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RELEVANCE OF NEW MEASUREMENTS OF LIGHT NUCLEI BREAKUP AT A ZERO ANGLE

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Актуальность новых измерений реакций развала легких ядер
под нулевым углом

Обсуждается важность новых измерений реакций развала легких ядер в широком диапазоне внутренних импульсов при энергиях серпуховского ускорителя. Предложен экспериментальный тест для выбора адекватной переменной, описывающей процессы развала дейтрона. Показано, что прецизионные измерения T_{20} реакции развала дейтрона при малых внутренних импульсах важны для поляриметрии. Обсуждаются экспериментальные проблемы измерений в этой области.

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Relevance of New Measurements of Light Nuclei Breakup
at a Zero Angle

The importance of investigation of light-nuclei breakup reactions in a wide region of internal momenta at Serpukhov energies is discussed. The experimental test for the choice of adequate variable for the description of the breakup reactions is suggested. It is shown that the precise measurement of T_{20} of the deuteron breakup reaction at small internal momenta is important for the polarimetry. The experimental difficulties of measurements in this region are discussed.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energies, JINR.

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Studying of the light-nuclei breakup reactions at a zero angle is an interesting task because of the predominance of the Impulse Approximation (IA) reaction mechanism, which gives a simple relation between wave functions of nuclei and measured observables. In this approach, the observables do not depend on colliding energy.

The features of light-nuclei fragments spectra at a zero angle, observed at Dubna about 15 years ago, have been discussed up to nowadays. The following reactions have been studied:

$$
\begin{aligned}
d + A &\rightarrow p + X, & (1)\\
{}^3\mathrm{He} + A &\rightarrow d, p + X, & (2)\\
{}^4\mathrm{He} + A &\rightarrow t, p + X. & (3)
\end{aligned}
$$

The results for the first reaction are published in [1, 2]. The data on the second and third reaction are presented in [6, 7], respectively.

The variables q, the fragment-spectator momentum in the fragmenting Nuclei Rest Frame (NRF), and the light front variable, k, are used to describe the data. The relation between k and q is expressed by the following

$$
\begin{aligned}
\alpha &= \frac{\sqrt{q^2 + m_p^2} + q}{M_d}, & (4)\\
M_{sf} &= \frac{m_s^2}{\alpha} + \frac{m_f^2}{1-\alpha}, & (5)\\
k &= (\alpha - \frac{1}{2})M_{sf} + \frac{m_f^2 - m_s^2}{M_{sf}}, \quad \text{or} & (6)\\
k^2 &= \frac{\lambda(M_{sf}^2, m_s^2, m_f^2)}{4M_{sf}^2}, & (7)\\
\lambda(a,b,c) &= a^2 + b^2 + c^2 - 2ab - 2ac - 2bc.
\end{aligned}
$$

Here m_s and m_f are masses of the fragment-spectator and of the interacting fragment, respectively. When k is used as an argument of a wave function, we call this approach the Relativistic Impulse Approximation (RIA).

The excess of the cross section over calculations (up to two times) in the vicinity of the **s**-wave node (see Figs. 1, 2) of the deuteron wave function was

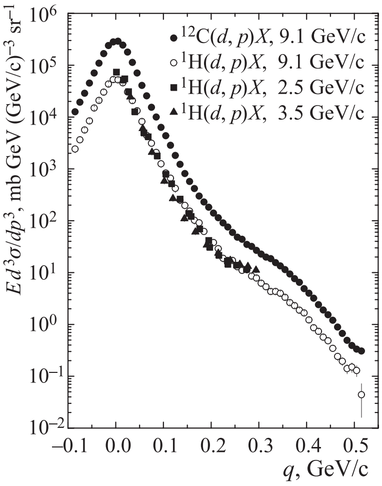

Fig. 1. Invariant cross sections of the deuteron breakup at 0^o for different targets and at different energies, measured at Dubna and Saclay

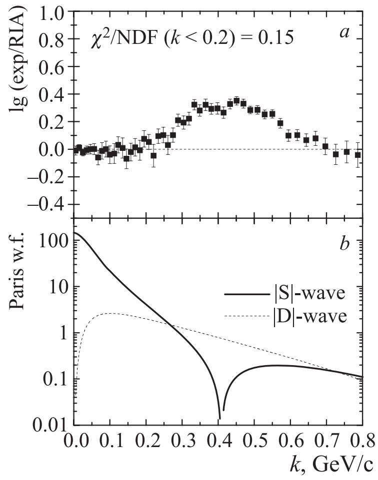

Fig. 2. The ratio of invariant cross sections of the deuteron breakup on hydrogen to RIA calculations with use of the Paris potential

interpreted as a signal about the 6-quark component of the deuteron [1] and as an effect of pion production and absorption in an intermediate state [3]. There is also another explanation, assuming systematic errors [4, 5] in the data [2]. Invalidity of such an explanation is discussed below.

The $^4\mathrm{He} \to t + p$ vertex is of especial interest because it can be described only by the **s** wave. Data both on electro- and on hadro-splitting $^4\mathrm{He} \to t + X$ show the coordinated absence of any spectra peculiarities in the area of the **s** wave node. Note, that all theoretical efforts (taking into account meson exchange currents and so forth) have not helped to avoid the features for the summary curve in this area (Fig. 3).

The analogous experiments at Serpukhov energies could be crucial ones to understand whether we deal with the structural effect [1] or with the reaction mechanism [3]. The matter is that in this case the mechanism contributes nothing in the region of $p_f/p_A > m_f/m_A$ (in the lab system). If we deal with the structural effect, the similarity of momentum spectra should be expected at the Dubna and Serpukhov energies. One can also expect the range of validity of the RIA to be extended to higher values of k. The matter is, the higher is the value of k, the higher is the squared 4-momentum transfer $|t|$ to a target in the breakup reaction. On the other hand, the higher is an incident nuclei energy, the less is the minimum (and the average) value of $|t|$ at fixed k. And the smallness of $|t|$, may be, is one of criteria of the validity of the RIA. When Mandelstam variable

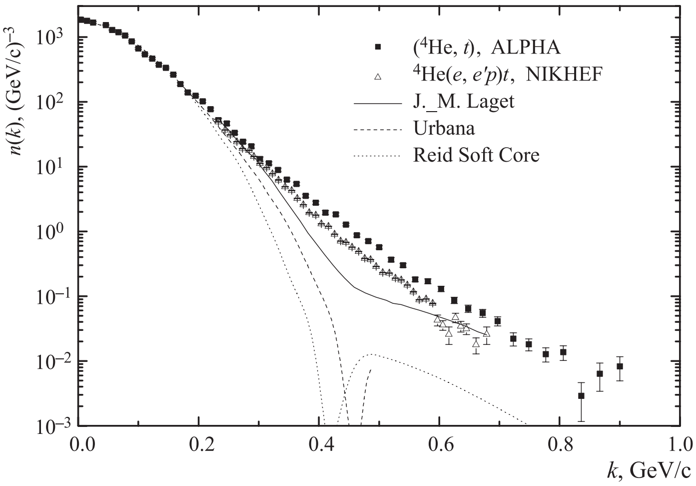

Fig. 3. Momentum distributions of tritons in ^{4}He, obtained by means of electron and hadron probes

$s \gg m_i$, the minimum value of $|t|$ can be expressed as

$$
\begin{aligned}
t_{\min} &\simeq \frac{(m_{sf}^2 - m_A^2)^2}{s}, &(8)\\
s &= (E_A + m_T)^2 - p_A^2 \simeq 2E_A m_T, &(9)
\end{aligned}
$$

where m_A is the mass of incident nuclei, m_T is the target mass, m_{sf} is defined in Eq.(5). The dependence of the minimum value of $|t|$ on k (which is related to m_{sf} by Eq.(7)) is shown in Fig. 4 at different momenta of incident deuterons.

The reliable identification of a spectrum peculiarity (for (d, p)) is possible only in case of correct normalization of the data. It can be achieved by measuring a

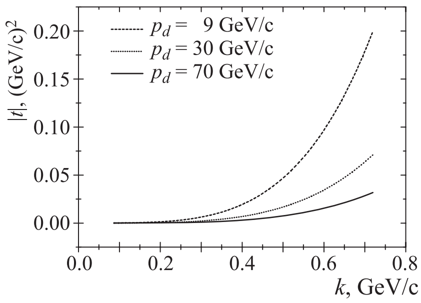

Fig. 4. The dependence of minimum value of $|t|$ on the value of internal momentum k at different momenta of incident deuterons

spectrum at $p_p \simeq p_d/2$ ($q \simeq k \simeq 0$). But just in this area experimentalists run up against some problems. The matter is that at a zero fragment longitudinal momentum in the NRF ($q_l \simeq 0$) the knowledge of the transversal momentum p_t becomes essential, but it has been measured not in all experiments. As a result, the maximum of spectra is proved to be underestimated. Measuring of a fragment emitting angle with sufficient accuracy allows one to avoid this problem. As at the measurement of cross sections at a zero angle, a separating magnet is always used, it is necessary to know the fragment deflecting angle in this magnet in order to reconstruct its emitting angle; that requires high accuracy of measuring the fragment momentum. All these conditions were abode in the setup (Fig. 5) used by us for measuring the breakup cross sections. The absence of lenses in the magnetic channel for fragments has facilitated this task.

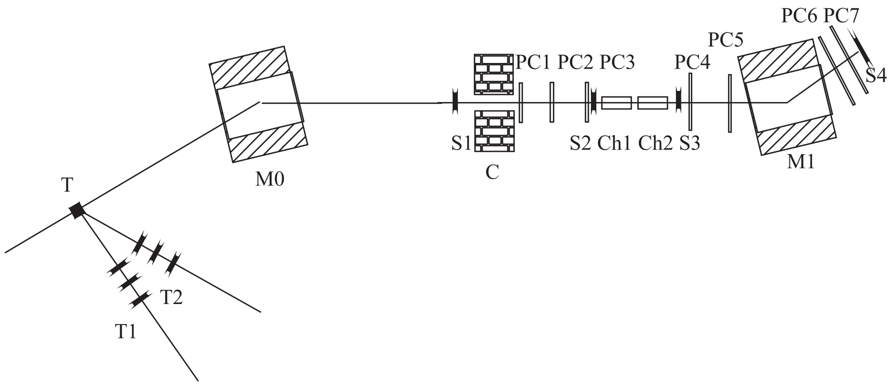

Fig. 5. T_i, S_i, — scintillator telescopes and counters, Ch_i — Čerenkov counters, PC_i — proportional chambers, T — target, M_0, M_1 — separating and analyzing magnets

Fragment emitting angles in the reactions, mentioned above, have been measured with the accuracy of $\simeq$ 2 mrad, that is equivalent to the accuracy of measurement of a fragment transversal momentum, $\Delta p_t \simeq 9$ MeV/c. As requirements to the accuracy of measurements of p_t remain invariant, the accuracy of measurement of emitting angles at Serpukhov energies should be increased in the ratio of the fragmenting nuclei momenta at Protvino and Dubna. Otherwise, it is necessary to do either deconvolution of the measured spectrum or convolution of an approximating curve in the spirit of corrections, considered in [5]. These corrections were applied to explain the data [2], but the convolution parameter was too overestimated (as if p_t was not measured).

In Fig. 6 the same data as in Fig. 2 are shown (the ratio in the logarithmic scale and the logarithm of the ratio in the linear scale). Note, that Fig. 2 (the top panel) has been published in [2]. It is seen from Fig. 6, that the deviation from

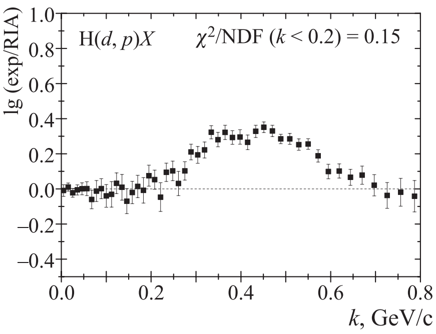

Fig. 6. Logarithm of the ratio of values of experimental points to calculations in the RIA for the Paris wave function

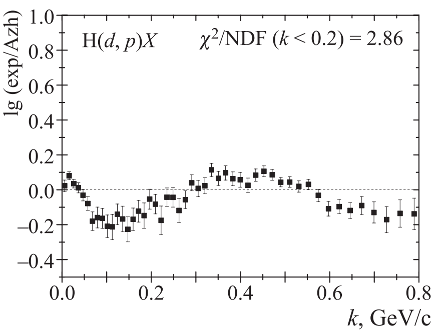

Fig. 7. The same, that in Fig.6, but for a curve, calculated in [5]

RIA begins at $q > 0.2$ GeV/c. At $q < 0.2$ GeV/c, the fit of data with RIA (in the chosen representation it is a straight line, $y = 0$) gives χ^2/NDF=0.15 (number of degree of freedom),i.e., the motivation to update the curve is completely absent in this area of internal momenta. Nevertheless, it was fulfilled in [5] and χ^2/NDF has increased more than by 20 times (Fig. 7), and that does not require additional comments.

More significant systematic errors arise while measuring T_{20}, when p_t is measured insufficiently precisely or is not measured at all. The matter is that measured T_{20} depends on mutual orientations of the fragment momentum in the NRF and the polarization axis. When p_t is not measured, we have

$$\sigma_0^m(k) \quad = \quad \int dk'_x \int dk'_y \sigma_0(k') f(\theta), \tag{10}$$

$$\sigma^m(k) \quad = \quad \int dk'_x \int dk'_y \sigma_0(k') f(\theta) \left(1 + \frac{3(\mathbf{n}_Q \mathbf{n}_k)^2 - 1}{2} \rho_{20} T_{20}(k)\right), \tag{11}$$

where $f(\theta)$ is the angular acceptance function, $\tan\theta = k_\perp/k$, $k'^2 = k^2 + k_\perp^2$, $\mathbf{n}_Q \mathbf{n}_{k'} = k'_y/k'$, $\mathbf{n}_Q$ is the unit vector in the direction of the deuteron polarization axis, $\mathbf{n}_k$ is the same in the direction of a proton internal momenta.

Expected experimental values T_{20}^m and the searched value ($T_{20}(k)$) are related as follows:

$$T_{20}^m(k) = -2\frac{\sigma^m(k) - \sigma_0^m(k)}{\rho_{20}\sigma_0^m(k)} = \\ = \frac{\int dk'_x \int dk'_y \sigma_0(k') f(\theta) T_{20}(k')(1 - 3(k'_y/k')^2)}{\int dk'_x \int dk'_y \sigma_0(k') f(\theta)}. \tag{12}$$

Such a convolution leads to positive values for measured $T_{20}^m(k)$ in the vicinity of $k = 0$ [8].

For the first time, T_{20} in the deuteron breakup reaction on carbon [9] has been measured by using the setup shown in Fig. 5 (LHE measuring hall, p_t was measured). These data are shown in Fig. 8.

The main thing worth paying attention to is that $T_{20} \to 0$, when $k \to 0$. It means, that in this case no hardware corrections for data are required.

As the beam polarization was measured not so precisely in those days, the curve with 10% correction of polarization is also drawn. It is possible to state that the RIA is valid up to $k \simeq 0.15$ GeV/c; that approximately coincides with the results of the cross-section analysis.

T_{20} in a wide range of momenta was measured [10] by using another setup in the hall 205. The magnetic channel VP-1 about 40 m long had the angular acceptance of $\simeq 15$ mrad and contained several doublets of lenses, so the measurement of p_t was impossible.

It is seen in Fig. 9, that the data show a tendency to cross 0 at $k > 0$. The curve modified by Eq.(12) agrees better with the data at small internal momenta. Taking into account the correction of the curve, the data confirm estimations on the area of applicability RIA, made above.

The deuteron breakup reaction

$$d + p(\mathrm{CH_2}, \mathrm{C}) \to p + X$$

is one of the highest aperture reactions to measure deuteron beam tensor polarization. Experimental data in the region of small momenta in the NRF agree well

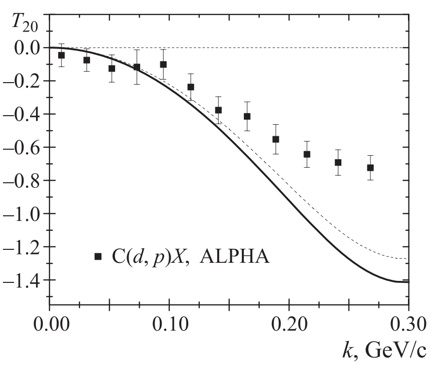

Fig. 8. T_{20} for $d + \mathrm{C} \to p + X$ (p_t was measured)

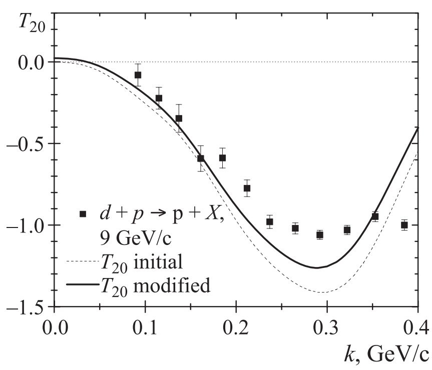

Fig. 9. T_{20} for $d + p \to p + X$ (p_t was not measured)

with RIA. The Figure of Merit within this approximation can be expressed as

$$\mathrm{C}\sqrt{\Psi^2(k)T_{20}^2(k)}.$$

This function has the maximum at $k \simeq 0.10$ GeV/c (Fig. 10).

It is relevant to measure T_{20} in the region $0.1 < k < 0.2$ GeV/c with better accuracy than it has been achieved up to now. Taking into account that the analyzing power for the hydrogen target is higher than for the carbon one [12,13], the most acceptable target for this measurement is the CH_2-target, because LH_2 target is not suit for the express measurements. The necessary accuracy (with measurements of emitting angles) can be achieved using the setup «Strela» at the LHE and also ANKE spectrometer at COSY.

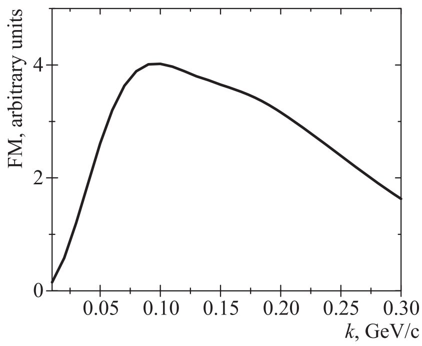

Fig. 10. Figure of Merit for the reaction $d + A \to p + X$

There is also a physical motivation to carry out the precise measurements of T_{20} at small internal momenta. The light front variable k, considered first by P.Dirak, up to now has not been commonly accepted as the internal constituent momentum in light nuclei. Many famous physicists up to now use a momentum in the NRF q as the wave-function argument.

In [11] it is shown that the certain asymmetry between k and q near zero momentum in the NRF allows one to investigate this problem experimentally. The relation between k and q at small k, q is given by equation

$$\frac{dk}{dq} \simeq 1 + \frac{1}{m_n} q, \tag{13}$$

that is, $dk/dq > 1$ at $q > 0$ and $dk/dq < 1$ at $q < 0$.

For an adequate variable, the measured observables should be an even function of an argument. In Figs. 11, 12 it is seen, that the variable k satisfies the parity condition better, however, this result requires the higher statistical confirmation.

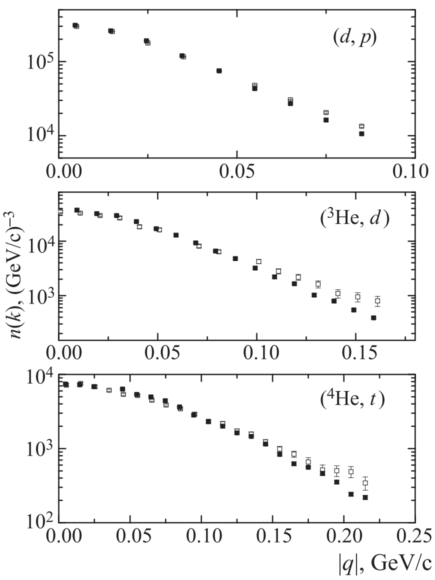

Fig. 11. Momentum distributions of fragments in light nuclei at small $|q|$ within the nonrelativistic IA. Points at negative values of q are represented by open circles

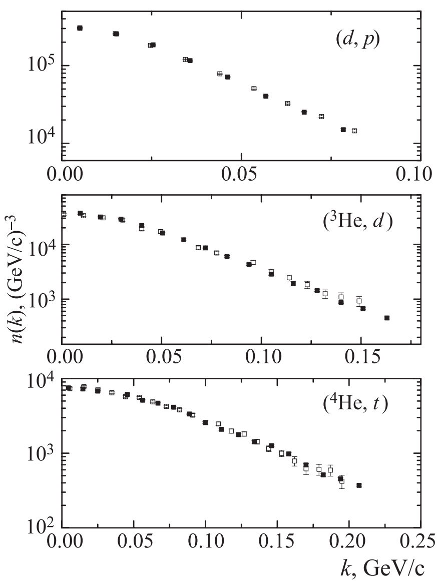

Fig. 12. The same as in Fig.11 within RIA

The more sensitive test of the parity condition is to measure T_{20} in the region of small k, q. In Fig. 13 the expected asymmetry on q is shown assuming that k is the adequate variable. The spectrometers, mentioned above, are good for this experiment.

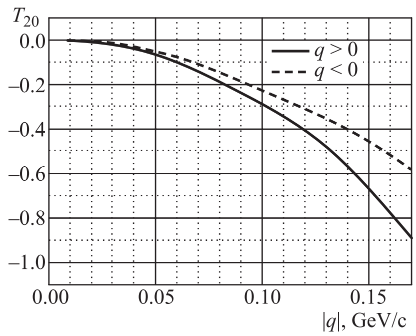

Fig. 13. Asymmetry T_{20}

CONCLUSIONS

1. Measurements of light-nuclei breakup reaction near zero angle energies in a wide region of internal momenta is important at Serpukhov energies;
2. precise measurements at small k, q are necessary for the polarimentry and allow one to make a choice of the correct variable to describe the breakup processes;
3. measurement of spectra in the small internal momenta area is a subject of special experimental carefulness.

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