimated to be about 8%, of which 5% was in the beam and timing parameters of a given bombardment and 3% was in the counting data and the thickness determinations for the individual foils.

Since the F^{18} and Na^{24} components were too weak to be statistically significant in the decays from the short bombardments described above, the data on these products were obtained by additional bombardments with about 25 μC of He^3 ions.

Because of the need for still more intense bombardments to produce enough Na^{22} for reliable counting, the $Al^{27}(He^3,2\alpha)Na^{22}$ excitation function was measured separately. Stacks of aluminum foils alone were used; materials otherwise suitable for use as catcher foils were found to introduce interfering long-lived activities. The stacks were given bombardments of the order of 5000 μC, and after a waiting period of one month to permit decay of shorter-lived species, the Na^{22} was beta counted. Examination of the scintillation gamma spectra of representative foils during the counting period showed no evidence of foreign activities, and the decay rate was consistent with a half-life of 2.60 yr.

The $C^{12}(He^3,2\alpha)Be^7$ excitation function was obtained from thick-target yield measurements on individual graphite disks. Sequences of bombardments were conducted at each of four different He^3 beam energies; within each sequence, the energy of the He^3 ions incident on the graphite targets was adjusted stepwise from one bombardment to the next by interposition of increasing thicknesses of aluminum foils as energy degraders. After bombardments of 1000 to 4000 μC, and waiting periods of the order of one month, the targets were counted. Corrections were made for the small (up to 1%) contribution from annihilation radiation from Na^{22} that had recoiled into the graphite from the aluminum foils.

RESULTS

$C^{12}(He^3,\alpha)C^{11}$ and $C^{12}(He^3,pn)N^{13}$

The excitation functions for the reactions leading to C^{11} and N^{13} are plotted in Fig. 2. Five pairs of bombardments, at mean He^3 beam energies 24.30, 18.95, 13.64, 12.82, and 10.22 MeV, plus a single bombardment at 15.92 MeV, were run. The carbon in the targets was treated as 100% C^{12} in the computations. The finite energy spans covered by the individual foils, and the errors involved in establishing the He^3 energy at each foil and in assessing the numbers of target and product nuclei produced, tend to smear out structural details in the excitation functions. In particular, although the maxima in the C^{11} curve at 8.9 and 15.5 MeV are definite, the scatter of the points between 9 and 11 MeV

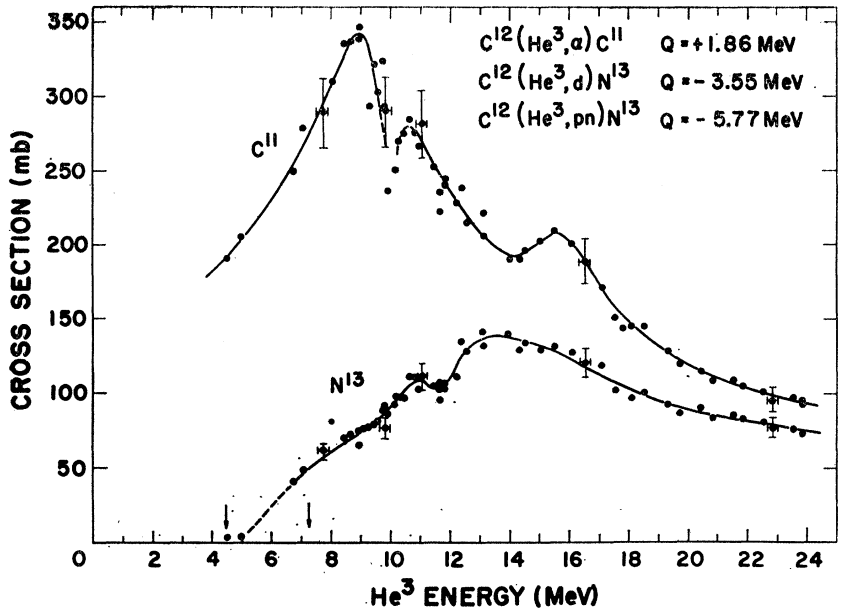

FIG. 2. $C^{12}(He^3,\alpha)C^{11}$ and $C^{12}(He^3,d)N^{13}+C^{12}(He^3,pn)N^{13}$ cross sections as a function of laboratory He^3 energy. Error flags indicate precision of representative individual measurements. Arrows indicate thresholds for the reactions leading to N^{13}.

appeared at first to be too large to establish the credibility of the maximum at 10.6 MeV. Examination of the data from the individual bombardments covering this energy region, however, showed the presence of a definite dip near 10 MeV; these groups of points, each group representing a common bombardment history and counting schedule, showed a better consistency than the data taken as a whole. A similar examination of the N^{13} data supported the indication of a maximum near 10.9 MeV.

A special experiment was conducted to determine whether significant amounts of C^{11} or N^{13} were lost in the form of gaseous products. It was prompted by the report of Cumming *et al.*,[7] who observed that up to 15% of the C^{11} produced in thin polyethylene foils by (p,pn) and $(p,2n)$ reactions escaped in the form of volatile hydrocarbons. The experiment consisted of a comparison of the C^{11} and N^{13} yields in ordinary target foil assemblies with the yields in assemblies designed for low gas loss. Three types of target foil assemblies were prepared:

(1) Foil stack: aluminum-polyethylene-aluminum;
(2) Foil stack: aluminum-polytetrafluoroethylene-aluminum;
(3) Foil stack with components sealed together around the edges by 1.00-in. o.d., 0.75-in. i.d. washers of "double-sided" Scotch tape: aluminum-washer-polyethylene-washer-aluminum.

TABLE I. Comparison of apparent cross sections for production of C^{11} and N^{13} in open and sealed targets.

Target	He^3 energy at mid-target (MeV)	Cross section (mb) Observed C^{11}	Observed N^{13}	Smooth curve Fig. 2 C^{11}	Smooth curve Fig. 2 N^{13}
Open polyethylene	23.61	99	78	94	76
Open polyethylene	22.31	104	85	102	80
Open Teflon	22.79	101	83	99	79
Open Teflon	19.38	130	93	126	93
Sealed polyethylene	23.52	92	81	95	76
Sealed polyethylene	22.22	101	84	102	81

The first type, essentially a duplication of standard target conditions, was a control. The second type, involving simply the substitution of Teflon for polyethylene, was intended to assess the effect of a different chemical environment; samples of the foil stock were chemically analyzed. The stacks of the third type, consisting of foils like the first, were assembled carefully and pressed firmly to insure air-tight seals at the washer-foil interfaces. Two assemblies of each type were prepared and bombarded together, i.e., a single bombardment for the type 1 targets, etc. Table I shows the results, expressed in terms of apparent cross sections for production of C^{11} and N^{13}. The differences between these three sets of data and the previous data in the same energy region appear to lie within the normal range of scatter, about 5%. It was concluded, then, that no more than about 5% of the C^{11} or N^{13} was lost from the ordinary foil stacks.

The C^{11} and N^{13} excitation functions obtained by Markowitz and Hall,[8] who used the stacked-foil technique with a He^3 beam energy of 31 MeV, had the same general shape as those from the present work down to

[7] J. B. Cumming, A. M. Poskanzer, and J. Hudis, Phys. Rev. Letters 6, 484 (1961).

[8] S. S. Markowitz and J. M. Hall, Bull. Am. Phys. Soc. 4, 8 (1959).

10 MeV, with some loss of the fine structure because of the straggling associated with large beam energy degradations. Their cross sections were about 20% smaller, but the N^{13}/C^{11} ratios computed from their data lie within 5% of those from the present work down to 15 MeV and within 10% down to 10 MeV.

The structure in the C^{11} excitation function at incident He^3 energies above 8.9 MeV may be associated with particle decay of excited states of C^{11}. The alpha, proton, He^3, and neutron binding energies of C^{11} are 7.55, 8.69, 9.23, and 13.09 MeV, respectively, and the corresponding He^3 energy thresholds for production from C^{12} of the resultant Be^7, B^{10}, Be^8, and C^{10} are 7.11, 8.54, 9.21, and 14.04 MeV, respectively. The fact that the first large drop in the C^{11} cross section, of the order of 100 mb, is not reflected in the production of Be^7 (cf. Fig. 3) suggests proton emission rather than alpha emission as the decay channel for excited C^{11} in this region; however, the second significant drop, beginning at 10.6 MeV, corresponds to the rapid increase in observed Be^7, i.e., to alpha emission.

The irregularities in the N^{13} excitation function do not appear to offer any simple interpretation. The N^{13} may be produced by $C^{12}(He^3,pn)N^{13}$, with either the proton or the neutron emitted first, or by $C^{12}(He^3,d)N^{13}$, and the present data do not distinguish between the three paths. However, recent angular distribution studies of the $C^{12}(He^3,d)N^{13}$ reaction at 13.9 MeV (laboratory He^3 energy) by Priest *et al.*[9] and at 21.0 and 24.0 MeV by Wegner and Hall[10] provide information from which its contribution may be computed at these energies. From an integration of the deuteron angular distribution data corresponding to the ground-state reaction (gamma de-excitation of the excited states of N^{13} is not significant) the $C^{12}(He^3,d)N^{13}$ cross sections at the three energies mentioned are 60, 23, and 18 mb, respectively; from Fig. 2, the total cross sections for production of N^{13} are 138, 85, and 75 mb, respectively.

$C^{12}(He^3,2\alpha)Be^7$

The thick-target yield data, expressed in terms of total atoms Be^7 produced per incident He^3, are plotted in Fig. 3. Calculation of the cross-section function was performed on the computer. The experimental Be^7/He^3 ratios were fitted by least squares by a sixth-degree polynomial in E, the He^3 incident energy; the line drawn through the points in Fig. 3 is a plot of the polynomial. The range-energy function was also expressed with a sixth-degree polynomial in E. The slopes of the two functions were then evaluated at 0.1-MeV intervals, and the corresponding cross sections were computed from the expression

$$\sigma = \text{const} \times [d(\text{Be}^7/\text{He}^3)/dE] \div (dR/dE).$$

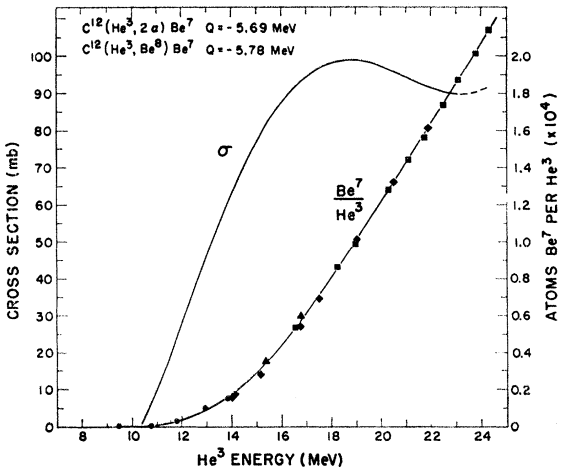

FIG. 3. Production of Be^7 from $C^{12}+He^3$. Right-hand scale indicates thick-target yield of Be^7 as a function of incident He^3 energy. Left-hand scale applies to cross-section curve derived from the thick-target yield data.

The cross section curve shown in Fig. 3 indicates an effective threshold at an incident He^3 energy about 10.4 MeV, although the theoretical threshold for $C^{12}(He^3,2\alpha)Be^7$ is 7.11 MeV. Since these measurements deal only with total long-lived radioactive products, they do not distinguish between the reactions $C^{12}(He^3,2\alpha)Be^7$ and $C^{12}(He^3,Be^8)Be^7$.

$Al^{27}(He^3,2\alpha)Na^{22}$, $Al^{27}(He^3,\alpha 2p)Na^{24}$, and $Al^{27}(He^3,3\alpha)F^{18}$

The excitation functions for the reactions induced in aluminum are plotted in Fig. 4. The Na^{22} data were obtained from two bombardments, the first with an incident beam energy of 21.60 MeV and a stack of thirteen 0.0005-in. foils and fifteen 0.00022-in. foils, and the

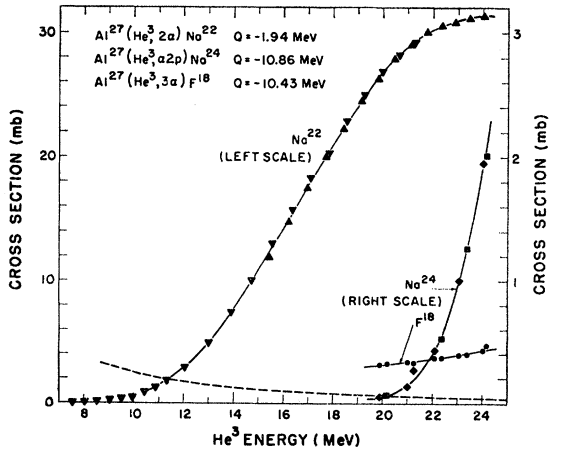

FIG. 4. $Al^{27}(He^3,2\alpha)Na^{22}$, $Al^{27}(He^3,\alpha 2p)Na^{24}$, and $Al^{27}(He^3,3\alpha)F^{18}$ cross sections as a function of laboratory He^3 energy. The points with different shapes indicate separate bombardments. Dashed line along lower edge indicates contribution from $O^{16}(He^3,p)F^{18}$.

[9] J. R. Priest, D. J. Tendam, and E. Bleuler, Phys. Rev. **119**, 1295 (1960).

[10] H. E. Wegner and W. S. Hall, Phys. Rev. **119**, 1654 (1960).

TABLE II. Yield of Be^7 from aluminum foils bombarded with He^3.

Foil number	Thickness (mg/cm²)	Average He^3 energy (MeV)	Cross section (mb)
1	7.93	23.29	0.12±0.03
2	13.16	21.50	0.15±0.02
3	7.95	19.59	0.04±0.01
4	13.20	17.49	0.05±0.01

second with a beam energy of 24.30 MeV and a stack of fourteen 0.001-in. foils. Separate experiments with catcher foils showed that the fraction of the Na^{22} activity lost from a nominal 0.0005-in. target foil by forward recoil was 17% at 24 MeV and 15% at 18.5 MeV; these data were used to estimate recoil corrections.

F^{18} and Na^{24} data were obtained from two bombardments of stacks of aluminum foils interleaved with polyethylene catcher foils. The data plotted in Fig. 4 are confined to incident He^3 energies above about 20 MeV. Below this region the Na^{24} component was too small to be reliably evaluated and the F^{18} component contained an appreciable contribution from the $O^{16}(He^3,p)F^{18}$ reaction from trace oxygen. The F^{18} points plotted in Fig. 4 represent the total F^{18} observed. The contribution of the oxygen reaction is indicated by the dashed line and is based on the excitation function reported by Markowitz and Mahony,[11] fitted to the F^{18} observed at low energies. The oxygen impurity, attributed to aluminum oxide, was assumed to be uniform.

Be^7 from He^3 Bombardment of Aluminum

Since Bouchard and Fairhall[12] and Porile[13] had observed that Be^7 is produced in small amounts in the bombardment of aluminum with 30- to 40-MeV He^4 ions, an exploratory experiment was conducted to look for a similar effect with He^3 bombardment. A stack of four aluminum foils was bombarded with 10 200 μC of 23.94-MeV He^3 ions and the individual foils were radiochemically analyzed for Be^7. The results, without correction for migration of recoil, are summarized in Table II.

The contribution of Be^7 from reaction of the He^3 with carbonaceous material in or on the aluminum cannot be wholly excluded; about 0.05 at. % of carbon could have accounted for the Be^7 observed in the last two foils. Since, however, the cross section for production of Be^7 from carbon is known to be substantially constant over the He^3 energy range involved, it may be concluded that two thirds or more of the Be^7 in the first two foils came from the aluminum itself and that the $Al^{27}(He^3,Be^7)Na^{23}$ cross section is about 0.1 mb in the He^3 energy range 21.5–23.3 MeV. This cross section is approximately the same as the cross section for production of Be^7 by He^4 bombardment of aluminum if the reactions are compared at the same energy over threshold. At an incident He^4 energy of 40.0 MeV, equivalent on a threshold basis to the He^3 reaction at 23.6 MeV, Bouchard and Fairhall[12] report a Be^7 formation cross section of 0.22 mb. The cross section for the same reaction at an incident He^4 energy of 41.2 MeV is reported by Porile[13] to be 0.14 mb. The present data indicate that the cross section for the $Al^{27}(He^3,Be^7)Na^{23}$ reaction is rising rapidly with He^3 energy between about 19 and 23 MeV, but a detailed comparison with the $Al^{27}(He^4,Be^7)Na^{24}$ reaction data would require study of the former at somewhat higher energies.

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[12] G. H. Bouchard, Jr., and A. W. Fairhall, Phys. Rev. **116**, 160 (1959).
[13] N. T. Porile, Phys. Rev. **127**, 224 (1962).