Emission of Heavy Fragments in Nuclear Disintegrations

O. SKJEGGESTAD AND S. O. SÖRENSEN
Institute of Physics, University of Oslo, Blindern, Norway
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A phenomenological description is given of the processes which lead to the emission of energetic heavy fragments from cosmic-ray stars. The energy spectra, angular distribution, and relative frequency of the particles have been determined, and a detailed comparison is made with the predictions from nuclear evaporation theory. A simple method for charge determination of the fragments is described.

INTRODUCTION

DURING the last years numerous reports have been given of the observation of heavy nuclear fragments emitted from stars in photographic emulsions.[1–12] The phenomenon represents a complex many-body reaction in high-energy nuclear physics, and the mechanism of ejection of such aggregates of nucleons is far from being understood. Apart from the general physical interest of the process, the phenomenon may have a bearing on the question of the emission of the hyperfragments, and further on various problems in radiochemistry, astrophysics, etc.

The present paper deals with the ejection of energetic lithium, beryllium, and boron isotopes from stars. As the phenomenon presents similar problems to that of the emission of energetic ($E>45$ Mev) helium particles, a study of the latter has also been included in the investigation. The experimental part is mainly phenomenological. In the following discussion an attempt is made to compare the observations with the predictions from nuclear evaporation theory, leaving open the question of cascade processes, fission, etc. as possible explanations of the mechanism of ejection.

The material was recorded in a stack of stripped Ilford *G*5 emulsions, each 600 μ thick, exposed at high altitude by means of free balloons. Figure 1 shows a photomicrograph of a boron nucleus, with kinetic energy $\sim$100 Mev, ejected from a star.

EXPERIMENTAL

A. Identification of Heavy Fragments

Multiply-charged particles in electron-sensitive photographic emulsions can easily be separated from singly-charged particles due to the large increase in total ionization with charge. For the energetic heavy fragments the most characteristic feature of the tracks is the large number of delta rays which the particles produce in their passage through the emulsions. A study of the distributions of these delta rays along the tracks provides a precise method for determining the charge of the fragments. For low-energy fragments (of range $<500\,\mu$) the delta-ray method is unsuitable, and a different method depending on measurement of the total ionization of the tracks has been developed.[13,14] As most of the fragments in the present investigation are of short range, the latter method has been used for charge determination. The delta-ray method has only been applied to identify the helium particles.

By means of a projection microscope, a drawing of the fragment has been made on tracing paper placed on a glass plate 150 cm above the microscope. Using a Leitz microscope with ordinary Leitz light bulbs (36w), a maximum magnification of $\sim$4500 was obtained with a $\times$95 objective and a $\times$10 ocular. By means of a special device the fine focus of the microscope could be regulated so as to keep the track in focus as the drawing was made. The drawing was subdivided into short lengths, each 5 cm long, and the area of each interval was measured with a high-precision planimeter. Upon integrating the area of the intervals over a certain track length, the tracks were clearly separated into groups corresponding to different values of charge.

Influence on track area of dip in the emulsions was tested by measuring Li^8 "hammer" tracks of different dip angle. For tracks with dip $<20°$ no corrections for dip were needed. Some helium particles with angle of dip $<5°$ and range $>1000\,\mu$, which were distributed in all layers of the emulsions, were also measured by the planimeter. There appeared to be no significant change in track area from one emulsion depth to another for particles between 50 μ and 550 μ from the surface of the emulsion. The helium particles are used for calibration in the charge spectrum represented in Fig. 2.

The rest of the tracks in Fig. 2 represent the result of measurements on 500 heavy fragments ejected from cosmic-ray stars, and which by visual inspection

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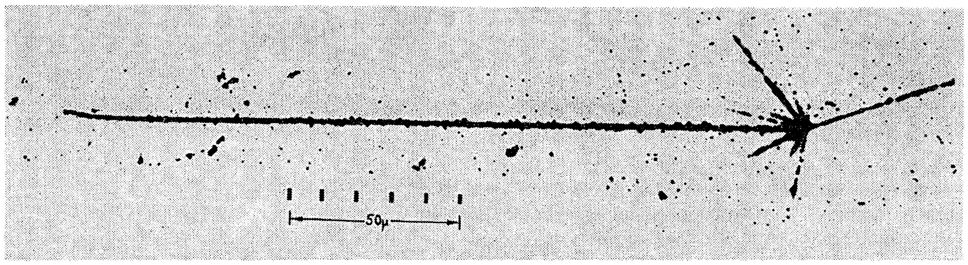


FIG. 1. Photomicrograph of a star accompanied by the emission of a boron fragment of kinetic energy ~100 Mev.

appeared to be more highly charged than helium nuclei. The criteria for the selection of the tracks were as follows:

(1) The tracks ended in the emulsion.
(2) The ranges were $>100\ \mu$.
(3) The angle of dip in the undeveloped emulsion was $<20°$.
(4) The tracks were located between $50\ \mu$ and $550\ \mu$ from the surface of the emulsion.

From Fig. 2 three groups of particles, *A*, *B*, and *C*, are clearly separable. Group *A* consists to a great extent of the identified helium nuclei represented by the shaded part of the histogram. The black portions in group *B* and *C* represent "hammer" tracks satisfying the criteria (1)–(4). As the over-all majority of "hammer" tracks are due to Li^8 nuclei, and as the main group of "hammer" tracks coincides with those of group *B*, we may conclude that the latter also represent lithium nuclei. The fact that the "hammer" tracks of group *B* are so clearly separated from those of group *C* proves that the latter most probably are due to B^8. Group *C* must therefore consist of a mixture of still heavier elements. The problem therefore arises how to distinguish between the different elements mixed in group *C*.

The magnification obtainable with the projection microscope is strongly limited by the intensity of the visible light from the microscope bulb relative to its thermal radiation because a too high heat absorption in the photographic plate destroys the emulsion. By means of a "Xenon-Hochdruckbrenner 150 w, XBO 162", combined with an ~7-cm water filter, however, we were able to increase the magnification to ~6500. This also seems to be the optimum magnification.

By this new arrangement all the particles of group *C* were remeasured. The result of this is presented in Fig. 3, where we also have included 95 heavy fragments detected after the measurements of the tracks included in Fig. 2 were finished.

Figure 3 also reveals three groups of particles *B*, *C′*, and *C″*. Group *B* clearly coincides with the Li^8 "hammer" tracks and are mainly composed of tracks from the 95 new heavy fragments mentioned above. Group *C* from Fig. 2 has, however, been split into two main groups *C′* and *C″* in Fig. 3. From the track area of the B^8 "hammer" tracks we may conclude that group *C′* is due to beryllium and *C″* mostly to boron nuclei. Poor statistics, however, forbids any conclusions to be drawn on the presence of nuclei heavier than boron.

The heavy fragments observed in the present experiment are taken from a stack of 80 stripped nuclear emulsions. Any small difference in the degree of development from one plate to another will tend to broaden the track area distributions. In order to investigate the accuracy of the planimeter method on tracks minimally influenced by emulsion inhomogeneity, we have measured tracks in a single Ilford *G*5 emulsion, $50\ \mu$ thick, exposed to C^{12} and O^{16} ions in the linear accelerator for heavy ions in Berkeley. The ion tracks

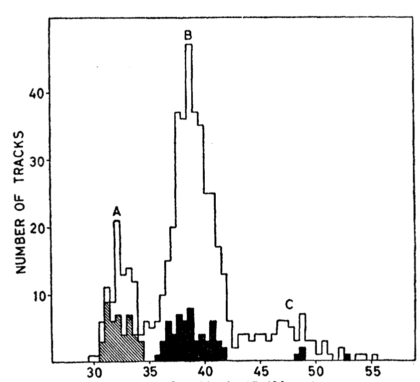


FIG. 2. Histogram showing the total track area, in arbitrary units, of the last $106\ \mu$ of 500 nuclear fragments.

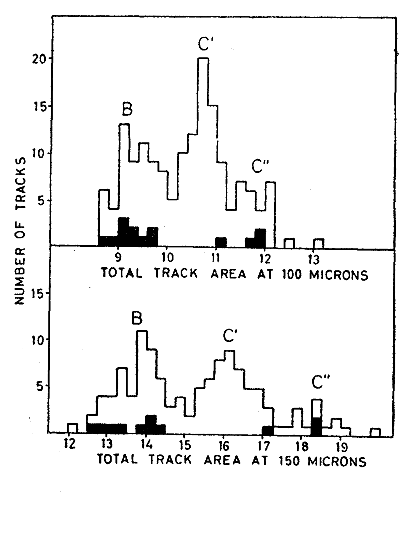


FIG. 3. Histogram showing the total track area, in arbitrary units, of the fragments in group *C* of Fig. 2. The measurements are made by means of a "Xenon-Hochdruckbrenner."

made an angle of 9° with the plane of the emulsion, and the C^{12} and O^{16} ions could be separated by different ranges.

Figure 4 represents the result of track area measurements on 64 heavy-ion tracks for different values of the residual range, and with a magnification of ~6500. It is seen from Fig. 4 that a statistical discrimination between carbon and oxygen is already possible at a residual range of ~30 μ. In order to get an individual charge determination of each track, however, we need a track length >60 μ. Assuming a similar spread in the track area distribution for nitrogen, we may also conclude from Fig. 4 that a residual range of >140 μ is necessary in order to separate the tracks of all the lighter nuclei.

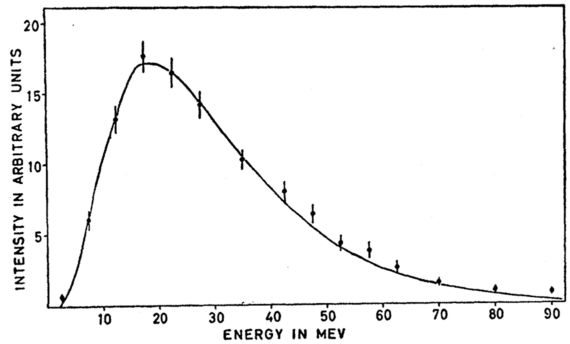


FIG. 5. Observed energy spectrum of Li^8 "hammer" tracks. The curve is calculated from the formulas (2a,b) with $T=11.5$ Mev, $V=6$ Mev and $v=0.016c$.

B. Energy Spectra of Heavy Fragments

Due to the very high probability of losing short lithium tracks during the scanning of the emulsions, the number of particles in groups B and C of Fig. 2 does not directly give the relative frequency of lithium >100 μ to heavier fragments >100 μ. This effect, which is very important in estimating the energy spectra and the relative frequency of the fragments, can be demonstrated as follows.

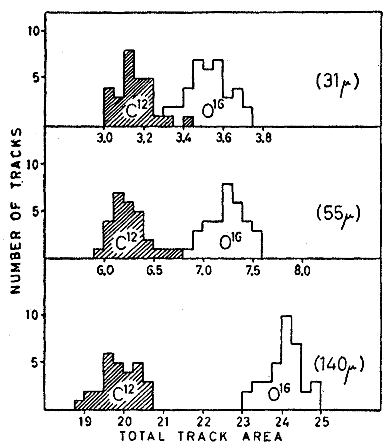


FIG. 4. Histograms showing the total track area, in arbitrary units, of tracks of C^{12} and O^{16}.

In Fig. 5 we have plotted the energy spectrum of 1481 Li^8 "hammer" tracks observed in the present experiment. The tracks have been selected irrespective of their range and angle of dip, and we assume the loss during scanning to be negligible due to the characteristic appearance of the tracks. The spectrum had been corrected in the usual way for loss of particles leaving the emulsion before coming to rest. In Fig. 6 the energy spectrum of all the stable lithium fragments (Li^6,Li^7) satisfying the above criteria (1)–(4) and identified by the planimeter measurements is plotted. The energy spectrum has been calculated assuming the particles to be an equal mixture of the two isotopes Li^6 and Li^7. The spectrum has a cutoff at 29 Mev corresponding to a selection of lithium fragments of range >100 μ.

The form of the spectra in Fig. 5 and Fig. 6 is seen to have marked differences in the energy region 30–50 Mev. As there is no reason to assume such a very great difference to be real, the lack of any strong increase in the number of (Li^6,Li^7) fragments in the energy region from 50 Mev to 30 Mev must be due to a heavy loss of short, stable lithium tracks during scanning.

We believe that (Li^6,Li^7) fragments of kinetic energy >60 Mev (corresponding range of Li^7 >370 μ) and angle of dip <20 degrees are rarely lost during scanning, due to the conspicuously heavy ionization of the tracks. This limit is of course rather arbitrary, but seems reasonable. We therefore regard Fig. 6 to give a correct picture of the energy spectrum of the stable (Li^6,Li^7) fragments only in the energy region >60 Mev.

In Fig. 7(a) is presented the energy spectrum in the region 60–130 Mev of (Li^6,Li^7) fragments ejected from

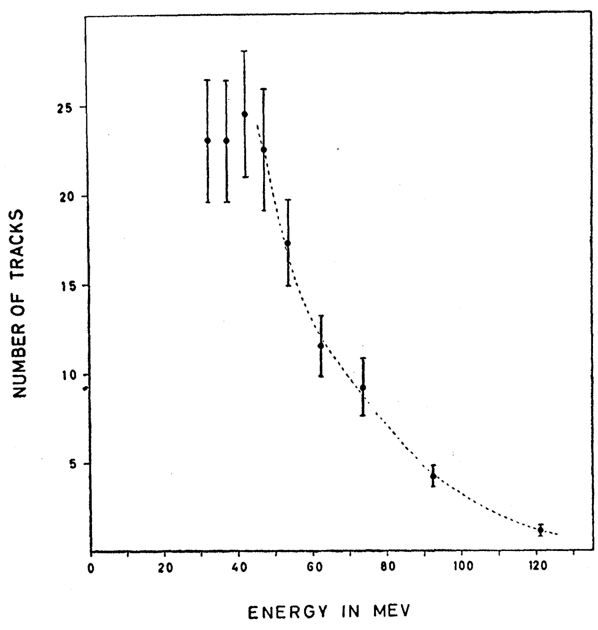


FIG. 6. Energy spectrum of Li^6, Li^7 fragments of kinetic energy >30 Mev.

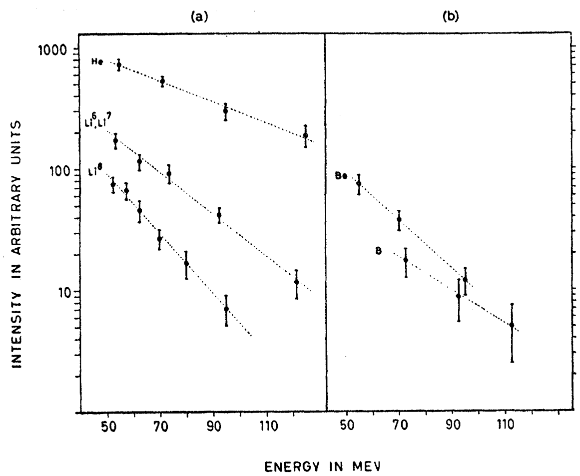


FIG. 7. Energy spectra of different nuclear fragments with energies >50 Mev.

cosmic-ray stars. In the same figure are presented the energy spectra of Li^8 "hammer" tracks 50–90 Mev and fast helium nuclei 50–100 Mev ejected from cosmic-ray stars. For the helium fragments, all the nuclei are assumed to be alpha particles.

In Fig. 7(b) are plotted the energy spectra of all the beryllium and boron fragments satisfying the above criteria (1)–(4) and identified by the planimeter method. In calculating the energy spectra we have assumed the two types of fragments to be isotopes of Be^9 and an equal mixture of the two isotopes B^{10} and B^{11}, respectively. We assume further that the loss of tracks of beryllium and boron $>100\ \mu$ in the present material is negligible, due to the very heavy ionization of the corresponding particles.

The five spectra represented in Fig. 7(a) and Fig. 7(b) are normalized so as to give the relative frequencies of the various types of heavy fragments ejected from the cosmic-ray stars observed in the present experiment.

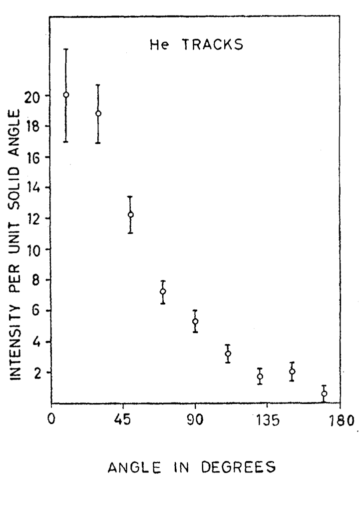


FIG. 8. Angular distribution of fast helium nuclei of kinetic energy >45 Mev.

C. Angular Distributions of Heavy Fragments

In those cases where the heavy fragment has been emitted from a star with a distinguishable incident particle, the angle between its track and the line of motion of the "primary" particle has been measured. During the cosmic-ray exposure, the plates were arranged with the emulsions lying in a vertical plane, and it is therefore possible to determine the direction of motion of a particle, in its passage through the emulsion, relative to the vertical. It has been assumed as a sufficient criterion, that a track is that of a particle producing a particular nuclear explosion if its specific ionization is near the minimum value for charge $|e|$, and if it is the only such track in the "upper hemisphere" of the star. We have excluded stars produced by heavy primaries, but included nuclear disintegrations produced by relativistic alpha particles representing $\sim 8\%$ of the stars. In Fig. 8 is represented the angular distribution of 398 helium nuclei with kinetic energies >45 Mev. In Fig. 9 is shown the angular distribution of the (Li^6,Li^7) and the Li^8 fragments grouped together for three intervals of kinetic energies, and in Fig. 10 is shown the corresponding distributions for the beryllium and boron fragments. All the various types of fragments are characterized by a strong forward collimation, and in the case of the lithium nuclei the degree of collimation is seen to increase from almost isotropy for energies <30 Mev to a very high degree of "forward" emission for the faster particles. Another illustration of this effect is given in Fig. 11, which shows the "forward to

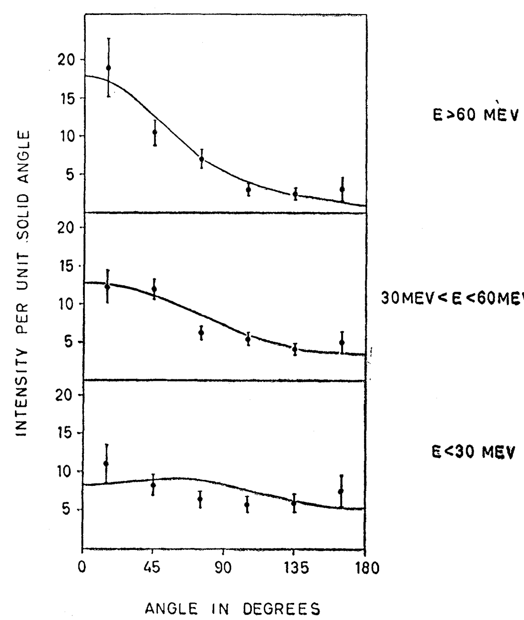


FIG. 9. Angular distribution of (Li^6,Li^7) and Li^8 fragments, grouped together, for three different intervals of kinetic energy. The curves are calculated from the formula (5) with $T=11.5$ Mev, $V=6$ Mev, and $v=0.016c$.

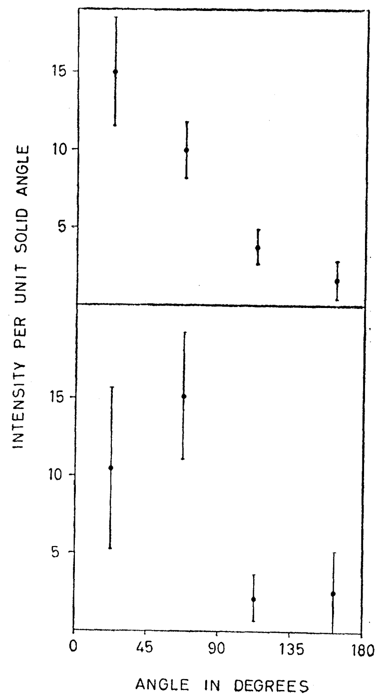


FIG. 10. Angular distributions of beryllium and boron fragments.

backward" ratio for (Li^6,Li^7) and Li^8 fragments grouped together, as a function of energy.

D. Fragment Production and Nuclear Excitation

In order to study the mechanism of ejection of heavy fragments, the energy spectra, angular distributions, and relative frequencies of the fragments have to be compared with the energy released in the nuclear disintegration. As a measure of the latter we use the number of heavily ionizing prongs N_h, defined as the number of tracks with grain density greater than 1.4 times minimum.

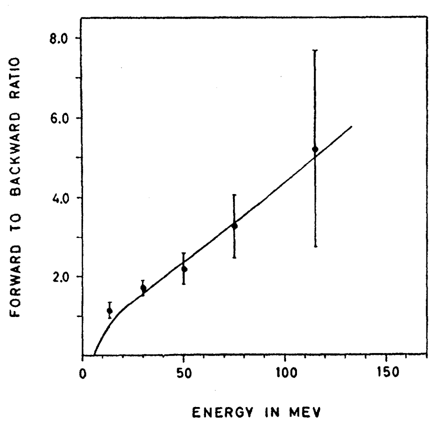


FIG. 11. The observed "forward to backward" ratio for (Li^6,Li^7) and Li^8 fragments grouped together as a function of energy. The curve shows the theoretical F/B ratios for Li^8 calculated from (3a,b) with $T=11.5$ Mev, $V=6$ Mev, and $v=0.016c$.

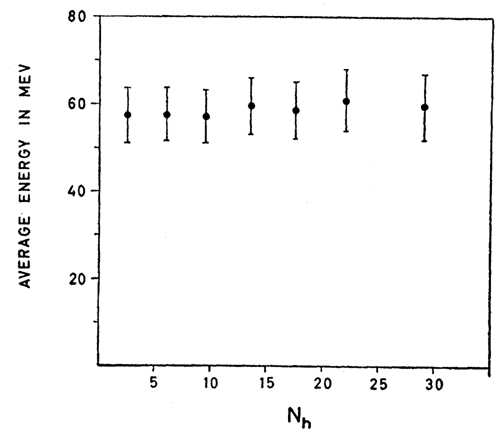


FIG. 12. The average kinetic energy of fast helium nuclei >45 Mev as a function of the number N_h of heavily ionizing prongs in the star.

In Fig. 12 is plotted the mean kinetic energy of fast helium nuclei in the interval 45–125 Mev ejected from cosmic-ray stars, as a function of N_h. As seen from the figure, no very strong correlation exists between the particular energy with which a fast helium nucleus is emitted and the energy release of the associated nuclear disintegration.

Further, we have divided the Li^8 "hammer" tracks in two groups corresponding to stars with $7\leqslant N_h\leqslant 19$ and $N_h\geqslant 20$. The lower limit of $N_h=7$ ensures that the majority of the stars are due to disintegrations of the silver and bromine nuclei of the emulsion. The corresponding two energy spectra are plotted in Fig. 13. As seen from the figure, the form of the two spectra does not depend very strongly on the energy release in the associated star.

In Fig. 14 is plotted the probability of emission of various types of nuclear fragments as a function of N_h. Here also only nuclei of range $>100\ \mu$ are considered.

In estimating the frequency of (Li^6,Li^7) fragments $>100\ \mu$ it is necessary to know the true form of the energy spectrum >30 Mev, which includes the region

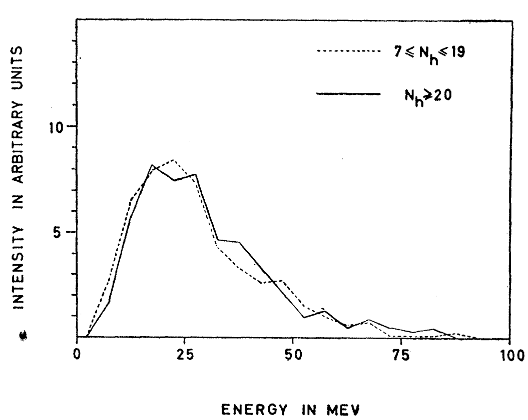


FIG. 13. Energy spectra of Li^8 fragments for two intervals of N_h.

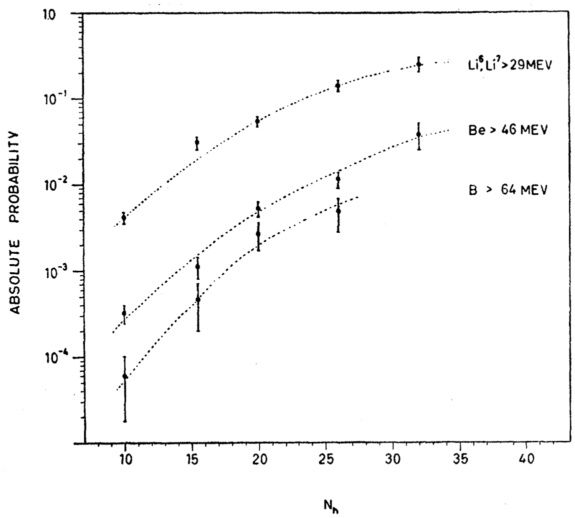


FIG. 14. The absolute probability of emission of different types of fast heavy fragments as a function of N_h.

30–60 Mev where the loss effect was shown to be very serious. We have made the reasonable assumption therefore that the (Li^6,Li^7) spectrum has approximately the same form as that of the Li^8 "hammer" tracks for kinetic energies in the interval 30–60 Mev. In constructing the total spectrum of the (Li^6,Li^7) nuclei $>100\,\mu$ we have used the observed spectrum (Fig. 6) for kinetic energies >60 Mev, and for the lower energies have fitted the spectrum to that of the Li^8 "hammer" tracks in Fig. 5.

In Fig. 15 is represented the probability of emission of Li^8 "hammer" tracks $>100\,\mu$ (corresponding energy >31 Mev) as function of N_h. As we assume no loss of "hammer" tracks during scanning, a determination of the total probability of ejection of a Li^8 fragment is possible. In Fig. 16 is presented the probability of ejection of a Li^8 nucleus of energy >3 Mev, the lowest energy of a "hammer" track observed in the present investigation.

Figures 14–16 show a very rapid rise in the probability of emission of all types of fragments as the size of the stars increases. Further, the observations seem to indicate a very slow decrease with N_h of the ratio of lighter to heavier fragments, as shown by Table I.

Four examples of the ejection of B^8 "hammer" tracks $>100\,\mu$ have been observed in the present experiment, the most energetic one with an energy of 250 Mev.

DISCUSSION

The emission of heavy fragments from stars represents a complex, many-body problem in high-energy nuclear physics, and the present observations do not allow anything like a complete explanation of the phenomena to be given. It may be, however, of interest to compare our results with what is to be expected from more well-known nuclear reactions like evaporation, nuclear cascades, fission, etc. Recently, intranuclear cascade calculations in the Bev region have been performed by various authors using Monte Carlo techniques.[15] All the calculations, however, have disregarded the possible existence in the nucleus, and interacting with the incoming particle, of aggregates of nucleons. Thus, the cascade emission of complex units such as alpha particles, lithium nuclei, etc., cannot be predicted. At the moment nuclear evaporation is the only theory from which relative frequency, energy spectra, etc. of heavy fragments can be calculated. In the present experiment we therefore have strictly limited ourselves to a detailed comparison of our observations with the predictions from nuclear evaporation theory. We have used the simplified representation of Le Couteur's theory[16] of nuclear evaporation given by Hagedorn and Macke,[17] which is very convenient for comparison with experiment.

The evaporation of charged particles from a highly excited nucleus (silver or bromine) is mainly determined by the mean temperature T and the average height V of the effective potential barrier. If the heavy fragments are the result of an evaporation process, the particles should be emitted isotropically. The anisotropy observed in the present experiment (Fig. 9 and Fig. 10) can therefore only be explained on the basis of nuclear evaporation theory by assuming the fragment emission to take place during the flight of the highly excited rest nucleus formed after the initial meson-nucleon cascade of the reaction is completed. This condition is in general acceptable, as the average momentum transfer of the incoming particle to the target nucleus mostly results in times of flight of the recoiling rest nucleus much longer

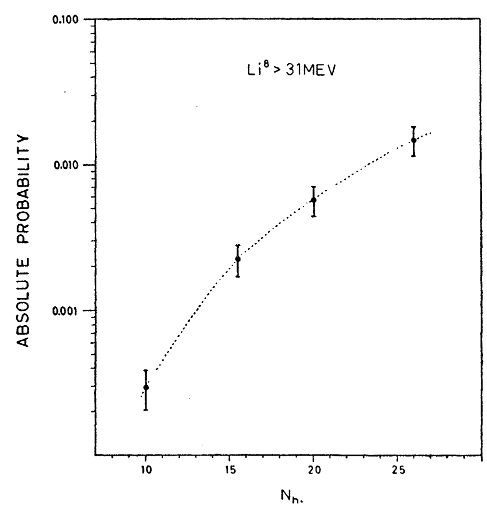


FIG. 15. The absolute probability of emission of Li^8 fragments of energy >31 Mev as a function of N_h.

[15] Metropolis, Bivins, Storm, Turkevitch, Miller, and Friedlander, Phys. Rev. **110**, 185 (1958); **100**, 204 (1958).
[16] K. Le Couteur, Proc. Phys. Soc. (London) **A63**, 259 (1950).
[17] R. Hagedorn and W. Macke, *Kosmische Strahlung* (Springer-Verlag, Berlin, 1953), p. 201.

than the time taken for the de-excitation of the nucleus by evaporation.

In the center-of-mass system of the evaporating nucleus the probability of a particle being emitted with kinetic energy between E' and $E'+dE'$ is given by the well-known formula[18]:

$$P(E')dE'=\frac{E'-V}{T^2}\exp\left(-\frac{E'-V}{T}\right)dE'. \quad (1)$$

If the evaporating nucleus is moving with a velocity v assumed to be small compared to the velocity of the emitted particles, the energy spectrum in the laboratory system is approximately given by

$$P(E)=\frac{1}{2Tb}\{1-e^{-(a+b)}(a+b+1)\}$$
$$\text{for}\quad V-(2mV)^{\frac{1}{2}}v<E<V+(2mV)^{\frac{1}{2}}v, \quad (2a)$$

$$P(E)=\frac{1}{2Tb}\{e^{-(a-b)}(a-b+1)-e^{-(a+b)}(a+b+1)\}$$
$$\text{for}\quad E>V+(2mV)^{\frac{1}{2}}v, \quad (2b)$$

with $a=(E-V)/T$ and $b=(2mE)^{\frac{1}{2}}v/T$, where m is the mass of the emitted particle and E is the kinetic energy in the laboratory system.

Further, the isotropic angular distribution in the center-of-mass system is transformed in the laboratory system into an anisotropic spectrum where the "forward to backward" ratio F/B is approximately given by

$$\frac{F}{B}=\frac{e^a-(a+1)}{(a+1)-e^{-b}(a+b+1)}$$
$$\text{for}\quad V<E<V+(2mV)^{\frac{1}{2}}v, \quad (3a)$$

$$\frac{F}{B}=\frac{e^b(a-b+1)-(a+1)}{(a+1)-e^{-b}(a+b+1)}$$
$$\text{for}\quad E>V+(2mV)^{\frac{1}{2}}v. \quad (3b)$$

The fragments in the present investigation are collected from stars with N_h values in the region from ~ 7 to ~ 35. This means large variations in the excitation energies of the individual disintegrating nuclei, and corresponding broad distributions in the values of T, V, and v. These parameters in (2a,b) and (3a,b) therefore have to be considered as mean values.

The problem which now arises is to find a set of values for T, V, and v which gives the best fit of the formulas (2a,b) and (3a,b) to both the observed energy spectra and the angular distributions. If these values are each within physically reasonable limits, nuclear evaporation must be considered as a possible explanation of the emission mechanism of heavy fragments.

In order to have data of sufficient statistical weight, the comparison between our observations and nuclear evaporation theory will mainly be confined to the energy spectrum of the Li^8 "hammer tracks" (Fig. 5) and the corresponding F/B distributions (Fig. 11). We do not regard the fact that the observations in Fig. 11 are based on a mixture of three different isotopes of lithium as important in using Fig. 11 as a good approximation for the F/B ratios for Li^8 fragments.

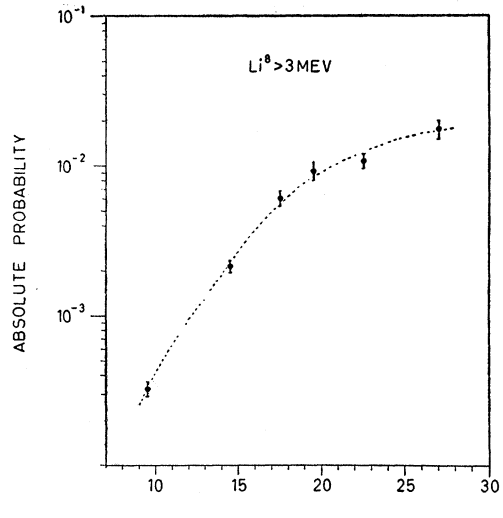


FIG. 16. The absolute probability of emission of Li^8 fragments of energy >3 Mev as a function of N_h.

It is found by a method of successive approximations that the set of values

$$T=11.5\text{ Mev},\quad V=6\text{ Mev},\quad v=0.016c \quad (4)$$

gives the best fit of the formulas (2a,b) and (3a,b) to both the observed energy spectrum and the F/B ratios.

In Fig. 5 is plotted the energy spectrum of ejected Li^8 nuclei calculated from (2a,b) with the mean values for T, V, and v given by (4). The agreement with the observations is seen to be very good. The corresponding values for the F/B ratios calculated from (3a,b) and (4) are presented in Fig. 11, and are seen to reproduce the experimental results very well. The anisotropy caused by the recoil of an evaporating nucleus increases very strongly with the energy of the emitted particles. This effect, which is somewhat surprising, is a result of the Maxwellian distribution of the evaporated particles.

In Fig. 17 is shown a similar F/B plot calculated for beryllium fragments (of an average mass number 9.5) with T and v given by (4) and $V(\text{Be})=8$ Mev. The latter value for the effective potential barrier depends on very uncertain assumptions, but it is shown below that the theoretical F/B curves are not very sensitive to variations in V. The observed F/B ratios are seen to be of the right order of magnitude, but the statistical errors are too large to permit a more detailed comparison with the lithium data.

If θ is the angle in the laboratory system between the direction of motion of the ejected fragment and the

[18] V. Weisskopf, Phys. Rev. 52, 295 (1937).

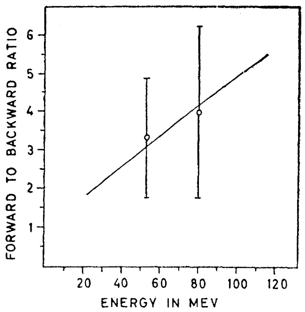


FIG. 17. The observed "forward to backward" ratio for beryllium fragments as a function of energy. The curve shows the theoretical F/B ratios for beryllium calculated from (3a,b) with $T=11.5$ Mev, $V=8$ Mev, and $v=0.016c$.

evaporating nucleus, the probability of observing a fragment emitted between θ and $\theta+d\theta$ is given by

$$W(E,\theta)d\theta$$

$$=\mathrm{const}\left[1+v\left(\frac{m}{2E}\right)^{\frac{1}{2}}\cos\theta\right]\frac{(E-V)-(2mE)^{\frac{1}{2}}v\cos\theta}{T^2}$$

$$\times\exp\left[-\frac{(E-V)-(2mE)^{\frac{1}{2}}v\cos\theta}{T}\right]\sin\theta d\theta. \quad (5)$$

In Fig. 9 is plotted the theoretical angular distribution of Li^8 nuclei calculated from (5), with T, V, and v given by (4), for the three energy values $E=18.1$ Mev, 40.4 Mev and 77.5 Mev. These figures correspond to the mean values for the kinetic energies of the observed Li^8 fragments in the three intervals $E<30$ Mev, 30 Mev $<E<60$ Mev and $E>60$ Mev. The agreement between the theoretical curves and the experimental values is satisfactory, particularly for $E>30$ Mev.

The comparison of the formulas (3a,b) and (5) with the observations depends, of course, on the assumption that the average direction of motion of the evaporating nuclei coincides with the direction of the incoming particle producing the nuclear disintegration. This assumption, however, is questionable, as the effect of the successive impulses to the residual nucleus during the evaporation is considerable, and in large stars the additional velocity due to successive random recoils is of the same order of magnitude as the initial velocity v imparted to the nucleus before evaporation.[19,20] One could get over this objection by assuming that the fragments always are emitted in the initial phase of the evaporation process. This view is supported by a preliminary investigation of the low-energy spectrum (<30 Mev) of protons from the stars emitting heavy fragments, indicating a mean evaporating temperature much lower than the value $T=11.5$ Mev given in (4).

The theoretical formulas of evaporation theory are therefore able to fit simultaneously, the observed energy spectrum, the angular distribution, and the F/B ratios of the ejected Li^8 fragments. The question now arises as to whether the mean values for the temperature, the effective potential barrier, and the recoil velocities given by (4) are realistic from a physical point of view. Further, the sensitivity of the fit of the theoretical curves to the observations for variations in the values (4) of T, V, and v has to be investigated.

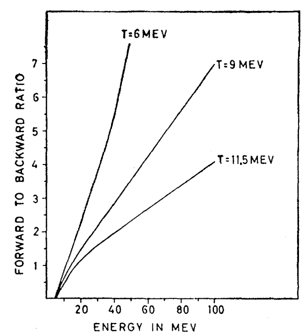


FIG. 19. Theoretical "forward to backward" ratios for Li^8 fragments calculated from (3a,b) with $V=6$ Mev, $v=0.016c$, and three different values of T.

It is generally assumed that evaporation theory breaks down when the excitation energy of the nucleus exceeds the total binding energy. The upper limit for the applicability of evaporation theory on excited silver or bromine nuclei in emulsions is commonly regarded to be of the order of $\sim$800 Mev corresponding to temperatures of $\sim$10 Mev.[17] The value 11.5 Mev for the mean temperature in (4) is therefore somewhat too high to be accepted. This conclusion is even further supported by the results of nuclear cascade calculations,[15] giving average excitation energies of the residual nuclei of the order of only a few hundred Mev.

An interesting feature of the observed energy spectrum (Fig. 5) is that a substantial part ($\sim$25%) of the Li^8 nuclei are ejected with kinetic energies below the generally assumed potential barrier, which corre-

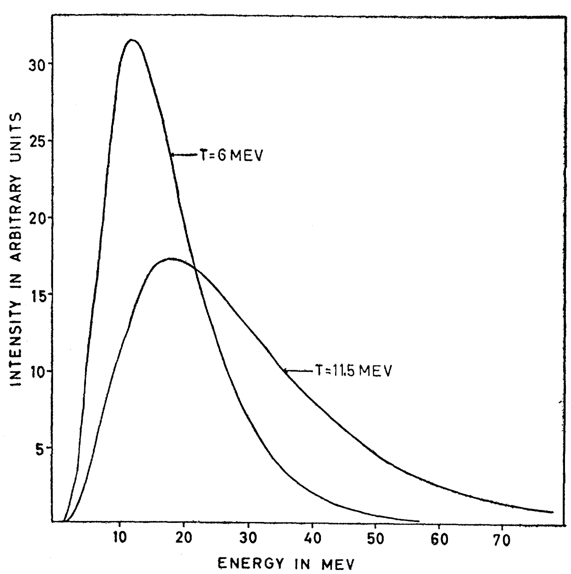


FIG. 18. Theoretical energy spectra of Li^8 fragments calculated from formula (2a,b) with $V=6$ Mev, $v=0.016c$, and $T=6$ Mev and 11.5 Mev, respectively.

[19] J. B. Harding, Phil. Mag. 40, 530 (1949).
[20] J. B. Harding, Phil. Mag. 42, 63 (1951).

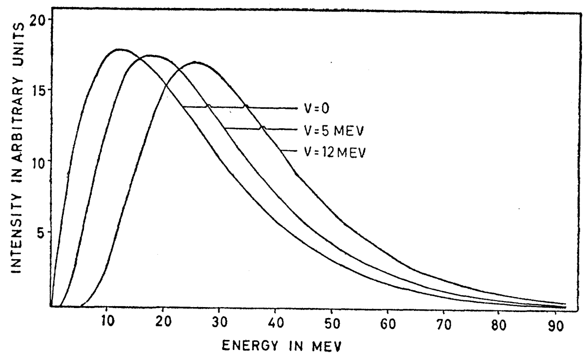


FIG. 20. Theoretical energy spectra of Li^8 fragments calculated from formula (2a,b) with $T=11.5$ Mev, $v=0.016c$, and three different values of V.

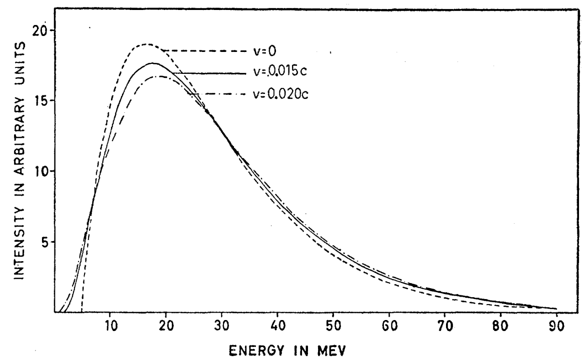


FIG. 22. Theoretical energy spectra of Li^8 fragments calculated from formula (2a,b) with $T=11.5$ Mev, $V=6$ Mev, and three different values of v.

sponds to about ~16.5 Mev for the heavy nuclei in the emulsion. This effect is most probably similar to the phenomenon observed by Harding, Lattimore, and Perkins[21] on the emission of alpha particles from high-energy cosmic-ray stars, where ~40% of the particles have kinetic energies below the corresponding potential barrier ~12 Mev. As suggested by Bagge[22] at the excitation energies we are considering, the barrier may be reduced by as much as ~50% due to an increase in the effective nuclear radius caused by large amplitude surface oscillations. Still, the value ~6 Mev for V in (4) seems somewhat too low.

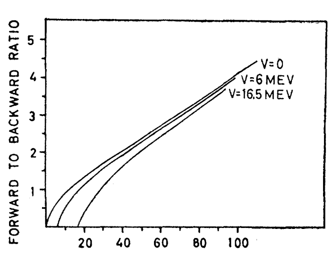
The value for v given in (4) is reasonable, and in agreement with the figures obtained by other investigators using different methods.[23]

In order to illustrate the influence of the variations of T, V, and v in more detail, we have calculated a number of different energy spectra and F/B ratios for Li^8 nuclei by varying partially the three parameters about the values represented in (4). The results are shown in Figs. 18–23, and give the following picture.

Both the form of the energy spectrum and the figures for the F/B ratios are very sensitive to variations in the nuclear temperature T. Figure 18 illustrates the well known fact that the energy spectrum of the particles becomes broader with increasing T, and Fig. 19 shows a strong decrease in the F/B ratios as T increases.

Variations in the height of the potential barrier V practically do not change the form of the Maxwellian energy distribution, as is shown in Fig. 20. The only effect on the energy spectrum is to shift it along the E axis. Further, as illustrated in Fig. 21, the values of the F/B ratios are not very sensitive to variations in V.

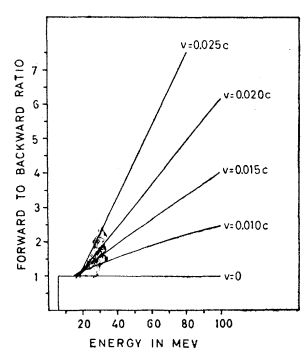
FIG. 21. Theoretical "forward to backward" ratios for Li^8 fragments calculated from (3a,b) with $T=11.5$ Mev, $v=0.016c$, and three different values of V.



It is reasonable to assume that the velocities of the evaporating nuclei do not exceed ~0.025c. It is shown in Fig. 22 that up to this limit variations in v do not significantly change the form of the energy spectrum. Figure 23, however, shows that the values of the F/B ratios are very sensitive to variations in v, and increase strongly with increasing velocity of the nucleus.

The major difficulty in reconciling the observed energy distribution (Fig. 5) with a pure evaporation spectrum is the broadness of the distribution, leading to temperatures for which nuclear evaporation theory is no longer valid. There may be two major possibilities of avoiding the very high values for the mean temperature and still retain the broad form of the energy spectrum: (a) Figure 22 shows that the peaking of the energy spectrum and the displacement of its maximum resulting from a lowering of T could be compensated by a corresponding strong increase in the value assumed for the mean recoil velocity v. However, as shown in Fig. 19 and Fig. 23, both the lowering of T and the increase in v very strongly increase the values of the F/B ratios. It is found that relatively small variations of T and v in these directions give curves for the F/B ratios far outside the observed values in Fig. 11. We therefore

FIG. 23. Theoretical "forward to backward" ratios for Li^8 fragments calculated from formula (3a,b) with $T=11.5$ Mev, $V=6$ Mev, and different values of v.



[21] Harding, Lattimore, and Perkins, Proc. Roy. Soc. (London) **A196**, 325 (1949).
[22] E. Bagge, Ann. Physik **33**, 389 (1938).
[23] D. H. Perkins, Phil. Mag. **41**, 138 (1950).

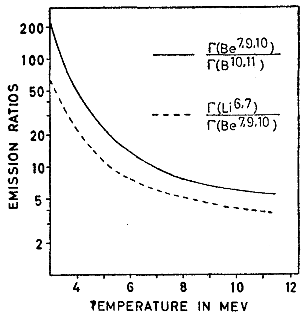


FIG. 24. The theoretical ratios $(Li^6+Li^7)/(Be^7+Be^9+Be^{10})$ and $(Be^7+Be^9+Be^{10})/(B^{10}+B^{11})$ as functions of the temperature T, calculated from nuclear evaporation theory. Only fragments of range $>100\,\mu$ are considered.

exclude the possibility of much higher recoil velocities as the main reason for the broad energy distribution.

(b) As the second possibility in overcoming the difficulty with the high temperature necessary for explaining the broad energy spectrum we may assume a very strong variation in the height of the potential barrier during the evaporation process. The observed energy distribution would then be the result of the overlapping of a large number of considerably more peaked spectra (with corresponding smaller mean temperatures) characterized by wide differences in the values of the effective potential barriers. This would also explain the large number of Li^8 nuclei observed with kinetic energies less than the "classical" potential barrier $\sim$16.5 Mev. As seen from Fig. 19, a decrease in the temperature would result in a strong increase in the values of the F/B ratios. This effect, however, may be compensated by assuming lower mean values for the velocity v of the evaporating nuclei, as shown in Fig. 23. As the actual values for the recoil velocities are very uncertain, rather large variations in v may be tolerated without upsetting the argument. Further, as illustrated in Fig. 21, the F/B ratios are not very sensitive to even large variations in V. The most probable reason for such wide differences in V might be a strong dependence of V on the excitation energy of the nucleus. If the number N_h of heavily ionizing tracks in a star is a good measure of the excitation energy of the evaporating nucleus, this dependence should show up in marked variations in the energy spectrum with N_h. However, the almost complete lack of such an effect, as illustrated in Fig. 13, is an argument against very strong variations of the potential barrier with the excitation energy of the nucleus. We therefore do not regard low mean temperatures and large differences in V as a possible explanation of the broad energy spectrum.

The above analysis is based on the demand that the formulas (2a,b) and (3a,b) simultaneously must fit both the observed energy spectrum and the F/B ratios. We therefore conclude that unless it is justifiable to use mean values for temperature, potential barrier, and recoil velocity very near to the figures given in (4), the observed emission of Li^8 fragments, and most probably also the ejection of heavier nuclei, are phenomena considerably more complex than pure evaporation processes.

Nuclear evaporation theory should also in principle

TABLE I. Observed relative frequencies of heavy fragments as a function of the number of heavily ionizing tracks in a star.

N_h	$Li^{6,7}/Li^8$	$Li^{6,7}/Be^{7,9,10}$	$Be^{7,9,10}/B^{10,11}$
10	14.4±4.6	13.4±3.5	5.4±1.7
15.5	14.1±3.8	28.5±8.7	2.4±0.8
20	9.4±2.4	10.5±2.4	2.0±0.4
26	9.6±2.4	12.7±3.0	2.3±0.6

be able to predict the relative frequency of different types of heavy fragments. In Fig. 24 are presented the lithium/beryllium and beryllium/boron ratios as functions of the temperature T, calculated from Le Couteur's evaporation theory.[17] Only stable and long-lived isotopes having energies corresponding to ranges $\geqslant 100\,\mu$ in a photographic emulsion are considered. In plotting these curves we have used a formula[17]

$$V=5.5Z \text{ Mev} \qquad (6)$$

for the effective potential barrier, where Z is the atomic number of the fragments. The expression (6) for V obviously gives too high values for the potential barriers when, for example, compared with the value $\sim$6 Mev for Li^8 nuclei indicated by the experiments. This makes a comparison between the theoretical and the observed values of the relative frequencies very problematic. Another difficulty is the very uncertain relationship between the average nuclear temperature T and the number of heavily ionizing tracks N_h in the star. The only qualitative information to be drawn from Fig. 24 is that evaporation theory predicts a decrease in the ratio of lighter to heavier fragments as the temperature increases. A similar tendency is observed in Table I where we have represented the experimental values for the $Li^{6,7}/Li^8$, $Li^{6,7}/Be^{7,9,10}$, and $Be^{7,9,10}/B^{10,11}$ ratios as a function of N_h. Only tracks $>100\,\mu$ are used. The data, however, are not of sufficient statistical weight to draw any further conclusions about this point.

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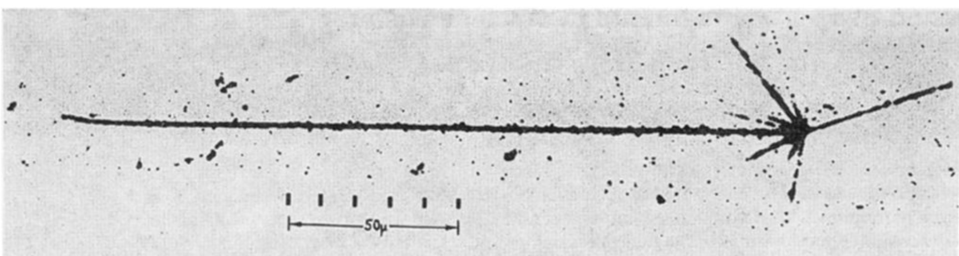

FIG. 1. Photomicrograph of a star accompanied by the emission of a boron fragment of kinetic energy ~100 Mev.