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Angular distributions of light projectile fragments in deep inelastic Pb + Em interactions at 160 A GeV

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Abstract. The nuclear emulsion was exposed at CERN by the lead projectile at 160 A GeV. The angles between any pair of fragments with $Z = 2 - 4$ have been measured in the emulsion plane for the events which did not contain heavy fragments. The constant characterizing the normal angle (φ) distribution of the fragment momentum projection onto the emulsion plane with respect to initial projectile momentum $\mathbf{p_0}$ is found to be $\sigma_\varphi = (0.37 \pm 0.02)$ mrad. Corresponding value $\sigma_0 = (121 \pm 6)$ MeV/c of nucleon momentum distribution in the lead nucleus coincides with that expected from Fermi momentum distribution for this nucleus. The peak in the pair-angle distribution of double-charged fragments, $^8Be \to 2\alpha$, is presented for the region of small angles ($<$ 0.1 mrad). The fraction of α-particles coming from the decay of the ground state ^8Be is found to be $(13 \pm 2)\%$ of their whole number.

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

1 Introduction

At present time the people try to find out a strict proof for the existence of the long–lived Quark–Gluon Plasma and observe qualitatively new phenomena [1,2] by using heavy-ion reactions at high energies.

Before the new type of the experiment, such as ALICE is [3], the photoemulsion experiments always gave the correct qualitative picture of nucleus–nucleus interactions at the energy range 160–200 A GeV. The investigation of relativistic nucleus fragmentation and multiparticle production was especially useful for understanding the basic mechanism of nucleus–nucleus interactions at superhigh energies. The fragmentation of relativistic nucleus such as ^6Li at 4.5 A GeV was found to be in agreement with the cold fragmentation hypothesis [4].

As it follows from the data obtained by EMU01 Collaboration, the angular distributions of fragments with $Z = 2$ in $Pb + Pb$ interactions [5] are practically identical in both longitudinal and transverse expositions and obey normal distribution with $\sigma_\varphi \simeq 0.45$ mrad. In [6] the authors conclude that the value $\sigma_0(P_F) = 119$ MeV/c expected from Fermi momentum for lead nucleus ($P_F = 265$ MeV/c) for the momentum projection in its rest frame onto any direction does not coincide with the experimental one which equals $\sigma_{0\,exp} = (162 \pm 2)$ MeV/c.

As is shown below, the discrepancy between the calculated and experimental values of σ_0 obtained in [5] is related to the data evaluation method used, it can be eliminated by the correct procedure of σ_0 estimation proposed in this work.

Over the energy range 160-200 GeV, the average angles between light fragments in the emulsion plane and initial projectile momentum $\mathbf{p_0}$ become ~ 0.3 mrad, so their direct measurement is impossible. The constant σ_φ of their normal distribution is determined, measuring relative angles between any pair of fragments with Z=2,3,4 [7]. The experimental value σ_φ is determined, although the true direction of vector $\mathbf{p_0}$ and angle φ between this vector and the fragment are unknown.

As a result, the disagreement with the cold fragmentation model observed in [5] is eliminated. In this work, the dispersion of the fragment angle distribution via $\mathbf{p_0}$ for deep inelastic $Pb + Em$ interactions at 160 A GeV is found to be in agreement with the expected value.

The high accuracy (0.01 mrad) achieved in measurement of angles between fragment tracks allowed us to observe the channel $^8Be \to 2\alpha$ and estimate its fraction.

2 Experimental details

Within the EMU01 Collaboration, we dealt with a part of the emulsion chamber (20 layers) exposed at CERN by lead projectiles at 160 A GeV. The search for events was carried out on the area and across the beam to detect the jets of secondary particles.

Only the events with the fragments with $Z < 9$ have been analyzed. The fragments with $Z = 1$ have not been taken into consideration because of the impossibility to isolate them from the particles produced. These 113 events also contained a great number of the produced single charged s-particles and target fragments (b and g-particles). As such events did not contain heavy projectile fragments they can be treated as deep inelastic ones. The charges of 672 fragments with $2 < Z < 9$ were determined by the blob length spectrum measurements described in [8]. So the fragments with $Z = 2, 3, 4$ were reliably separated from heavier fragments.

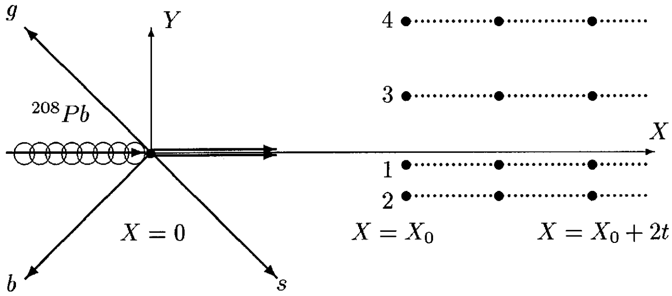

Fig. 1. The measurement scheme of Y, coordinates of tracks of fragments $2, 3, 4$, with respect to the fiducial track 1. In the points labelled by (•) the X, Y, Z coordinates are recorded

The coordinates X,Y for 10 points were measured at distances $10 - 20$ mm downstream the interaction point on the tracks of each fragment moving across the beam with 1 mm intervals for X coordinate — see Fig. 1. The angle $\varphi_{i,j}$ between any two fragment tracks was obtained by the χ^2 method as follows:

$$\varphi_{i,j} = \frac{N \cdot \sum_{k=1}^{k=N} x_k \cdot (y_{i,k} - y_{j,k}) - \sum_{k=1}^{k=N} (y_{i,k} - y_{j,k}) \cdot \sum_{k=1}^{k=N} x_k}{N \cdot \sum_{k=1}^{k=N} (x_k)^2 - (\sum_{k=1}^{k=N} (x_k))^2}, \quad (1)$$

where N is the number of x_i, y_i coordinates.

The accuracy for measurement of angle between tracks is restricted by "grain noise" which average value is found to be (0.203 ± 0.004) μm [9]. In our experiment the grain noise is reduced in an order, because the reading of Y coordinate has been made using the group of grains and the point number N=10.

Using the measured coordinates we can also determine the angle between two consecutive track intervals with cell value t=1,2,3,4 mm like in the coordinate method for multiple Coulomb scattering. For every three consecutive points the angle of succeeding track interval with respect to previous one is $\varphi_Y = D_Y/t$, where $D_Y = y_1 - 2 \cdot y_2 + y_3$. The value of this second difference is determined, in general, by layer distortion and spurious scattering increasing as a power of t.

The relative measurements of tracks closely-spaced to each other (less than 10 μm along the OY axis) eliminate both layer distortion, spurious scattering and stage noise [9]. The advantages of relative measurements are shown in Table 1. In this table we put the average values of the angle modules $< \varphi >_Y$ and $< \varphi >_d$ between the consecutive track intervals obtained by relative measurements

Table 1. Dependence on the cell value t of average angles between the consecutive track intervals $\langle|\varphi|\rangle_Y$, obtained by the coordinate method, and $\langle|\varphi|\rangle_d$, obtained by relative measurements (in mrad)

t mm	N points	$\langle\varphi\rangle_Y$	N points	$\langle\varphi\rangle_d$	$N\ \rangle 4\langle\varphi\rangle_d$
1	2523	15.1	3257	0.23	45
2	973	12.3	2309	0.12	41
3	492	11.0	1387	0.08	23
4	252	12.0	543	0.06	15

when the second differences were calculated using the distances d between tracks. In the first case the angles between neighbouring intervals are rather large because of large values of layer distortion and spurious scattering. This angle does not depend on the cell value t when the cell value increases. In the second case the average angle reduces with the increase of the cell value t, because both the layer distortion and spurious scattering are eliminated, and the grain noise does not depend on the cell value.

The main result is that even in the relative angle measurements the distribution of angle modules is not the normal one in the range of large angular values. About $1.5-2.0\%$ of these angle values are above the four-multiplied average. This effect has been also observed previously [9]. This fact can be interpeted as a presence of high-momentum component in the transverse momentum distribution of α-particles observed in [5].

3 Handling of measurements

Using the measured coordinates of the tracks of n fragments in every event one can estimate the dispersion of fragment angle distribution with respect to unknown initial projectile momentum $\mathbf{p_0}$ in the whole sample of events with different multiplicities n. To do this we used the empirical risk minimization method, which is as follows. The general idea is to determine the pair angles ε between all the unreplicated pair tracks in the event ($n\cdot(n-1)/2$ pair angles). The empirical distribution function for all values ε in a complete set of experimental events $F(\varepsilon)$ depends on the distribution of this set on a number of fragments in the event n and single free parameter σ which characterizes normal distribution of true angle φ with respect to unknown direction of vector $\mathbf{p_0}$ of the initial nucleus.

To estimate the parameter σ we are interested in it is necessary to find the minimum of a functional called the empirical risk [7]:

$$I(\sigma)=\int\{F(\varepsilon)-F_T(\sigma,\varepsilon)\}^2 f(\varepsilon)\,d\varepsilon, \qquad (2)$$

where $f(\varepsilon)\,d\varepsilon = d\,F_T(\sigma,\varepsilon)$.

This procedure is correct because with the increase of a sample the empirical distribution function tends uniformly to a true distribution function with a probability equal to unity. So σ tends to its true value. The functional $I(\sigma)$ does not depend on the form of distribution function and has the parabolic-type dependence on σ.

The details of the practical finding of minimum of $I(\sigma)$ with an unknown analytical expression $F_T(\sigma,\varepsilon)$ may be found in [7]. The efficiency of this method was checked up by Monte Carlo method, it appeared to be rather good. The application of this method to our set of 1321 values of $F(\varepsilon)$ gives a minimum of $I(\sigma)$ at $\sigma = 0.375$ mrad. With a 98% probability the true value of the estimated parameter lays between 0.35 and 0.39 mrad. Thus, the constant of the normal distribution of fragment angles φ with respect to initial projectile momentum direction $\mathbf{p_0}$ is found to be $\sigma_\varphi = (0.37\pm0.02)$ mrad.

To obtain the corresponding constant for the transverse momentum projection distribution onto the emulsion plane from the experimental constant of angular distribution σ_φ the two assumptions are necessary. First, the velocity of a fragment and that of initial nucleus are equal to each other and, second, the fragment mass number is $A_F = 2Z_F$. In such a way the constant of nucleon momentum distribution for lead nucleus is $\sigma_0 = (121\pm6)$ MeV/c, thus being the value expected from Fermi momentum for lead nucleus.

4 Discussion of angle measurements

The estimation of the angle φ' between the fragment and initial vector $\mathbf{p_0}$ has been performed summing up the angles φ and φ_{fid}; φ is the angle between the fragment and fiducial track and φ_{fid} is that between the fiducial track and initial one. The experimental φ'-distribution with respect to the probable direction of $\mathbf{p_0}$ and the expected Fermi momentum distribution for lead nucleus, P_F, are shown in Fig. 2. The constant for this normal distribution is found to be $\sigma_{exp} = (0.43\pm0.02)$ mrad.

The distribution of angles φ_{fid} is in agreement with the normal one, with zero average and constant value $\sigma_{fid} = 0.2$ mrad. Supposing this value to be the error for the initial momentum direction $\mathbf{p_0}$, the constant of normal distribution of fragment angles with respect to initial momentum is $\sigma_\varphi = (0.38\pm0.02)$ mrad. This magnitude coincides with the value estimated from pair fragment angles within the empirical risk minimization method.

Actually, in our experiment the angular distribution for fragments with Z=2–4 is a mixture of normal distributions with various dispersions corresponding to different isotopes. The hypothesis about its normality means that in their mixture the leading components with the dispersions which differ strongly from each other are not present. Therefore, the sample volume is insufficient to find out so small differences between the dispersions.

The projectile fragment production has been simulated by Monte Carlo method under the assumption that they are formed as virtual nucleon clusters at the breakdown of projectile interacting with a target. So the true random value of a fragment angle with respect to initial projectile momentum is determined only by the value $\sigma_0^2 = P_F^2/5$. The calculation shows that the true values of fragment

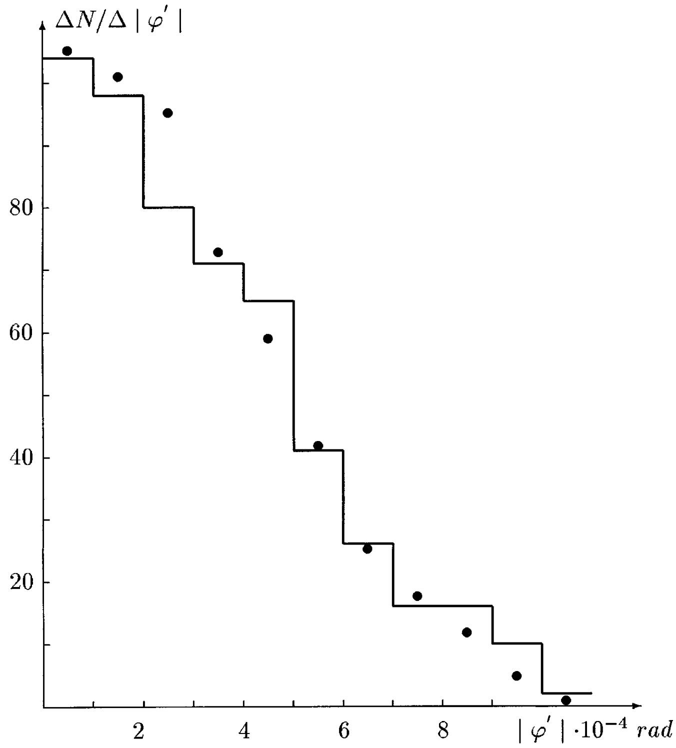

Fig. 2. Experimental distribution of the absolute value of angle φ' for lead fragments with $Z = 2, 3, 4$ (histogram). The points • stand for the expected distribution

angles in real isotope mixture with Z=2–4 obey the normal distribution, provided their charge distribution corresponds to the experimental one.

5 The channel $^8Be \rightarrow 2\alpha$

The ^8Be nucleus decays into two α-particles during 10^{-16} sec without a visible track in the emulsion. But the fact of its existence is established by the peak in the distributions of spatial pair angles between double-charged fragments for different relativistic nuclei at 4.5 A GeV [11]. This channel is also known among the fragments of different targets [12]. We also tried to prove the existence of $^8Be \rightarrow 2\alpha$ channel among the double-charged lead fragments at 160 A GeV. The maximal angle in the emulsion plane between two α-particles which is due to from the decay of the ground state ^8Be is about 0.004mrad. And the average angle is two times smaller. So the expected peak is not seen in the angular distribution, if the measurement capacity is insufficient for that. The Fig. 3 shows the peak in the pair angle distribution at the angle value corresponding to the decay of the ground state ^8Be. The fraction of such α-particles is about $(13 \pm 2)\%$. The peak at the angle about 0.1 mrad corresponding to the decay of the excited state ^8Be is not observable in our case because of low statistics.

The yield of α-particles due to the ^8Be decay in the lead projectile fragmentation at 160 A GeV coincides with the magnitude obtained in [11] for moderately–heavy nuclei at 4.5 A GeV. This fact supports the assumption that

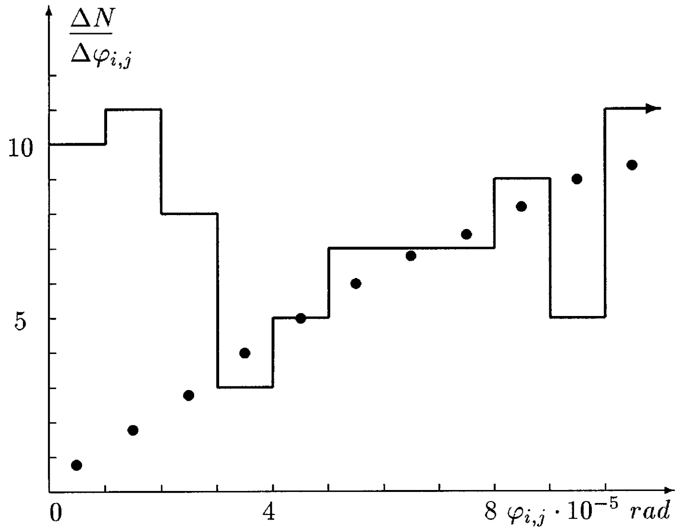

Fig. 3. The part of distribution of pair angles φ_{ij} between α-particles in the region 0.1 mrd (histogram) from the reaction $Pb + Em \rightarrow n \cdot \alpha + X$ at 160 A GeV. The points correspond to the expected distribution. The peak in the angle region less than $3 \cdot 10^{-5}$ rad corresponds to the decay $^8Be \rightarrow 2\alpha$

the fragmentation of heavy nuclei at 160 A GeV is the same as at 4.5 A GeV.

Still, both nuclei, ^8Be from the projectile fragmentation and ^8Li from the target fragmentation, are the unique so-called "pre-fragments" — the excited fragments of relativistic nuclei emitting observable fragments due to the two-step mechanism of the fragmentation process [13,14]. The leading role of these channels in the fragmentation of relativistic projectiles and targets has no experimental evidence. In both processes the mechanism of fast fragmentation is the main one. The channels for the production of ^8Be and ^8Li are the examples of isotopic effects.

6 Conclusion

The experience in the investigation of the fragment angular distributions at 4.5 A GeV, when the angle φ between the momentum projection onto the emulsion plane and initial momentum direction has been measured, is inapplicable for the case of the lead projectile fragmentation at 160 A GeV. It is also shown that, the projectile momentum direction being unknown, it is still possible to estimate the dispersion of normal distribution of the fragment flow angles. The value σ_φ for the fragments with Z=2-4 from deep inelastic $Pb + Em$ at 160 A GeV interactions agrees with that obtained from the fragment–angle measurements with respect to the fiducial track, assuming the error of initial momentum prolongation and the dispersion of fiducial track via initial one to be the same.

Thus, we conclude that even in deep inelastic interactions of the lead nuclei with photoemulsion nuclei the angular distribution of fragments with $Z = 2, 3, 4$ is determined by Fermi momentum for projectile nucleus in its ground state.

The existence of the channel $Be^8 \rightarrow 2\alpha$ indirectly supports this statement. It is the unique projectile "pre-fragment" which decays into observable fragments. Probably, there exist other short-living α-decaying nuclei, but it is difficult to observe them in photoemulsion.

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