EMISSION OF FAST LITHIUM FRAGMENTS IN INTERACTIONS OF 25 GeV/c PROTONS WITH Ag AND Br NUCLEI

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Production of ^{6}Li and ^{7}Li fragments with $E \gtrsim 10$ MeV/nucleon in the interactions of 25 GeV/c protons with heavy emulsion nuclei has been investigated. In particular, the influence of the fast fragment on the emission of the heavy product has been analysed.

1. Introduction

The production of nuclear fragments ($Z > 2$) is a characteristic phenomenon for the interactions of high energy particles with nuclei [1–3]. It is interesting that some of the fragments with masses about 10% of the initial mass of the target nuclei have kinetic energies as large as 10 MeV/nucleon and higher. The series of recently performed experiments provided abundant information about the emission of various fragments [3–6]. In particular, Poskanzer *et al.* [3] in an experiment performed with the counter technique have obtained information about the energy and angular distributions of the fast fragments. These experiments did not give any information on the dependence of the emission of a fragment on the production of other nuclei in the same interaction. In the present work, low sensitivity emulsions were chosen as the detector which made possible to select heavy products ($A \gtrsim 10$) of the interactions and to investigate the influence of the fast fragment emission on the production of these heavy nuclei [7].

Up to now the investigations have indicated that the process of the emission of fragments has some properties of the low energy evaporation. In particular, the shape of the energy spectrum of the fragments has a general trend as that proposed by Weisskopf [1–3]. However, the experimentally observed difference between the average values of longitudinal velocities of the fragments and of the heavy products of interactions [7–10] disagreed with the predictions of the evaporation model. It was suggested that the analysed fragments are the mixture of fragments produced in the evaporation process and in the more fast process [3]. The fragments of second group should be then faster in average

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than evaporated fragments. In order to clarify this situation the experimental results on the simultaneous production of fast fragments and heavy nuclei in the same interaction may be of decisive importance. In the evaporation process heavy products should be the residual nuclei which sustain recoils after emission of all evaporated nuclei, also fast fragments if they are evaporated too.

2. *The experimental material*

A stack of nuclear emulsions irradiated with 25 GeV/c protons from the Proton Synchrotron at CERN was used. The emulsions Ilford-KO were chosen which registered protons and α particles with energies below about 5.5 MeV (range $R \sim 200$ μm) and

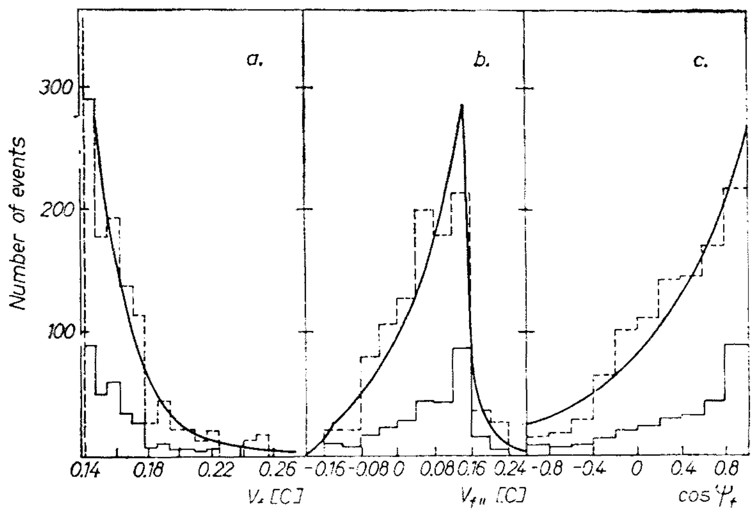

Fig. 1. The fast fragments distributions: a) of the velocity, b) of the longitudinal velocity, c) of the angle of emission. The histograms represent the experimental sample (——) and corrected sample (- - -). The fitted curves of the evaporation model with parameters $T = 15$ MeV and $v_{\parallel} = 0.018c$ are shown

125 MeV, respectively, and heavier nuclei without any energy restrictions. Area scanning was performed by looking for tracks with a dip angle $\vartheta < 25°$ and with range $R \geqslant 385$ μm. The identification of the fragments was based on the counting of black grains on the chosen sector of a track. It was estimated that after cut-off in the ionization distribution, about 90% of the selected sample of 257 fragments with energies $E \geqslant 9.8$ MeV/nucleon consisted of ^{6}Li and ^{7}Li isotopes. The accepted fragments were observed in stars with at least two visible tracks. The stars with such number of visible tracks in Ilford-KO emulsion are statistically equivalent to the interactions with Ag and Br nuclei only ($N_h > 8$ in electron sensitive emulsions).

The tracks with a large ionization, higher than that observed on the boron hammer--tracks in Ilford-K1 emulsions [7], were chosen in the analysed interactions. Later the nuclei with such an ionization will be reffered to as the heavy products of the interactions.

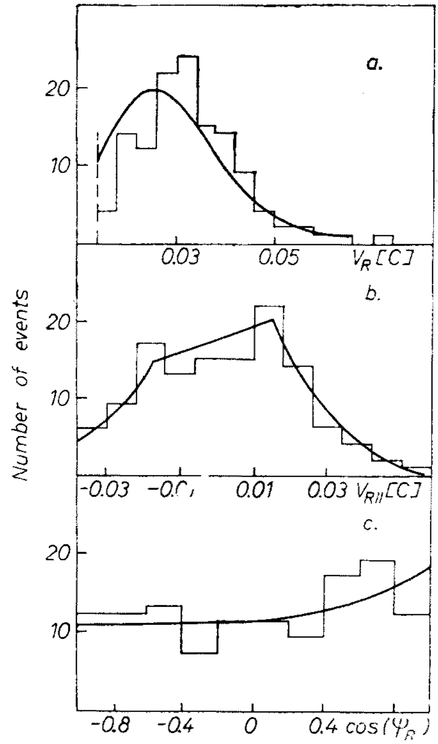

Fig. 2. The heavy products distributions: a) of the velocity b) of the longitudinal velocity, c) of the angle of emission. The histograms represent the experimental sample. The fitted curves of the evaporation model with parameters $v_{\parallel} = 0.002c$ and $\sigma(v_{\parallel}) = 0.020c$ are shown. The smallest registered velocity $v_{R_0} = 0.016c$ was fitted in order to account for the experimental biasses

Several corrections of systematical biasses were introduced. These biasses were connected with:

1) The investigation of tracks in only one pellicle;

2) The analysis of a track of fragments with dip angle less than 25°;

3) The dependence of the efficiency of the scanning on the configuration of a track in the field of view of a microscope.

The experimental data on the velocities and the angles of emission of fast lithium fragments and of heavy products as well as on the correlations between these nuclei are presented in Figs 1–3.

3. *Analysis of the experimental data*

In order to obtain information on differences between processes of production of the fast and slower fragments the analysis of the experimental data has been done. The experimental data on the fast fragments and heavy nuclei produced in the same interaction were analysed on the basis of the evaporation model as it had been usually done for fragments

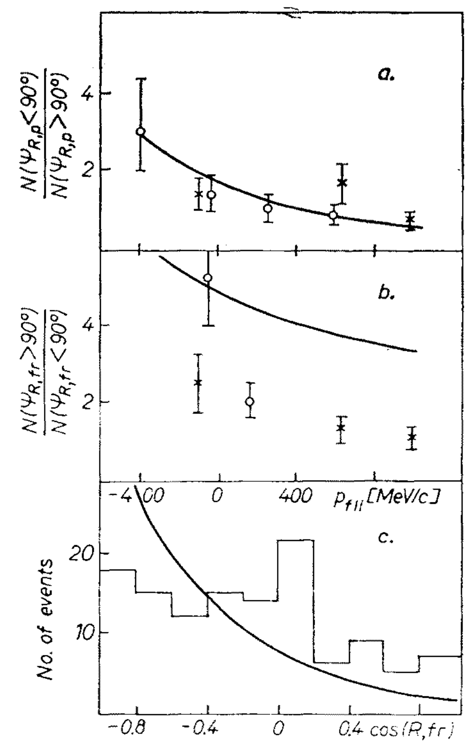

Fig. 3. The dependence of the forward-to-backward ratio of heavy products emission refered to the primary particles direction (a), and to the fragment emission direction (b), on the longitudinal velocity momentum of fragments; the distribution of the angle between the directions of the fast fragment and the heavy product (c). The curves are obtained from the evaporation model (with $v_{\|} = 0.005c$) after the experimental cuts. The experimental x-points are for the fast fragments sample and o-points for the ^{8}Li fragments sample [7]

of any energy [1–3, 7]. In so doing, it was assumed that the nucleus with mass number $A = 77$, temperature T, and velocity $v = v_{\|}$ in the beam direction only, was left on the average after the cascade process. Two parameters, T and $v_{\|}$, have been estimated from the kinematical characteristics of the fast fragments (Fig. 1) by comparison with the curves obtained from the evaporation energy distribution

$$P(E)dEd\cos\psi d\varphi = \frac{E - V_{\text{eff}}}{T^2} \exp\left(-\frac{E - V_{\text{eff}}}{T}\right) dEd\cos\psi d\varphi$$

transformed to the laboratory system with the velocity $v_{\|}$. The cut-off on the velocity of fragments as in the experiment was used, and the influence (small in the region of big energy of fragments) of the effective Coulomb barrier was neglected. The values $T = (15 \pm 2)$ MeV and $v_{\|} = (0.018 \pm 0.003)\,c$ were obtained from the fit to the experimental data.

The average value of the longitudinal velocity of the evaporated nuclei, $v_{\|}$, can be obtained also from the characteristics of other products of interactions, for example of residual nuclei which have been left after the evaporation process [7, 8]. The average longitudinal velocity $v_{\parallel} = (0.002 \pm 0.002)\, c$ has been obtained for heavy products (Fig. 2). This value is very different from that obtained in the fast fragments analysis. Similar, but slightly smaller, difference in longitudinal velocities was previously obtained in the analysis of interactions producing fragment of any energy [7].

The further analysis was based on the evaporation model too. The influence of the emission of fast fragments on the residual nucleus momentum distribution, predicted in the evaporation model, was calculated with the additional, usually done, assumption that the fast fragment was evaporated as the first nucleus. The emission of the further nuclei was taken into account by the smearing of the components of the velocity of the nucleus recoiled by the fast fragment. For the dispersion of the Gaussian smearing we choose

$$\sigma(v_x) = \sqrt{\frac{\sum_l n_l p_l^2}{3(M-m_{fr})M_R}},$$

where l denotes the kind of emitted nuclei (n, p, d, α, fragments), n_l — their numbers, p_l^2 — the average square momenta of these nuclei, and M, M_R and m_{fr} — the masses of nuclei after the cascade process ($M = 77$ amu), and nuclei after evaporation process ($M_R = 30$ amu), and the fast fragment ($m_{fr} = 6.5$ amu), respectively. The first three parameters were taken from other experiments [11, 12] as it was done in analysis of the low energy fragments [7]. The generated events were used for the comparison with the experimental data taking into account the experimental cuts (Figs 1 and 2). The comparison of the predicted, and experimental characteristics is shown in Fig. 3 and in Table I, where the data on the randomly chosen interactions and interactions containing ^{8}Li fragments, without any energy restrictions, are also given.

4. *Discussion*

Two facts observed in the present work are in disagreement with the assumed model of evaporation from a single excited nucleus moving in the direction of incoming particle.

1) The distinct difference between the longitudinal velocities of fast fragments ($0.018 \pm \pm 0.003\, c$) and heavy products from the same sample of interactions ($0.002 \pm 0.002\, c$) — Figs 1 and 2.

2) Angles between the fast fragment and heavy product from the same interaction are smaller than predicted in the model — Fig. 3.

The second effect can be a result of neglecting, in model calculations, the transversal components of the nucleus velocity after the cascade process. However, the first effect can not be in any way explained in the evaporation model. Simultaneously the other analysed kinematical characteristics are, in their general trend, in agreement with this model.

The average longitudinal velocities of the heavy products of the interactions of different class (Table I) are small and, within the errors, equal to about $0.004\, c$. On the contrary, for emitted fragments they are noticeably bigger: $0.015 \pm 0.003\, c$ for the whole sample of

TABLE I

The results for the different classes of interactions of 25 GeV/c protons with heavy emulsion nuclei

	Interactions containing fragments				Random interactions	
	$^{6,7}Li$: E $\geq$10 MeV/nucl		^{8}Li			
	exp.	model	exp.	model	exp.	model
Stars with one heavy product track [%]	48 ± 4		50 ± 3		48 ± 2	
Stars with two heavy product tracks [%]	7 ± 2		4 ± 2		3 ± 2	
Stars with a light residual nuclei [%]	35 ± 6		28 ± 6		8 ± 4	
The average range of heavy products [μm]	5.7 ± 0.3		5.3 ± 0.2		4.7 ± 0.2	
The average velocity of heavy products [10^{-3}c]	29 ± 2	30	26 ± 2	25	21 ± 2	18
The forward to backward emission ratio						
for heavy products	1.2 ± 0.2	1.4	1.4 ± 0.2	1.4	1.7 ± 0.3	1.8
for fragments	3.6 ± 0.6		1.5 ± 0.2		~1.2 x)	
for heavy products relative to fragment directions	$1.9^{+0.7}_{-0.4}$	4.9	2.9 ± 0.6	2.7		
The average longitudinal velocity [10^{-3}c]:						
of heavy products	2 ± 2		4 ± 2		5 ± 2	
of fragments	18 ± 3		15 ± 3		≤10 x)	
The dispersion of longitudinal velocity distribution of heavy products [10^{-3}c]	20 ± 2	20	16 ± 2	17	14 ± 2	11
The temperature of evaporating nuclei [MeV]	15 ± 2		12		≤10 x)	

x) for α particles [11]

^{8}Li fragments and $0.018 \pm 0.003\ c$ for fast lithium fragments. The small frequency (exponentially decreasing with fragment energy) of the emission of fast fragments and their too small longitudinal velocity ($0.018\ c$) are in disagreement with the hypothesis that the main part of fragments is evaporated from the slowly moving nucleus ($\sim 0.004c$), while the experimentally obtained value $0.015c$ for all the fragments results from the admixture of fast fragments which would be then produced in more direct process. It seems more probable that the majority of fragments is produced before the equilibrium is totally established [14–18] when the direction of the primary particle is more distinguished than for a residual nucleus. The distinction of the direction of the primary particle in this process seems to be correlated with the transfer of energy to a nucleus. In fact, passing in Table I from random interactions, through interactions producing fragments of any energy, to interactions producing fast fragments one observes the rise of the average transfer of energy to a nucleus left after the cascade. The rise is indicated by the rising tendency:

1) of the frequency of interactions without heavy products in the final state;
2) of the momenta of the heavy products, if they were produced;
3) of the temperature necessary to describe the energy distributions of the heaviest of all light nuclei produced.

Simultaneously the rise of the average longitudinal velocity of the light products of interaction is observed while it remains small for heavy products from the same interaction.

5. *Conclusions*

For the interactions in which fragments, in particular fast fragments, are produced one observes that energy transfer to a nucleus left after the cascade process is big. The average longitudinal velocity of fragments appears to be big also, while it remains small for heavy products. Simultaneously the other kinematical characteristics are similar to those of evaporated nuclei for fragments (*e. g.* the shape of the energy distribution), and to those of residual nuclei for heavy products. These properties of the products of the interactions would hopefully agree with the model of the precompound state discussed by some authors [14–18]. We note that the occurence of the residual nuclei exhibited in 95% of interactiontions [19] is in agreement with such a picture.

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