The internal energy of the alpha particle, $E_\alpha(\mathbf{R})$, is determined by the wave function φ^α of Eq. (17), and, in general, is greater than that for a free alpha. If f is able to adjust adiabatically to the local Fermi cutoff so as to minimize $E_\alpha(\mathbf{R})$, the internal energy will remain negative or be at most zero. On the other hand, $E_\alpha(\mathbf{R})$ can go positive if f is not able to adjust adiabatically.[8] This would be the case, for example, if the only change in the wave function were the Fermi cutoff. The effect leads to an alpha-particle potential which is considerably shallower than four times the single-nucleon potential. Moreover, single-particle optical potentials are momentum-dependent, so the increase of the alpha particle's internal kinetic energy due to the Fermi cutoff further decreases the single-particle optical potential. Experiments on the elastic scattering of alpha particles have been analyzed[9] in terms of an optical potential with a real well-depth about equal to that of a single-particle potential. This indicates the extent of the above effects.

The foregoing qualitative theoretical considerations and the analysis of the experiments are in contrast with the model of Tolhoek and Brussard,[10] who argued that the effective alpha-particle potential should be nearly four times the single-particle optical potential. The Tolhoek-Brussard model requires that the alpha-particle internal energy remain negative.

[8] If the alpha-particle energy is positive, the four-body system is unstable with respect to breakup as well as to decay into non-positive-energy functions. This is manifested in the large imaginary part of the optical potential (reference 9).

IV. ACKNOWLEDGMENTS

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[10] H. A. Tolhoek and P. J. Brussard, Physica **21**, 449 (1955).

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Production of F^{18} and Na^{24} in Irradiations of Various Targets with Protons between 1 and 6 Bev*

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Cross sections are reported for the formation of Na^{24} and F^{18} in the interaction of Cu, Ag, Ta, Au, Pb, and U with protons of several energies between 1 and 6 Bev. The cross sections all increase with increasing energy. At each energy the cross sections go through a minimum when plotted against target mass number. The data are interpreted in terms of a spallation mechanism for Cu and Ag targets, with some contribution from fission especially in the case of Ag, and in terms of a fragmentation process for the heavy-element targets.

INTRODUCTION

ONE of the most interesting observations resulting from the study of products formed by bombardment of lead with protons in the Bev energy range[1] was the fact that light products such as F^{18}, Na^{24}, Mg^{28}, and P^{32} were formed with relatively high yields. At 3 Bev the formation cross sections for these light products ranged from 0.5 to 3 mb. In addition it was found that the production of these light nuclides requires very high incident energies. The excitation functions have thresholds at 300–500 Mev, rise rapidly between 0.5 and 2 Bev, and then seem to level off between 2 and 3 Bev. A so-called fragmentation mechanism, i.e., a rapid break-up of an excited nucleus without equilibration of energy, was postulated by Wolfgang *et al.*[1] to account for the observed phenomena.

It seemed of interest to see how the yields of such light products vary with target material as well as bombarding proton energy, and therefore the cross sections for formation of Na^{24} and F^{18} from Cu, Ag, Ta,[2] Au, Pb, and U at 1.0, 2.0, 3.0, 4.5, and 5.9 Bev have been determined.

EXPERIMENTAL

Pure foils of Cu, Ag, Ta, Au, and U were bombarded with protons of 1.0, 2.0, and 3.0 Bev in the circulating

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[1] Wolfgang, Baker, Caretto, Cumming, Friedlander, and Hudis, Phys. Rev. **103**, 394 (1956).

[2] F^{18} formation cross sections were not determined from tantalum targets because of the necessity of using HF to dissolve the target foil.

beam of the Brookhaven Cosmotron. Additional bombardments with protons of 2.0, 3.0, 4.5, and 5.9 Bev were performed in the Berkeley Bevatron. At the two highest energies lead irradiations were also performed. Two metal foils and an aluminum monitor foil were aligned precisely in the standard target holder and irradiated for about 1 hr. Details of Cosmotron targeting, irradiations, and monitoring of the proton beam intensity are identical with those described in reference 1. The irradiation procedure for targets at the Bevatron is similar to irradiations at the Cosmotron in that the targets were placed in the circulating beam of the machine. The targets were rammed to a position inside the vacuum chamber such that they would intercept the collapsing proton beam at the end of the rf cycle. During the early part of the acceleration cycle the target was protected from low-energy protons by being pulled back to a position shielded by the magnet iron.

Targets were dissolved in the appropriate acid containing ~5 mg of fluorine carrier (as NH_4F) and 20 mg of sodium carrier (as NaCl). Fluorine was separated as CaF_2 from the target solution (except in the case of lead targets, where PbClF was precipitated) and further purified as described in reference 1. The filtrate from the first fluoride precipitation was then taken, the target material separated by appropriate chemical means, and sodium separated and purified as described in reference 1. All sample activities were measured in end-window beta proportional counters of known geometry. Combined effects of counting geometry, counting efficiency, self-absorption, and self-scattering were determined in separate experiments for both Na^{24} and F^{18}. For Na^{24}, coincidence counting was used to determine the absolute disintegration rate of a number of samples of $Na^{24}Cl$ which were then counted under standard conditions. The weights of the samples covered the range encountered in this work. For F^{18}, a similar procedure was used, but here the absolute disintegration rate of F^{18} was determined in a scintillation spectrometer by comparison of the F^{18} annihilation radiation with the annihilation radiation from a calibrated Na^{22} source. Chemical analyses were performed on the counting samples at the end of the decay measurements, to determine the chemical yields of the separations.

TABLE I. Formation cross sections (in mb) of F^{18} and Na^{24} from various target elements.

Target element	Cross section	Proton energy (Bev) 1.0	2.0	3.0	4.5	5.9
Cu	$\sigma_{Na^{24}}$	1.0[a]	3.3[a]	4.0[a]	4.6	4.8[b]
	$\sigma_{F^{18}}$	0.51	1.4	1.7	2.5	3.4
	σ_{Na}/σ_F	2.0	2.4	2.3	1.8	1.4
Ag	$\sigma_{Na^{24}}$	0.30	1.4	2.7	4.1	3.3
	$\sigma_{F^{18}}$	0.20	0.55	1.7	1.9	1.5
	σ_{Na}/σ_F	1.5	2.5	1.6	2.2	2.2
Ta	$\sigma_{Na^{24}}$	0.20	0.85	2.3	...	8.7[c]
Au	$\sigma_{Na^{24}}$	0.44	2.2	5.0	7.4	9.4[d]
	$\sigma_{F^{18}}$	0.07	0.25	0.73	1.7	2.5
	σ_{Na}/σ_F	6.3	8.8	6.8	4.4	3.8
Pb	$\sigma_{Na^{24}}$	0.36[e]	2.3[e]	4.4[e]	7.2[d]	9.2[d]
	$\sigma_{F^{18}}$	0.05[e]	0.49[e]	0.83[e]	1.1[d]	1.4[d]
	σ_{Na}/σ_F	7.2	4.7	5.3	6.5	6.5
U	$\sigma_{Na^{24}}$	0.63	2.9	5.6	11.3	12.0[d]
	$\sigma_{F^{18}}$	0.13	0.55	1.4	2.0	3.2
	σ_{Na}/σ_F	4.9	5.3	4.0	5.7	3.8

[a] Data from reference 4.
[b] D. Barr (private communication).
[c] J. R. Grover (private communication).
[d] Result of a single determination.
[e] Data from reference 1, corrected for improved counting efficiency and monitor cross-section data.

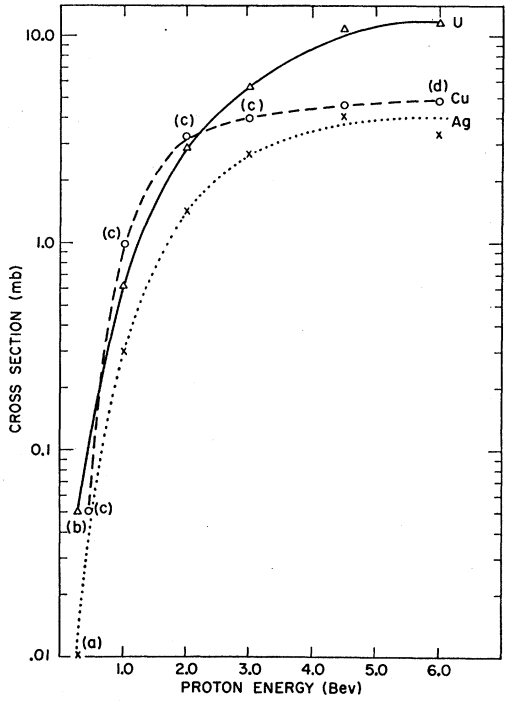

FIG. 1. Excitation functions for the production of Na^{24} from Cu, Ag, and U. (a) Reference 10; (b) Folger, Stevenson, and Seaborg, Phys. Rev. **98**, 107 (1955); (c) Reference 4; (d) D. Barr (private communication).

The observed activities of Na^{24} and F^{18} were converted to cross sections by means of appropriate corrections for counting efficiency, self-absorption, self-scattering, length of bombardment, and chemical yield. Absolute cross sections were based on the value of 10.8 mb for the $Al^{27}(p,3pn)Na^{24}$ monitor reaction between 0.4 and 6 Bev.[3]

RESULTS AND DISCUSSION

The observed cross sections are listed in Table I. Each entry, unless otherwise indicated, is an average of at least two and usually three determinations. The accuracy of the cross section values is estimated as ±25% on the basis of known errors arising from uncer-

[3] R. L. Wolfgang and G. Friedlander, Phys. Rev. **96**, 190 (1954), and **98**, 1871 (1955); Cumming, Swartz, and Friedlander, Bull. Am. Phys. Soc. Ser. II, **1**, 225 (1956).

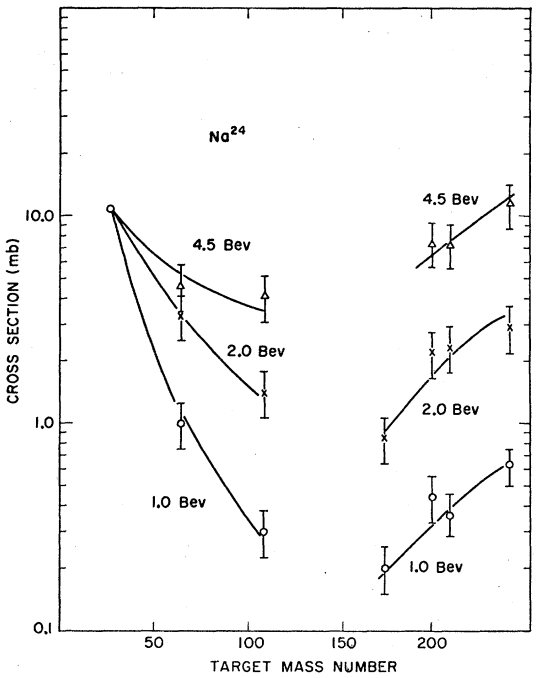

FIG. 2. Formation cross section of Na^{24} *vs* target mass number.

tainties in the over-all counting efficiency, from uncertainties in the monitor cross section, from imperfect superposition of target and monitor foils, and from the chemical yield determinations. In the case of F^{18} yields from uranium there may be an additional uncertainty due to possible lack of complete chemical exchange between carrier fluoride and the fluorine atoms produced during bombardment, which may be tightly bound in uranium fluoride complex ions.

Excitation functions for the production of Na^{24} from Cu, Ag, and U are shown in Fig. 1. The Cu data are taken from the study by Miskel *et al.*[4] of the Na^{24} yields from Cu in the 0.5–3.0 Bev region. It can be seen from Fig. 1 that all of the excitation functions are similar in shape and that, at any given energy, the cross sections for Na^{24} formation from the various target elements are the same within a factor of 3. The F^{18} cross sections exhibit the same behavior. It is evident from the curves that the production of Na^{24} and F^{18} is a high-energy process, since all of the cross sections increase rapidly as the proton energy is raised from 0.4 to 2.0 Bev. Although the excitation functions are similar, a different way of plotting the data reveals interesting trends. This is shown in Figs. 2 and 3, where the cross sections for Na^{24} and F^{18} formation, respectively, are plotted against the mass number of the target nucleus. For each bombarding energy, a curve with two branches results, one for low-Z targets and one for high-Z targets.

Light-nuclide production in Bev proton irradiation of aluminum, copper, and silver is most easily explained by a spallation-type mechanism. From aluminum, only relatively simple nuclear reactions are necessary to produce F^{18} and Na^{24}, and excitation functions for these reactions show maxima at less than 100 Mev.[5] A complete study of the products resulting from the interaction of copper with 2.2-Bev protons[6] indicates that the yields of F^{18} and Na^{24} fall in line as spallation products. A theoretical mass-yield curve for the interaction of copper with 1.83-Bev protons has been obtained by Metropolis *et al.*[7] from a Monte Carlo calculation of the knock-on phase of the reaction plus a crude evaporation calculation, and it agrees quite well with the experimental results down to mass ~ 15.

The Monte Carlo calculations[7] also indicate that the observed yields of Na^{24} and F^{18} from silver may be explained by a spallation mechanism when the energy of the irradiating proton is 2 Bev or greater. With proton energies less than 2 Bev, there is, according to these calculations, not enough excitation energy deposited in the struck nucleus to evaporate the 75 to 80 nucleons necessary to reach Na^{24} and F^{18}. Since appreciable yields of Na^{24} and F^{18} are observed experimentally with 1.0- and, at least in the case of Na^{24},

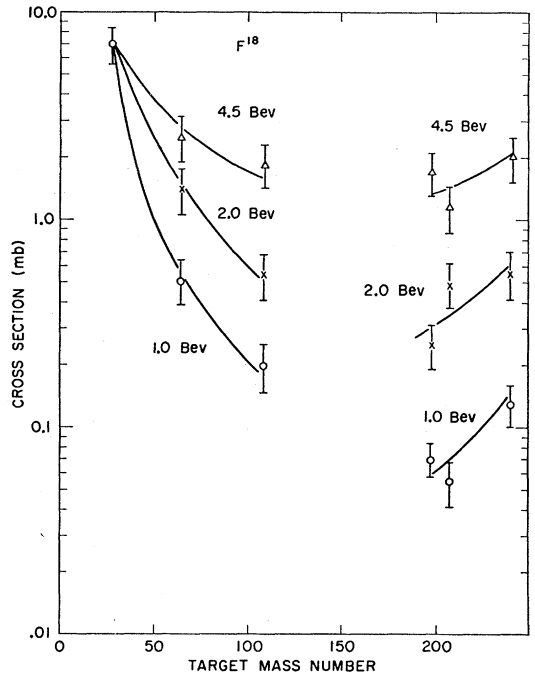

FIG. 3. Formation cross sections of F^{18} *vs* target mass number. The Al point (for 1 to 3 Bev), plotted for comparison, is from Friedlander, Hudis, and Wolfgang, Phys. Rev. **99**, 263 (1955). P. Benioff (private communication) states that there is no apparent change in this cross section up to 5.9 Bev.

[4] Miskel, Perlman, Friedlander, and Miller, Phys. Rev. **98**, 1197(A) (1955).

[5] N. M. Hintz and N. F. Ramsey, Phys. Rev. **88**, 19 (1952).

[6] Friedlander, Miller, Wolfgang, Hudis, and Baker, Phys. Rev. **94**, 727 (1954).

[7] Metropolis, Bivins, Storm, Miller, Friedlander, and Turkevich, Phys. Rev. **110**, 204 (1958).

even with 0.48-Bev protons,[8] it is assumed that a mechanism other than spallation is responsible for light-nuclide production at low energies. On the other hand, the shapes of the σ *vs* A curves of Fig. 3 make it seem unlikely that the same mechanism which accounts for formation of Na^{24} and F^{18} from high-Z targets can be responsible for the observed yields from Ag. Thus still a third type of process such as the previously reported fission of medium-weight nuclei[9,10] may be responsible for the (rather low) yields of Na^{24} and F^{18} from silver at the lower energies.

It is obvious that a spallation mechanism would not be sufficient to explain the yields of F^{18} and Na^{24} from targets in the region tantalum to uranium, particularly since the yields increase with increasing size of target nucleus in this region. Some other mechanism, presumably one involving breakup into larger fragments, must be responsible. Wolfgang *et al.*[1] have introduced the term "fragmentation" to describe such a process, which they postulated to account for the high yields of light nuclides observed in Bev proton bombardment of lead.

Fragmentation has been defined as a rapid breakup taking place in a time short compared to the time required for equilibration of energy throughout the nucleus and it may be thought of as resulting from local heating caused by the production and reabsorption of pions in nuclear matter. Such a fragmentation process would result in highly excited fragments with n/p ratios similar to that of the struck nucleus. One would thus expect particle evaporation to follow the fragmentation process. The light partner in this process would be quite neutron-rich. Thus neutron emission back toward the stability valley followed by neutron and proton emission down the valley would be the path by which the light fragments would lose their initial excitation energy. De-excitation in this manner would lead to peak yields of light products near stability or perhaps a little to the neutron-excess side of stability. The observation that the yield of Na^{24} is always greater by a factor of 4 to 7 than the yield of F^{18} from any heavy-element target at the energies studied is in accord with such a mechanism. Within experimental error the ratio of $\sigma_{Na^{24}}/\sigma_{F^{18}}$ is the same from the heavy-element targets at all energies. If F^{18} and Na^{24} were formed directly or were the products of very short evaporation cascades it would be difficult to account for this constancy of their relative yields from various high-Z targets between 1 and 6 Bev. However, the fragmentation hypothesis of highly excited, neutron-rich light fragments would demand that Na^{24} and F^{18} be the products of relatively long evaporation cascades. Drastic changes in the yield, type, and excitation energy of the light fragmentation partner would not necessarily show up in the ratio of $\sigma_{Na^{24}}/\sigma_{F^{18}}$ because of the washing-out effect of the long evaporation cascade. The large values of the $\sigma_{Na^{24}}/\sigma_{F^{18}}$ ratio for the high-Z targets show that the evaporations must start far on the neutron-excess side of stability. The $\sigma_{Na^{24}}/\sigma_{F^{18}}$ ratios for Cu and Ag targets are much lower (in the neighborhood of 2) and presumably correspond to evaporations beginning near stability, in fact probably slightly on the neutron-deficient side.[7]

The steep rise in the σ *vs* A curve starting with tantalum seems to set a minimum size of the target nucleus from which the fragmentation process can produce F^{18} and Na^{24} to any large extent at these energies. Since an important part of the fragmentation picture is local heating by interaction of mesons in the nucleus in which they were produced, one would expect the probability of fragmentation to decrease with decreasing nuclear size. However, the magnitude of the change in Na^{24} formation cross section in going from U to Ta appears to be much too large to be accounted for by the 10% decrease in nuclear radius. Other factors, perhaps akin to a general fissionability parameter, must be important in enhancing fragmentation in the heaviest elements.

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[8] Kurchatov, Mekhedov, Borisova, Kuznetsova, Kurchatova, and Chistyakov, *Proceedings of the Conference of the Academy of Sciences, U.S.S.R., on the Peaceful Uses of Atomic Energy, Moscow, July 1–5, 1955* (Akademiia Nauk, S.S.S.R., Moscow, 1955), Session of Division of Chemical Sciences, p. 178 [English translation by Consultants Bureau, New York, U. S. Atomic Energy Commission Report TR-2435, (1956), Part 2, p. 111].

[9] R. E. Batzel and G. T. Seaborg, Phys. Rev. **79**, 528 (1950).

[10] P. Kofstad, University of California Radiation Laboratory Report UCRL-2265, 1953 (unpublished).