PART V.1

EMISSION OF LIGHT FRAGMENTS FROM THE DISINTEGRATION OF HEAVY NUCLEI IN PHOTOGRAPHIC EMULSION CAUSED BY HIGH-ENERGY PARTICLES; FIRST COMPARISON WITH HYPERFRAGMENT EMISSION.

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In high-energy physics, fragmentation is the best means of liaison between nuclear physicists and the physicists studying strange particles. The former excite the nucleus to higher and higher energies in order to obtain, after fragments, unstable hyperfragments which they would like to be able to consider as convenient indicators of fragmentation, whereas the strange particle physicists view these hyperfragments simply as a means of studying the hyperon-nucleon, or even hyperon-hyperon, forces.

Fragmentation is a very complicated history of the disintegration of a nucleus. In principle, a fragment consists entirely of nucleonic matter ejected from a nucleus in a state of excitation or broken. Therefore, every case must be studied with the utmost care, if possible on a given nucleus with a given projectile at a given energy.

In this preliminary study, which is mainly to clear up a little the clouds surrounding the comparison between the emission of fragments and of hyperfragments, we confine ourselves to examples of fragments well identified by us. For convenience, the comparisons which follow were made for fragments with charge 3, 4 and 5, especially Li^8, Be^8, and B^8. Since the proportion of Li^9 and of B^8 amongst the fragments is only a few per cent, we have studied in particular the emission of Li^8 and Be^8, which allows us to connect our results with the work carried out at a lower energy, especially by the groups of Perfilov and Lozhkin in Leningrad, and of Pniewski in Warsaw (energy range several hundred MeV to 9 GeV). The global comparisons were made, in this first stage, with the emission of all hyperfragments of charge 3 and 4. In the absence of standardization between the different schools which investigate fragments and hyperfragments, which would be most desirable, the fragments and hyperfragments tabulated are those obtained by our own group during the last two years.

These results were obtained by Drs. H. Braun and G. Baumann of our Laboratory from a study of emulsion stacks exposed at CERN, thanks to the courtesy of Drs. Lock and Combe, either stacks exposed especially for the Strasbourg Group or CERN co-operation stacks (for example, for the π^- mesons of 17.2 GeV/c) or stacks exposed with Hamburg for the K^- of 1.5 GeV/c, thanks to the kindness of Professor Teucher of Hamburg and of Dr. Winzeler of Bern.

As an initial indication for the classification of these phenomenological comparisons one can choose the evaporation characteristics without evident prejudice of the fundamental mechanism. This choice is based, however, on previous results and also on the general tendency of most of the results obtained. The chosen fragments of Li^8 and Be^8, as well as the hyperfragments, are related to heavy nuclei disintegrations so that all comparisons are statistically valid. The presentation of the results is given in the order in which they were obtained, namely as incident particle protons of 24 GeV, π^- mesons of 17.2 GeV, protons of 14 GeV, K^- of 1.5 GeV, and some results from stopping π^- mesons.

The emission of fragments of charge greater than 2 is a nuclear phenomenon which is important at these incident high energies because in this field we obtain a ratio of $Li^8 / Li^6 + Li^7$ of the order of some per cent and the proportion of stars containing Li^8 also of the order of 1 to 2%. It is therefore probable that several fragments of $Z \geq 3$ are emitted during the course of only one inelastic interaction of a high-energy particle with a nucleus of silver or bromine. The relative proportion of hyperfragments is an important fraction, in general, of the emission of Li^8, mainly in the case of K^- when their production becomes a quantitatively comparable phenomenon, even greater for slow K^- than the emission of ordinary fragments.

In order to facilitate these quantitative experimental comparisons with the classical nuclear theory, the energy spectra have been measured as well as the angular distribution which could give a preliminary indication of the emission mechanism.

The identification of Li^8, thanks to hammer tracks, is immediate; those of Be^8 were made from the two α particles emitted with a small calculable correlation angle; this identification is evidently only possible for the ground state. The comparison is therefore only applicable to the fundamental levels of fragments and hyperfragments. It seems, in any case, in agreement with other studies, that until now one can only observe a very small production (if any) of excited states.

If the fragmentation theory was definitely known, that of hyperfragmentation would certainly be facilitated. However, actually nuclear physicists and particle physicists count on each other, to some extent, the one hoping to find indications in the hyperfragmentation, and the particle physicist trying to invoke the more or less known mechanisms of fragmentation which they have a strong tendency to consider as certain.

Our experimental results are not decisive enough to choose between the 7 or 8 mechanisms which are proposed to explain and to calculate the characteristics of fragmentation of an excited nucleus by high-energy particles. Sometimes the production of nuclear hot points is invoked, sometimes an almost complete mechanical dissociation of the nucleus with the help of fission phenomena, which are due to the secondary interactions of the cascade. Several mechanisms seem to play a part. We believe that the hypothesis of the pick-up or the coalesence of similar particles, which are close together and of high energy, is worth investigation as well as the simultaneous interaction of particles near each other on the same nucleon or group of nucleons for which a theory has still to be developed.

With the statistics which we have at present, a certain number of results, in the chosen phenomenological terminology, seem to be definitely established. The parameters for the evaporation curves give the best fit to the results with a temperature, T, of 8 to 10 MeV, a potential barrier of 5 to 10 MeV, and a velocity for the centre of gravity of about 0.01 c.

These parameters are evidently not critical except for T and have been empirically adjusted. This adjustment is not very sensitive to the velocity of the centre of mass, and therefore to the inelasticity factor. This is favourable for the important presentation of the angular distributions in the C-system which do not vary much from those in laboratory system.

It is evidently quantitatively possible to invoke several temperatures during the same process in order to explain the global aspect of the experimental results. On the other hand, the graphs of the fragmentationd stribution as a function of the number of star prongs of different energies confirms that which was already reported by other experimentalists, that the correlation of the emission of fragments and hyperfragments is not directly with the "shower" but with the cascade.

The two extreme interpretations whi h have been invoked, that is, pure evaporation at low energies or secondary interactions provoked by the cascade, are both compatible with most of the results. Nevertheless, some important nuclear remarks are necessary: the temperature seems too high (greater than the binding of a nucleon) to indicate a normal mechanism of evaporation from a thermodynamic equilibrium which is due to the many secondary interactions. The fragment does not seem to arise from a primary interaction because the angular distribution of most of the fragments or hyperfragments does not reflect it, except for those of high-energy or those emitted from a light nucleus.

As many experimental results (for emission from heavy nuclei) seemed phenomenologically compatible with some kind of evaporation mechanism, we have looked to see if this morphology of the presentation of results was too gross and too global, and if it did not contain, in fact, several different mechanisms.

With this in mind, we used some recent results obtained in our laboratory on the interactions of slow π^- mesons with light nuclei; in particular, those which have interested us for a long time, because of their possible temporary sub-structures, namely C^{12}, N^{14} and O^{16} giving Li^8. If we study carefully a certain number of favourable reactions, then by a detailed study of the energy and momentum balances we can determine the detailed mechanism of the interaction, and especially the transition via (Be^{10}) and (B^{12}) giving us, respectively, d or α by transition to ground state Li^8. In this precise case we evidently know that the evaporation theory is badly applicable or not at all applicable. The excited levels are not numerous enough, and the number of nucleons is too small. The energy distribution of the Li^8 fragments is, however, compatible with the evaporation curve with parameters which seem reasonable for this excitation energy and no barrier for these recoil fragments of Li^8.

A certain reserve should therefore be shown towards the presentation of the results in the form of evaporation, and the parameters which may differentiate between the different mechanisms which occur remain to be determined.

We think that the detailed and comparative study of nuclear balances with the identification of the initial nucleus (loaded emulsions), all the other conditions remaining identical between the fragments and the hyperfragments of the same nature, would soon enable us to give a more concrete reply on the exact mechanism of their production. But already it seems well established that there is no basic difference between the production of fragments and of hyperfragments.

Table 1

Number of Li^8 or Li^9 fragments emitted per star for different primary particles of varying energy

Incident particle	energy	Frequency of emission of fragments of Li^8 or Li^9	Authors and Laboratory
Protons	5.7 GeV	0.013 ± 0.001 $n_h \geq 5$	Goldsack et al. (1957) [Birmingham]
	9 GeV	0.0188 ± 0.0018 $n_h > 8$	Gajewski et al. (1962) [Warsaw]
		0.015 ± 0.0016 all n_h	
	14 GeV	0.015 ± 0.003 all n_h	Strasbourg
	25 GeV	0.015 ± 0.002 all n_h	Warsaw and Strasbourg (1962)
	28 GeV	0.014 ± 0.002 $n_h \geq 7$	Milwaukee (1962)
π^-	at rest	0.0019	Alumkal and Barkow (1960) [Milwaukee]
		~ 0.002	Strasbourg
	4.5 GeV	0.0046 ± 0.0010 $7 \leq n_h \leq 17$	Skjeggestad (1959) [Oslo]
	4.5 GeV	0.031 ± 0.011 $n_h > 17$	
	17.2 GeV/c	0.015 ± 0.002 all n_h	Strasbourg
K^-	1.5 GeV/c	~ 0.01 all n_h	Strasbourg

Editorial note

The figures show data on fragment and hyperfragment emission from stars caused by protons of 25 GeV (Figs. 1 to 8), π^- mesons of 17.2 GeV/c (Fig.s 9 and 10), protons of 14 GeV (Figs. 11 and 12), K^- mesons of 1.5 GeV/c (Figs. 13 and 14), and π^- mesons at rest (Fig. 19). Figures 15, 16 and 17 show data on the size of the stars which emit fragments or hyperfragments for different primary particles. Figure 18 shows the spatial distribution of pairs of fragments.

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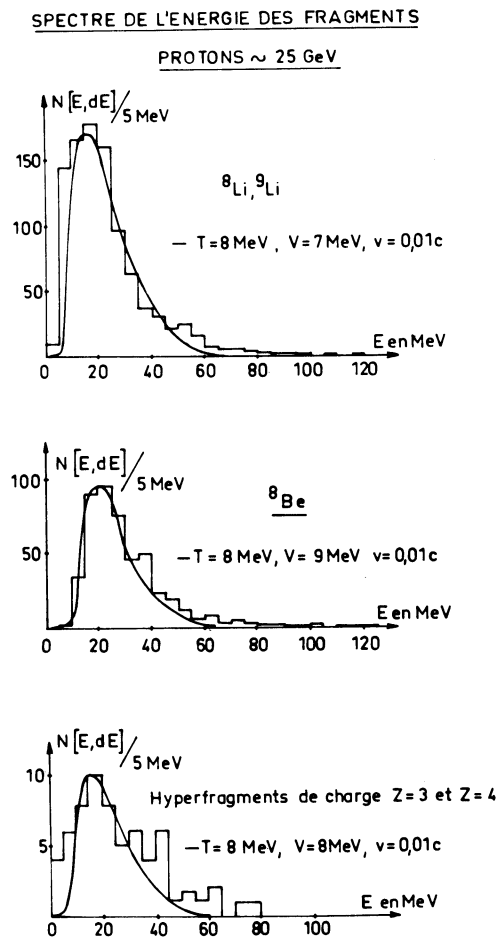

Fig. 1. - Energy spectrum of
a) Li^8, Li^9 fragments
b) Be^8 fragments
c) hyperfragments of charge Z = 3 and 4

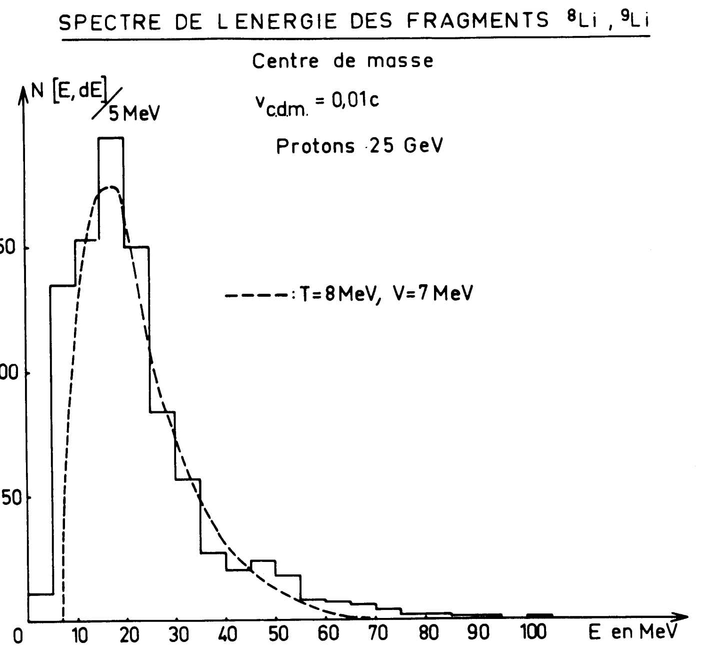

Fig. 2. - Energy spectrum of Li^8 and Li^9 fragments in the centre of mass system with v = 0.01c.

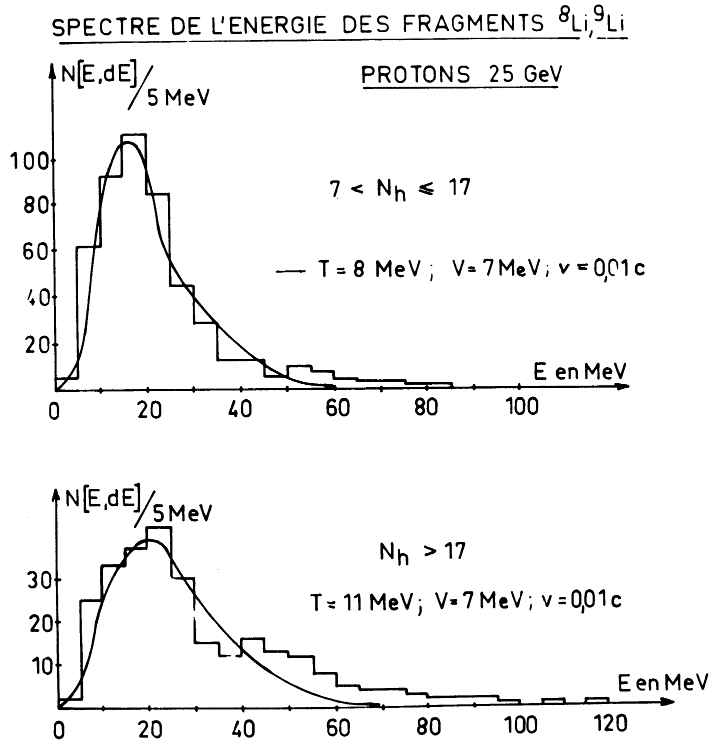

Fig. 3. - Energy spectrum of Li^8 and Li^9 fragments for

a) $7 < n_h \leq 17$

b) $n_h > 17$.

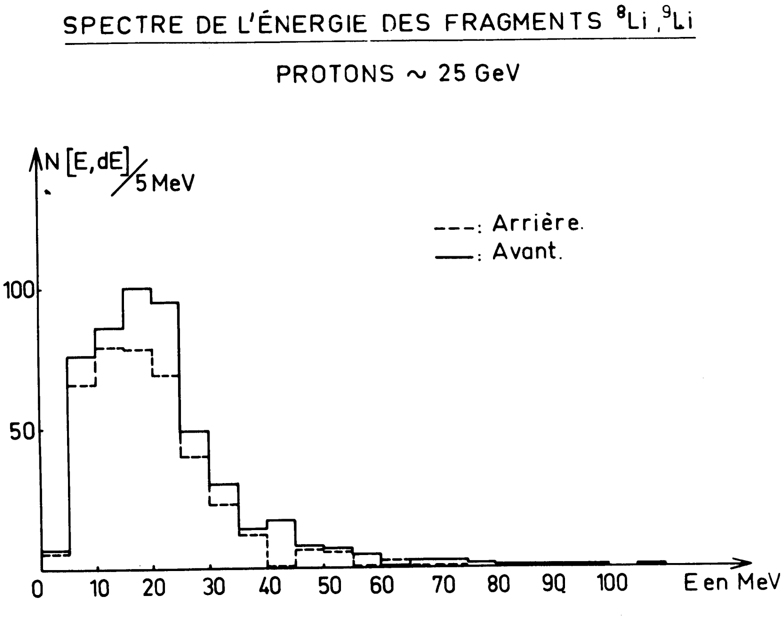

Fig. 4. - Energy spectrum of Li^8 and Li^9 fragments divided in two groups : forward emission and backward emission.

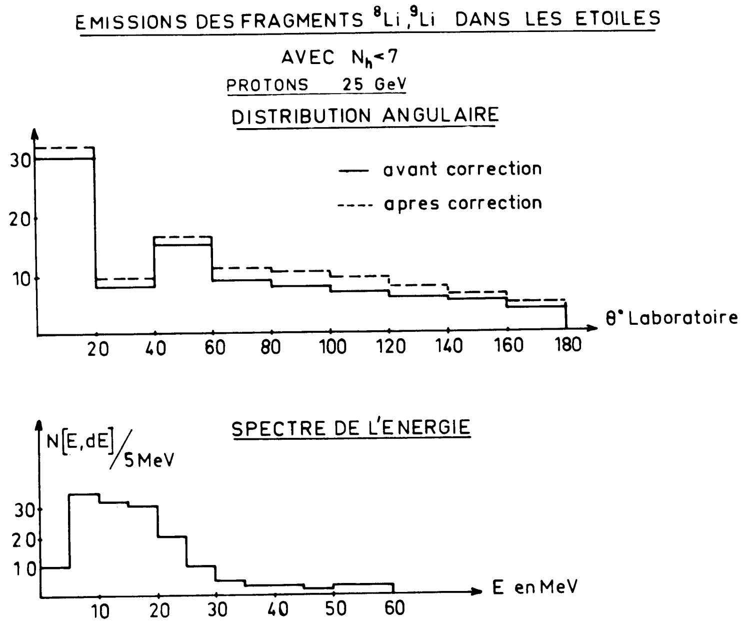

Fig. 5. - Energy and angular distribution of Li^8 and Li^9 fragments for $n_h < 7$ (corrected for scanning loss)
Θ = space angle between the direction of the incident proton and that of the fragment.

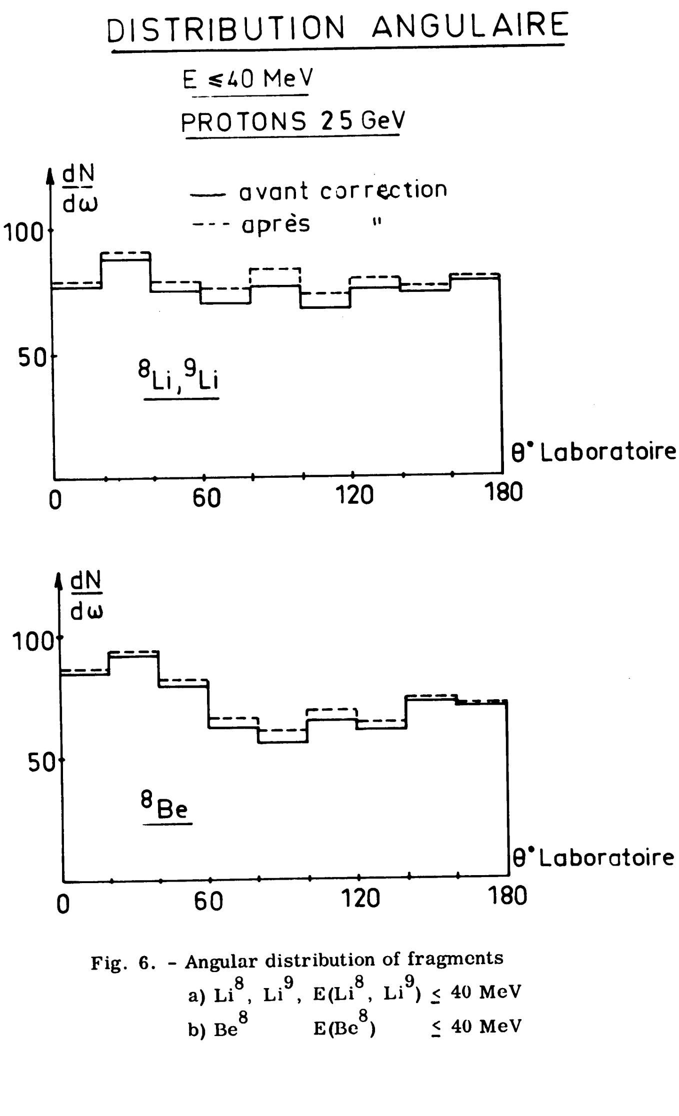

Fig. 6. - Angular distribution of fragments
a) Li^8, Li^9, $E(Li^8, Li^9) \leq 40$ MeV
b) Be^8 $E(Be^8)$ ≤ 40 MeV

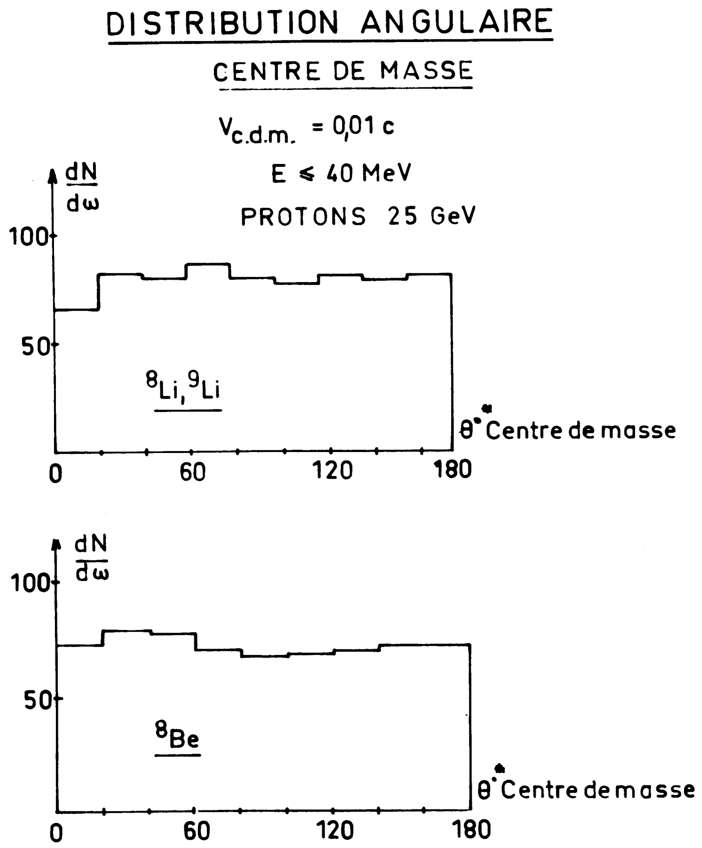

Fig. 7. - Angular distribution of fragments in the centre of mass system with v = 0.01 c.

a) Li^8, Li^9 $E(Li^8, Li^9) \leq 40$ MeV

b) Be^8 $E(Be^8) \leq 40$ MeV

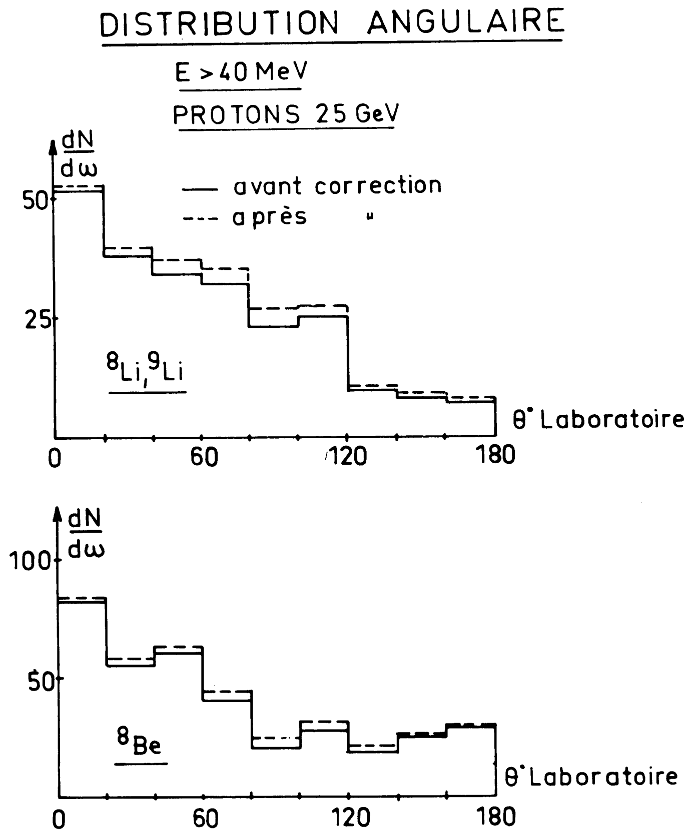

Fig. 8. - Angular distribution of fragments

a) Li^8, Li^9 $E(Li^8, Li^9) \geq 40$ MeV

b) Be^8 $E(Be^8) \geq 40$ MeV

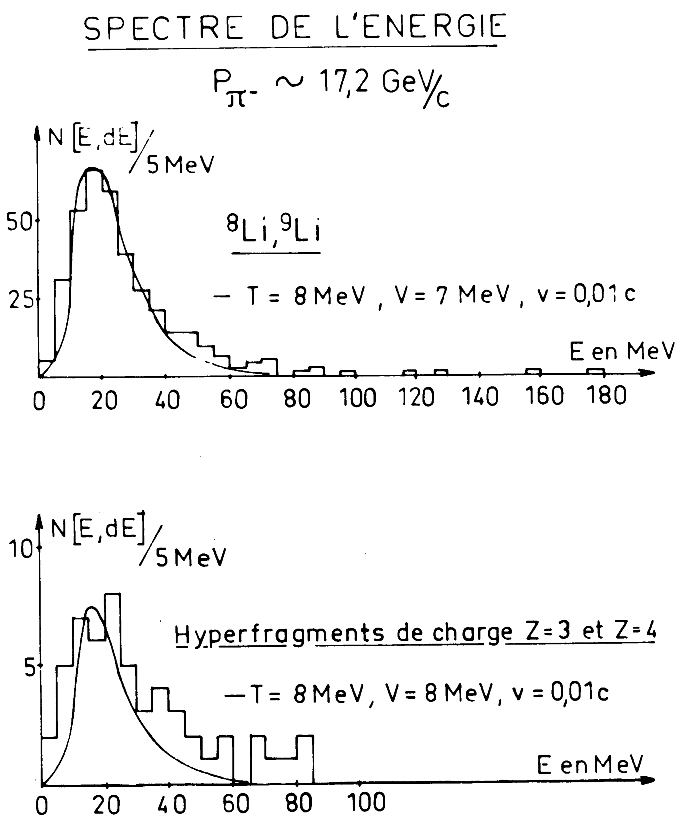

Fig. 9. - Energy spectrum of
a) Li^8, Li^9 fragments
b) hyperfragments of charge Z = 3 and Z = 4

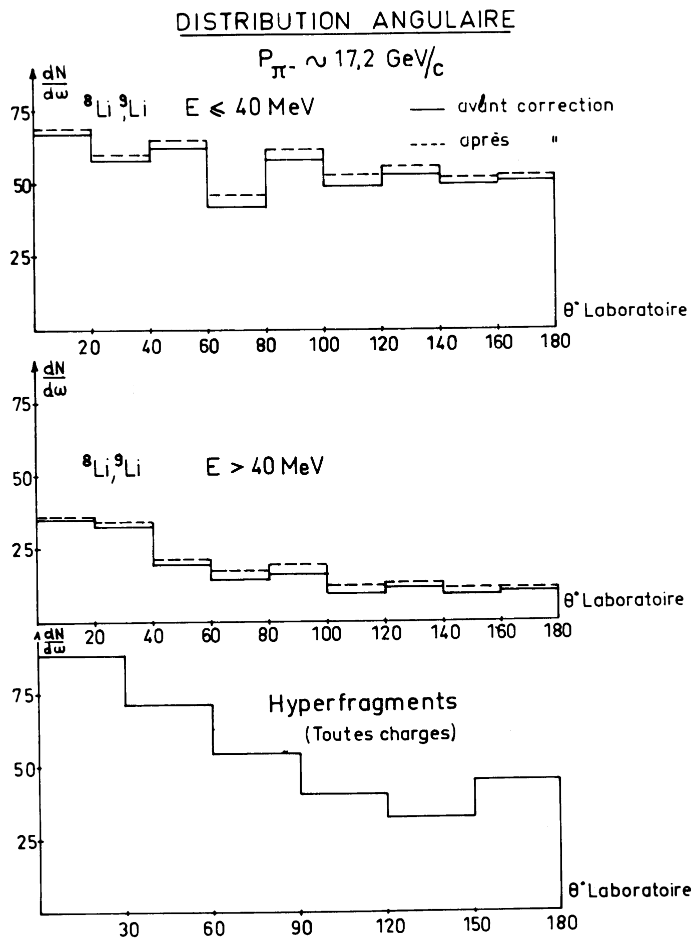

Fig. 10. - Angular distribution of
a) Li^8, Li^9 fragments $E(Li^8, Li^9) \leq 40$ MeV
b) Li^8, Li^9 fragments $E(Li^8, Li^9) > 40$ MeV
c) hyperfragments (all charges)

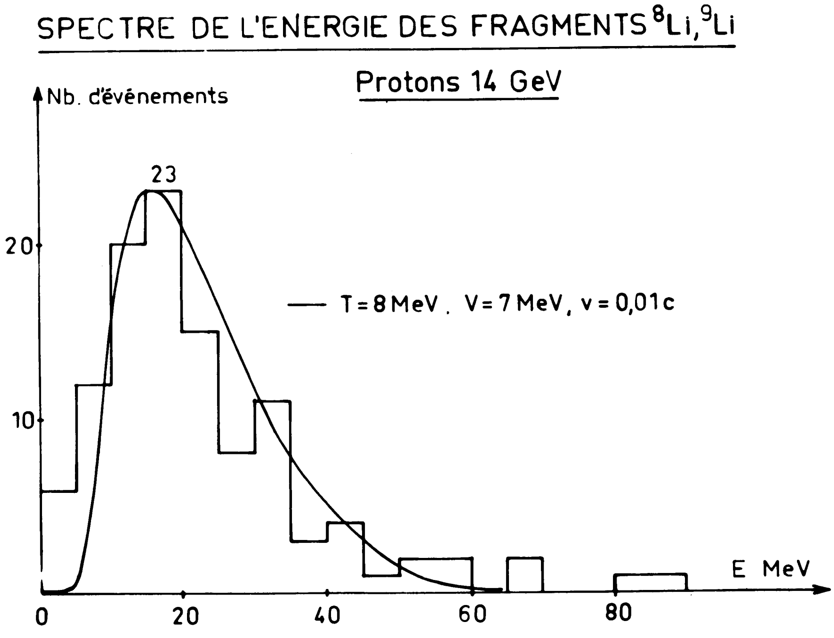

Fig. 11. - Energy spectrum of Li^8, Li^9 fragments.

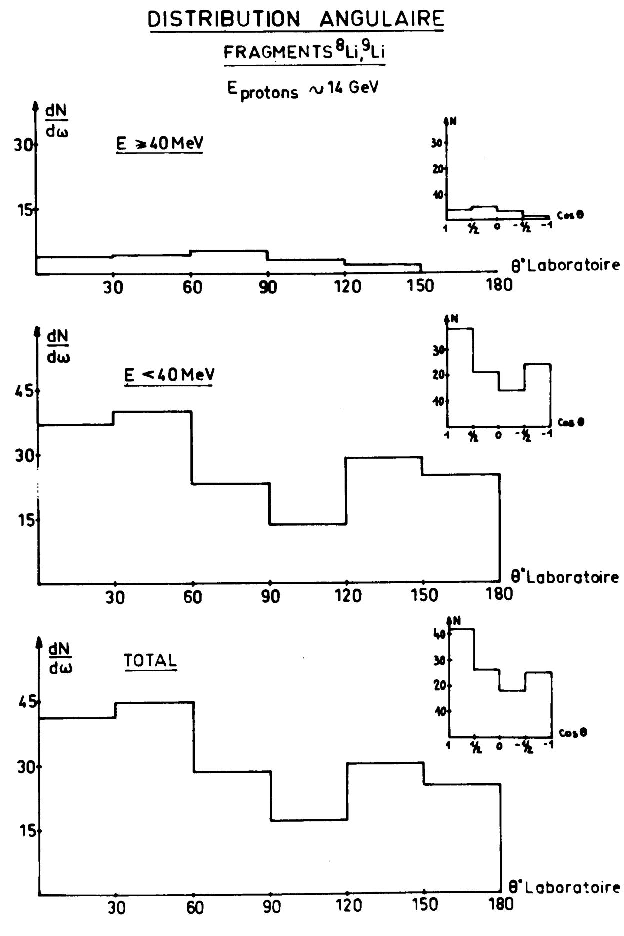

Fig. 12. - Angular distribution of fragments

a) Li^8, Li^9 $E(Li^8, Li^9) \geq 40$ MeV

b) Li^8, Li^9 · $E(Li^8, Li^9) < 40$ MeV

c) Li^8, Li^9 Total

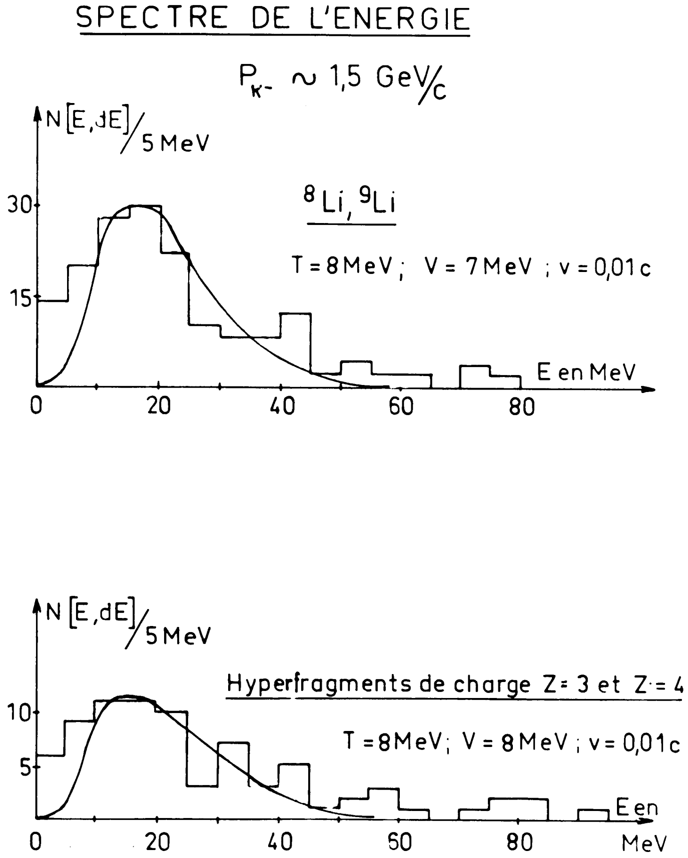

Fig. 13. - Energy spectrum
a) of Li^8, Li^9 fragments
b) hyperfragments of charge Z = 3 and Z = 4

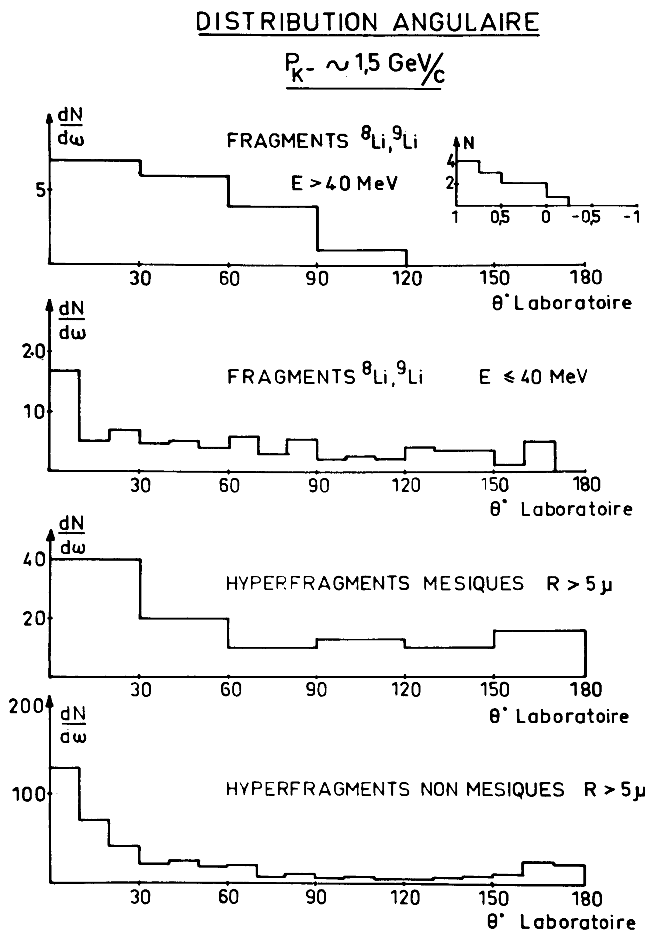

Fig. 14. - Angular distribution of
a) Li^8, Li^9 fragments $E(Li^8, Li^9) > 40$ MeV
b) Li^8, Li^9 fragments $E(Li^8, Li^9) \leq 40$ MeV
c) mesonic hyperfragments with $R > 5\ \mu$
d) non-mesonic hyperfragments with $R > 5\mu$

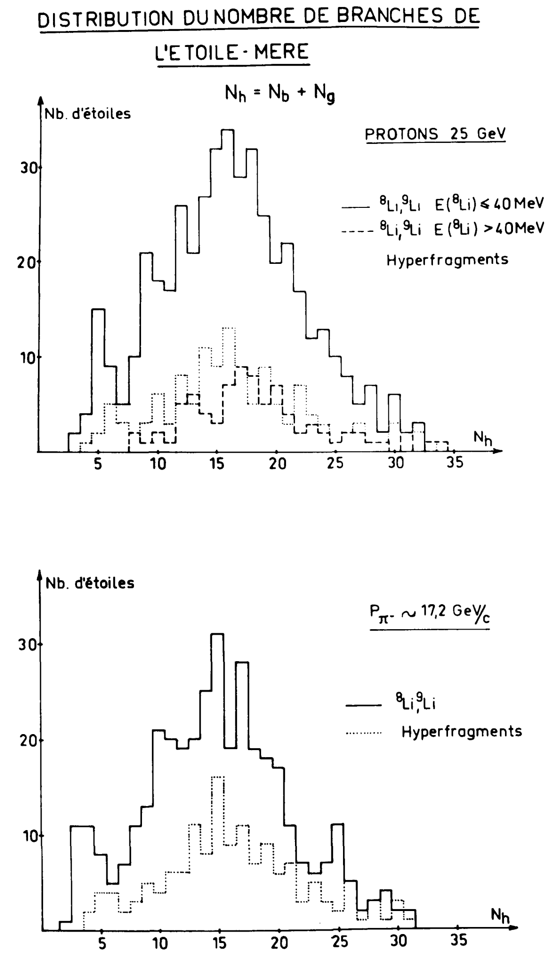

Fig. 15. - Distribution of the number of heavy prongs n_h for the stars emitting Li^8, or Li^9 fragments or hyperfragments for
a) protons of 25 GeV as primary particles
b) π^- mesons of 17.2 GeV/c as primary particles.

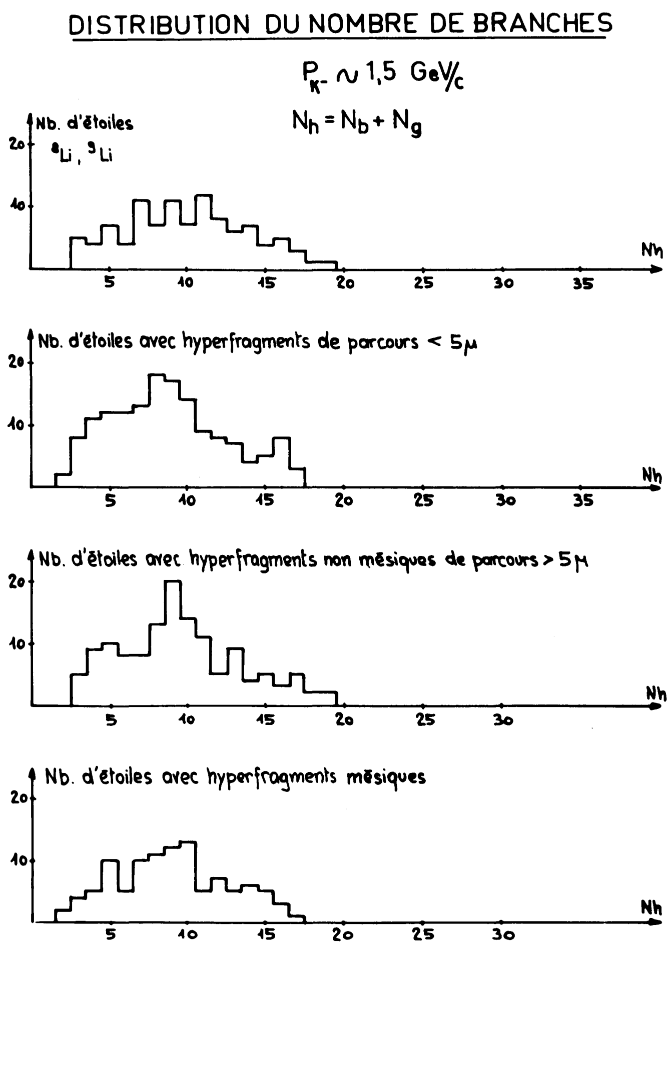

Fig. 16. - Distribution of the number of heavy prongs n_h of the parent stars produced by K^- mesons of 1.5 GeV/c for the emission of
a) Li^8 or Li^9 fragments
b) hyperfragments of range < 5 μ
c) hyperfragments of range > 5 μ
d) mesonic-hyperfragments.

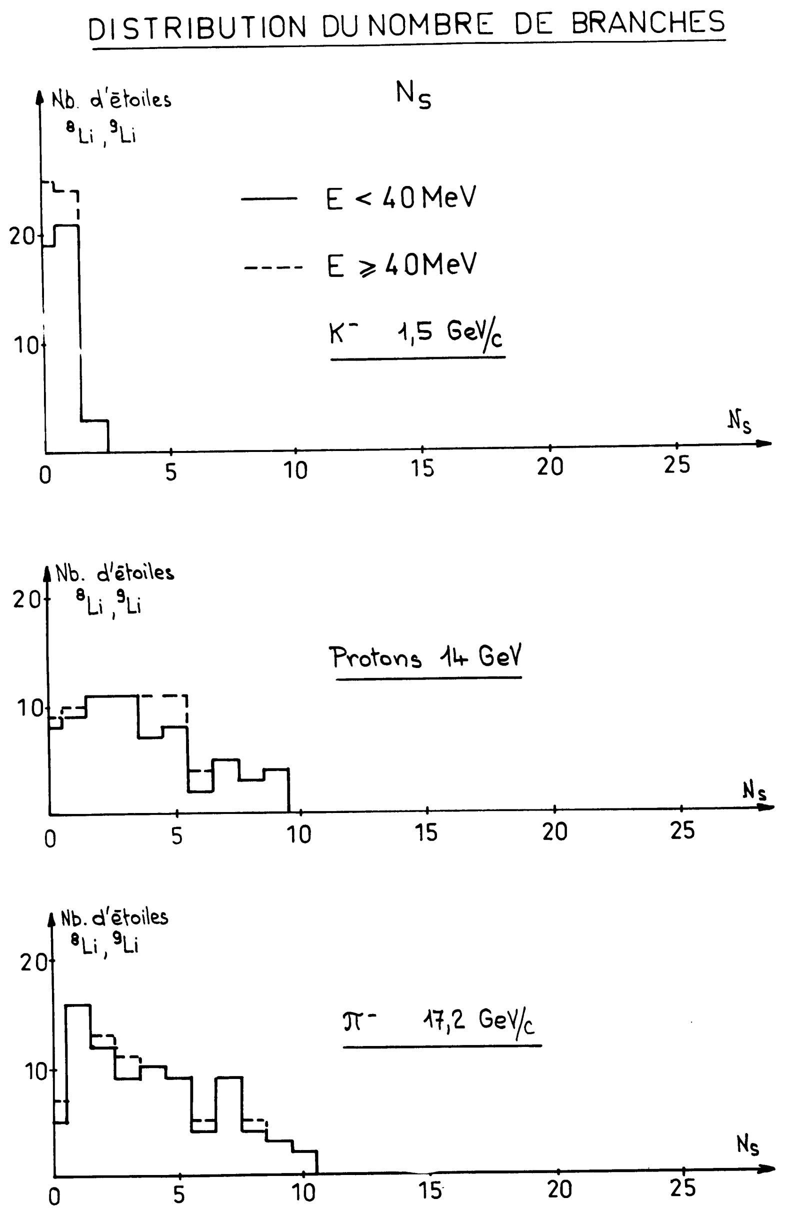

Fig. 17. - Distribution of the number of shower particles n_s of the parent stars

a) Interactions of K^- mesons of 1.5 GeV/c

b) Interactions of protons of 14 GeV

c) Interactions of π^- mesons of 17.2 GeV/c.

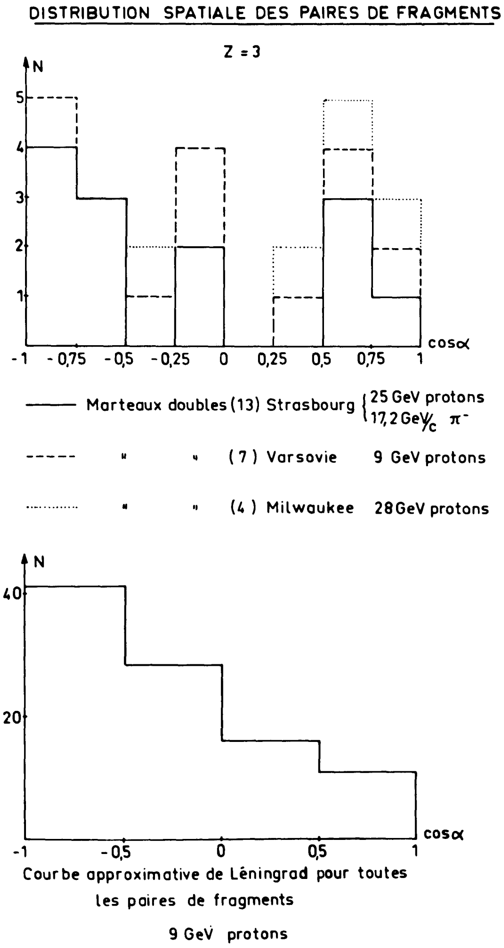

Fig. 18. - Spatial distribution of pairs of fragments

a) double hammers

b) all fragments (Leningrad curve).

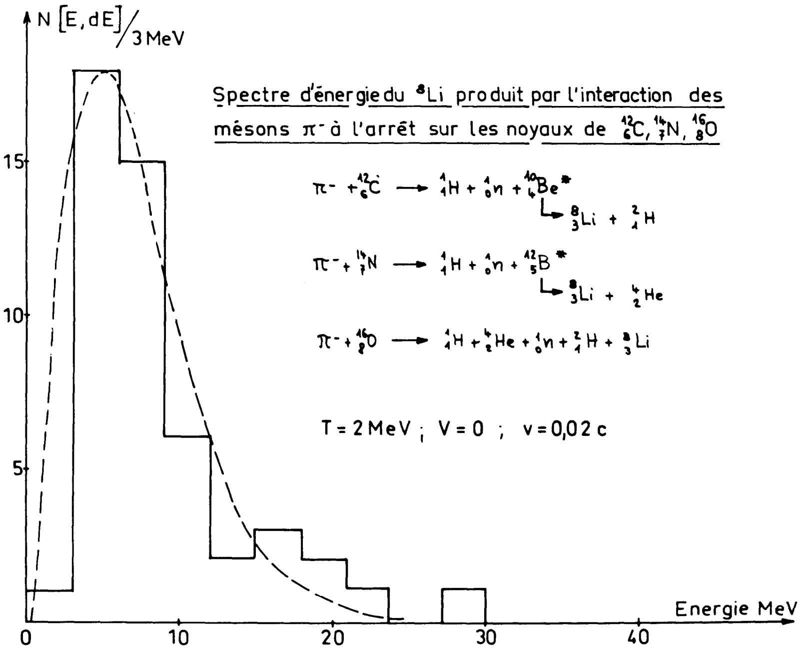

Fig. 19. - Energy spectrum of Li^8 fragments produced by the interaction of π^--mesons at rest with the nuclei of ${}^{12}_{6}C$, ${}^{14}_{7}N$, and ${}^{16}_{8}O$.