Energy Distributions of Li^8 Fragments Emitted from C, Al, Cu, Ag, Au, and U Bombarded by 2.2-Bev Protons*

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Targets of C, Al, Cu, Ag, Au, and U were irradiated with 2.2-Bev protons at the Brookhaven Cosmotron. The secondary fragments were collected in nuclear emulsions placed at various angles to the beam. From a study of the numbers and lengths of the "hammer tracks," the energy distributions of the ejected Li^8 fragments were derived for each target element at two or more angles. Analysis of the results, and comparison with evaporation calculations for Cu, Ag, and Au targets indicated the following. (1) In general, the observed spectra show considerably more high-energy Li^8 fragments than the calculated spectra. (2) The higher the fragment energy, the greater the tendency for emission in a forward direction. (3) From Ag, Au, and U targets, Li^8 may be ejected partially by an evaporation mechanism, but some other process must also play an important role. (4) For C, Al, and Cu targets, evaporation of Li^8 fragments from residual nuclei does not seem to be operating to any appreciable extent. (5) The Li^8 spectrum from Cu is surprising in that it lies higher in energy by several Mev than the Li^8 spectrum from Ag. (6) The spectrum of Li^8 from U is very similar to that from Au; there is no evidence for emission of Li^8 fragments from excited fission products. (7) The cross section is estimated to increase monotonically from roughly one millibarn for Al to roughly ten millibarns for U.

INTRODUCTION

THE products of high-energy nuclear reactions can be studied by a variety of experimental techniques: radiochemistry, mass spectrometry, cloud chamber, nuclear photographic emulsions, and direct detection of the fragments with proportional and scintillation counters. Each method has its advantages and limitations. For example, radiochemistry can identify the mass and atomic number of the radioactive products but it cannot relate them directly to the specific kinds of events in which they were produced. On the other hand, cloud chamber and emulsion techniques can record all products (except neutrons) from individual events, but identification of the mass and charge of these products above neon is very difficult, if not impossible; and in the range from Li to Ne, identification is only approximate, especially for the shorter tracks. Also, in nuclear emulsion studies identification of the target element is often subject to some doubt.

The present investigation was started as part of a program at the Brookhaven Cosmotron to supplement the radiochemical studies[1–3] with studies employing the nuclear emulsion technique. However, in the work described here, part of the advantage of this technique was sacrificed in order to have freedom of choice in the selection of target elements and in order to be almost certain of product identification. The targets were placed outside of the emulsion and only "hammer tracks" (which are characteristic of Li^8 and B^8) were selected for measurement. The "hammers" result from the decay of Be^{8*} (daughter of Li^8 and B^8) into two α particles. Targets of C, Al, Cu, Ag, Au, and U were irradiated with 2.2-Bev protons and the energy distributions of the ejected Li^8 fragments were measured at various angles to the beam.

Previous investigations of Li^8 ejected from elements irradiated in the Bev region were all performed by passing the beam through the nuclear emulsion. Munir[4] used 950-Mev protons and divided the observed Li^8 fragments into a group coming from the light elements of the emulsion and another group emitted by the Ag and Br. More recently, Goldsack, Lock, and Munir[5] irradiated nuclear emulsions with 5.7-Bev protons and studied the energy distribution of Li^8 fragments emitted from the heavier elements only (Ag and Br). In a similar investigation, Nakagawa, Tamai, and Nomoto[6] studied all Li and Be fragments emitted in the larger stars produced in nuclear emulsion irradiated by 6.2-Bev protons. Several earlier papers[7–9] were concerned with emission of Li^8 and other fragments from stars produced by cosmic rays. Most of these investigators conclude that the lower energy fragments may be emitted by an evaporation mechanism but that the higher energy fragments are ejected by some other mechanism during the nuclear cascade. Measurements

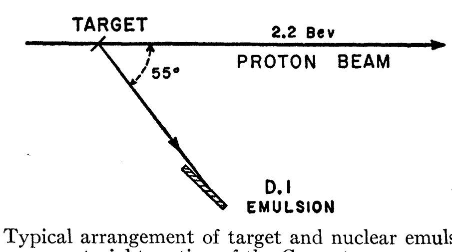

FIG. 1. Typical arrangement of target and nuclear emulsion in a straight section of the Cosmotron.

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

[2] Friedlander, Hudis, and Wolfgang, Phys. Rev. **99**, 263 (1955).

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

[4] B. A. Munir, Phil. Mag. **1**, 355 (1956).

[5] Goldsack, Lock, and Munir, Phil. Mag. **2**, 194 (1957).

[6] Nakagawa, Tamai, and Nomoto, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958 (United Nations, New York, 1958), Paper No. 1964; Nuovo cimento **9**, 780 (1958).

[7] D. H. Perkins, Proc. Roy. Soc. (London) **A203**, 399 (1950).

[8] S. O. C. Sörensen, Phil. Mag. **42**, 188 (1951).

[9] P. E. Hodgson, Phil. Mag. **42**, 207 (1951).

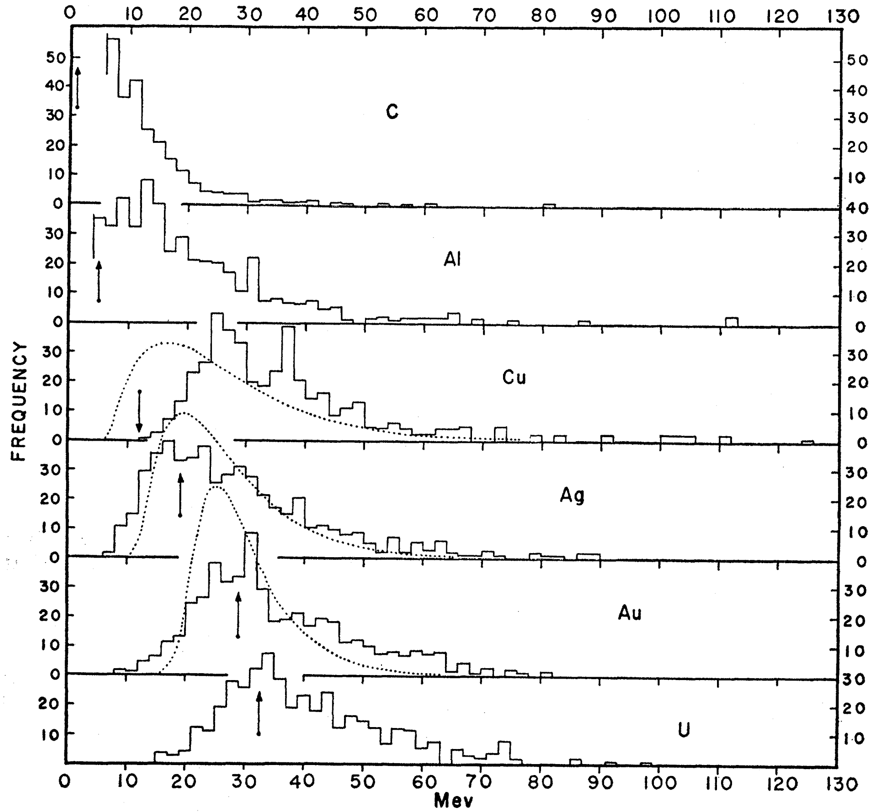

FIG. 2. Observed energy spectra of Li^8 fragments emitted from various targets bombarded with 2.2-Bev protons. The dotted curves for Cu, Ag, and Au are calculated evaporation spectra as described in the text. The arrows indicate upper limits of the Coulomb barriers.

of secondary fragments in bombardments of somewhat lower energy were carried out by Lozhkin and Perfilov,[10] by Denisenko *et al.*,[11] by Deutsch,[12] and by Wright.[13] The last author studied Li^8 emission from various gas targets by means of a counter technique.

EXPERIMENTAL

Thin ribbon targets, 0.25 in.×3.0 in., of polyethylene, aluminum, copper, silver, gold, and uranium were irradiated with 2.2-Bev protons in the Brookhaven Cosmotron. The polyethylene targets were made by careful stretching of a sheet 3.6 mg/cm² thick until the thickness was reduced to 1.7±0.1 mg/cm². The aluminum targets were cut from 0.00025-in. pure Al foil. The copper, silver, and gold targets were made by vacuum evaporation of these metals onto glass plates. The glass was covered with a thin film of silicone oil so that the evaporated foils could be removed easily. The uranium targets were made by etching 24 mg/cm² foil with nitric acid until the thickness was reduced to 11.5±1.0 mg/cm². In order to prevent the formation of an appreciable oxide coat on the uranium, the etching was effected immediately before the irradiation. Secondary particles emitted from each target were intercepted by an Ilford D.1 emulsion placed at 3 in. from the target and at a predetermined angle to the primary beam. Figure 1 shows a typical arrangement where the average angle of the intercepted secondaries is 55° to the proton beam and 10° to the surface of the emulsion.

The nuclear plate was enclosed in a brass box with a very thin gold window (0.5 mg/cm² evaporated onto 0.1 mg/cm² of plastic) to protect the emulsion from light. The window was arranged to be perpendicular to the plate so that the incoming particles would always pass through at an angle close to the normal. The plate box and ribbon target were firmly attached to a metal frame which could be rotated about an axis parallel to the ribbon; thus the relative orientation of target and emulsion always remained fixed while the angle between the intercepted secondary particles and the proton beam could be varied. The apparatus was inserted into one of the straight sections of the Cosmotron while a large copper block was placed in a second straight section at such a radius that the emulsion would be well back in the shadow of the block while the target would be exposed to the beam. A thick aluminum "shutter" at the end of a pneumatic plunger was employed in a third straight section[3] to protect the target from low-energy protons lost from the beam during the early part of the acceleration cycle. The targets were irradiated with about ten pulses of 2.2-Bev protons, $\sim 2\times10^9$ protons per pulse.

[10] O. V. Lozhkin and N. A. Perfilov, Soviet Phys. JETP 4, 790 (1957).
[11] Denisenko, Ivanova, Novikova, Perfilov, Prokoffieva, and Shamov, Phys. Rev. **109**, 1779 (1958).
[12] R. W. Deutsch, Phys. Rev. **97**, 1110 (1955).
[13] S. C. Wright, Phys. Rev. **79**, 838 (1950).

After most of the irradiations the radioactivity induced in the central 2 in. of the target was measured. In this way experiments at various angles could be normalized to each other. C^{11} activity was measured[14] from the polyethylene targets, Na^{24} from aluminum,[14] gross γ activity from copper, and Tb^{149} α activity from the gold targets. The experiments with silver and uranium targets were normalized by means of the Cosmotron circulating beam monitor. This method was found to agree, within $\pm 5\%$, with the induced radioactivity measurements when successive irradiations were performed on the same day. When experiments were separated by long time intervals, the two methods sometimes led to results that disagreed by as much as a factor of two. Both irradiations with silver targets were performed on the same day, as were two of the three irradiations of uranium.

The 1-in.×3-in. nuclear emulsions were 100 μ thick for C, Al, Ag, and Au targets and 200 μ thick for Cu and U targets. The thinner emulsions were processed at constant temperature with 10-fold diluted D-19 developer; the thicker ones were processed by the "temperature development" technique with 20-fold diluted D-19. The plates were under-developed in order to minimize the background tracks. The surfaces of the emulsions were not rubbed for removal of surface deposit (except for a few of the aluminum runs) so as not to affect the lengths of the tracks. Where surface deposit was troublesome, the experiment was repeated. About 2 cm^2 of each plate was area scanned for the hammer tracks characteristic of Li^8 and B^8. Criteria for selection of the tracks were: (1) they must start at the surface of the emulsion; (2) they must be at least 5 μ long; (3) they must point back toward the target; and (4) the α's of the hammer head must be nearly collinear and of nearly equal length. Well over 90% of all the hammer tracks met these requirements. All but three of the plates were scanned twice in order to ascertain the scanning efficiency and in order to be more certain of proper track identification. The efficiency varied from about 75% to 95% and depended mainly on the absolute density of all tracks in the plate. Table I gives the conditions of each irradiation and the number of hammer tracks observed in each plate.

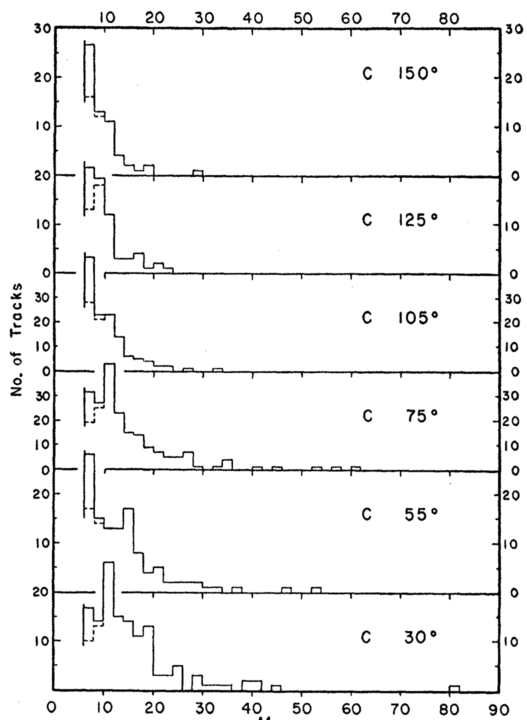

FIG. 3. Energy spectra of Li^8 fragments emitted at various angles to the proton beam from polyethylene targets. From top to bottom, the number of observed tracks for each histogram is 50, 59, 110, 186, 117, and 127, respectively.

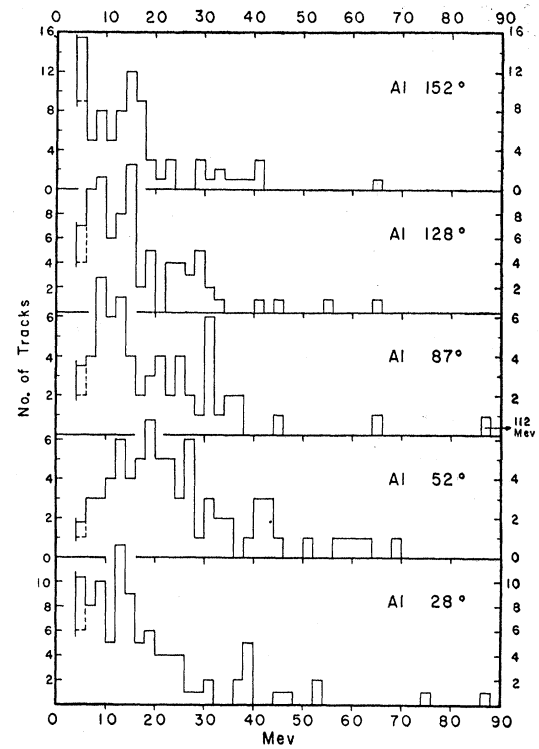

FIG. 4. Energy spectra of Li^8 fragments emitted at various angles to the proton beam from aluminum targets. From top to bottom, the number of observed tracks for each histogram is 76, 86, 61, 80, and 95, respectively.

RESULTS AND DISCUSSION

The results are summarized in Figs. 2–9, and in Tables I to III. The energy spectra shown in Figs. 3–8 are for Li^8 fragments emitted at the indicated angles to the proton beam from the various targets. The energies

[14] No corrections were applied for the variation of recoil loss of C^{11} or Na^{24} from the targets as a function of angle to the beam. These corrections are no more than a few percent in the worst cases and they cancel completely for pairs of angles symmetrical about 90°. See R. Wolfgang and G. Friedlander, Phys. Rev. **94**, 775 (1954).

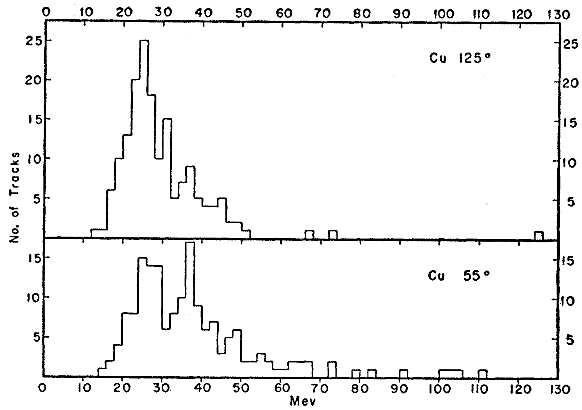

FIG. 5. Energy spectra of Li^8 fragments emitted at 55° and 125° to the proton beam from copper targets. At 125° there are 170 Li^8 tracks and at 55° there are 174 tracks.

were derived from the measured lengths of the tracks and range-energy relations for Li^8 in nuclear emulsion given by Barkas[15] and by Livesey.[16] It was assumed that all of the hammer tracks are due to Li^8 although B^8 also gives rise to very similar tracks. This assumption appears to be at least approximately correct from a study of the hammer track densities in some of the plates. Corrections to the measured ranges were made for self-absorption in the targets (3-10 μ emulsion equivalent) and absorption by the window (0.7 μ). Because of self-absorption and the requirement that at least 5 μ of track be visible, no data could be obtained for fragment energies below $\sim$5 Mev. Thus for carbon there is a low-energy cutoff in the data at 6 Mev, and for aluminum at 4 Mev. Between 4 Mev and 10 Mev, where necessary, the observed number of tracks was corrected for self-absorption loss. In Figs. 3, 4, and 6 the uncorrected numbers of tracks in this energy interval are indicated by the dashed lines. On the high-energy side, above 80 Mev for C, Al, Ag, and Au, there is a slowly increasing probability of losing tracks due to their passing completely through the 100-μ thick emulsion. For Cu and U, 200-μ thick emulsions were used so that this effect does not start until the Li^8 fragment energy exceeds 120 Mev. No attempt was made to correct for loss of high-energy tracks (above 80 or 120 Mev) but inspection of Fig. 2 shows that no more than a very few tracks could have been missed.

The histograms of Fig. 2 were derived from Figs. 3–8. For each target the results obtained at various angles

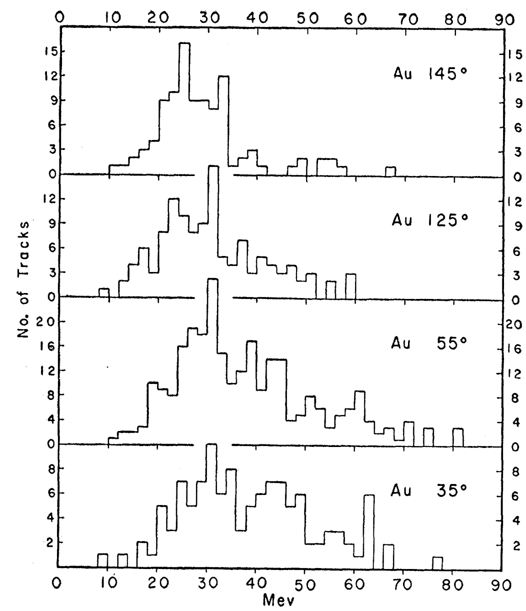

FIG. 7. Energy spectra of Li^8 fragments emitted at various angles to the proton beam from gold targets. From top to bottom, the number of observed tracks for each histogram is 101, 125, 271, and 119, respectively.

were combined according to the normalization indicated by the last column of Table I and with appropriate corrections for solid angle. Thus the distributions of Fig. 2 represent approximate energy spectra of Li^8 fragments emitted from the various targets into 4π solid angle. The scale of ordinates for each of these histograms is arbitrary. The arrows show the upper limit of the Coulomb barrier for each target calculated on the assumptions that r_0 is 1.4×10^{-13} cm and that the Li^8 fragments are the first ones to be emitted from the struck target nuclei.

The dotted curves of Fig. 2 are calculated spectra based on the assumption that all of the Li^8 fragments were evaporated from residues of excited target nuclei during the evaporation phase which follows the prompt

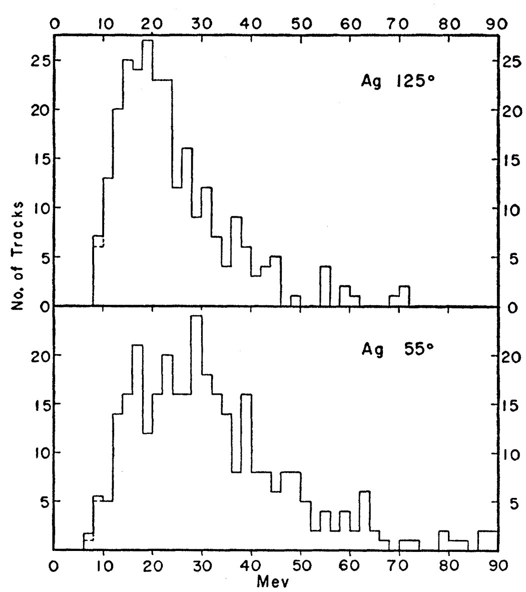

FIG. 6. Energy spectra of Li^8 fragments emitted at 55° and 125° to the proton beam from silver targets. At 125° there are 265 Li^8 tracks and at 55° there are 322 tracks.

[15] W. H. Barkas, Phys. Rev. 89, 1019 (1953).
[16] D. L. Livesey, Can. J. Phys. 34, 203 (1956).

TABLE I. Conditions of irradiation and the number of hammer tracks observed from various targets irradiated with 2.2-Bev protons.

Target	Thick-ness (mg/cm²)	Lab angle to beam	Area scanned (cm²)	No. hammer tracks observed	Average scanning efficiency (%)	Beam intensity ×10⁻¹⁰ (protons)	Activity in target	Target activity ÷beam intensity	Normalized No. of tracks
C	1.8	30°	1.68	127	86	2.19	224	102	89
C	1.7	55°	2.40	117	71	1.65	180	109[a]	71
C	1.7	75°	2.40	186	87	2.46	298	121	68
C	1.7	105°	2.88	110	84	2.31	273	118	36.6
C	1.8	125°	2.40	59	81	3.03	321	106[a]	20.0
C	1.6	150°	2.88	50	90	2.80	215	77	21.2
Al	1.6	28°	2.40	95	83	1.28	535	418[b]	80
Al	1.6	52°	2.40	80	84	~1	500	~500[c]	72
Al	1.6	87°	2.40	61	92	1.2	540	450[c]	64
Al	1.6	128°	2.40	86	78	~2	1150	~580	38
Al	1.6	152°	2.40	76	85	1.91	805	421[b]	42
Cu	3.7	55°	1.68	133	74	1.56	995	638[d]	125
Cu	3.7	55°	~2.4	41		0.69	244	354[e]	~110
Cu	3.4	125°	2.40	128	74	4.30	2600	605[d]	32.4
Cu	3.7	125°	~2.4	42		1.90	725	382[e]	~ 36
Ag	4.2	55°	1.68	322	85	3.23		[f]	142
Ag	4.1	125°	1.68	265	85	4.15		[f]	91
Au	6.2	35°	1.68	119	85	1.19	33.0	27.7	182
Au	6.6	55°	2.40	104	95	0.56	17.5	31.3	208
Au	6.6	55°	1.68	167	95	0.93	35.0	37.6[g]	238
Au	6.1	125°	1.68	125	90	1.28	43.2	33.8[g]	144
Au	5.7	145°	2.40	101	92	0.74	27.2	36.8[g]	131
U	12.5	55°	1.68	125	85	0.94		[h]	190
U	12.5	125°	1.68	168	76	1.77		[h]	135
U	10.4	125°	~0.6	60		2.20			~110

[a–h] Runs identified with the same letter were performed on the same day.

knock-on cascade. The distributions of excited nuclei produced by the knock-on phase were derived from the Monte Carlo calculations of Metropolis *et al.*[17] for the interaction of 1.84-Bev protons with Cu^{64}, Ru^{100}, and Bi^{209}. Small extrapolations were made[18] from Ru^{100} to Ag^{108}, and from Bi^{209} to Au^{197}. No attempt was made to correct the energy of the incident protons from 1.84 Bev to 2.2 Bev. The evaporation paths followed by the excited nuclei were derived from another Monte Carlo calculation kindly made available to the author by Hudis.[18] As a first approximation, it was then assumed that Li^8 fragments will evaporate with equal probability from any nucleus whose excitation exceeds 250 Mev, and that no Li^8 will be evaporated from nuclei whose excitation is below 250 Mev.[13] For each excitation energy E (in Mev), the nuclear temperature T (in Mev) was calculated from the relation

$$E = aT^2, \tag{1}$$

where a was taken[19] as $A/12.4$ (A = atomic weight). The effective Coulomb barrier, $V_{\rm eff}$, was calculated from the relation

$$V_{\rm eff} = V/(1+0.001E). \tag{2}$$

V was calculated with $r_0 = 1.4\times10^{-13}$ cm and with the radius of the Li^8 fragment added to the radius of the residual nucleus. This equation gives only a weak dependence of the Coulomb barrier on the excitation energy.[19] Finally for each target element, the distribution of excited nuclei was divided into small groups according to the average excitation energy E, average A, and average Z. For each group, a spectrum of evaporated Li^8 fragments was calculated from the equation

$$P(E)dE = [(E - V_{\rm eff})/T^2]e^{-(E-V_{\rm eff})/T}dE. \tag{3}$$

These spectra were weighted by the appropriate probabilities, combined, and normalized to the area of the experimental histogram for each case. The results are shown as dotted curves in Fig. 2.

Agreement between experiment and calculation is approached only in the case of silver. Minor adjustment of the parameters and assumptions mentioned above

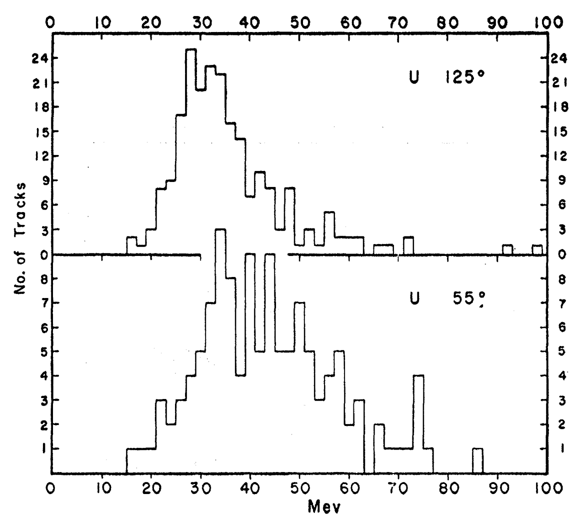

FIG. 8. Energy spectra of Li^8 fragments emitted at 55° and 125° to the proton beam from uranium targets. At 125° there are 228 Li^8 tracks and at 55° there are 125 tracks.

[17] Metropolis, Bivins, Storm, Miller, Friedlander, and Turkevich, Phys. Rev. **110**, 204 (1958).
[18] J. Hudis and J. M. Miller, Phys. Rev. **112**, 1322 (1958).
[19] K. J. LeCouteur, Proc. Phys. Soc. (London) **A63**, 259 (1950).

TABLE II. Ratios of Li^8 fragments emitted 55° to the proton beam to those emitted at 125°. Data are given as a function of Li^8 energy for each target.

Target \ Li^8 energy (Mev)	5–10	10–20	20–30	30–40	40–50	50–60	60–70
Carbon	1.9±0.3	4.3±0.8	$7.6_{-3.8}^{+7.6}$				
Aluminum	0.6±0.2	1.6±0.3	2.5±0.6	$5.3_{-2.0}^{+6.0}$	>4		
Copper		1.5±0.5	2.6±0.3	4.7±0.7	6.0±1.5	>11	
Silver		0.8±0.1	1.4±0.2	2.4±0.4	3.8±1.0	$3.6_{-1.3}^{+4.0}$	
Gold		0.9±0.3	1.1±0.2	1.8±0.3	2.0±0.5	$2.7_{-0.7}^{+1.4}$	
Uranium		1.2±0.7	0.6±0.1	1.2±0.2	2.6±0.5	3.7±1.0	$4.4_{-1.5}^{+4.4}$

TABLE III. Ratios of Li^8 fragments emitted at a forward angle θ to those emitted at a backward angle $\pi-\theta$.

$\theta/(\pi-\theta)$ \ Target	C	Al	Cu	Ag	Au	U
55°/125°	(3.6±0.5)[a]	(1.9±0.3)[a]	3.9±0.4	1.6±0.1	1.5±0.2	1.4±0.2
30°/150°	(4.2±0.6)[a]	(1.9±0.3)[a]			1.4±0.1	

[a] In these cases the low-energy portions of the spectra were not measured.

could improve the agreement for silver for fragment energies below 40 Mev, but no reasonable adjustment can give a sufficient number of calculated events above this energy. The calculated spectrum from gold is much too narrow and predicts far too few high-energy Li^8 fragments. The calculated *shape* of the spectrum from copper is in fair agreement with the observations but the *position* on the energy scale is about 10 Mev too low.

The results from copper targets require a separate discussion because the position of the observed spectrum seems anomalous with respect to the upper limit of the Coulomb barrier (arrow in Fig. 2). In fact, the spectrum from Cu, $Z=29$, lies higher in energy than the spectrum from Ag, $Z=47$. The experiments were carefully checked for possible sources of error. The copper targets were chemically analyzed and found to be essentially 100% copper; likewise, the gold targets were analyzed spectroscopically and found to contain only traces (<0.1%) of impurities such as Ag, Cu, Ni, and Fe. Two of the nuclear plates used for copper (identified by *d* in Table I) were from a new batch in which the emulsions were less sensitive than those in previous batches. There was a tendency for some of the tracks to be very light near the surface, and thus more of the shorter ones would escape detection. This effect was shown to be negligible by scanning two more plates from another pair of runs (identified by *e* in Table I) where none of the tracks were unusually light near the surface of the emulsion. Within the statistics of the measurements, the spectra from both pairs of runs were identical. Figures 2 and 5 contain the combined data from all four copper runs. Further experimental checks of this phenomenon must await reactivation of the Brookhaven Cosmotron which is now undergoing repair. In the meantime these data should be taken as tentatively correct.

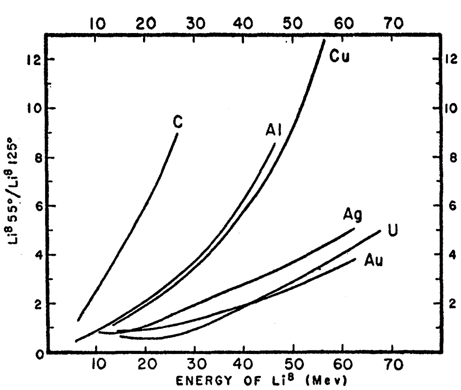

FIG. 9. Ratios of Li^8 fragments emitted 55° to the proton beam to Li^8 emitted at 125°. Curves are shown as a function of Li^8 energy for each target. The data for this figure are given in Table II.

The Li^8 fragments produced from carbon represent residual nuclei from reactions such as $C^{12}(p,4pn)Li^8$ or $C^{12}(p,2pHe^3)Li^8$. In the case of aluminum targets, Li^8 can be ejected from residues most probably in the region of nitrogen to neon,[17] or the Li^8 can itself be the residue in reactions such as $Al^{27}(p,3p4\alpha n)Li^8$. The spectra from aluminum (Figs. 2 and 4) result from a combination of both of these processes. For the copper target and targets of higher Z there is virtually no chance of Li^8 being the spallation residue.

The Li^8 fragments emitted from uranium were measured (Figs. 2 and 8) in order to investigate any possible influence of fission on the shape and position of the spectrum. For example, if Li^8 fragments were emitted from excited fission products following fission of the uranium, then the spectrum of Li^8 might approximate the one obtained from silver targets, since silver is near the peak of the fission yield distribution observed at high bombarding energies. On the other hand, if the Li^8 were emitted before fission of the uranium, then the spectrum might approximate that observed from gold targets. Figure 2 shows that the second situation obtains except for a small upward shift in energy corresponding to a 4-Mev shift in Coulomb barrier. There is no evidence for emission of any Li^8 fragments from excited fission products.

In view of these results and the generally poor agreement with the calculations, it may be concluded that the evaporation mechanism does not adequately describe the emission of Li^8 fragments from elements bombarded by 2.2-Bev protons. For Ag, Au, and U targets, evaporation may contribute to a substantial degree, but it is clear that some other mechanism is also playing an important role. The fair agreement between calculation and experiment for silver may be only fortuitous. It seems likely that one cannot clearly separate an observed spectrum (from Ag, Au, or U) into a low-energy region where the evaporation mechanism is dominant, and into a high-energy region where another mechanism is dominant. Very probably these two regions strongly overlap. For Cu targets, it appears that the evaporation mechanism does not contribute to any appreciable extent toward emission of Li^8 fragments, since the spectrum (Fig. 2) is so greatly deficient in lower energy particles. For Al targets, it is also likely that evaporation is unimportant since the peak of the spectrum (Fig. 2) seems to be considerably above the Coulomb barrier, as with Cu targets. The Al case, however, is complicated by the additional processes which lead to formation of Li^8 as spallation residues. For carbon targets, the concept of evaporation does not apply, since the Li^8 has $\frac{2}{3}$ the mass of the target.

Previous investigators[3–8,20] have suggested that the Serber description of high-energy nuclear reactions (fast nucleon-nucleon knock-on stage followed by slow evaporation) must be supplemented by other processes. However, so far no precise model has been developed for an additional mechanism nor is there any exact knowledge of the relative importance of competing mechanisms. A recent comparison[18] of the experimental yields of Be^7 emitted in high-energy reactions from Cu, Ag, and Au, with yields calculated on the basis of an evaporation mechanism, indicates that most of the Be^7 nuclei are emitted as evaporated particles. This conclusion appears to be in disagreement with the conclusions drawn here from the experiments with Li^8. Further refinement of the Monte Carlo calculations on the knock-on stage and on the evaporation stage[21] coupled with more detailed experimental investigations should help to resolve this discrepancy and to define more clearly the scope of the Serber picture.

Additional support for the above conclusions is provided by a study of the angular distribution of the Li^8 fragments as well as by comparisons of the spectra observed in the forward and backward directions with respect to the proton beam. Figure 9 and Table II show that the higher the energy of the Li^8 fragments, the greater their tendency to be emitted in a forward direction. This effect is much more pronounced for carbon, aluminum, and copper than it is for silver, gold, and uranium. Table III shows forward to backward ratios for Li^8 fragments of all energies at two pairs of angles. The numbers given there for carbon and aluminum targets are in parentheses because in these two cases the low-energy portions of the spectra were not measured. Again, a sharp difference is noted between copper and silver where the ratio changes from 3.9 to 1.6. Examination of Figs. 3–8 shows that for each target element, the Li^8 spectrum is broadened and shifted toward higher energies as the angle of observation changes from backward to forward. Calculations show that the observed changes are larger than could be accounted for by center-of-mass motion.

No precise values of the cross sections for production of Li^8 from the various target elements could be obtained from these experiments. A rough estimate indicates that for irradiation by 2.2-Bev protons, the cross section increases monotonically from approximately one millibarn for aluminum to about 10 millibarns for uranium. This behavior is also characteristic of the emission of He^6 fragments from various targets.[22] Be^7 fragments, on the other hand, are produced[23] with a constant cross section of about 11 millibarns (at 2.2 Bev) from C, Al, Cu, and Ag with a decrease to about 6 millibarns from Au. It should also be noted that the yield of Li^8 from uranium shows no depletion due to fission.

In nuclear emulsion studies of high-energy events it has been customary to consider interactions with silver and bromine nuclei together in one group. For purposes of calculation,[17] Ru^{100} has been selected as a nucleus representing an "average" of Ag and Br. In view of the very different behavior of copper and silver described in the present work, such practice should be used with caution or avoided where possible. Further high-energy studies of Li^8 energy spectra from elements between copper and silver will be of considerable interest in this connection.

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