THE DEUTERON D-STATE PROBABILITY

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Abstract

A method of direct determination of the deuteron D-state probability from the experiment, based on the $d\uparrow p \rightarrow ppn$ reaction analysis is suggested. Using the known results on the vector analyzing power in elastic NN-scattering, the values of the overall nucleon polarization and the deuteron vector polarization have been obtained. The probability of the deuteron D-state is estimated to be $w_D = 0.078 \pm 0.046$.

1. Introduction

The research of deuteron structure, in connection with fundamental quantum chromodynamics (QCD) problems is of eminent interest, namely at small distances ($< 1.fm$) or at large internal momenta ($> 0.2\ GeV/c$), when its size becomes less than that of the free constituents, nucleons overlap and may form a droplet of quark matter. The transition to the QCD level description requires the full understanding of the differences between the real deuteron characteristics and the predictions in terms of nucleon physics.

The deuteron structure can be experimentally investigated by measuring the spectrum of spectator nucleons $\rho(k)$, which can be in impulse approximation directly related to the deuteron wave function (DWF) $\Psi(k)$ in momentum representation $\rho(k) = \Psi^2(k) = u^2(k) + w^2(k)$, where $u(k)$, $w(k)$ stands for the S- and D-states, respectively, and k is the momentum of the nucleons inside the deuteron. The small k ($< 0.2\ GeV/c$) behaviour of the $u(k)$ and $w(k)$ functions can be theoretically predicted using various NN potentials with nuclear core (Reid, Bonn, Paris) and supposing point-like nonrelativistic nucleons [1]. The S-wave is dominant in this region. This approach becomes unreliable at large k ($> 0.2 \div 0.3$ GeV/c) because of possible internal nucleon structure effects, relativistic corrections, etc. In the frame of nuclear core hypothesis the D-wave domination at nucleon momenta of $0.3 \div 0.6$ GeV/c and oscillating $u(k)$ behaviour with zero crossing at $k = 0.4$ GeV/c have been predicted [3]. Another $u(k)$ behaviour with filling the dip at 0.4 GeV/c and a decreasing D-wave dominance is predicted in this region by alternative deuteron models such as bag models, quark counting rules [4]. This structure of the DWF is rather untrivial since the total D-wave contribution $w_D = \int w^2(k)dk = 0.04 \div 0.08$ is small and not precisely determined [2].

However, the real $u(k)$ and $w(k)$ structure in this region has not yet been checked. Since the D-wave predominance leads to a strong cross section dependence on the orientation of the deuteron spin, so polarization experiments with deuterons seem to be very important. They enable to measure not only the summary momentum distribution $\rho(k)$ but also to obtain the D/S-state ratio $x(k) = u(k)/w(k)$ at any internal momentum and thus to separate the $u(k)$ and $w(k)$ contributions. So, the existing uncertainties concerning the D-state contribution at distances below 1.5 fm and especially inside the core can be overcome.

In this paper the relation between the deuteron polarization and the polarization of its constituents will be investigated. The former depends on D/S-state ratio $x(k)$. Based on this relation an experimental method for determination of the deuteron D-state probability has been proposed. This method has been used in the study of the direct break-up reaction $d \uparrow p \rightarrow (pn)p$ induced by a vector polarized deuteron beam.

2. Nucleon Polarization in Polarized Deuteron

The DWF expressed in the momentum representation has the following structure:

$$\Psi_1^M(\vec{k}) = \sum_L \Phi_L(k) \sum_{\lambda,\mu} < L\lambda 1\mu \mid 1M > Y_L^\lambda(\vec{k}_0)\chi_1^\mu. \qquad (1)$$

M denotes the spin projection to the quantization axis and $\vec{k}$ is the nucleon relative internal momentum. The radial dependences of S- and D-state are explicitly expressed by the functions $\Phi_0(k) = u(k)/k$ and $\Phi_2(k) = w(k)/k$. The last parts include the angular dependence expressed by the spherical harmonics $Y_L^\lambda(\Theta, \phi)$, spin information on DWF and the coupling of the orbital angular momentum L with the spin $S = 1$ described by Clebsh-Gordan coefficients. The triplet spin function χ_1^μ with the projection μ expresses the coupling of two $\frac{1}{2}$ spins - proton and neutron ones:

$$\chi_1^{\pm 1} = \mid p >^\pm \mid n >^\pm, \quad \chi_1^0 = \frac{1}{\sqrt{2}}(\mid p >^+ \mid n >^- + \mid p >^- \mid n >^+),$$

where $\mid p >^\pm, \mid n >^\pm$ are proton and neutron spinors with $\pm\frac{1}{2}$ projections. The normalization condition is:

$$\int (u^2(k) + w^2(k))dk = 1. \tag{2}$$

The probability densities $\rho_{d=1}^M = | \Psi_{d=1}^M |^2$ of the deuteron in $M = +1, 0, -1$ magnetic substates can be obtained from the equations (1) by use of the ortogonality conditions and taking into account the relations:

$$| \chi_1^{\pm 1} |^2 = \rho^\pm, \quad | \chi_1^0 |^2 = \frac{1}{2}(\rho^+ + \rho^-),$$

where $\rho^\pm$ are the probabilities for the nucleon to be found with spin projections $\pm\frac{1}{2}$,

$$4\pi\rho_d^{\pm 1} = \rho^\pm[\Phi_0^2(k) + \frac{\Phi_2^2(k)}{4}(1 + P_2(\Theta)) + \sqrt{2}\Phi_0(k)\Phi_2(k)P_2(\Theta)] + \rho^\mp\frac{3\Phi_2^2(k)}{4}[1 - P_2(\Theta)], \tag{3}$$

$$4\pi\rho_d^0 = \frac{\rho^+ + \rho^-}{2}[\Phi_0^2(k) + \Phi_2^2(k)(1 + P_2(\Theta)) - 2\sqrt{2}\Phi_0(k)\Phi_2(k)P_2(\Theta)], \tag{4}$$

with $P_2(\Theta) = \frac{1}{2}(3cos^2\Theta - 1)$. One obtains thus the relation between ρ_d^M and $\rho^\pm$.

Let us consider the deuteron in a magnetic field $\vec{H}$. In a coordinate system with the quantization axis parallel to $\vec{H}$ (axis of symmetry) two independent parameters:
$P_z^d = (n_+ - n_-)/(n_+ + n_0 + n_-)$ - the vector polarization and
$P_{zz}^d = (n_+ + n_- - 2n_0)/(n_+ + n_0 + n_-)$ - the tensor polarization,
expressed in terms of deuteron populations n_+, n_0, n_- in magnetic substates $M = +1, 0, -1$, respectively, are enough to describe the polarization state of this system.

Taking into account these populations and the distributions of probability densities ρ_d^M in individual states (3), (4) one can calculate the relative numbers of nucleons in the states with spin projection $+\frac{1}{2}$ and $-\frac{1}{2}$ denoted as N_+ and N_-, respectively. Then the constituent nucleon polarization can be obtained from the definition: $P_z^N = (N_+ - N_-)/(N_+ + N_-)$ and one arrives to a general relation between the deuteron polarization and the polarization of its nucleons:

$$P_z^N(k, \theta) = \frac{P_z^d[x^2(k) + \sqrt{2}x(k)P_2(\theta) + P_2(\theta) - 1/2]}{P_{zz}^d[\sqrt{2}x(k)P_2(\theta) - P_2(\theta)/2] + x^2(k) + 1}. \tag{5}$$

The polarization P_z^N of nucleons inside the deuteron depends on the internal motion in the nucleus (momentum k, polar angle θ) and on the polarized deuteron beam characteristics (vector P_z^d and tensor P_{zz}^d polarizations). Formula (5) can be simplified if only vector polarization is present, as it is in the present experiment. The predictions for angular and momenta distributions of relative nucleon polarization from two widely used nucleon-nucleon potentials - the Bonn (the first version) [5] and the Paris ones [6] are represented in Fig.1.

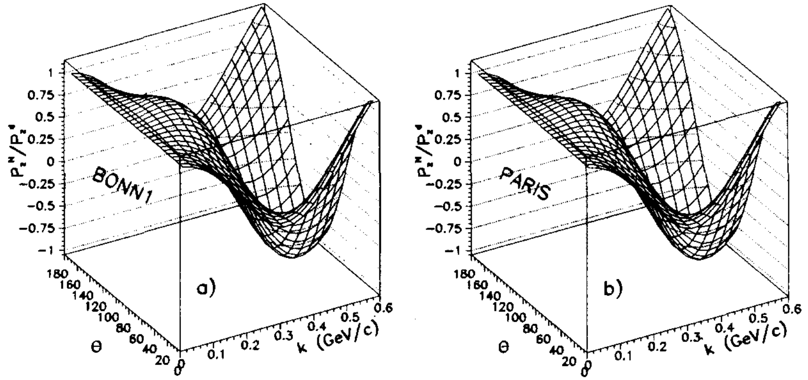

Figure 1: The angular vs momentum dependences of the relative nucleon polarization for Bonn and Paris DWF's.

Integrating the number of nucleons over the full solid angle, just suitable in case of bubble chambers, the expression for momentum dependence of the relative nucleon polarization is as follows:

$$P_z^N(k) = P_z^d \frac{x^2(k) - \frac{1}{2}}{x^2(k) + 1}. \tag{6}$$

The results of calculations with all three Bonn potentials, Paris one, Gartenhaus-Moravcsik (GM) [7] and a simple OPE potential [8] are presented in Fig.2.

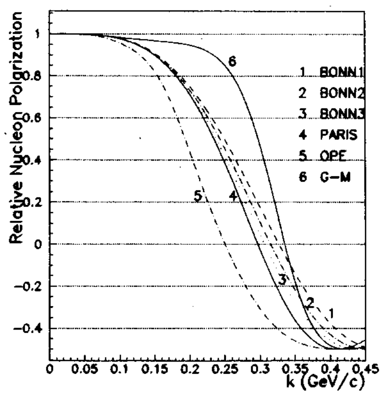

Figure 2: Relative nucleon polarization predicted for different DWF's.

One can see that P_z^N/P_z^d is close to unit up to $0.06 \div 0.07 GeV/c$ for all DWF's. The following integration over the nucleon momenta leads to the overall polarization of the nucleons in the deuteron:

$$P_{z,o}^N = P_z^d\Big(\int u^2(k)dk - \int \frac{1}{2}w^2(k)dk\Big) = P_z^d(1 - \frac{3}{2}w_D). \tag{7}$$

It can be seen that if the vector polarization of the deuteron and that of the nucleons are known, one can determine the probability of the D-state component of the DWF. Note that the presented method does not depend on the concrete form of the DWF.

3. Experimental Results

A possible method of the deuteron D-state probability determination consists in the study of the $d \uparrow p \to (pn)p$ break-up reaction which proceeds mainly like a quasifree NN- scattering. The detection of these events is practically without losses, due to the accelerated deuterons. The data have been obtained by means of the 1m hydrogen bubble chamber of LHE JINR irradiated by vector polarized deuterons at 3.34 GeV/c. Thus the condition of 4π-geometry was fulfilled and the expression (7) may be used. The set of data consists of 31,150 events.

The nucleon polarization can be experimentally measured analysing the azimuthal asymmetry of the recoiled nucleons from the quasifree nucleon scattering on the proton target. As it can be seen from Fig.2 $P_z^d \approx P_z^N$ for small k and therefore one can within the same experiment determine both parameters - the overall nucleon and the deuteron polarizations.

To determine the nucleon polarization it is necessary to know the analyzing power A of the $d \uparrow p \to (pn)p$ reaction. They are simply related by $P_z = \frac{\epsilon}{A}$, where ϵ is the azimuthal asymmetry of the polarized recoiled particles. Using the results on polarization in pp- and np- elastic scattering at our kinetic energy from [9], [10] and equality of the analyzing power and polarization for elastic scattering one can determine the analyzing power of the studied reaction assuming quasielastic processes.

The analyzing power of the $dp \to (pn)p$ reaction has been calculated in two steps. Polarizations have been averaged separately in both pp and np reactions over the four-momentum transfer squared. Finally the searched analyzing power is obtained by weighting the pp and np averages with the numbers of quasifree pp and np events from the $d \uparrow p \to (pn)p$ reaction.

The analysis was performed for a) all events and b) events with spectator momenta k below 0.065 GeV/c, because the deuteron and nucleon vector polarizations as shown before are approximately equal in this region. The mean values of analyzing powers are:

- $\bar{A}_a = 0.3296 \pm 0.0117$ for the a) sample,
- $\bar{A}_b = 0.3320 \pm 0.0124$ for the b) sample.

The azimuthal distribution of the recoiled nucleons for these two samples are displayed in Fig.3a and Fig.3b, respectively.

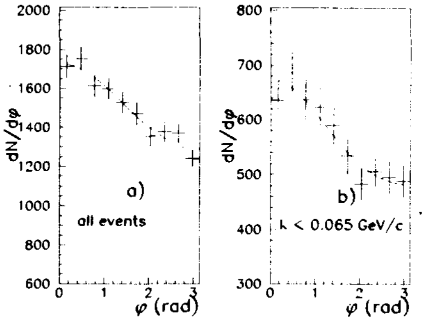

Figure 3: The azimuthal distributions of the recoiled nucleons for all events (a) and for the data set with spectator momenta below 0.065 GeV/c (b)

A function of form

$$N(\phi) = N_0(1 + \epsilon cos\phi + C cos2\phi) \tag{8}$$

was fitted to the data, where ϵ describes the asymmetry related to the vector polarization and coefficient C is connected with the deuteron tensor polarization. The results of the fit are shown in table 1.

Table 1

Parameters	*all events*	$k < 0.065 GeV/c$
N_0	$1,508 \pm 17$	567 ± 11
ϵ	0.143 ± 0.015	0.162 ± 0.020
C	0.009 ± 0.016	0.018 ± 0.020
χ^2/ND	0.70	0.47

The corresponding polarizations for this two samples are:
- the overall nucleon polarization $P_z^N = 0.434 \pm 0.044$ (a) and
- the deuteron polarization $P_z^d = 0.488 \pm 0.061$ (b).

One can now estimate the deuteron D-state probability from (7):

$$w_D = 0.078 \pm 0.046.$$

Note that the analyzing powers A_a and A_b are practically equal, so, one does not need to evaluate polarizations to obtain w_D. The full experimental verification of the predicted momenta and angular dependences of the nucleon polarization especially near the kinematical limit is of great interest.

4. Summary

- relative nucleon polarization inside the deuteron has been derived and discussed,
- a method of direct determination of the deuteron D-state probability was proposed,
- on the basis of $d \uparrow p \to (pn)p$ reaction analysis a method of the w_D estimation was demonstrated and the possibility to use the presented method in a full solid angle experiment.

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