Determination of the deuteron momentum distribution in the ^{4}He nucleus from data on the reaction $^4\mathrm{He}p \to pdd$ at an initial nuclear momentum of 2.7 GeV/c

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The deuteron momentum distribution $\rho_{dd}(q)$ in the ^{4}He nucleus has been determined, for the first time, from data on the reaction $^4\mathrm{He}p \to pdd$ at an initial nuclear momentum of 2.7 GeV/c, for momenta $q < 0.3$ GeV/c of the spectator deuterons. The experimental data were obtained with the help of the two-meter liquid-hydrogen bubble chamber of the Institute of Theoretical and Experimental Physics. The pole-dominance criteria are analyzed. An extrapolation of the nuclear vertex function to the pole yields a lower limit on the vertex constant, $G^2_{\alpha dd} = 5.97 \pm 1.09$ fm. The experimental data are compared with theoretical predictions.

The momentum distributions of nucleons, deuterons, and ^{3}H's (^{3}He's), especially in the lightest nuclei, have been the subject of active research for many years now.[1] A comparison of empirical data with theoretical predictions can provide valuable information on nuclear models, the structure of a realistic nucleon–nucleon potential, and the nature of short-range correlations in nuclei. The role played by quark corrections is more important for the ^{4}He nucleus than for the deuteron or tritium, because of the higher nuclear density of ^{4}He (Ref. 2). A knowledge of the momentum distributions would make it possible to describe the cross sections for various reactions [(e,e') scattering, the interactions of photons and hadrons with nuclei, and few-nucleon transfer reactions: (d,t), (d,α), etc.].

In an effort to learn about the reaction mechanism in few-nucleon systems at intermediate energies, a systematic study is being carried out at the Institute of Theoretical and Experimental Physics (ITEP). This study is making use of accelerated beams of ^{3}H, ^{3}He, and ^{4}He nuclei and liquid-hydrogen bubble chambers as targets.

In this letter we are reporting the first experimental data on the deuteron momentum distribution $\rho_{dd}(q)$ in the ^{4}He nucleus from a study of the interaction of α particles with protons at the two-meter liquid-hydrogen bubble chamber of the ITEP.[3] The chamber was exposed to the separated beam of α particles from the synchrotron of the ITEP. (The average momentum in the chamber was 2.7 GeV/c; this figure corresponds to a kinetic energy $T_p = 220$ MeV for the primary protons in the rest frame of the nucleus.) The experimental procedure is described in detail in Ref. 4. The same paper gives results on the total and topological cross sections and also on the cross sections for various exclusive channels for αp interactions. The total cross section

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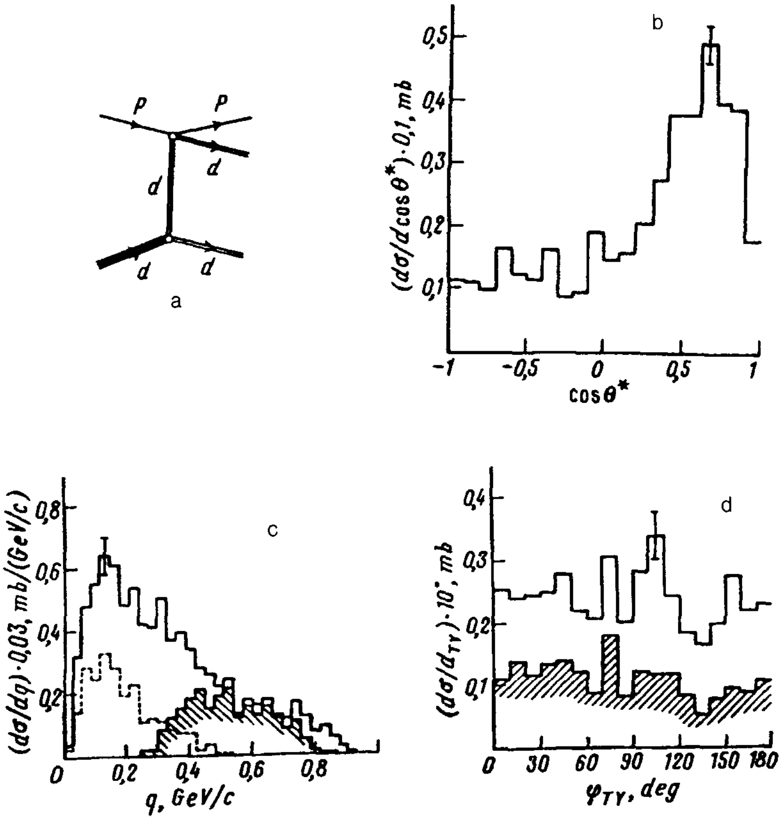

FIG. 1. a: QFS diagram. b: Distribution with respect to $\cos\theta^*$ in reaction (1), where θ^* is the proton scattering angle in the c.m. frame of the pd_F system. c: Momentum distribution of the deuterons in reaction (1). Solid histogram—All events (both combinations of deuterons); dashed and hatched histograms—distributions with respect to the momenta of the d_S and d_F deuterons, respectively, after selection I. d: Distribution with respect to the Treiman–Yang angle φ_{TY} (see the text proper for a definition) before (solid histogram) and after (hatched histogram) selections I and II.

for the αp interactions was found to be 109.4 ± 1.8 mb (this is the statistical error; the systematic error is $\simeq 3\%$).

A total of 705 events of the reaction

$$^4\mathrm{He}p \to pdd, \qquad (1)$$

were distinguished. The corresponding cross section is 4.3 ± 0.1 (stat.) mb. The method used to extract the spectral functions from the experimental data is described in detail in Refs. 5 and 6. In the pole approximation, which corresponds to the QFS diagram in Fig. 1a below, the momentum distribution $\rho_{dd}(q)$ of deuterons from the virtual decay $\alpha \to dd$ is associated with the differential cross section $d\sigma/dq^2$ for reaction (1) in the following way:

$$\rho_{dd}(q)=\frac{\pi^2}{m}\frac{\lambda(s,m^2,m_\alpha^2)}{\Phi(t)}\frac{d\sigma}{dq^2}, \tag{2}$$

$$\Phi(t)=\int_{\max[s_1^-(t),(m+m_d)^2]}^{s_1^+(t)} ds_1\sigma_{el}^{pd}[s_1(t)]\lambda^{1/2}[s_1(t),m^2,m_d^2], \tag{3}$$

$$\sigma_{el}^{pd}(s_1(t))=2\pi\int_{-C}^{C}\frac{d\sigma_{el}^{pd}[s_1(t)]}{d\Omega^*}d\cos\theta^*. \tag{4}$$

Here q is the momentum of the spectator deuteron (d_s), i.e., the deuteron with the smaller momentum in the proper frame of the ^{4}He; m, m_d, and m_α are the masses of the nucleon, the deuteron, and the ^{4}He nucleus; s and $s_1(t)$ are the squares of the invariant masses of the p^4He system and of the pd_F system in the final state (d_F is the deuteron with the larger momentum); t is the square of the 4-momentum transfer from the ^{4}He nucleus to the spectator deuteron; $d\sigma_{el}^{pd}[s_1(t)]/d\Omega^*$ is the off-shell cross section for elastic pd scattering; θ^* is the scattering angle between the primary and secondary protons in the c.m. frame of the pd_F system;

$$s_1^{\pm}(t)=s+m_d^2-\frac{1}{2m_\alpha^2}\{(s+m_\alpha^2-m^2)(m_\alpha^2+m_d^2-t)$$

$$\mp\lambda^{1/2}(s,m_\alpha^2,m^2)\lambda^{1/2}(t,m_\alpha^2,m_d^2)\},$$

$$\lambda(x,y,z)=(x+y+z)^2-4yz.$$

The parameter C will be discussed a bit further on.

The deuteron momentum distribution $\rho_{dd}(q)$ is determined by the square of the modulus of the overlap integral of the wave functions of the ^{4}He nucleus and the deuterons, summed over their spin variables. This distribution is related to the nuclear vertex function[7] $W_{dd}(q)$, i.e., the amplitude for the virtual decay $\alpha\rightarrow dd$, in the following way:

$$\rho_{dd}(q)=\frac{m_d^2}{(q^2+\kappa_{dd}^2)^2}W_{dd}^2(q), \tag{5}$$

$$W_{dd}^2(q)=\sum_{l=0,2}|W_{dd}^{(l)}(q)|^2. \tag{6}$$

Here $\kappa_{dd}^2=m_d(\epsilon_\alpha-2\epsilon_d)$, ϵ_α and ϵ_d are the binding energies of the α and the d (κ_{dd}=0.212 GeV), and the values $l=0$ and 2 correspond to the S and D waves of the dd system.

The approximations used in the derivation of expression (2) require some explanation. The distribution $\rho_{dd}(q)$ is not a quantity which can be observed directly in an experiment. Its relationship with the cross section for reaction (1), as described by (2), was derived in the pole approximation, by ignoring the contribution of D waves, which disrupt the factorization of the vertices. It follows from theoretical work on the momentum distribution of the deuterons in the ^{4}He nucleus,[8,9] based on realistic wave functions, that the ratio $|W_{dd}^{(2)}(q)/W_{dd}^{(0)}(q)|$ does not exceed 0.1 up to $q\simeq0.2$ GeV/c, and it increases to $\simeq 0.3$ at $q = 0.3$ GeV/c. A correct estimate of the extent to which the approximation of the factorization in (2) is disrupted by D waves requires calculating the interference of the S and D amplitudes $W_{dd}^{(1)}(q)$, with allowance for the explicit expression for the amplitude for elastic pd scattering. We intend to carry out such calculations. As will be seen from the experimental values of $\rho_{dd}(q)$ given below, the uncertainties which stem from the neglect of the D-wave contribution lie within the statistical errors, even at $q \simeq 0.3$ GeV/c. The factorization approximation can therefore be regarded as valid.

The cross sections for elastic pd scattering which are required for determining $\rho_{dd}(q)$ in (2)–(4) are parametrized on the mass shell. We use both the results of a phase-shift analysis and a compilation of experimental cross sections in the process. The off-shell effects which depend on the value of κ for the virtual decay $\alpha \to dd$ are larger than those for the decays $\alpha \to pt(n^3\mathrm{He})$ $\{\kappa = [3m(\epsilon_\alpha - \epsilon_{(^3\mathrm{He})t})/2]^{1/2} = 0.167\ (0.144)\ \mathrm{GeV}\}$. We have previously used the Mongan model to study[5,10] the influence of off-shell effects of elastic pN scattering in an extraction of the momentum distribution of nucleons in the ^{4}He, ^{3}He, and ^{3}H nuclei. We found that the off-shell effects in the pN amplitude increase the values of $\rho(q)$ for the virtual decays $\alpha \to Nt(^3\mathrm{He})$ by 10% at $q < 85$ MeV/c and by an average of 30% at $85 < q < 160$ MeV/c. For the decays $t(^3\mathrm{He}) \to \mathrm{Nd}$ $\{\kappa = [4m(\epsilon_{t(\tau)} - \epsilon_d)/3]^{1/2} = 8.84 \times 10^{-2}$ (8.29×10^{-2}) GeV$\}$ at $q < 160$ MeV/c, this increase amounts to less than 1%.

In order to reliably distinguish the contribution of the diagram of quasifree scattering with deuteron exchange (Fig. 1a) from other possible FSI diagrams (e.g., diagrams with pd_S and $d_S d_F$ rescattering in the final state), we impose two restrictions:

I. $|\cos\theta^*| < C, \quad C = 0.6$

II. $q < 0.3$ GeV/c.

Restriction I reduces the number of events to 386; when restriction II is also taken into account, we are left with 317 events of reaction (1). Analysis of the experimental data shows that by excluding the region $\cos\theta^* > 0.6$ it becomes possible to substantially reduce the fraction of events which have a small relative deuteron momentum. In the region $\cos\theta^* < -0.6$, it becomes possible to substantially reduce the fraction of events which have a small relative momentum of the proton and of the spectator deuteron (d_S). Restriction I thus makes it possible to substantially reduce the contribution of that part of the phase volume in which the final-state interaction is important (the FSI region). Restriction II (on the one hand) strengthens the first restriction and (on the other) singles out that part of the phase volume in which relativistic corrections and off-shell effects should not (in our opinion) significantly exceed our statistical errors. Figure 1b shows a distribution with respect to $\cos\theta^*$. This figure clearly demonstrates the need for restriction I: If there were no destructive interference of the QFS and FSI diagrams, the differential cross section should have reproduced the behavior of the cross section for elastic pd scattering on the mass shell, with the characteristic forward and backward peaks. As C is varied from 0.7 to 0.5, the values we find for $\rho_{dd}(q)$ vary within the statistical errors.

Another circumstance, no less important, is that under restriction I the momentum of the d_F deuteron has a lower bound: $q(d_F) \geqslant 0.3$ GeV/c. It thus becomes possible to eliminate the uncertainties associated with the identical nature of the deuterons, by going through an unambiguous procedure of selecting the spectator deuteron and thereby calculating $\rho_{dd}(q)$ in the region $q(d_s) \leqslant 0.3$ GeV/c. Figure 1c shows distributions with respect to the deuteron momentum d_S (the dashed histogram) and d_F (the hatched histogram) after selection I. The solid histogram shows the spectrum of deuterons (both combinations) before the selections. We see that the position of the peak in the spectrum for the d_S deuterons corresponds to the pattern of quasifree scattering (the QFS region).

In selections I and II, the conditions for dominance of the pole approximation, as formulated in Ref. 11, are satisfied. 1) We see in Fig. 1d that the distribution with respect to the Treiman–Yang angle φ_{TY} is essentially isotropic. (The angle φ_{TY} is the angle between the planes formed by, on the one hand, the momenta of the ^{4}He nucleus and the deuteron d_S and, on the other, the momenta of the final proton and of the deuteron d_F. All the momenta are taken in the proper frame of the initial proton.) 2) The fraction of events in which the relative kinetic energy of the pd_S and d_Sd_F systems is less than 20 MeV (in this case we can expect a significant manifestation of the FSI effect) is reduced by a factor of about 1.5 by selection I, and it does not exceed 4.5 and 20%, respectively. 3) Most of the events lie at small values of the "noncoplanar" angle: For $q \leqslant 0.3$ GeV/c, it is $\leqslant 10°$ for 75% of the events (for $q \leqslant 0.16$ GeV/c, the same fraction of events have a noncoplanar angle $\leqslant 6°$, while angles $\leqslant 10°$ correspond to 93% of the events). 4) The average value of the momentum transferred from the initial proton to the final proton, $\langle \Delta q \rangle = 0.54$ GeV/c, is larger than the reciprocal radius of the α particle (0.12 GeV/c). All these results indicate that the selection of QFS events is sufficiently correct.

Our final results for the momentum distribution of the deuterons in the α particle are shown in Fig. 2 (the errors are statistical). Also shown there are theoretical results on $\rho_{dd}(q)$ for two NN potentials, the Urbana potential[8] (the dashed curve) and the RSCV$_8$ potential[9] (the solid curve). Shiavilla *et al.*[8] have used a variational wave function for ^{4}He found from realistic Hamiltonians and incorporating the three-nucleon interactions and the S- and D-wave states in ^{4}He. As a result, a good description was found for the statistical characteristics of the ^{4}He nucleus, of the density of various physical quantities for light nuclei, and of the density of nuclear matter. Morita *et al.*[9,12] calculated various momentum distributions in the α particle with the help of wave functions found by the ATMS method.[13] It can be seen from Fig. 2 that the theoretical results of Refs. 8 and 9 are at odds with our data.

We approximated $\rho_{dd}(q)$ at $q \leqslant 0.3$ GeV/c by a function (χ^2/DF=0.86)

$$\rho_{dd}(q) = a_1 \exp(-b_1 q^2) + a_2 \exp(-b_2 q^2)$$

with the parameter values

$$a_1 = (1.26 \pm 0.54) \times 10^4 \quad (\text{GeV})/c)^{-3}, \quad a_2 = (7.6 \pm 2.3) \times 10^3 \quad (\text{GeV}/c)^{-3},$$

$$b_1 = (1.91 \pm 0.95) \times 10^2 \quad (\text{GeV}/c)^{-2}, \quad b_2 = (5.26 \pm 0.56) \times 10^1 \quad (\text{GeV}/c)^{-2}.$$

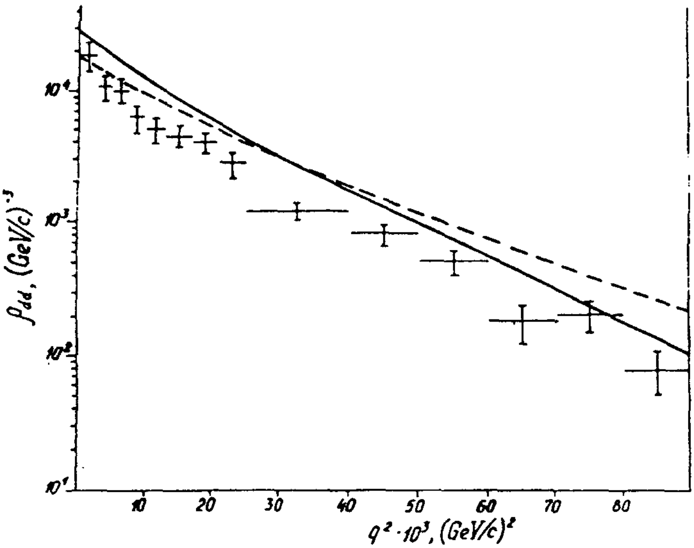

FIG. 2. Momentum distribution of the deuterons, $\rho_{dd}(q)$, in the ^{4}He nucleus. Points—Experimental data of the present study; curves—theoretical predictions for the Urbana NN potential[8] (the dashed curve) and the $RSCV_8$ NN potential[9] (solid curve).

At $q \leqslant 0.16$ GeV/c, it is convenient to use the approximation (χ^2/DF = 0.85):

$$\rho_{dd}(q) = A \exp(-Bq^2)$$

with the parameter values $A = (1.45 \pm 0.25) \times 10^4$ $(\mathrm{GeV}/c)^{-3}$ and $B = (0.75 \pm 0.12) \times 10^2$ $(\mathrm{GeV}/c)^{-2}$. The experimental values of the nuclear vertex function $W_{dd}(q)$ [see Eq. (5)] in the region $q \leqslant 0.16$ GeV/c conform well to a straight line (χ^2/DF=1.37):

$$W_{dd}(q) = a_0 + a_1 q^2,$$

with $a_0 = (2.66 \pm 0.17)$ $(\mathrm{GeV}/c)^{-1/2}$ and $a_1 = -(63.32 \pm 10.46)$ $(\mathrm{GeV}/c)^{-5/2}$.

An approximation of the nuclear vertex function by a straight line at small values of q indicates that the selection of QFS events is correct.

Extrapolating the nuclear vertex function $W_{dd}(q)$ at $q \leqslant 0.16$ GeV/c to the pole at $q^2 = -\kappa_{dd}^2$, we find the nuclear vertex constant (in the notation of Ref. 7): $G_{\alpha dd}^2 = 5.97 \pm 1.09$ fm. The phenomenological values of $G_{\alpha dd}^2$ have a very large scatter.[7] The nuclear vertex function in the nonphysical region has a highly nonlinear behavior. The value which we found is thus a lower limit on the nuclear vertex constant. It agrees with the estimate $G_{\alpha dd}^2 = 8.6$ fm found in Ref. 14 for a simplified S-wave NN potential in the method of composite quark bags. (A theoretical value derived through a calculation with the help of Faddeev–Yakubovskiĭ equations for the separable Yamaguchi potential[15] with $l = s = 0$ is $G_{\alpha dd}^2 = 18$ fm.)

Finally, we would like to stress once more that a selection of events with conditions I and II in an exclusive experiment makes it possible to single out that part of the phase volume in which the deuteron cluster in the ^{4}He nucleus can be treated as a quasifree deuteron. On the other hand, at a qualitative level, because of the tight binding (the small size) of ^{4}He ($R_c = 1.67 \pm 0.1$ fm) and the small binding energy (the large size) of the free deuteron ($R_c = 2.095 \pm 0.006$ fm), it is generally not obvious that the knockout of a deuteron cluster can be described by a quasielastic mechanism [in this connection, see the discussion in Refs. 16 and 17 of the mechanism for the ^{4}He$(e,e'd)^2$H reaction].

It would be of interest to study reaction (1) at higher initial energies. Such a study would make it possible to expand the range of applicability of the QFS approximation and to reduce the influence of off-shell effects. We are presently analyzing the results of an exposure of the two-meter liquid-hydrogen bubble chamber at an initial α momentum of 5 GeV/c . From the theoretical standpoint, it would be extremely desirable to incorporate off-shell effects and to study diagrams with a FSI. The purpose here would be to make a comparison with experimental data on reaction (1) over the entire phase volume and to test the range of applicability of the impulse approximation.

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