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Proton and Triton Momentum Distributions from ⁴He Fragmentation at Relativistic Energies

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Abstract. The $0°$ differential cross sections of the $^{12}C(^4He, p)$ and $^{12}C(^4He, t)$ reactions have been measured at beam momenta of 4.52 and 2.69 GeV/c/nucleon, respectively. The proton and triton momentum distributions in ^4He are extracted from the cross sections using a relativistic impulse approximation. Some theoretical models based on realistic N-N potentials are examined for our data.

The differential cross sections of the $^{12}C(^4He, p)$ and $^{12}C(^4He, t)$ reactions with a fragment emission angle of $\theta < 0.4°$ were measured by the magnetic spectrometer "ALPHA" installed at the Dubna synchrophasotron. The momenta of a beam of α-particles were 4.52 and 2.69 GeV/c/nucleon for the $(^4He, p)$ and $(^4He, t)$ reactions, respectively. Preliminary data were reported earlier [1].

The experimental set-up did not in the main differ from the one used for studying deuteron fragmentation [2]. The one-arm spectrometer was placed after the bending magnet M used to separate secondary particles from the primary beam. Thus, the measurements with a beam intensity of up to 10^{10} α-particles per pulse were allowed. The statistics was collected within the momentum intervals $|(p - p_i)/p| < 0.05$. The momentum p_i was selected by setting the current of the magnet M. The proton spectrum was obtained at a maximum α-beam momentum. For this momentum the bending force of the magnet M is insufficient to turn a high momentum part of the triton spectrum to the spectrometer. Thus, the $(^4He, t)$ reaction was investigated at a lower beam momentum for which a maximum triton momentum in the ^4He rest frame was reached. In some regions of the momentum p_i it was difficult to identify protons among other particles (d, t, ^3He, ^4He). The protons were reliably registered when the yield of other particles was smaller than 1000 times of the proton one

(which is not the case in the momentum region $p_i \geqslant 0.5p_{^4\text{He}}$). Threshold gas Čerenkov counters and scintillation counters were used for particle identification.

This experiment allowed a measurement of the relative cross sections. The absolute cross sections were obtained by normalizing the (^{4}He, ^{3}He) cross section in the region of a fragmentation peak, measured in this experiment, to the absolute data obtained in our previous experiment [3]. A main contribution to the systematic error ($\approx 20\%$) of the absolute normalization results from uncertainties of the ^{3}He emission angle (± 1 mrad). The uncertainties are caused by the magnetic field induced by the accelerator near the magnet M. The statistical error of normalization is evaluated to be about 4%. The absolute cross sections in the region of the fragmentation peak for the ^{12}C(^{4}He, p) and ^{12}C(^{4}He, t) reactions are in good agreement with the data [4] obtained at an α-particle beam momentum of 1.75 GeV/c/nucleon for the corresponding reactions.

Fig. 1 presents the invariant cross sections for the ^{12}C(^{4}He, p) and ^{12}C(^{4}He, t) reactions versus the fragment momentum q in the projectile rest frame along with the high-momentum proton data [5] for the ^{4}He(p, p(180°)) reaction (in the laboratory frame) at 8.6 GeV/c multiplied by a factor 3. This factor was estimated in the
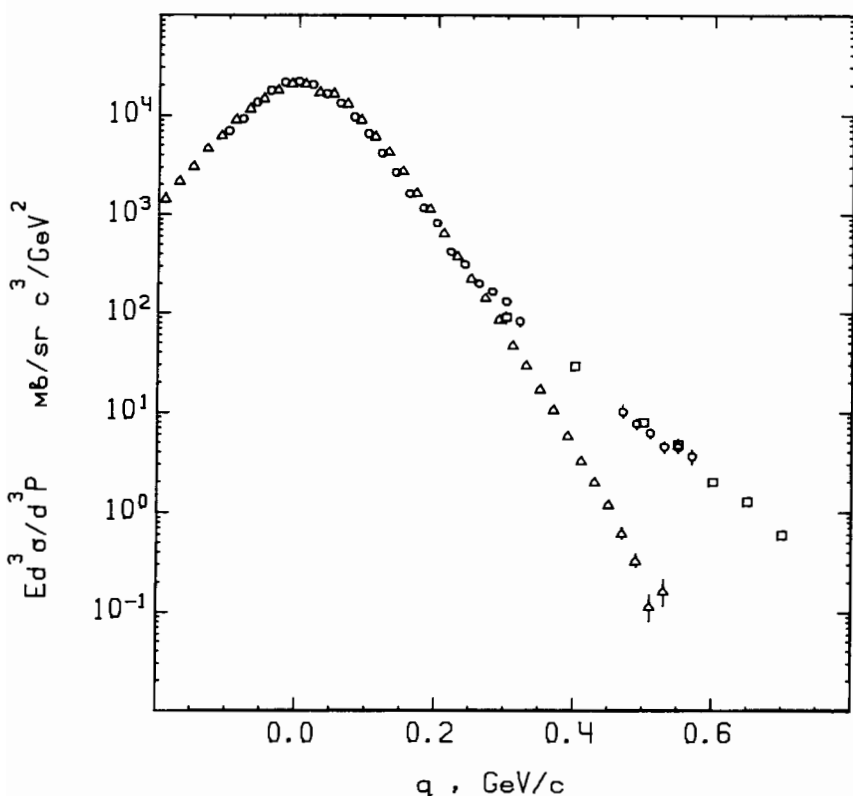

Fig. 1. Invariant differential cross sections versus fragment momentum q in the ^{4}He rest frame for the ^{12}C(^{4}He, t) reaction ($\triangle$ our data); the ^{12}C(^{4}He, p) reaction ($\bigcirc$ our data) and the ^{4}He(p, p(180°)) data [5] ($\square$) multiplied by a factor 3. The error bars indicate statistical uncertainties only

overlap region of both sets of data. This procedure is correct if the ⁴He fragmentation cross sections on carbon and hydrogen are similar[1].

A relativistic impulse approximation (IA) in the framework of the so-called light-cone dynamics will be used to analyze our data. Such an approximation was also used in our previous paper [7] in the case of ³He fragmentation. The reason for such an approximation has been discussed elsewhere by us [8] and other authors [9].

By analogy with ref. [10], where the (³He, d) cross section was obtained in the relativistic IA, the ⁴He fragmentation cross section in the forward direction is connected with the momentum distribution $n_s(k)$ of the fragment s in ⁴He as follows,

$$E\frac{d^3\sigma}{d^3q} = FC_f \frac{\varepsilon_s \varepsilon_f}{(1-\alpha_s)M_{sf}} n_s(k).$$ (1)

In this approach, $n_s(k)$ depends on the so-called "internal" momentum k: the momentum of the spectator s and the fragment-participant f in the $(s+f)$ rest frame inside ⁴He. This momentum differs (in the relativistic case) from the momentum q of the spectator s in the ⁴He rest frame and is related to it by

$$k^2 = \frac{\lambda(M_{sf}^2, m_s^2, m_f^2)}{4M_{sf}^2}, \qquad M_{sf}^2 = \frac{m_s^2}{\alpha_s} + \frac{m_f^2}{1-\alpha_s}, \qquad \alpha_s = \frac{E+q_\parallel}{m_{^4\text{He}}},$$

$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2ac - 2bc.$$ (2)

Here M_{sf} is the effective mass of the $(s+f)$ system and α_s is the part of the momentum carried away by the spectator in the longitudinal direction in the infinite-momentum frame. The quantities E and $q_\parallel$ are the energy and longitudinal momentum of the spectator in the ⁴He rest frame, m_s is the spectator mass (m_p or m_t, respectively). The quantity m_f is the effective mass of the fragment-participant, which is equal to m_p for the (⁴He, t) reaction and supposed to be m_t for the (⁴He, p) reaction (the value of k is minimal in this case [7]).

In Eq. (1) F is a kinematic factor and $\varepsilon_{s(f)} = \sqrt{m_{s(f)}^2 + k^2}$. The constant C_f is proportional to the total cross section of the participant f on the target nucleus σ_{fC}^{tot}. We have extracted the momentum distributions $n_s(k)$ using Eq. (1). These distributions are normalized to

$$\int n_s(k)\, d^3k = N_s, \qquad N_p = 2, \qquad N_t = 1.6.$$ (3)

The effective number of tritons, $N_t = 1.6$, has been theoretically estimated in ref. [11]. Using the effective numbers N_p and N_t, one obtains from Eq. (1) the ratio $C_t/C_p = 2.04$, which is close to the ratio of the total tC and pC cross sections (estimated to be 1.93, see ref. [12]).

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[1] We have shown [6] that such a similarity arises for $A(d, p)$ reactions at $q > 100$ MeV/c. The ratio of the cross sections for this reaction on carbon and hydrogen is 2.7 ± 0.3 which is close to the above factor. Using the same ratio [6], a better description of ³He fragmentation on carbon was achieved [7]. This allows one to conclude that the ratio is the same for the fragmentation of all lightest nuclei
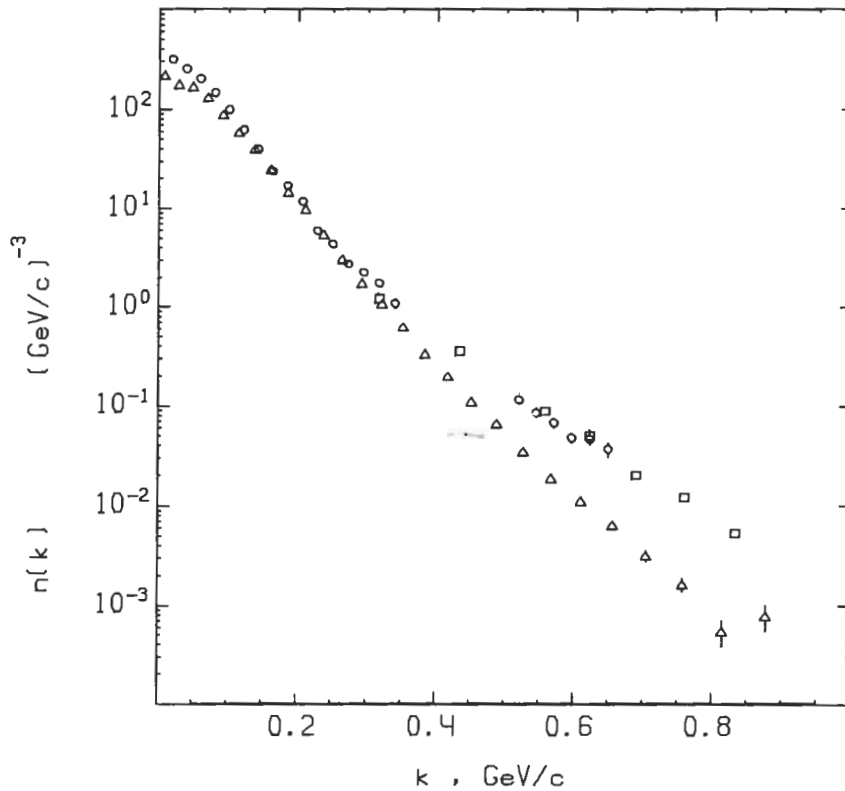
Fig. 2. Momentum distributions in ^{4}He for protons ($\bigcirc$ and $\square$) and tritons ($\triangle$) versus internal momentum k obtained from the cross sections in Fig. 1 using Eq. (1)

The momentum distributions of protons (n_p) and tritons (n_t) are shown in Fig. 2. From theoretical considerations [11] it follows that in the low-momentum region the $(p + t)$-configuration predominates over the other $(p + (nnp))$-ones and governs the total momentum distribution $n_p(k)$ of ^{4}He. An approximate coincidence of the distributions $n_p(k)$ and $n_t(k)$ up to $k \approx 350$ MeV/c agrees with such a conclusion. At higher values of k the ratio $n_p(k)/n_t(k)$ becomes larger and reaches one order of magnitude at $k \approx 800$ MeV/c hence indicating an increasing role of the configurations other than the $(p + t)$-one. In accordance with this conclusion, for the high-momentum region of the proton spectrum one can put in Eq. (2) a value of m_f larger than the triton mass. This will cause some shift of the proton points (Fig. 2) in this region to the right (a shift of 100 MeV/c corresponds to an (nnp)-excitation energy of 400 MeV), hence the conclusion remains valid.

As is seen from Fig. 3 a, the proton momentum distribution $n_p(k)$ extracted from the ^{4}He fragmentation experiments is in agreement with the one derived in ref. [13] from the electro-distintegration data of ^{4}He(e, e') measured at SLAC. The results of some theoretical calculations [14–16] for $n_p(k)$ are also shown in Fig. 3 a. The theoretical curve of ref. [11], calculated for the interval $0 < k < 350$ MeV/c using the Urbana potential, is very similar to the curve of ref. [14]. We note a distinctive deviation of the data points from the calculations with realistic N-N potentials at values of $k \approx 400$ MeV/c. Recently this conclusion has been confirmed [17] by
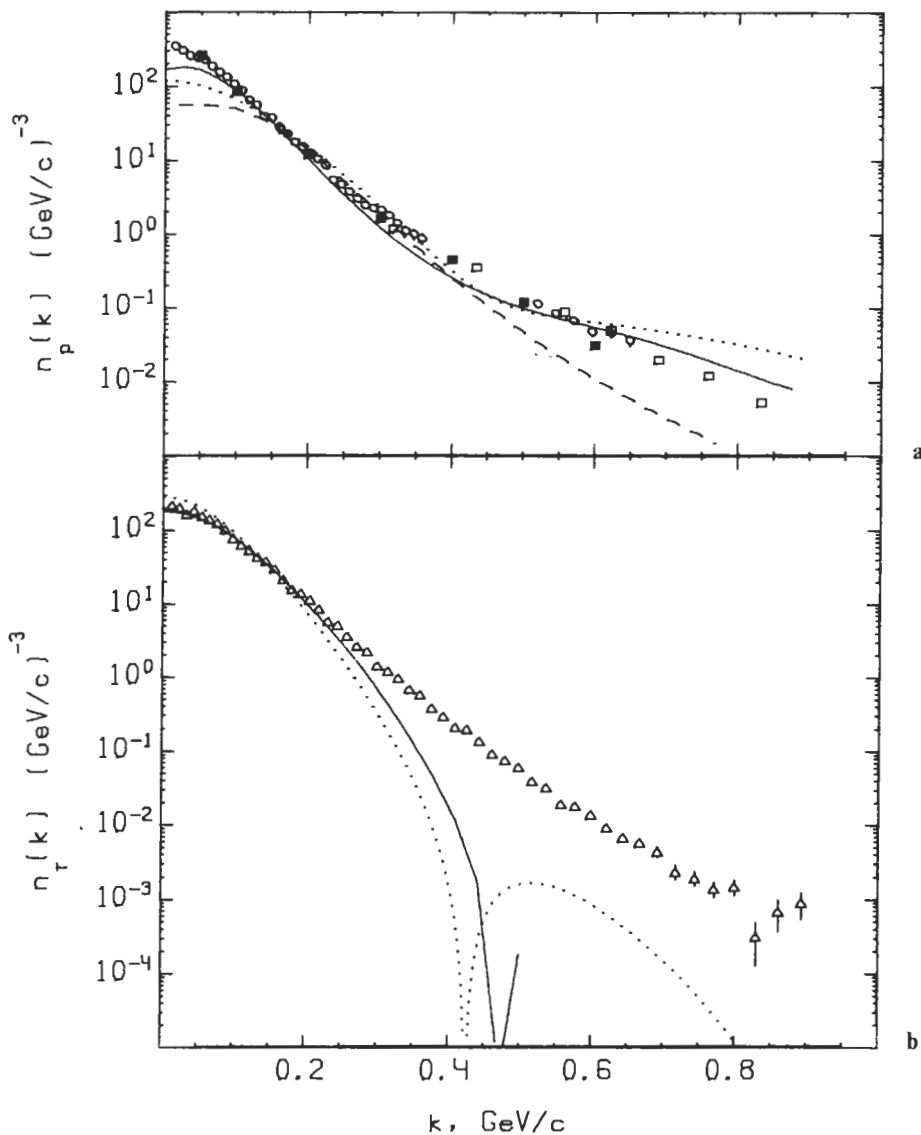
Fig. 3. **a** Comparison of the proton momentum distribution in ⁴He from Fig. 2 (○ and □) with the data [13] (■), extracted from the ⁴He(e, e') reaction, with the theoretical calculations [14] (solid line) and [15] (dotted line) using the Reid SC potential and with the flucton model calculations [16] (dashed line); **b** comparison of the triton momentum distribution in ⁴He from Fig. 2 (△) with the theoretical calculations [11] (solid line) using the Urbana potential and [15] (dotted line) using the Reid SC potential

analyzing the proton momentum distribution in ⁴He extracted from the Kharkov data for the ⁴He(e, e') reaction.

The triton momentum distribution $n_t(k)$ not only deviates from the theoretical calculations [11, 15] but also does not confirm the existence of a dip at $k \approx 400$ MeV/c predicted theoretically (Fig. 3 b). The preliminary data [18] from the exclusive ⁴He($e, e'p$)t reaction also show no minimum in this region.

Such a deviation from the theory of the momentum distributions extracted in the relativistic IA could be related to some effects beyond the IA (final-state interaction and some others). In the case of triton momentum distribution a small correction to the IA could be important in filling in the minimum at $k \approx 400$ MeV/c. The following analysis could throw some light on the nature of this deviation.

The theoretical proton distribution can be presented [13] as $n_p^{th} = n_t^{th} + n_{exc}^{th}$, where n_{exc}^{th} is the proton momentum distribution when the participant (nnp) differs from the triton. To describe the data, additional terms can be introduced for the proton and triton momentum distribution,

$$n_p = n_t^{th} + n_{exc}^{th} + n_p^{add}, \qquad n_t = n_t^{th} + n_t^{\ 1d}. \tag{4}$$

We obtain the additional terms n_p^{add} and n_t^{add} by subtracting the theoretically estimated momentum distributions from the data. To this end, we use the estimations for the proton [14] and triton [11] momentum distributions. Fig. 4, where the result of this procedure is shown, indicates similarity of the additional terms, $n_p^{add} \approx n_t^{add}$, for a rather broad momentum region of $200 < k < 600$ MeV/c. Furthermore, n_p^{add} is approximately the same for two different types of reactions, fragmentation and electro-disintegration. It is difficult to explain such an independence in the excess from the type of the spectator and from the type of the reaction by the corrections to the IA. At the same time this fact does not contradict the hypothesis of the existence of degrees of freedom other than nucleonic ones in the ^{4}He structure,

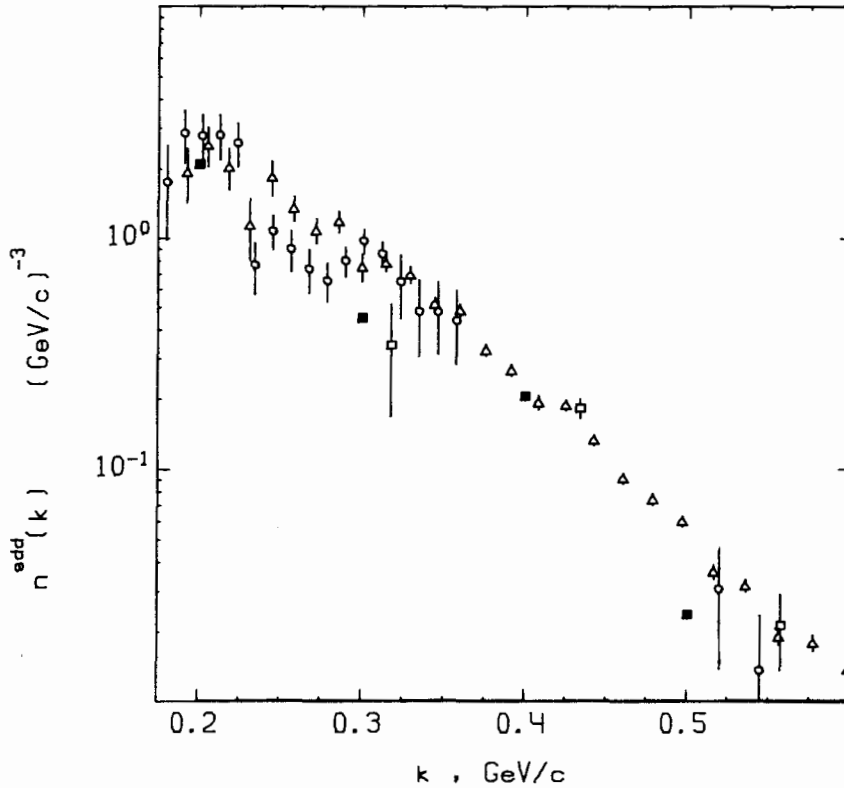Fig. 4. $n_p^{add}(k)$ (O, □ and ■) and $n_t^{add}(k)$ (△) (see Eq. (4) for definition) obtained from the data in Fig. 3 for protons (O, □ and ■) and tritons (△). Errors for the ^{4}He(e, e') data [13] (■) are not given

which affect the $(p + t)$-configuration in ^{4}He. However, the quantity n_p^{add} (in contrast to n_t^{add}) depends strongly on the choice of the theoretical momentum distribution n_p^{th}. If we use the estimation [15] as n_p^{th}, the region where $n_p^{\mathrm{add}} \approx n_t^{\mathrm{add}}$ becomes narrower ($400 < k < 600$ MeV/c). In any case a careful analysis of the corrections to the IA is required before making any final conclusion.

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