E1-2006-156

L. S. Azhgirey*, V. P. Ladygin, V. N. Zhmyrov, L. S. Zolin

PROPOSAL OF THE EXPERIMENT ON INVESTIGATION OF THE (d, p) REACTION AT THE EXTRACTED DEUTERON BEAM OF THE U-70 ACCELERATOR

Submitted to «Particles and Nuclei, Letters»

* E-mail: azhgirey@jinr.ru

Ажгирей Л. С., Ладыгин В. П., Жмыров В. Н., Золин Л. С. E1-2006-156
Предложение эксперимента по исследованию реакции (d, p) на ускорителе U-70

Предлагается эксперимент по исследованию реакции $A(d, p)X$ на выведенном пучке дейтронов, создаваемом на ускорителе U-70 в Серпухове. Точные измерения импульсных спектров протонов, испускаемых в реакции (d, p) при начальных импульсах дейтронов 20–40 ГэВ/c, могут дать незаменимую информацию о структуре дейтрона на малых расстояниях. При таких энергиях вполне можно ожидать проявления вклада ненуклонных степеней свободы в дейтроне.

Работа выполнена в Лаборатории высоких энергий им. В. И. Векслера и А. М. Балдина ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2006

Azhgirey L. S., Ladygin V. P., Zhmyrov V. N., Zolin L. S. E1-2006-156
Proposal of the Experiment on Investigation of the (d, p) Reaction at the Extracted Deuteron Beam of the U-70 Accelerator

An experiment on the investigation of the $A(d, p)X$ reaction at the extracted deuteron beam created at the Serpukhov U-70 accelerator is proposed. Precise measurements of the momentum spectra of protons emitted in the (d, p) reaction at initial deuteron momenta of 20–40 GeV/c can give unique information on the deuteron short-range structure. A manifestation of contribution of non-nucleonic degrees of freedom in the deuteron is entirely possible over this energy range.

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

Preprint of the Joint Institute for Nuclear Research. Dubna, 2006

The investigation of the fragmentation of relativistic deuterons in their collisions with protons and nuclei, $A(d,p)X$, serves as an important source of information on the internal deuteron structure at short distances between the constituents. This investigation provides the most stringent test of our understanding of nuclear structure based on microscopic models. On the other hand, the study of collisions of relativistic deuterons with nucleons and nuclei is extremely important for clarifying fundamental problems of the relativistic description of fast moving composite objects. Of prime interest in the recent past, motivating experimental studies in the GeV range, is that whether one should use quark or hadronic degrees of freedom to describe the deuteron.

Measurements of differential cross sections of deuteron inclusive breakup on nuclei at a zero proton emission angle [1, 2, 3, 4] have shown that these data can be explained within the framework of the relativistic impulse approximation (RIA) using standard deuteron wave functions except for the vicinity of the internal nucleon momentum $k \sim 0.35$ GeV/c in the deuteron defined in the light-front dynamics [5]. The observed broad shoulder at these k was explained by the manifestation of the quark degrees of freedom [6] as well as by taking into account the mechanisms additional to RIA [7]. However, it was shown [8] that there were essential factors which could lead to better agreement of the data with the calculations using deuteron wave function (DWF) for the Paris potential [9]: allowance made for the finite angular resolution of the apparatus used in the measurements [1], the renormalization of the spectrum resulting from that allowance made, and an additional contribution from the scattering of intradeuteron nucleons on the target proton.

Momentum spectra of protons emitted at angles of 103, 139, and 157 mrad (i. e., with large transverse momenta) were measured in the interactions between deuterons with a momentum of 9 GeV/c and the nuclei ^{1}H, ^{2}H, and ^{12}C [10]. The measurements covered almost the entire high-momentum range (higher than 3.2 GeV/c) kinematically accessible to the proton emission in the $A(d,p)$ reaction.

As an example of these data the proton momentum spectrum for an angle of 139 mrad is shown in Fig. 1.

The data obtained show universality of high-momentum parts of proton spectra, i. e., similarity of their shape for different targets. This means that it is possible to present the invariant differential cross section for the proton emission in the $A(d,p)$ reactions at the given angle as

$$E d\sigma/d\mathbf{p} = \gamma_A \gamma_d(\mathbf{p}), \tag{1}$$

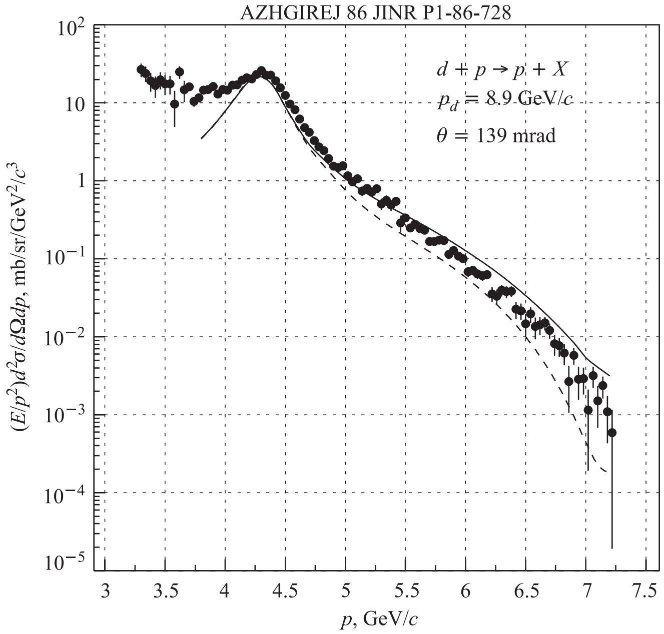

Fig. 1. Momentum spectrum of protons detected at an angle of 139 mrad in the interactions between deuterons with a momentum of 9 GeV/c and hydrogen nuclei. The curves correspond to the results of calculations using the deuteron wave function for the Paris potential (dashed curve) and with Karmanov's relativistic deuteron wave function (solid curve)

where the entire dependence on the target properties is reduced to the factor γ_A, while the momentum–spectrum shape $\gamma_d(\mathbf{p})$ depends on the deuteron structure and reaction mechanism.

The data obtained have been satisfactorily described using the impulse-approximation mechanism within the framework of the light-front dynamics. The Feynman diagrams shown in Fig. 2 can illustrate this mechanism. Here, d de-

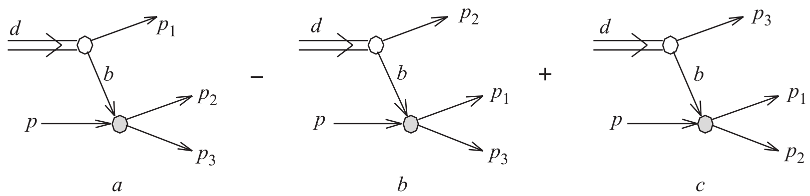

Fig. 2. Feynman diagrams describing fragmentation of deuterons on protons

notes the impinging deuteron; p is the target proton; p_1 is the detected proton; b is the exchanged virtual nucleon, which is off the mass shell; p_2 and p_3 are the nucleons resulting from the interaction between particle b and target p. The diagram in Fig. 2, a corresponds to the case where the detected proton is formed in the stripping process and the np interaction takes place at the lower vertex. In the diagrams of Fig. 2, b and c, the lower vertices correspond to the np charge exchange and pp elastic scattering, respectively.

In the analysis of the above data [10] the fragmentation reaction of relativistic deuterons was described in terms of the light-front dynamics or, in other words, in the reference system in which the deuteron momentum tends to infinity — the infinite momentum frame (IMF). Due to the absence of z-diagrams (reverse-time diagrams) in the IMF, the effects of the relativistic system structure are naturally described by the wave function with the probabilistic meaning [11]. At the first stage of the analysis the light-front deuteron wave function was connected with the non-relativistic DWF in a simple way, by the kinematical transition from the equal-time variables to the light-front variables.

Now we have a relativistic deuteron wave function at our disposal. Such a function was found by Carbonell and Karmanov within the framework of the light-front dynamics [12]. This function, in distinction to the non-relativistic wave functions, allowed the experimental data on the tensor analyzing power of the nuclear fragmentation of relativistic deuterons to be qualitatively described [13].

To understand requirements to the experimental setup for the proposed measurements, momentum spectra of protons emitted at angles of 0, 2, 4, and 6 degrees in the $^1\mathrm{H}(d,p)$ reaction at the initial deuteron momenta of 20 and 40 GeV/c were calculated within the framework of the formalism developed in [10, 13]. The contributions of the diagrams shown in Fig. 2, a and c, were taken into account. To this end, the approximations of the experimental data on the total cross section of np scattering and on the differential cross section of the elastic pp scattering were used.

The values of the total cross section of np scattering (325 points of experimental data) were approximated up to the neutron momentum of 26.5 GeV/c using the cubic spline model with free knots developed in [14].

The values of the $\sigma_t(np)$ were calculated according to the approximations

$$\log \sigma_t = \sum_{i=0}^{3} a_i \log(p_{\mathrm{lab}}) \qquad (2)$$

in eight adjacent intervals of p_{lab}, where p_{lab} is the neutron momentum in the lab system. The quality of the approximation can be seen in Fig. 3, and the values of the coefficients a_i are given in the Appendix.

To describe the differential cross section of the elastic pp scattering, the approximation proposed by Krish [15] was used.

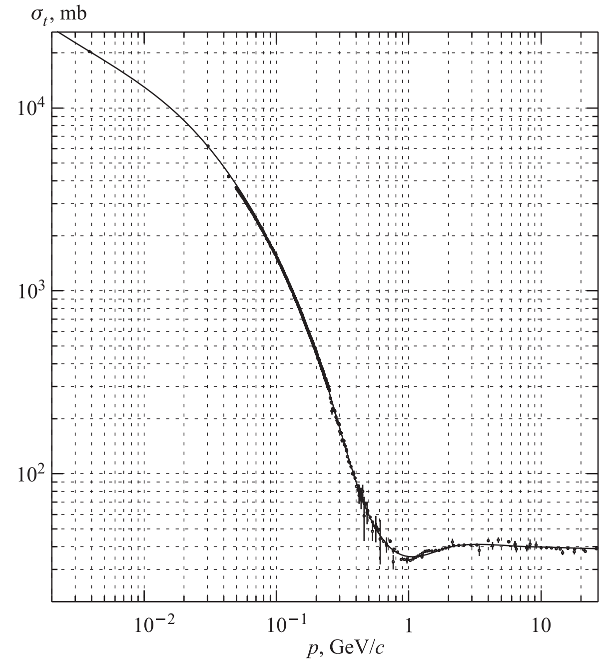

Fig. 3. Approximation of the data on the total cross section of np scattering by the spline model with the free knots [14]

To take into account the off-mass-shell nature of the virtual particle b in the calculations, the analytic continuations of the cross section parameterizations to the invariant variables $s' = (b+p)^2, \quad t' = (b-p_1)^2$ defined at the low vertex of the pole diagram at $b^2 \neq m^2$ were used (here the momentum symbols mean four-vectors).

The calculations were made using two-deuteron wave functions: the standard DWF for the Bonn charge-dependent potential [16], and Karmanov's relativistic DWF [12]. Karmanov's function is given in the table form up to the light-front internal momentum $k = 1.5$ GeV/c [12]. The authors of that paper, however, put at our disposal the table of values of the relativistic deuteron wave function calculated up to $k = 2.5$ GeV/c. To carry out calculations at higher values of k, we made «reasonable» extrapolations of the relativistic deuteron wave function to $k = 5$ GeV/c. Therefore, our results corresponding to the k range from 2.5 to 5 GeV/c should be taken with a definite caution.

The results of the calculations of the invariant differential cross sections of the proton emission at an angle of $4°$ in the ${}^1\mathrm{H}(d,p)X$ reaction at the deuteron momenta of 20 and 40 GeV/c are shown in Fig. 4.

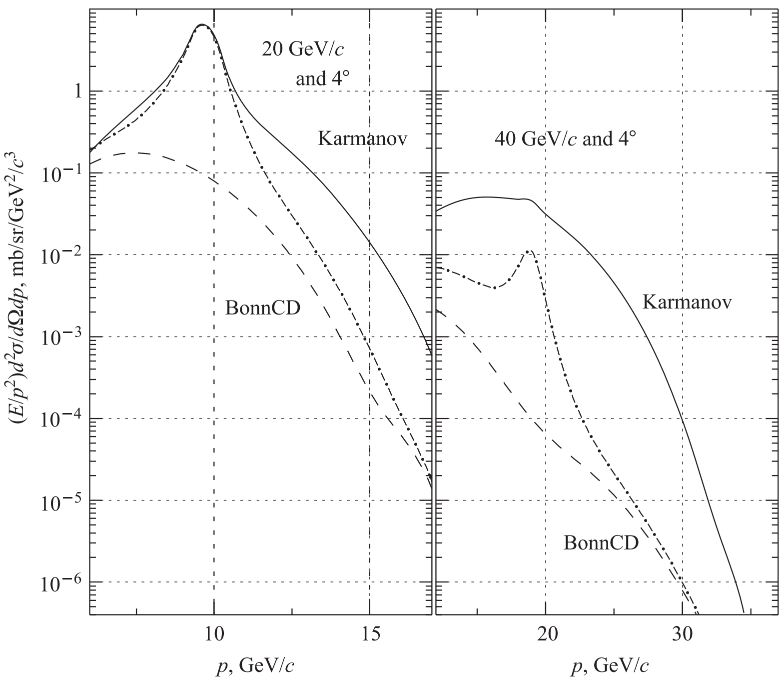

Fig. 4. Momentum spectra of protons emitted at an angle of 4° in the ${}^1\mathrm{H}(d,p)X$ reaction at 20 and 40 GeV/c. The curves were calculated with Karmanov's relativistic DWF [12] (solid curves), and with the DWF for the BonnCD potential [16] (dash-dotted curves). Dashed curves show the single contribution of the stripping (diagram of Fig. 2, a)

In Fig. 5, a comparison between proton momentum spectra obtained in dp collisions at different angles is made. These spectra were calculated at the initial deuteron momenta of 20 and 40 GeV/c and the proton detection angles of $0^\circ, 2^\circ, 4^\circ$, and 6°, using BonnCD and Karmanov's DWFs. The contributions of the stripping process at angles of 2° are shown with dash-dotted curves. The spectra at an angle of 0° are almost completely defined by stripping.

If one is left within the framework of hadronic degrees of freedom to describe the deuteron, it is instructive to consider to what values of the internal nucleon momentum the differential cross section of the ${}^1\mathrm{H}(d,p)X$ reaction can be measured at the initial deuteron momenta 20 and 40 GeV/c. An answer to this question is provided by Figs. 6 and 7, where the calculated dependencies of the differential cross sections of the ${}^1\mathrm{H}(d,p)X$ reaction on the internal momentum k (defined in the light-front dynamics) are shown. It should be stressed that

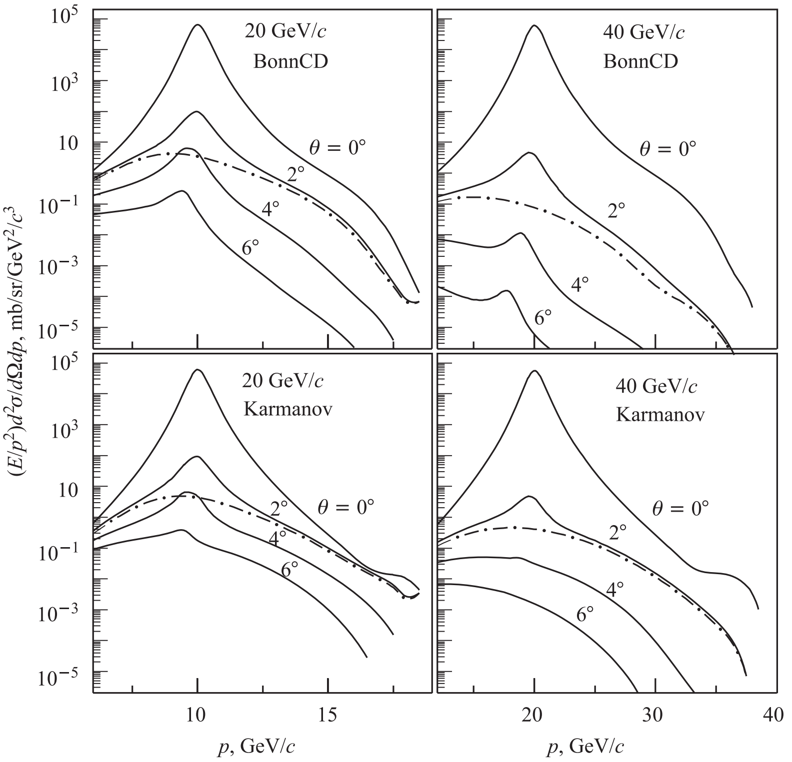

Fig. 5. Momentum spectra of protons emitted at angles of $0°, 2°, 4°$ and $6°$ in dp collisions calculated at the initial deuteron momenta of 20 and 40 GeV/c using BonnCD and Karmanov's DWFs. The contributions of the stripping process at angles of $2°$ are shown with dash-dotted curves

these values of k refer to the stripping process. In the case of other processes, integration over some region of k is made when cross sections are calculated.

Some kinematical characteristics of the reaction $^1\mathrm{H}(d,p)X$ useful for planning the experiment are given in Table 1. Here $p_{\max}$ is the maximal proton momentum possible in this reaction:

$$p_{\max} = \frac{2m\rho}{1-\rho^2}, \qquad (3)$$

where $\rho = (p_0\cos\theta)/(E_0+m)$, m is the proton mass, E_0 and p_0 are the energy and momentum of the incident deuteron, and θ is the observation angle. The light-front variables p_T (transversal momentum) and x (the fraction of the deuteron

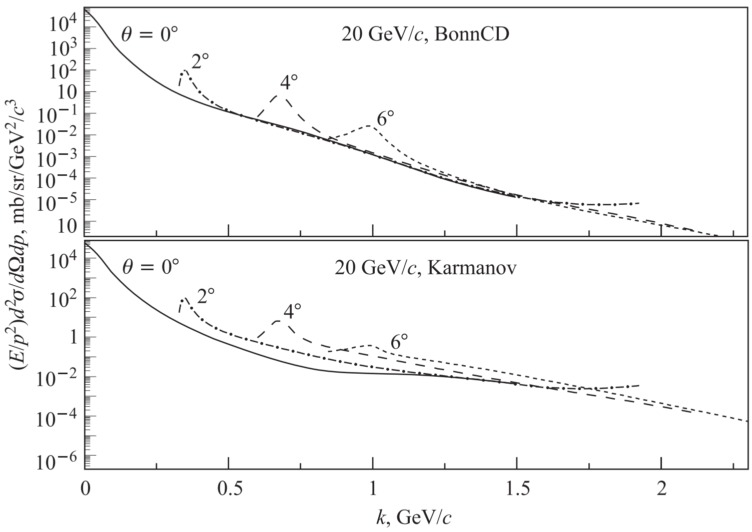

Fig. 6. Dependencies of the differential cross sections of the proton emission in the (d, p) reaction at angles of $0^\circ, 2^\circ, 4^\circ$, and 6° on the internal momentum k at an initial deuteron momentum of 20 GeV/c. The spectra at angles of $0^\circ, 2^\circ, 4^\circ$, and 6° are shown by the solid, dash-dotted, long-dashed and short-dashed curves, respectively

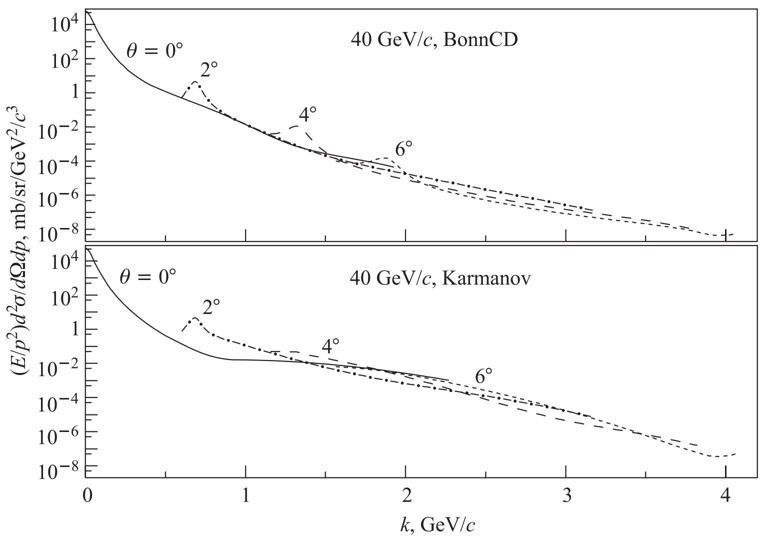

Fig. 7. Same as in Fig. 6, but for an initial deuteron momentum of 40 GeV/c

Table 1. Some kinematical characteristics of the $^1\mathrm{H}(d,p)X$ reaction

	$p_d = 20$ GeV/c				$p_d = 40$ GeV/c			
θ	$0°$	$2°$	$4°$	$6°$	$0°$	$2°$	$4°$	$6°$
$p_{\max}$ (GeV/c)	18.75	18.52	17.88	16.89	38.67	37.72	35.14	31.53
$p_{T\max}$ (GeV/c)	0	0.65	1.25	1.76	0	1.32	2.45	3.30
$x_{\max}$	0.936	0.924	0.891	0.841	0.966	0.942	0.877	0.786
$k_{\max}$ (GeV/c)	1.67	1.94	2.32	2.57	2.43	3.34	3.89	4.07
$z_{\max}$	–1.00	–0.94	–0.84	–0.73	–1.00	–0.92	–0.78	–0.59
Δt (ns)	0.62	0.64	0.69	0.77	0.15	0.16	0.18	0.22

longitudinal momentum taken away by the proton in the infinite momentum frame) corresponding to the proton momentum p are given by

$$p_T = p \cdot \sin\theta, \quad x = \frac{E_p + p_{\|}}{E_0 + p_0}, \quad k = \sqrt{\frac{m^2 + p_T^2}{4x(1-x)} - m^2}. \tag{4}$$

Here k is the internal momentum of the nucleons in the deuteron (defined in the light-front system), E_p is the energy of the detected proton, $p_{\|}$ is the longitudinal component of its momentum, and m is the mass of the nucleon.

The relativistic deuteron wave function in the light-front dynamics found in Ref. [12] is determined by six invariant functions $f_1, \ldots, f_6$ instead of two ones in the non-relativistic case. In the non-relativistic limit there are only two first functions f_1 and f_2 corresponding to the usual S- and D-waves in the deuteron. Each of the invariant functions $f_1, \ldots, f_6$ depends on two scalar variables k and $z = \cos(\widehat{\mathbf{k} \cdot \mathbf{n}})$, where the quantity $\mathbf{k}$ is defined above, and

$$(\mathbf{n} \cdot \mathbf{k}) = \left(\frac{1}{2} - x\right) \cdot \sqrt{\frac{m^2 + \mathbf{p}_T^2}{x(1-x)}}. \tag{5}$$

It is assumed that $\mathbf{n}$ is directed opposite to the beam direction, i. e., $\mathbf{n} = (0, 0, -1)$.

In the last line of Table 1 Δt is the difference of the times of flight of the proton and the deuteron with the same momentum $p_{\max}$ over the base of 50 m.

The following conclusions can be drawn from the aforesaid:

• Precise measurements of the momentum spectra of protons emitted in the (d, p) reaction at initial deuteron momenta of 20–40 GeV/c can give unique information on the deuteron short-range structure. Within the framework of nucleon degrees of freedom the momentum distribution of nucleons in the deuteron can be probed up to momenta of ~ 3 GeV/c, which corresponds to the distances of ~ 0.1 fm. It means that the extracted deuteron beam at the Serpukhov

U-70 accelerator gives a unique possibility of studying the deuteron single-particle properties at distances unattainable (or hardly attainable) with other methods.

• Moreover, it should be kept in mind that in the course of these investigations one can expect to see a signature of the manifestations of non-nucleonic (quark) degrees of freedom in the deuteron. The absence of such a signature would be somewhat surprising in itself.

• The main experimental difficulty of the proposed measurements is the necessity of separating protons from the deuteron admixture. To this end, the time-of-flight technique may be supplemented with Cherenkov counters.

Acknowledgements. We wish to thank J. Carbonell and V. A. Karmanov for supplying numerical values for their relativistic deuteron wave function up to $k = 2.5$ GeV/c, N. D. Dikoussar and Cs. Török for supplying coefficients of approximation (2), and Professor A. M. Zaitsev for his active interest in this study. This work was supported in part by the Russian Foundation for Basic Research under grants No. 06-02-16728 and 06-02-16842.

Appendix

Table 2. Coefficients of the formula (2)

Momentum interval of $p_{\rm lab}$, MeV/c	a_0, mb	a_1, mb(MeV/c)$^{-1}$	a_2, mb(MeV/c)$^{-2}$	a_3, mb(MeV/c)$^{-3}$
3.85–149	4.600783919583	–0.62018537709612	0.31120518591338	–0.17718534821201
149–255	16.229125722773	–16.672663424879	7.6978144387156	-1.310177527388
255–344	–117.49638958973	150.02995528502	–61.572842996645	8.2846007243714
344–448	–70.492313122888	94.438004405775	–39.656552362147	5.4045447235837
448–775	55.55745463227	–48.19105997844	14.139791651834	-1.3590291238769
775–2022	80.998151071701	–74.606469379028	23.282280543755	–2.4137809402799
2022–4747	–28.485637899859	24.750189272443	–6.7731450466931	0.61681147188943
4747–26500	2.825690597417	–0.80021151071471	0.1766609980723	–0.013313073837135

REFERENCES

1. *Ableev V. G. et al.* // Nucl. Phys. A. 1983. V. 393. P. 491; A. 1983. V. 411. P. 54(E).

2. *Anderson L. et al.* // Phys. Rev. C. 1983. V. 28. P. 1224.

3. *Perdrisat C. F. et al.* // Phys. Rev. Lett. 1987. V. 59. P. 2840;
Punjabi V. et al. // Phys. Rev. C. 1989. V. 39. P. 608.

4. *Ableev V. G. et al.* JINR Rapid Comm. 1992. V. 1[43]-52. P. 10.

5. *Dirac P. A. M.* // Rev. Mod. Phys. 1949. V. 21. P. 392.

6. *Kobushkin A. P., Vizireva L.* // J. Phys. 1982. V. G8. P. 993;
Kobushkin A. P. // Phys. Lett. B. 1998. V. 421. P. 53.

7. *Lykasov G. I., Dolidze M. G.* // Z. Phys. A. 1990. V. 336. P. 339;
Lykasov G. I. // Part. Nucl. 1993. V. 24. P. 140.

8. *Azhgirey L. S., Ignatenko M. A., Yudin N. P.* // Z. Phys. A. 1992. V. 343. P. 35.

9. *Lacombe M. et al.* // Phys. Lett. B. 1981. V. 101. P. 139.

10. *Azhgirey L. S. et al.* // Nucl. Phys. A. 1991. V. 528. P. 621.

11. *Weinberg S.* // Phys. Rev. 1966. V. 150. P. 1313.

12. *Carbonell J., Karmanov V. A.* // Nucl. Phys. A. 1994. V. 581. P. 625.

13. *Azhgirey L. S., Yudin N. P.* // Yad. Fiz. 2005. V. 68. P. 163. [Phys. Atom. Nucl. 2005. V. 68. P. 160].

14. *Dikoussar N.D., Török Cs.* // Mathem. Modeling. 2006. V. 18. P. 23 (in Russian).

15. *Krish A. D.* // Phys. Rev. Lett. 1967. V. 19. P. 1149.

16. *Machleidt R.* // Phys. Rev. C. 2001. V. 63. P. 024001.

Received on November 17, 2006.

Редактор *В. В. Рудниченко*

Подписано в печать 19.02.2007.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,81. Уч.-изд. л. 1,07. Тираж 365 экз. Заказ № 55671.

Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@jinr.ru
www.jinr.ru/publish/