LETTERS TO THE EDITOR

ANISOTROPY OF ANGULAR DISTRIBUTIONS OF SPECTATOR NUCLEONS FROM DEUTERON DISINTEGRATION

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It is shown that the relativistic contraction of the wave function of deuteron results in a small positive forward-backward asymmetry of the spectator nucleon from the disintegration of deuteron. This effect is compared with the Dubna experiment of dp → ppn process at 3.3 GeV/c deuteron momenta.

We consider the disintegration process of deuteron initiated by a particle X; Xd → Xpn. If one neglects the multiple scattering, as well as the final state interaction, and moreover, if the momentum transfer is larger than the spectator momentum, then the momentum distribution of the nucleons is given by the well known formula

$$\frac{dn}{d^3p} \sim |\psi_0(\boldsymbol{p}^2)|^2. \tag{1}$$

Here $\boldsymbol{p}$ is the spectator momentum in the lab-system (where the deuteron is at rest), and ψ_0 is the momentum representation of the deuteron ground state wave function. According to (1) the isotropy of spectators is due to the spherical symmetry of ψ_0, but it also takes place if the D-state admixture is taken into account, provided that the deuterons are unpolarized [1].

The investigation of the spectator momentum distribution becomes of particular interest because of the improved precision of experiments with the deuteron as one

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of the best neutron targets. Several recent papers are devoted to the explanation of the high-momentum ($p \gtrsim 200$ MeV/c) tail of spectators which disagrees with the Hulthén wave function. This can be due to the final state interaction [2], or to the multiple scattering of X inside the deuteron [3], as well as to wrong fit of the Hulthén function [4], which should be modified by a hard-core component. The final state interaction and the multiple scattering correction imply some small anisotropy of spectators which will be mentioned further on.

Apart from the above reasons of the departure of the spectator spectrum from (1), we suspect another one of quite different origin. Under the mentioned assumptions formula (1) works when the deuteron can be regarded as an infinitely heavy centre. The situation changes for very high energy collisions, when the momentum P of impinging X becomes comparable with the deuteron mass M_d. Then, much as in the elastic scattering [5], the question arises as to the relativistic description of many-body bound systems (here the deuteron). A now widely discussed problem is that of similar-nature of high-energy forward amplitude for inelastic processes [6], where the transformation properties of the wave function under the boost operation play the central role.

In paper [7] the hypothesis was proposed which determines the transformation properties of the internal wave function under the boost transformation, and implies that the overall centre of mass system of the colliding particles is (*a posteriori*) a distinguished system to account for the interaction between particles with internal structure. Below we confine ourselves to the analysis of a particular consequence of this hypothesis concerning the disintegration, of the deuteron, which seems to be interesting from the experimental point of view.

According to the mentioned hypothesis, the same assumptions which in low-energy physics lead to the formula (1), for high-energy collisions result in

$$\frac{dn}{d^3p} \sim |\psi_0[(p - v g(p))^2]|^2, \tag{2}$$

$$g(p) = (M^2 + p^2)^{1/2} - M_d/2; \qquad v = \frac{P}{(M^2+p^2)^{1/2} + M_d}.$$

Here ψ_0 is the same as in (1) internal wave function of the ground state of the deuteron, M is the nucleon mass, and v means the velocity of the centre of mass system in the lab--system expressed in (2) by the lab-momentum P of the impinging nucleon. Because of the monotonic decrease of ψ_0 with increasing p, formula (2) results in a weak positive forward-backward asymmetry of the nucleon spectators in the lab-system. The shift of the argument of ψ_0 is due to 1° finite value of v, and simultaneously to 2° the virtuality of nucleons inside the deuteron. First factor (hence the asymmetry effect) disappears in the nonrelativistic limit ($v/c \to 0$), as well as in the limit of the infinitely heavy centre ($M_d \to \infty$). The second factor $g(p)$ is due to the difference between the energy $(M^2+p^2)^{1/2}$ of the spectator nucleon released from the deuteron, and its mean energy $M_d/2$ inside the deuteron — both in the lab-system. It should be remembered that in the first order approximation of v^2/c^2, the nonrelativistic wave function accounts correctly for the relativistic off-mass shell effect of nucleons inside the deuteron.

Fig. 1 from Ref. [8] represents the spectrum of the spectator nucleon momenta (in lab.) obtained from the proton-deuteron disintegration process. Up to the momenta $p \leqslant 200$ MeV/c this spectrum is very well reproduced by the Hulthén function

$$p^2 = N[(a^2+p^2)^{-1}-(b^2+p^2)^{-1}], \tag{3}$$

with $a = 52.9$ MeV/c, and $b = 240.3$ MeV/c, which indicates that the spectator nucleon of $p \leqslant 200$ MeV/c is a well defined particle. Let $n_{f,b}$ $(p; v)$ denote the number of spectator

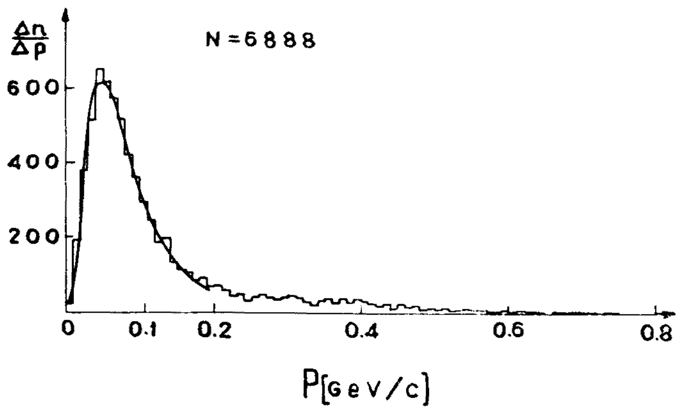

Fig. 1. Momentum distribution of spectator nucleons — smooth curve represents the Hulthén function with $a = 52.9$ MeV/c, $b = 240.3$ MeV/c; [8]

nucleons of momenta less than p, for given value of v, emitted in the forward (backward) directions with regard to the impinging nucleon.

$$\frac{dn_{f,b}}{dp} = Bp^2 \int_0^1 dz[(a^2+p^2+v^2p^2g^2(p)\mp 2vpg(p)z)^{-1} -$$

$$-(b^2+p^2+v^2p^2g^2(p)\mp 2vpg(p)z)^{-1}]^2,$$

where $z = \cos\Theta, \Theta$ is the angle between the momenta of the spectator and impinging nucleon, and B is some irrelevant normalization constant. In Fig. 2 the asymmetry function $F(p; v)$ of spectators of given momentum p is plotted $vs.$ p for different values of v;

$$F(p; v) = \frac{(d/dp)n_f(p; v)-(d/dp)n_b(p; v)}{(d/dp)n_f(p; v)+(d/dp)n_b(p; v)}. \tag{4}$$

The function $F(p; v)$ increases with p from zero, with the slope proportional to v. In order to compare the theoretical predictions with the experiment [8], we define the asymmetry of spectators of momenta between the values p and $p+\Delta p$ equal to

$$A(p, \Delta p; v) = \frac{[n_f(p+\Delta p; v)-n_f(p; v)]-[n_b(p+\Delta p; v)-n_b(p; v)]}{[n_f(p+\Delta p; v)-n_f(p; v)]+[n_b(p+\Delta p; v)-n_b(p; v)]}. \tag{5}$$

Table I presents the values of A evaluated from (5) and known from experiment [8] for a particular value $v = 0.44$. The agreement between theory and experiment is on a rather high confidence level $\alpha \simeq 0.25$, in comparison with negligible α ($\alpha \lesssim 10^{-5}$) in the case of isotropic distribution ($A = 0$).

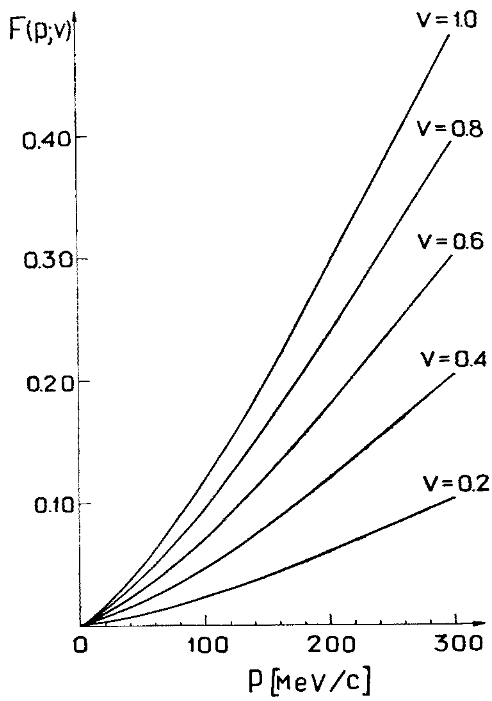

Fig. 2. Forward-backward asymmetry of spectators of momentum p

According to (2), the angular distributions in z are almost straight lines, of the slope determined by the corresponding value of asymmetry A. In Fig. 3 the angular distribution of all spectators is plotted for $v = 0.44$ and compared with the experimental points taken from paper [8]. Here the agreement occurs on an even higher confidence level $\alpha \cong 0.80$.

However, one must be careful, because final state interaction works qualitatively in the same direction. Also the double scattering modifies the distribution of "spectators", although for small momentum transfer t it favours the angles close to 90° with regard to primary direction of X, which is rather unobserved in the angular distribution of spectators — *cf.* Fig. 3. From this point of view, it should be interesting to investigate

TABLE I

Asymmetry $A(p, \Delta p; v)$

$\frac{v}{c}$ / Momentum intervals [MeV/c]		0–40	40–80	80–120	120–160	160–200	200	0–∞
.44	experiment	.037 ∓.027	−.008 ∓.018	.064 ∓.032	.069 ∓.032	.114 ∓.047	.142 ∓.027	.051 ∓.011
	theory	.0105	.0263	.0502	.0789	.111	.196	.0496
.20	,,	.00478	.0119	.0228	.0359	.0506	.0897	.0225
.40	,,	.00957	.0239	.0457	.0718	.101	.178	.0450
.60	,,	.0143	.0358	.0684	.107	.151	.266	.0677
.80	,,	.0191	.0477	.0911	.143	.200	.350	.0906
1.00	,,	.0239	.0596	.144	.178	.249	.432	.114

the electrodisintegration process of the deuteron, as the double scattering amplitude, is here negligible.

For our purpose, it is of first importance to look at the momentum distribution of spectators resulting from the disintegration initiated by X of higher energy. The point is that according to (2) the asymmetry increases proportionally to v, *i.e.* it increases with energy E of X. This is at variance with both aforementioned mechanisms which depend only on t, and therefore for given interval of t they should result in an anisotropy which is almost independent of the energy of the incident particle X.

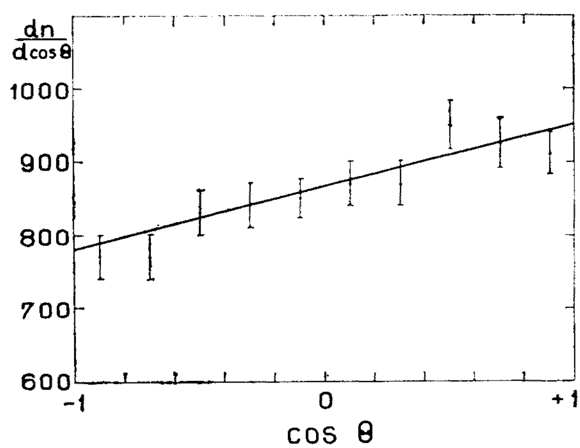

Fig. 3. Angular distribution of all spectators for $v = 0.44$. Smooth line-theory ($A = 0.050$), experimental points from Ref. [8]

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