Eur. Phys. J. A **1**, 137–141 (1998)

THE EUROPEAN PHYSICAL JOURNAL A

Yields and transverse momenta of the ^{6}Li fragments in the emulsion at 4.5 GeV/c per nucleon

F.G. Lepekhin, D.M. Seliverstov, B.B. Simonov

St.Petersburg Nuclear Physics Institute, Russian Academy of Sciences, RU-188350 Gatchina, Russia

Received: 4 August 1997
Communicated by V.V. Anisovich

Abstract. We present the results of the study of interaction of the relativistic ^6Li nucleus with the momentum 4.5 GeV/c per nucleon with the photoemulsion. Yields of the ^1H (^3He) and ^2H (^4He) isotopes due to the fragmentation of ^6Li are found to be almost equal. Cross sections for the charge exchange and pickup reactions are found to be $\sigma_{exch} = 9 \pm 2$ mb. The distributions of the fragment transverse momenta projected onto the emulsion plane are used to obtain the nucleon Fermi momentum of ^6Li, P_F, this value being equal to 129 ± 8 MeV/c. The high momentum component in the transverse momentum distributions of ^3He and ^4He isotopes is observed.

PACS. 25.10.+s Nuclear reactions involving few-nucleon systems

1 Introduction

At present time the hypothesis of sudden or so-called "cold" relativistic nucleus fragmentation in nuclear interactions [1] is proved by the experiments [2]- [6]. The fragments with the mass number A_F formed by the fragmentation of relativistic nucleus A interacting with the emulsion nuclei obey the normal distribution of the transverse momentum $P_{\perp\varphi}$ projected on the Y-axis of the emulsion plane. This distribution has the mean value equal to zero and the dispersion as follows:

$$\sigma_F^2 = \sigma_0^2 \frac{A_F(A - A_F)}{A - 1}. \tag{1}$$

Here φ is the plane angle between the X-axis of the laboratory frame and the projection of the fragment track onto the emulsion plane, σ_0^2 is a nucleon momentum dispersion on a random direction for the nucleus A in the ground state in its rest frame. An estimation of σ_0 can be made using the nucleon Fermi momentum P_F, which is known from the electron scattering of nuclei [7], then $\sigma_0^2 = P_F^2/5$, or using r_0 which enters the definition of nucleus radius ($R = r_0 A^{1/3}$) [8] as follows:

$$\sigma_0(r_0) = \frac{(9\pi)^{1/3}}{\sqrt{5}} \frac{\hbar}{2} \frac{1}{r_0}. \tag{2}$$

The φ distribution also obeys the normal distribution with the mean value equal to zero and the standard deviation $\sigma_\varphi = \sigma_F/(A_F P_0)$. P_0 is the projectile momentum per nucleon.

The parabolic law (1) has been obtained in [1] using simple combinatoric considerations.

After the interaction of relativistic nucleus, the fragments are found out (by means of measurement of transverse momenta) with the properties common with those of a nucleus before interaction (such as Fermi momentum P_F of projectile nucleons or radius R of this nucleus). The *vice versa* is also valid. This picture is similar to the limit fragmentation hypothesis for hadron-hadron interactions suggested by Yang [9]. In total, the fragmentation looks as a process of independent emission of fragments.

The interest to the fragmentation of relativistic ^6Li is stressed by its unique properties. "Nuclear matter" is not formed in it yet. There is no region of constant nuclear density. The radius of ^6Li is surprisingly large and the constant $r_0 \simeq 1.6$ fm [8]. It provides $\sigma_0(r_0) \simeq 70$ MeV/c that agrees with $\sigma_0(P_F) = 76$ MeV/c found in the experiment [7]. Because of that, the simple laws established for the multi-body Fermi systems are already true for ^6Li. Six nucleons are already a large multi-body system. In this paper the validity of such an approach will be shown by means of the investigation of the fragmentation of ^6Li.

2 Experimental method

Preliminary results of the analysis of the fragmentation of ^6Li with the momentum 4.5 GeV/c per nucleon in the inelastic interaction with the emulsion nuclei are given in [10]. In this paper we report the results based on the statistics of 934 events.

A photoemulsion chamber which consists of 600 μm thickness 10×20 cm^2 sheets of BR-2 emulsion irradiated by the beam of ^6Li ions with the momentum 4.5 GeV/c per nucleon from the synchrophasotron of the Laboratory of High-Energy Physics at JINR (Dubna). 201.409 m of track length were scanned and 1377 events were found. In our experiment the average interaction free path in emulsion for ^6Li is $< l >= (14.6 \pm 0.4)$ cm. Fragments of the initial ^6Li are observed in 1040 events, 934 events of those found to be measurable, they will be discussed later on. The remaining 106 events cannot be measured and they are rejected. Nevertheless, the sample of events remains representative.

The 934 survived events have been analyzed to determine:

(a) the fragment charge Z;

(b) the angles φ and α between the fragment momentum and the direction of $\mathbf{P_0}$ (parallel to the X-axis) in the XOY and XOZ planes, respectively;

(c) the quantity $p\beta c$ and its error $\Delta p\beta c$ obtained from the data on multiple scattering (p is the absolute value of the measured fragment momentum).

The measured accuracy of the zero angle φ is estimated to be about $\simeq \pm 0.26$ mrad, while the middle angle φ of all the two-charge fragments $< \varphi > \simeq 9.6$ mrad. It is clear that the estimated error of the transverse momentum projection $P_{\perp\varphi} = A_F P_0 \mathrm{Sin}\,\varphi$ onto the emulsion plane may be neglected. The uncertainty of P_0 is more essential.

At the measurement of the multiple scattering of fragments, the signal from the Coulomb scattering should exceed > 0.3 μm: this is more, by the factor of 3, than the noise, connected with the accuracy of the Y-coordinate measurement. To satisfy these requirements, the cell length has been increased, so the final result is mainly obtained using 2- or 3-mm cells.

3 Yields of the ^6Li isotopes. Charge exchange and pickup processes

The problem of the fragment classification with respect to their mass number is simplified for Z =1,2. The number of classes should be not more than three and in every class the momentum $p \simeq p\beta c$ be equal *a priori* about P_0, $2P_0$ and $3P_0$ ($A = 1, 2, 3$) or $3P_0$ $4P_0$ and $6P_0$ ($A = 3, 4, 6$), since in our experiment we can observe only ^1H, ^2H, ^3H or ^3He, ^4He, ^6He. The maximum probability to belong to a given class is reached if we find the minimum of the value

$$t_i = \frac{|p - iP_0|}{\Delta p} \tag{3}$$

at $i = 1, 2, 3\,(Z = 1)$ and $i = 3, 4, 6\,(Z = 2)$.

The weight of a given measurement in the construction of histograms is defined by $\sim exp(-t^2/2)$, under the assumption that the estimation of p is proportional to the normal distribution density, with the mean value $P_0 A$ and the variance $(\Delta p)^2$.

Then the mean weighted value of the momentum $< P >$ can be found for every class of fragments together with its error. Such values are shown in Table 1. Results of statistical separation of fragments are given in the same place. In this case the probability to observe the momentum P_i of a given fragment depends on 8 parameters, being

Table 1. Experimental values of momenta and yields of fragments with $Z = 1, 2$ in the ^6Li fragmentation

Z=1	N fr.	<P> *exper*	*P mixture*	%	% *mixture*
^1H	257	4.4 ± 0.5	4.50 ± 0.01	47.5 ± 1.9	45.7 ± 1.8
^2H	248	8.1 ± 0.7	8.20 ± 0.06	45.8 ± 1.6	41.2 ± 2.9
^3H	36	11.6 ± 0.9	11.6 ± 0.3	6.7 ± 0.3	13.1 ± 2.2
Z=2	N fr.	<P> *exper*	*P mixture*	%	% *mixture*
^3He	169	12.7 ± 1.6	12.7 ± 0.8	50.7 ± 2.3	55.4 ± 4.3
^4He	155	16.5 ± 1.4	15.8 ± 0.6	46.6 ± 2.1	40.9 ± 3.8
^6He	9	22.8 ± 3.3	15.6 ± 12.2	2.7 ± 0.9	3.7 ± 1.2

a mixture of 3 normal distributions:

$$f(p_i, c_i, \sigma_i^2) = \sum_{i=1}^{i=3} c_i N(p_i, \sigma_i^2), \tag{4}$$

where $i = 1, 2, 3$, $c_3 = 1 - c_1 - c_2$. $N(p_i, \sigma_i^2)$ is a density of normal distribution with the middle p_i and appropriate dispersion.

It can be seen from Table 1 that both methods of the fragment separation give approximately the same result.

Distributions of the single- and two-charge fragments obtained by measuring their momenta are presented in Fig. 1,2. One can see that the classification of these fragments by their mass number is quite reliable.

Yields of isotopes ^1H (^3He) and ^2H (^4He) at the fragmentation of relativistic ^6Li are approximately equal. It is interesting to compare the yields of helium isotopes ^3He and ^4He with the yields of the same isotopes at the fragmentation of (Ni, Ag, Sn, Au, U) targets induced by the 1 GeV protons [11]. Even in the fragmentation of ^{58}Ni and ^{112}Sn with $N/Z = 1$, ^3He the yield is less than 0.1 of ^4He. In the ^6Li fragmentation ($N/Z = 1$) an effort should be made to understand the strong enrichment of ^6Li fragmentation products with the ^3He isotope in the framework of statistical mechanism of relativistic nucleus fragmentation.

In total, we found 18 events which may be assign, by the Z and $p\beta c$ measurements, either to the charge exchange between incident and target nuclei (13 events) or to the pickup of target nucleus (5 events). Among them, 9 charge exchange events contain ^6He and 4 events contain the fission products of excited $^6He^*$ in two ^3H with $p\beta c$ of every fragment equal to 12 ± 1 GeV. The fission of the excited $^7Li^*$ (formed by the pickup of target neutron) into $^3H\,(13.7 \pm 0.9\,\mathrm{GeV}) +^4 He\,(19 \pm 3\,\mathrm{GeV})$ (2 events) and $^1H\,(5.5 \pm 1)\,\mathrm{GeV}) +^6 He\,(27 \pm 2\,\mathrm{GeV})$ (1 event) is observed. The excited $^7Be^*$ disintegrates into $^3He +^4 He$ and $^3He +^3 He$ observed in two events of the target proton pickup through intermediate excited state $^6Be^* + n$. The latter 2 events of "pure" fragmentation of ^6Li by the photoemulsion nucleus with the pickup of proton are not followed by a shower or slow particles from the disintegrated target. Using the total number of such events (18 in all) and the values given by the description of the experiment [10], one can estimate the charge exchange cross section

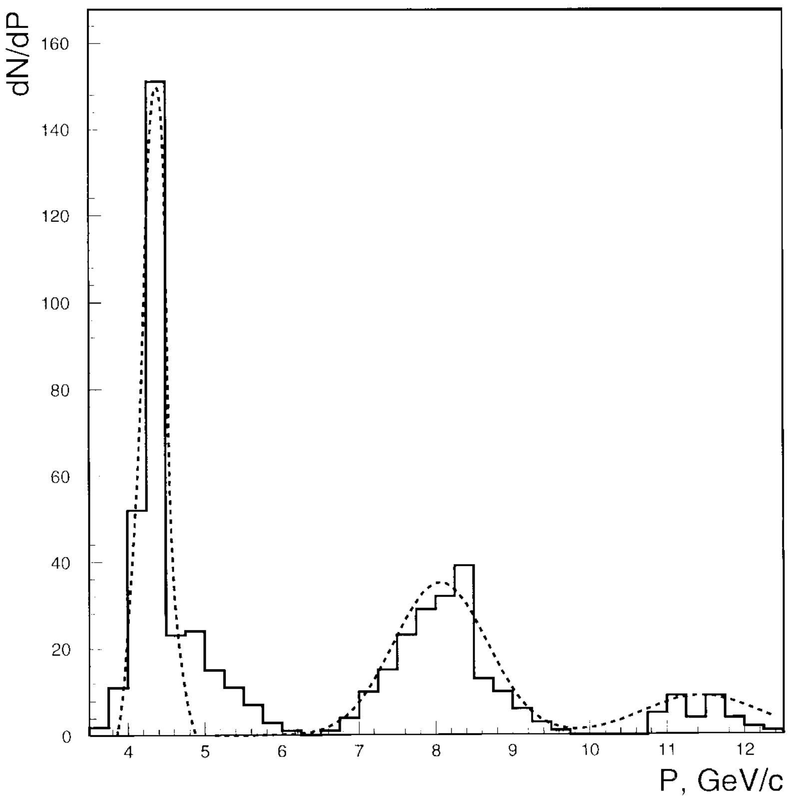

Fig. 1. Separation of hydrogen isotopes on the basis of $p\beta c$ measurement. The *histogram* is the experiment. *Smooth curve* is the mixture of 3 normal distributions found by the least-square method

between nucleons of the relativistic ^6Li and the emulsion nucleus (EmN) (or the pickup of the target nucleon by relativistic nucleus) $\sigma_{exch} = 9 \pm 2$ mb ($\simeq 1.3 \pm 0.3$)% of σ_{inel} ($^6Li + EmN$)). Approximately 0.75 of this cross section is due to the production of ^6He.

4 Transverse momenta of fragments

Consider now the distribution of the proton projections onto the emulsion plane, $P_\varphi = P_0 \mathrm{Sin}\ \varphi$, of relativistic ^6Li. It obeys the normal distribution N[0,σ_0^2] with $\sigma_0 = 57.7 \pm 3.6$ MeV/c. To verify the agreement of experimental distribution with the normal one, below the statistical parameter-free Kramers-Mizes criterion (ω^2-criterion) has been used. It is defined as a sum of difference squared of empirical distribution function and hypothetical (verified) one. The critical value of the parameter $N\omega^2$ for N values observed in the experiment does not depend on the distribution function and with the 1% confidence level is equal to 0.743. Histograms are used here for illustration only. For N=257 protons the value of this parameter is equal to 0.035. Consequently, the verified hypothesis of normal distribution is not denied. Therefore, transverse momenta themselves follow the Rayleigh distribution with the density $f(P_\perp) = (P_\perp/\sigma_0^2) exp(-P_\perp^2/(2\sigma_0^2))$. The value of $\sigma_0 = 57.7 \pm 3.6$ MeV/c found for protons in this study is significantly less than the expected value (76 MeV/c) which follows from the Fermi momentum (169 MeV/c) and is obtained from the quasi-elastic scattering of electrons off ^6Li [7]. Note, however, that in our experiment σ_0 is an observable quantity, whereas in [7] P_F is one of model parameters fitted to data on the dependence of the cross section on the electron momentum. Our data suggest a value of Fermi momentum for ^6Li to be 129 ± 8 MeV/c. This quantity was not determined in [7].

In the first approximation the ground state of ^6Li is described by the "$\alpha+$ deuteron" model according to which the α-particle ($(1s)^4$ state) is in the center, while the deuteron is in $(2s)^2$ state, for the quadrupole moment is equal to zero. This simple picture does not agree with the levels of ^6Li, so the assumption about the existence of two nucleons in $(1p_{3/2})^2$ state becomes necessary. The coupling of an intermediate type (LS- and jj-connection) with the dominance of LS-connection is most likely in ^6Li. The α+deuteron structure of ^6Li, i.e. the real existence of the core and the periphery of nuclear matter in ^6Li, is most probable; it must show itself by its fragmentation. The existence of external neutron shell in $^{9,11}Li$ isotopes is generally recognized.

So, in the study [12] of the fragmentation of relativistic ^{11}Li, the distribution of projections of transverse momenta of the ^9Li fragments does not obey the normal one and can be described by the mixture of two normal distributions with $\sigma_1 = 95 \pm 12$ MeV/c and $\sigma_2 = 23 \pm 5$ MeV/c. This means that the high momentum fraction is available in the transverse momentum distribution of fragments of ^9Li and the existence of the second source of fragments.

Experimental estimations of $\sigma_1(^3He) = 114 \pm 9.7$ MeV/c and $\sigma_2(^4He) = 120 \pm 9.6$ MeV/c at fragmentation of ^6Li show that they are a little above the expected value of Fermi momentum [7] $\sigma_\alpha(P_F) \simeq 102$ MeV/c. But the dis-

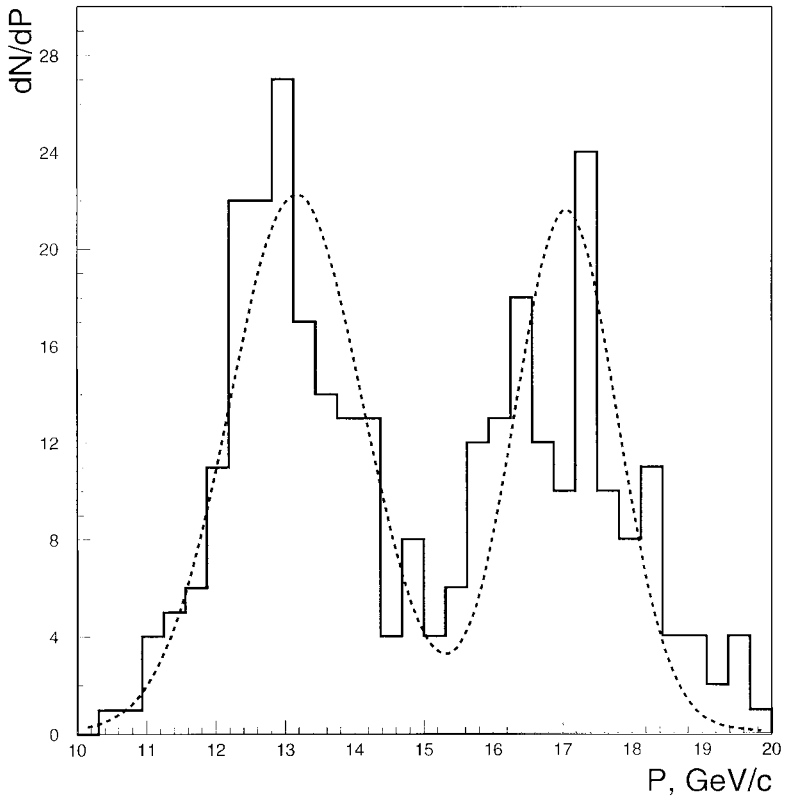

Fig. 2. Separation of helium isotopes on the basis of the $p\beta c$ measurement. The *histogram* is the experiment. *Smooth curve* is the mixture of 3 normal distributions found by the least-square method

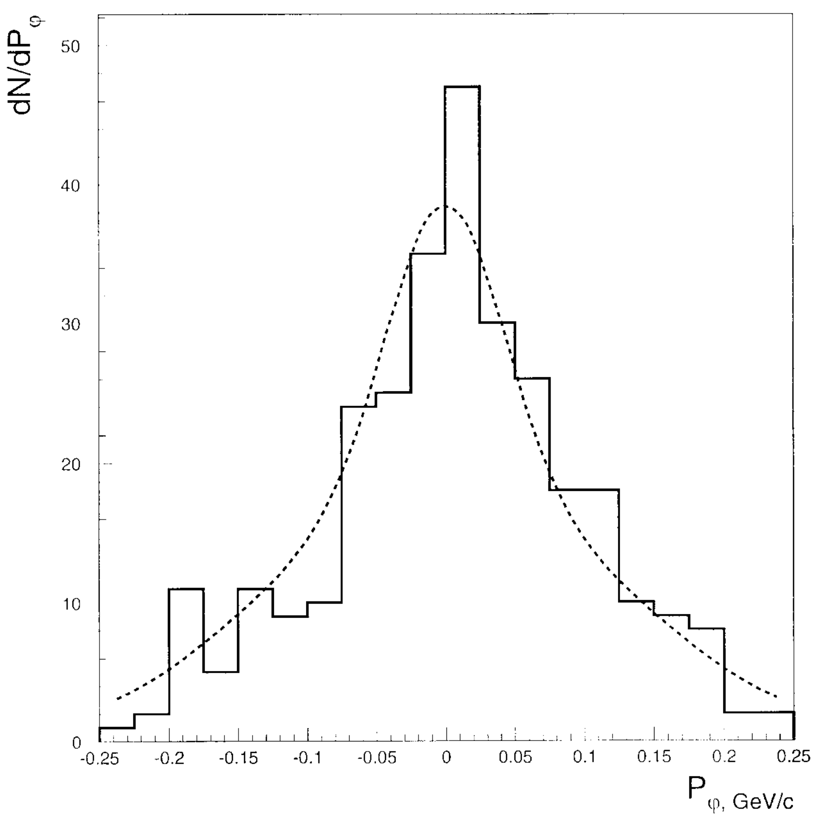

Fig. 3. *Histogram* is the experimental distribution P_φ ^3He and ^4He at the fragmentation of ^6Li. *Dotted curve* is the mixture of two normal distributions with parameters: $N = 316$, $\sigma_1 = 40.0$ 4 p/$\sigma_2 = 125.0$ MeV/c, $c = 0.257$, $N\omega^2 = 0.34$

tribution of projections onto the emulsion plane does not agree with the hypothesis of normal distributions either for one or for the mixture of two helium isotopes (see Fig.3). It can be described by mixture of two normal distributions with parameters given in the capture of Fig.3.

It is seen that about 1/4 of the two-charge fragments at the fragmentation of relativistic ^6Li is formed on the periphery of a nucleus, while the remaining fragments are formed in the central part, in the range of the order of 2 fm. Our experiment confirmed these expectations and allowed us to estimate the quantitative characteristics of the emission zone of nuclear matter in ^6Li. High-momentum fraction in the transverse momentum distribution really exists here, but it is not related to some warming-up of fragmenting nucleus and the increase of its temperature. This effect is due to the nucleus structure in its ground state.

5 Conclusion

The results obtained for the fragmentation of relativistic ^6Li with the momentum 4.5 A GeV/c in photoemulsion allow us to make the following conclusions:

1. Relative yields of hydrogen isotopes ($\simeq$ 47% protons, $\simeq$ 46% deuterons, $\simeq$ 7% tritons) and helium ($\simeq$ 51% ^3He, $\simeq$ 46% ^4He, $\simeq$ 3% ^6He) show the approximately equal probabilities for ^6Li fragmentation into $p+d$ and $^3He+^4He$, that is essentially different from data on the target fragmentation induced by the high energy light charged particles.

2. The processes of charge exchange between nucleons of relativistic ^6Li and target nucleus and the pickup of target nucleon by ^6Li are responsible for the production of ^6He, $^7Li^*$, $^6Be^*$ and $^7Be^*$ isotopes among the products of investigated reaction. Their cross section is 9 ± 2 mb or 1.3 ± 0.3% of all inelastic cross section.

3. The Fermi momentum P_F of nucleons in ^6Li is 129 ± 8 MeV/c. The high momentum component, with $\sigma_1 = 40.0$ MeV/c and the fraction c=0.257, is observed in the transverse momentum distributions of ^3He and ^4He isotopes. Its existence is connected with the nucleus structure in the ground state and is explained by the formation of two-charge fragments not only in ^6Li nucleus center but on the periphery as well.

References

1. Goldhaber J.S.: Phys. Lett. B **53,** 306 (1974)
2. Lepekhin F.G., Simonov B.B.: Preprint PNPI **1885,** (Gatchina, 1993) pp.33
3. Adamovich M.I. et.al.: Mod. Phys. Lett. **8,** 21 (Gatchina, 1993)
4. Brady F.P. et.al.: Phys. Rev. Lett. **60,** 1699 (1988)
5. Madey R. et.al.: Phys. Rev. C**38,** 184 (1988)
6. Greiner D.E. et.al.: Phys. Rev. Lett. **35,** 152 (1975)
7. E.J.Monitz et.al.: Phys. Rev. Lett. **26,** 445 (1971)
8. Elton L.: Nuclear sizes. Oxford University press 1961
9. Beneke J., Chou T.T., Yang C.N., Yen E.: Phys. Rev. **188,** 2159 (1969)
10. Lepekhin F.G., Seliverstov D.M., Simonov B.B.: Yad.Fiz. **53,** 381 (1995); Pis'ma Zh. Eksp. Teor. Fiz. **59,** 312 (1994)
11. Volnin E.N. et.al.: Phys. Lett. B **55,** 409 (1975)
12. Bertulani C.A., Hussein M.S.: Phys. Rev. Lett. **64,** 1099 (1990)