MOMENTUM DISTRIBUTIONS OF NUCLEAR FRAGMENTSIN $\alpha\alpha$ COLLISIONS AT $\sqrt{s} = 125$ GeV

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ABSTRACT

We have measured the longitudinal (p_L) and transverse (p_T) momentum distributions for p, d, t, and ^3He fragments in quasi-elastic alpha-alpha collisions at $\sqrt{s} = 125$ GeV, using the upgraded Split-Field Magnet detector at the CERN Intersecting Storage Rings. The p_T distributions reflect elastic scattering among the nuclear constituents as a main mechanism. The p_L distributions are only weakly perturbed by this mechanism, and reflect mainly the internal motion of the nuclear constituents; their widths are consistent with expectations from statistical models.

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1. INTRODUCTION

The nuclear fragmentation, i.e. the breakup of a nucleus has been extensively studied both at low and intermediate energies [1-4]. Two concepts have been used to systematize the data: scaling/limiting fragmentation [5-6] and factorization [7]. Scaling implies that the momentum distribution of the fragments in the rest frame of the fragmenting nucleus is independent of the collision energy. Factorization implies that the cross-section for production of a particular fragment decomposes into two factors. One factor depends on the type of fragment and the mass number of the fragmenting nucleus, whereas the other one depends on the mass number A of the other nucleus. The mass dependence of the last factor is found experimentally to be $\sim A^\alpha$, where α ranges from 1/4 to 1/3. This indicates that fragmentation mainly results from large impact parameter collisions [8,9]. In statistical models the momentum spectra of fragments are believed to be ruled by the momenta of the nucleons or nucleon clusters within the nucleus, prior to breakup [10]. This may still hold for the spectator (non-interacting) fragments if the breakup is caused by the quasi-elastic scattering of a nucleon (or cluster) from one nucleus on a nucleon (or cluster) in the other nucleus [11,12]. The fragmentation yields of heavy nuclei have been seen to follow a power-law behaviour $y \propto A_f^{-\tau}$, where $\tau \approx 2.6$ [13,14] and A_f is the mass number of the fragment, indicating that collective phenomena (a liquid-to-gas phase transition) occur for these nuclei. Also in this case the high-energy tails of the kinetic energy distributions reflect the Fermi motion of a nucleon in a nucleus. Recently, parton models for hadron fragmentation have been generalized to incorporate also the fragmentation of nuclei into nucleons and clusters of nucleons in high-energy nuclear collisions [11, 15]. In reactions with small p_T transfer the constituents used in the counting rules are the nucleons [15].

2. THE EXPERIMENT

The storage of two beams of α particles in the CERN ISR gave us an opportunity to test prevailing models for fragmentation at a centre-of-mass energy $\sqrt{s} = 125$ GeV, an order of magnitude higher than previously achieved in experiments with nuclei. The experiment was done with the upgraded Split-Field Magnet (SFM) detector. The part of the experimental set-up used for this particular study is sketched in Fig. 1. The trigger conditions for fragmentation events were:

- i) coincidence between the large scintillator arrays T1 and T2,
- ii) one or two track candidates in each forward arm of the detector,
- iii) veto when tracks were detected in the central chambers, thus rejecting events with large-angle tracks.

Conditions (ii) and (iii) suppress channels with charged meson production, i.e. we observe mainly channels where $\alpha\alpha \rightarrow \sum_i F_i$ (n_i being the number of nuclear fragments of type F_i).

Tracks were defined by coincidence among different wire planes in the multiwire proportional chambers (MWPCs) surrounding the beam pipe. The trigger logic was built from MBNIM electronics developed at CERN [16] and required, firstly, the presence of hits in three or more different wire planes and, secondly, approximate linearity in the non-bending plane.

3. ANALYSIS

The events were processed by the standard SFM reconstruction programs. Events with negative tracks were rejected. Separation between singly and doubly charged particles was made using the pulse-height information from the trigger scintillators. The pulse height is proportional to the energy loss dE/dx and hence to the square of the charge. To eliminate a possible ambiguity arising when two particles passed through the same counter the pulse-height level for separation between singly and doubly charged particles was set well above the level corresponding to two singly charged particles passing through the same counter.

In order to obtain the most correct $\alpha\alpha$ centre-of-mass system (c.m.s.) the precise incident α -particle momenta (which vary with the position across the beam band) were determined using the correction formula [17]:

$$\Delta p_{\alpha, inc} = 0.0043 \cdot V_d \cdot 62.9 \text{ GeV/c}, \quad (1)$$

where V_d , in cm, denotes the transverse displacement of the α -particle from the centre of beam in each beam band. A negative V_d value means the α -particle circulates in the ISR with a smaller than average radius.

To obtain the best possible momentum resolution two different cuts were applied. Firstly, vertex cuts requiring the tracks to originate in a small diamond defined by $|V_d| < 2.5$ cm and height $h < 1.0$ cm and, secondly, various $\Delta p/p$ cuts for the different fragments were applied. $\Delta p/p$ is the momentum resolution estimated from the track fit. The chosen cuts were for protons: $\Delta p/p \leq 0.06$, for deuterons: $\Delta p/p \leq 0.12$, for tritons: $\Delta p/p \leq 0.18$, and for helium: $\Delta p/p \leq 0.09$. The momentum resolutions obtained in the two approaches were found (from Monte Carlo studies) to be comparable and the momentum spectra obtained were of similar shape. However, in the latter case the data sample was reduced to 75%, whereas only 40% of the data passed the vertex cuts. Consequently the data presented here are obtained after applying the $\Delta p/p$ cuts.

Knowing the charge of the measured particles and the incident α -particle momenta the rigidities p/Z were converted to momenta in the $\alpha\alpha$ c.m.s. In this initial transformation the proton mass was assigned to all detected particles. In Fig. 2 we give the rigidity spectra in the c.m.s. as a function of the pulse height in the scintillator. The peaks corresponding to different fragments are marked; they are positioned at rigidities expected for fragments with approximate beam velocity, i.e. around $(62.9/Z_f) \cdot (m_f/m_\alpha)$ GeV, where m_f denotes the mass of the fragment and m_α the α -particle mass. Classification of the fragments was then made by applying momentum cuts around the peak values. The chosen limits were:

protons	$p \in [9,23] \text{ GeV/c}$
deuterons	$p \in [23,39] \text{ GeV/c}$
tritons	$p \in [39,55] \text{ GeV/c}$
^3He	$p \in [37,54] \text{ GeV/c}$

Then the kinematics were recalculated with the assumed fragment rest masses. It should be emphasized that, since no velocity information is available in this region of the detector, solely momentum and charge information were used for classification. It is therefore possible that the fragments could be misidentified to a certain extent and also that mesons with high energy, although rare, could be labelled as protons.

4. ACCEPTANCE

The extension of the beam pipe makes it impossible to cover the whole forward region. The protons are bent out of the beam pipe by the magnetic field, owing to their smaller rigidity, thus allowing detection down to $p_T \approx 0 \text{ GeV/c}$. Large-momentum particles with small p_T , however, cannot be observed. This means that deuterons with $p_T \leq 0.2 \text{ GeV/c}$ were not detected. For tritons and ^3He the detection cut was at $\sim 0.3 \text{ GeV/c}$, and for α at $\sim 0.4 \text{ GeV/c}$.

The acceptance was calculated using approximately 100,000 generated tracks with an empirical vertex distribution and covering the investigated kinematic region. Firstly, the generated tracks were followed through the detector. The simulation included reaction losses in the material and tracks generated from secondary vertices. Secondly, the tracks were reconstructed and thereafter analysed in the same way as tracks from real events. The ratio of particles generated within a certain (p_T, p_L) bin to the number of accepted tracks from this bin gave the acceptance function $\epsilon(p_T, p_L)$, integrated over the azimuthal angle. Each observed track was then given the weight $\omega = 1/\epsilon(p_T, p_L)$.

In order to cross-check the acceptance we used minimum-bias pp data at $\sqrt{s} = 63$ GeV, taken with the SFM detector, and compared it with published inclusive cross-sections for the production of positively charged secondaries [18-20]. In this way an empirical acceptance function for positive track detection was obtained. We parametrized the inclusive cross-section for π^+ and K^+ as in Ref. 18:

$$E \frac{d^3\sigma}{dp^3}(p_T, x_R) = \frac{(1-x_R)^{\bar{n}_h} A_h}{(1+p_T^2/m_h^2)^4} \quad (2)$$

with $\bar{n}_{\pi^+} = 3.2$, $A_{\pi^+} = 30.2$ mb/GeV², $m_{\pi^+}^2 = 0.66$ GeV², and $\bar{n}_{K^+} = 30$, $A_{K^+} = 5.3$ mb/GeV², $m_{K^+}^2 = 0.64$ GeV². In Eq. (2) x_R is the radial scaling variable $x_R \approx 2E^*/\sqrt{s}$ (E^* is the c.m. energy of the produced hadron).

For protons we used the following parametrization [19]:

$$E \frac{d^3\sigma}{dp^3}(x_F, t, s) = G_{PPP}(t) (1-x_F)^{-1-2\alpha't} + G_{RPP}(t) (1-x_F)^{-2t} + (\pi\pi P + \pi\pi R) \quad (3)$$

for $x_F \geq 0.80$, where x_F is the Feynman scaling variable $x_F \approx 2p_L^*/\sqrt{s}$. The parameters used for this triple-Regge representation can be found in Ref. 19. For $x_F < 0.80$ we used a different parametrization:

$$E \frac{d^3\sigma}{dp^3}(x_F, p_T) = [1.09 + 35.3x_F + 68.0x_F^2] \exp[-p_T(2.47 + 5.69x_F - 1.95x_F^2)] \text{mb/GeV}^2. \quad (4)$$

In this region the cross-sections scale in a rather wide energy range [18] and do not factorize. We therefore obtained the coefficients (using least square methods) from the set of data given in Refs 18-20 for $pp \rightarrow p+X$ inclusive cross-sections. A good agreement was obtained between the Monte Carlo and empirical acceptance except for a few low- p_T bins, where the Monte Carlo acceptance is known to be overestimated. For this region $0 < p_T < 0.30$ GeV/c the empirical acceptance was used. Since data exist only down to $p_T = 0.15$ GeV/c, the acceptance below 0.15 is based on an extrapolation and therefore the data have a systematic uncertainty in this p_T range.

5. INCLUSIVE CROSS-SECTION FOR THE PROTON FRAGMENTATION CHANNEL

To estimate the total inclusive cross-section for breakup of one α -particle into a proton we used data obtained with a minimum-bias trigger which required only a minimum of one track somewhere in the detector, and a corresponding single-track acceptance function calculated from Monte-Carlo-generated tracks. The inclusive cross-section for fragmentation into protons was thus determined to be 73 ± 18 mb. The error estimate is based on a 10% uncertainty in the luminosity monitor, a 10% uncertainty in the acceptance calculation, and a possible reduction of 5% due to cuts in rigidity and dE/dx . We also estimated the semi-inclusive cross-section for breakup of one α -particle into a proton when we reject events with charged mesons. For a minimum-bias event to be accepted as fragmentation we required in this case:

- i) no negatively charged tracks and
- ii) no tracks with rigidity less than 9 GeV/c.

This cross-section was determined to be 10 ± 3 mb. As expected, the ratio of this semi-inclusive to the fully inclusive cross-section for fragmentation into protons corresponds approximately to the ratio of elastic to total NN cross-section

$$\sigma_{el}^{NN} / \sigma_{tot}^{NN} \approx 7/41.$$

At lower energies α -particle fragmentation has been studied on hydrogen targets with a magnetic spectrometer at LBL [4] and with the 1 m hydrogen bubble chamber at Dubna [21-23], at $\sqrt{s}_{NN} \approx 2.3$ and 2.5 GeV, respectively. The α fragmentation on Li targets has also been measured using the 2 m streamer chamber (SKM-200) at Dubna at $\sqrt{s}_{NN} \approx 3.2$ GeV [24], where the inclusive cross-section for p, d, t, and ${}^3\text{He}$ production in α fragmentation were measured to be ~ 100 mb, 75 mb, 45 mb, and 48 mb, respectively. The cross-section of 100 mb can be compared with our 73 ± 18 mb for α fragmentation into protons, and they agree reasonably well if one accounts for the difference of the total cross-sections (given the difference of target mass and $\sqrt{s}_{NN}$).

6. MOMENTUM DISTRIBUTIONS

For the fragmentation trigger the integrated luminosity was $2.41 \cdot 10^5 \text{ mb}^{-1}$, corresponding to $\sim 120,000$ events. This trigger correlated the two sides (the multiplicity requirement). No attempts have been made to normalize the data since such a calculation must be model-dependent.

In Fig. 3 we show the proton and deuteron p_L spectra in the c.m.s. for different p_T slices. We did a simultaneous fit of the spectra using two Gaussian distributions of the form:

$$\frac{d\sigma}{dp_L^*} = \frac{\sigma}{\delta_L^* \sqrt{2\pi}} \exp [-(p_L^* - \langle p_L^* \rangle)^2 / (2\delta_L^{*2})], \quad (5a)$$

where $\delta_L^* = \sqrt{(\langle p_L^{*2} \rangle - \langle p_L^* \rangle^2)}$ and variables in the c.m.s. are indicated by asterisks. The results are given in Table 1. The following information can be extracted:

- i) The proton spectrum is well separated from the deuteron spectrum.
- ii) For each type of fragment the distribution looks symmetric and has a width which is independent of p_T for $p_T < 0.6 \text{ GeV/c}$.
- iii) The distributions are shifted towards lower p_L^* values compared to what is expected for a fragment moving with the velocity of the beam.
- iv) The tails of the momentum distribution show non-Gaussian behaviour.
- v) The deuteron p_L spectrum is broader than the corresponding distribution for the proton.

In Fig. 4 we show the p_T^2 spectra for protons, deuterons, and tritons. These were fitted using the following parametrization:

$$\frac{d\sigma}{dp_T^2} = \frac{\sigma}{2 \delta_T^2} \exp[-p_T^2 / (2\delta_T^2)], \quad (5b)$$

implying $\langle p_T \rangle = \sqrt{(\pi/2)} \delta_T$ and $\sqrt{\langle p_T^2 \rangle} = \sqrt{2} \delta_T$. In Table 2 we give the values of the fitted widths.

To be able to compare with fragmentation data at lower incident energies we have also calculated the distributions in the rest frame of the fragmenting α -particle. In Fig. 5 we show the p_L distribution in the α rest frame, and the parameters obtained from the corresponding Gaussian fits are given in Tables 2 and 3. It is easy to show that, starting from

$$p_L = \gamma (p_L^* - \beta E^*), \quad (6)$$

one obtains

$$p_L \approx p_L^* / \gamma - \sqrt{(p_T^2 + m_f^2)}, \quad (7)$$

which, if $p_T \ll m_f$, $p_L^* \gg \sqrt{(p_T^2 + m_f^2)}$ and $\beta \approx 1 - 1/2\gamma^2$, means that under these conditions the distributions are Gaussian in both frames with the width related by

$$\delta_L \approx \delta_L^* / \gamma, \quad (8)$$

where $\gamma \approx 16.7$. As can be seen from Fig. 5a, the distribution in p_L for protons is, however, slightly asymmetric. By examining the p_L distribution of protons for different p_T bins (see Table 3) we find that the width and asymmetry of the p_L distribution increase with increasing p_T . It is expected that the region $p_L > 0$, which is kinematically less accessible, would mainly reflect the internal momentum distribution of the nucleons in the α -particles. Therefore the Gaussian fit was done only for p_L greater than the peak value. The causes for the observed asymmetry of the p_L distributions will be examined in the following two sections.

7. ESTIMATION OF CHANNELS WITH UNOBSERVED NEUTRAL PIONS

To isolate pure nuclear fragmentation channels we required:

- i) no negatively charged tracks, and
- ii) no tracks with rigidity less than 9 GeV/c.

This condition suppresses breakup channels with production of charged mesons. We can estimate the maximum contamination of breakup channels leading to formation of only neutral pions from the measured $pp \rightarrow pp + \pi^0$ cross-sections $\sigma_{\pi^0}^{NN} \approx 1.7$ mb at $\sqrt{s_{NN}} = 24$ GeV [25]. This estimate gives a maximum admixture of

$$\sigma_{\pi^0}^{NN} / (\sigma_{\pi^0}^{NN} + \sigma_{el}^{NN}) \approx \frac{1.7}{1.7 + 7} \approx 20 \%$$

The tail of the p_L distribution below -0.4 GeV/c in the α rest frame can be explained by the above-mentioned admixture of inelastic processes [26].

8. EXPECTED DISTRIBUTIONS FOR THE QUASI-ELASTIC NN PROCESS

It is expected from Glauber theory [27] and also found experimentally at low incident energies [28,29] that the quasi-elastic NN scattering mechanism plays an important role in the fragmentation process of a light nucleus. This process, where one single nucleon in each nucleus is struck and knocked out, has been called the knock-out, quasi-free, or spectator process and has been examined in more detail in some recent papers [30,31]. If this is the main process we can derive the distributions in longitudinal and transverse momentum of knock-out protons in the following way.

The differential elastic pp scattering cross-section can be parametrized at high energy as

$$\frac{d\sigma}{dt} \propto e^{bt}, \quad (9)$$

where t is the squared four-momentum transfer. For the region $|t| \in [0.25-0.60] \text{ (GeV/c)}^2$ the slope factor b is measured to be $10.3 \pm 0.3 \text{ (GeV/c)}^2$ (for $\sqrt{s_{NN}} = 23$ to 62 GeV) [32]. We assume for a moment that the internal motion is zero so that the c.m.s. of the α -beam particles coincides with the c.m.s. of the scattered nucleons. In the c.m.s. the scattering angles are small so that

$$-t = 2p^* (p^* - p_L^*) \approx p_T^2. \quad (10)$$

Only the longitudinal momentum,

$$p_L^* \approx p^* - p_T^2 / (2p^*) \quad (11a)$$

has to be transformed to the α -particle rest frame through the transformation

$$p_L = \gamma (p_L^* - \beta E^*) \approx \gamma (p_L^* - p^*) = -p_T^2 / (2m_N \beta), \quad (11b)$$

where β is the velocity of the incident α beam in the $\alpha\alpha$ c.m.s and $\gamma = 1/\sqrt{1-\beta^2}$. Now the expected distributions in the α -particle rest frame become

$$\frac{d\sigma}{dp_L} \propto e^{2bm_N \beta p_L} \quad p_L \in [-\infty, 0] \quad (12a)$$

and

$$\frac{d\sigma}{dp_T^2} \propto e^{-bp_T^2} \quad p_T \in [0, \infty]. \quad (12b)$$

Thus one sees that knock-out processes of nucleons, when internal motion is neglected, give rise to a distribution in p_L with a slope factor $\approx 2bm_N \beta = 19.3 \text{ (GeV/c)}^{-1}$ in the α -particle rest frame. The effect of Fermi motion can be included approximately by convoluting the exponential distribution, Eq. (12a), with the Gaussian distribution which describes the Fermi motion (see Fig. 5a):

$$\frac{d\sigma}{dp_L} \approx \frac{\sigma 2bm_N \beta}{\delta_L \sqrt{2\pi}} \int_{p_L}^{\infty} e^{-(p'_L - \kappa)^2 / 2\delta_L^2} e^{2bm_N \beta (p_L - p'_L)} dp'_L. \quad (13)$$

Here κ is the projected momentum transfer to bring particles on shell.

In Fig. 5a we show the result of such a calculation. It is found that this process perturbs the p_L distribution only weakly but can cause the slight asymmetry for p_L below -0.3 GeV/c in the α rest system.

9. WIDTHS OF THE MOMENTUM DISTRIBUTIONS

The advantage of parametrizing the distributions in the α rest frame as Gaussians is the following: suppose we only observe the effect of the internal motions of the nucleons: then the widths δ_T and δ_L would be equal when corrected for the resolution of the detector. From Goldhaber's statistical model [10] we can estimate the widths as $\delta_T \approx \delta_L \approx p_F/\sqrt{5} \approx 76$ MeV/c for protons and $\delta_T \approx \delta_L \approx 2p_F/\sqrt{15} \approx 87$ MeV/c for deuterons. For p_F (the Fermi momentum) we used 169 MeV/c as measured in electron scattering on light ($A = 6$) nuclei [33]. Distributions of the type described by Eqs. (5a) and (5b) would also result from a harmonic oscillator model if we make a Fourier transformation to get the wave functions in momentum space. In such an analysis we would get for protons $\delta_T \approx \delta_L \approx 94$ MeV/c, using the harmonic oscillator range parameter $\alpha \approx 144$ MeV/c obtained from electron-scattering experiments on He nuclei [34]. In Table 2 we compare the widths obtained from the experiment and also give the resolution of the detector, which was calculated using the Monte Carlo simulated data. The resolution did not allow a determination of δ_L for t and ^3He . We found $\delta_L = 70 \pm 3$ MeV/c for protons. In Ref. 4, where the 0° spectra were fitted to a sum of one exponential and one Gaussian-shaped distribution, the δ_L for protons was determined to be $\delta_L \approx 55$ MeV/c, i.e. somewhat smaller than our value. Note, however, that their data correspond to very low p_T values, whereas our data extend to $p_T \approx 1$ GeV/c. For $0 < p_T \leq 150$ MeV/c (Table 3) we get $\delta_L = 67 \pm 2$ MeV/c for proton fragments.

In Fig. 4 we observed that the p_T distributions are much broader than the distribution expected from a model only considering Fermi motion giving $\delta_L = \delta_T$ (dotted curve in Fig. 4).

We have shown above that quasi-elastic proton-proton scattering within the interacting α nuclei affects the p_T distribution much more drastically than the p_L distribution, Eqs. (12b) and (13). By comparing Eqs. (5b) and (12b) we see that the fitted transverse width, δ_T in GeV/c, is related to the slope factor b , assuming quasi-elastic scattering as the mechanism,

$$b = \delta_T^{-2}/2. \quad (14)$$

Equation (14) gives the value $\delta_T = 220 \pm 4$ MeV/c for a slope $b = 10.3 \pm 0.3$ (GeV/c)⁻².

From Ref. 18 we can estimate the spectator contribution in our spectra by comparing the measured cross-section for proton (p_s) or triton (t_s) spectators: $\alpha \rightarrow t_s + p$, 8.8 mb, and $\alpha \rightarrow p_s + t$, 1.4 mb. Thus we can expect the contribution from the Goldhaber mechanism to be roughly $1.4 / (1.4 + 8.8) \approx 14$ %. The spectator protons are expected to be in the region defined by $p_L \in [-0.3, 0.3]$ GeV/c and $p_T^2 \in [0, 0.09]$ (GeV/c)². Note that the proton spectrum changes its slope at $p_T^2 \approx 0.06$ (GeV/c)², possibly as a consequence of the orthogonality of the final-state and initial-state wave functions.

It is also worth noticing that the experimental widths, δ_T , are quite similar for p and d. This may suggest that the observed deuterons are formed by final-state interactions, i.e. in pick-up processes [31]. Quasi-elastic deuteron-proton scattering would give $\delta_T \approx 205$ MeV/c [35,36].

10. SHIFTS OF THE LONGITUDINAL MOMENTUM DISTRIBUTIONS

The average p_L in the α -particle rest frame is shifted with respect to a fragment moving with the beam velocity. The observed shifts are -70 ± 30 MeV/c and -120 ± 50 MeV/c for p and d, respectively. The given error is estimated by comparing the shifts on the two sides of the detector to trace a possible misalignment of the chambers. This error due to misalignment is typically < 10 MeV/c for protons and < 30 MeV/c for deuterons. Furthermore, elastic events (pp and $\alpha\alpha$) were examined in the c.m. frame and the systematic error was found to be < 20 MeV/c. Shifts of the average p_L are expected as a result of momentum transfer in quasi-elastic interactions and of the minimum energy and momentum transfer to

overcome the binding energy of the α -particle. From Eqs (11a) and (11b) one can see that the shifts due to quasi-elastic momentum transfer are small (approaching 0 as $1/p^*$) in the c.m.s. compared to the system where one α is at rest; this explains why the p_L distributions are apparently more symmetric in the c.m.s. than in the α rest system (since in addition, the internal motion, which is symmetric, is amplified when transformed to the c.m.s.). Expression (12a) yields an average momentum shift in the α rest system $\langle p_L \rangle \approx -50$ MeV/c for protons, and the shifts due to the binding energy effects were estimated to be of the order of -10 MeV/c for p and d. Thus the observed shifts can be explained (within the experimental errors).

11. SUMMARY

The widths δ_L of the p_L distributions were found to be smaller than the δ_T obtained from the p_T distributions for $p_T > 0.3$ GeV/c. This implies that the statistical production discussed by Goldhaber [10] is not the dominating process for p and d production at higher p_T values observed by our fragmentation trigger. We assumed quasi-elastic scattering (knock-out processes) of nucleons or nucleon clusters as the main mechanism. Such a picture [23] is supported by our measured width $\delta_T = 225 \pm 2$ MeV/c for protons and by the observed shifts of the p_L distribution of $\approx -70 \pm 30$ MeV/c and -120 ± 50 MeV/c for p and d, respectively. It was shown that the width δ_L of the p_L distributions is only weakly perturbed by this mechanism (in particular, for small p_T bins) and still reflects the width of the internal motion of nucleons. By studying the correlation of fragments from both sides (a unique possibility using storage rings) the hypothesis of knock-out processes can further be tested. This will be the subject of a forthcoming paper.

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TABLE 1

Simultaneous fits of two Gaussian distributions [compare with Eq. (5a)]
to the p_L spectra of protons and deuterons in the $\alpha\alpha$ c.m.s.
All quantities in GeV/c

	Protons		Deuterons	
	δ_L^*	$\langle p_L^* \rangle$	δ_L^*	$\langle p_L^* \rangle$
0.15 $\langle p_T \rangle \leq 0.30$	1.5 ± 0.05	15.1 ± 0.05	3.1 ± 0.1	30.6 ± 0.2
0.30 $\langle p_T \rangle \leq 0.45$	1.7 ± 0.05	15.2 ± 0.05	3.2 ± 0.1	30.9 ± 0.1
0.45 $\langle p_T \rangle \leq 0.60$	1.8 ± 0.1	15.0 ± 0.1	3.5 ± 0.1	30.4 ± 0.1
0.60 $\langle p_T \rangle \leq 1.00$	2.5 ± 0.2	15.1 ± 0.2	4.1 ± 0.2	30.2 ± 0.2

TABLE 2

The widths δ_L^{ex} and δ_T^{ex} in MeV/c obtained from Gaussian fits to the experimental data. Also shown is the resolution of the detector δ_L^{res} and δ_T^{res} in MeV/c obtained from Monte Carlo simulations. δ_L and δ_T in MeV/c are calculated from the formula

$$\delta = \sqrt{(\delta^{\text{ex}})^2 - (\delta^{\text{res}})^2}$$

	p	d	t	³ He
δ_L^{ex}	92 ± 2	190 ± 4	(a)	(a)
δ_T^{ex}	225 ± 2	247 ± 3	220 ± 4	279 ± 6
δ_L^{res}	60 ± 1	146 ± 2	236 ± 3	263 ± 3
δ_T^{res}	58 ± 1	74 ± 1	81 ± 1	102 ± 1
δ_L	70 ± 3	122 ± 8	(a)	(a)
δ_T	217 ± 3	236 ± 3	205 ± 4	259 ± 7

(a) limited by detector resolution.

TABLE 3

The widths δ_L^{ex} in MeV/c for protons in different p_T slices obtained from Gaussian fits to the experimental data

	0 < p_T ≤ 150	150 < p_T ≤ 300	300 < p_T ≤ 450	450 ≤ p_T ≤ 600
δ_L^{ex}	90 ± 1	88 ± 1	101 ± 1	114 ± 2
δ_L	67 ± 2	64 ± 2	81 ± 3	97 ± 3

FIGURE CAPTIONS

- Fig. 1 : A horizontal view of the experimental set-up in the Split-Field Magnet detector. T1 and T2 are the trigger scintillator hodoscopes and 313 to 417 are the MWPCs defining the forward regions.
- Fig. 2 : Measured rigidities for tracks in events accepted by the fragmentation trigger versus dE/dx signals from the hit counter(s) in the scintillator hodoscopes T1 and T2.
- Fig. 3 : The longitudinal momentum distributions for protons and deuterons in the $\alpha\alpha$ c.m.s. for different p_T slices (bin width $\Delta p_L^* = 0.5$ GeV/c). Also shown is a simultaneous fit of the proton and deuteron spectra to two Gaussian distributions. Note that the distributions are non-Gaussian for protons for $p_L^* < 12$ GeV/c and $p_L^* > 18$ GeV/c.
- Fig. 4a : Transverse momentum distribution of protons in the rest frame of the fragmenting α nucleus. Also shown is the Gaussian fit to the data (dashed line) with $\delta_T \approx 225$ MeV/c. The expected result from pp quasi-elastic scattering $\sigma_T \approx \sqrt{[220^2 + 70^2 + 58^2]} \approx 238$ MeV/c (dash-dotted line) and for a breakup characterized by the intrinsic widths and resolution of the detector $\sigma_T \approx \sqrt{[70^2 + 58^2]} \approx 91$ MeV/c (dotted line) are shown for comparison. The different curves are normalized to the same content. The bin width for the data is $\Delta p_T^2 = 0.025$ (GeV/c)².
- Fig. 4b : Transverse momentum distribution of deuterons in the rest frame of the fragmenting α nucleus. Also shown is the Gaussian fit to the data (dashed line) with $\delta_T \approx 247$ MeV/c. The expected result from pd quasi-elastic scattering $\sigma_T \approx \sqrt{[146^2 + 122^2 + 74^2]} \approx 205$ MeV/c (dash-dotted line) and for a breakup characterized by the intrinsic widths and resolution of the detector $\sigma_T \approx \sqrt{[122^2 + 74^2]} \approx 143$ MeV/c (dotted line) are shown for comparison. The different curves are normalized to the same content. The bin width for the data is $\Delta p_T^2 = 0.025$ (GeV/c)².
- Fig. 4c : Transverse momentum distribution of the tritons in the rest frame of the fragmenting α nucleus. Also shown is the Gaussian fit to the data (dashed line) with $\sigma_T \approx 220$ MeV/c. The bin width for the data is $\Delta p_T^2 = 0.025$ (GeV/c)².
- Fig. 5a : The longitudinal momentum distribution for protons in the rest frame of the fragmenting α nucleus. The bin width Δp_L is 0.0375 GeV/c. The shift of the peak position is ≈ -70 MeV/c. Also shown is the Gaussian fit to the data with $\delta_T \approx 92$ MeV/c (dashed line) and a convolution (dash-dotted line) of an exponential distribution with a Gaussian [Eq. (13)] with $\kappa \approx -36$ MeV/c. Note the slight asymmetry of the experimental distribution.
- Fig. 5b : The longitudinal momentum distribution for deuterons in the rest frame of the fragmenting α nucleus. The bin width Δp_L is 0.0375 (GeV/c). The shift of the peak position is ≈ -120 MeV/c. Also shown is the Gaussian fit to the data with $\delta_L \approx 190$ MeV/c (dashed line).

Fig. 1

Fig. 2

PROTONS AND DEUTERONS $0.15 < P_T \leq 0.30$

PROTONS AND DEUTERONS $0.30 < P_T \leq 0.45$

PROTONS AND DEUTERONS $0.45 < P_T \leq 0.60$

PROTONS AND DEUTERONS $0.60 < P_T \leq 1.00$

Fig. 3

Fig. 4

Fig. 5