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COMMENTS ON EXPERIMENTAL TESTS OF D-STATES

IN THE ${}^3\text{He} - {}^3\text{H}$ GROUND STATE

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A B S T R A C T

Recent experiments relevant for D-state components in the ground state of the $A = 3$ systems are discussed in a simple scheme. This displays the close connection between the tensor force and the D-state components and allows one to interpret the experimental results in a transparent way. Suggestions for a complete experimental test of the D-state are given.

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It is known since the pioneering work by Gerjuoy and Schwinger¹⁾ that the NN tensor force generates several D-wave components in the ground state of ^3He and ^3H . Their total probability represents about 8 to 9 per cent^{2),3)}. The tensor interaction is crucial to the binding energy of the $A = 3$ nuclei. In fact, most of the potential energy comes from the S-D coupling due to such a force^{2),3)}.

More direct and unambiguous evidence for D-state components in the $A = 3$ systems has been provided by recent experiments^{4),5)}. The analysis of the most recent, and also the most interesting, experiment has been carried within the context of sophisticated Faddeev calculations⁵⁾. Although this approach is reliable, it obscures the close connection between the D-state components and the tensor interaction. This connection is well known for the closely related deuteron D-state⁶⁾.

The aim of the present note is to display this relation between the tensor interaction and the dominant D-wave components. For this purpose it is enough to generate the D-state by operating with the tensor potential on the completely space-symmetric S-state, which is by far the dominant component (about 88 per cent in probability) of the $A = 3$ ground state^{2),3)}. The D-state so obtained has the same geometrical structure as the corresponding state derived in perturbation theory⁷⁾. Moreover, according to Faddeev calculations²⁾, these components are the most important ones and account for about 80 per cent of the total D-state probability. This approach provides a qualitative transparent scheme for the interpretation of the experiments. In particular it allows one to ascertain in a straightforward way which D-state components can be explored in any given experiment. The S-wave component of the $A = 3$ ground state is given by

$$\psi_0 = \frac{1}{\sqrt{2}} \psi_S(r_{12}, r_{13}, r_{23}) \left[\chi^{\frac{1}{2}}([12]-) \{([12]+) - \chi^{\frac{1}{2}}([12]+) \{([12]-)\} \right] \quad (1)$$

The spatial part ψ_S depends on the three interparticle distances r_{12} , r_{13} and r_{23} and is completely symmetric with respect to the interchange of the three nucleons. The completely antisymmetric spin-isospin components are a linear combination of products of mixed symmetry states. The spinors $\chi^{\frac{1}{2}}([12]-)$ and $\chi^{\frac{1}{2}}([12]+)$ are respectively antisymmetric and symmetric in nucleons 1 and 2:

$$\begin{aligned}\chi^{\frac{1}{2}}([12]-) &= \frac{1}{\sqrt{2}} (\alpha_1 \beta_2 - \alpha_2 \beta_1) \alpha_3, \\ \chi^{\frac{1}{2}}([12]+) &= \frac{1}{\sqrt{6}} [2\alpha_1 \alpha_2 \beta_3 - (\alpha_1 \beta_2 + \alpha_2 \beta_1) \alpha_3].\end{aligned}\quad (2)$$

Similar expressions hold for the isospinors $\xi([12]-)$ and $\xi([12]+)$.

The total wave function ψ_0 can be usefully written in the form

$$\psi_0 = -\frac{1}{\sqrt{3}} (1 + P_+ + P_-) \psi_S(r_{12}, r_{13}, r_{23}) \chi^{\frac{1}{2}}([12]-) \pi_1 \pi_2 \nu_3 \quad (3)$$

where the isospinors π and ν refer to $t_z = -\frac{1}{2}$ (proton) and $t_z = \frac{1}{2}$ (neutron) respectively and P_+ and P_- are cyclic permutation operators.

Apart from a normalization constant, the D-state is given in our approach by

$$\psi_D = \sum_{i,j} \tau_i \cdot \tau_j S_{ij} V_T(r_{ij}) \psi_0, \quad (4)$$

where $V_T(r)$ is the radial part of the tensor potential and S_{ij} is the well-known tensor operator for particles i and j :

$$S_{ij} = 3 \vec{\sigma}_i \cdot \hat{r}_{ij} \vec{\sigma}_j \cdot \hat{r}_{ij} - \vec{\sigma}_i \cdot \vec{\sigma}_j. \quad (5)$$

We consider for simplicity only the isovector component of the tensor force. It has the same spin-isospin structure as the one-pion-exchange potential, which plays a dominant role in the corresponding problem for the deuteron⁶⁾. For the present purpose it is not necessary to consider the less important isoscalar part since this does not change the geometrical structure of the D-state component in Eq. (4).

After some straightforward manipulation Eq. (4) becomes

$$\psi_D = -\sqrt{\frac{8}{3}} (1 + P_+ + P_-) V_T(r_{12}) [T(\hat{r}_{12}, \hat{r}_{12}) \otimes \chi^S] \chi^{\frac{1}{2}}([12]-) \psi_S \quad (6)$$

Here $T(\hat{r}_{12}, \hat{r}_{12})$ is a spatial second-rank tensor carrying relative angular momentum $l_{12} = 2$ for particles 1 and 2 and χ^s is a completely symmetric $s = 3/2$ spinor. They are coupled so as to give a $j = \frac{1}{2}$ state. In Cartesian co-ordinates we have

$$[T(\hat{r}_{12}, \hat{r}_{12}) \otimes \chi^s]^{\frac{1}{2}} = \sum_{kl} T_{kl}(\hat{r}_{12}, \hat{r}_{12}) \chi_{kl}^s, \quad (7)$$

where

$$T_{kl}(\vec{x}, \vec{y}) = \frac{1}{2} (x_k y_l + x_l y_k) - \frac{1}{3} \delta_{kl} \vec{x} \cdot \vec{y} \quad (8)$$

and

$$\chi_{kl}^s = S_{kl}^{(12)} \chi^{\frac{1}{2}}([12]-), \quad (9)$$

$$S_{kl}^{(12)} = \frac{3}{2} (\sigma_k^{(12)} \sigma_l^{(3)} + \sigma_l^{(12)} \sigma_k^{(3)}) - \vec{\sigma}^{(1)} \cdot \vec{\sigma}^{(3)} \delta_{kl}$$

$$\vec{\sigma}^{(12)} = \frac{1}{2} (\vec{\sigma}^{(2)} - \vec{\sigma}^{(1)}).$$

Equation (6) for ψ_D shows clearly that the D-state in ^3He or ^3H is a linear combination of deuteron-like components. This makes plausible the fact that the D-state probabilities in $A = 2$ and $A = 3$ nuclei are comparable. It also suggests that the test of D-wave components is essentially a test of deuteron-like D-state correlations in $A = 3$ systems.

In order to relate ψ_D to the experimental analysis it is useful to introduce the new co-ordinates

$$\vec{x} = \vec{r}_2 - \vec{r}_1, \quad \vec{y} = \vec{r}_3 - \frac{1}{2}(\vec{r}_1 + \vec{r}_2). \quad (10)$$

As illustrated by Fig. 1, $\vec{x}$ is the relative co-ordinate between the two "interacting" particles 1 and 2 and $\vec{y}$ is the co-ordinate of the third "free" particle with respect to the center-of-mass of the other two. We denote by l and λ the relative angular momenta corresponding to $\vec{x}$ and $\vec{y}$ respectively.

Expressed in these new co-ordinates, ψ_D assumes the form:

$$\begin{aligned} \psi_D = & -\sqrt{\frac{2}{3}} F_T(x) [T(\hat{x}, \hat{x}) \otimes \chi^S]^{\frac{1}{2}} \xi([12]-) \psi_s \\ & - \sqrt{\frac{2}{3}} F_T(|\vec{y} - \frac{1}{2} \vec{x}|) \{ [T(\hat{y}, \hat{y}) + \frac{1}{4} T(\hat{x}, \hat{x}) - \frac{1}{2} T(\hat{x}, \hat{y})] \otimes \chi^S \}^{\frac{1}{2}} \xi([12]-) \psi_s \\ & + \sqrt{\frac{2}{3}} F_T(|\vec{y} + \frac{1}{2} \vec{x}|) \{ [T(\hat{y}, \hat{y}) + \frac{1}{4} T(\hat{x}, \hat{x}) + \frac{1}{2} T(\hat{x}, \hat{y})] \otimes \chi^S \}^{\frac{1}{2}} \xi([13]-) \psi_s, \end{aligned} \quad (11)$$

where $F_T(x) = V_T(x)/x^2$.

To lowest order in the multipole expansion, ψ_D becomes

$$\begin{aligned} \psi_D = & -\sqrt{\frac{2}{3}} [F_T(x) - \frac{1}{4} F_T^{(0)}(x, y)] [T(\hat{x}, \hat{x}) \otimes \chi^S]^{\frac{1}{2}} \xi([12]-) \psi_s \\ & + \sqrt{\frac{2}{3}} F_T^{(0)}(x, y) [T(\hat{y}, \hat{y}) \otimes \chi^S]^{\frac{1}{2}} \xi([12]-) \psi_s \\ & - \sqrt{\frac{2}{3}} F_T^{(0)}(x, y) [T(\hat{x}, \hat{y}) \otimes \chi^S]^{\frac{1}{2}} \xi([12]+) \psi_s, \end{aligned} \quad (12)$$

where $F_T^{(0)}(x, y)$ is the angle-independent term in the expansion of $F_T(|\vec{y} \pm \frac{1}{2} \vec{x}|)$. The first term carries angular momenta $l = 2$, $\lambda = 0$, the second $l = 0$, $\lambda = 2$ and the third $l = \lambda = 1$. The D-state derived by perturbative methods has exactly the same components⁷⁾. According to Faddeev calculations²⁾ (Table) the three $l = 2$, $\lambda = 0$, $l = 0$, $\lambda = 2$ and $l = \lambda = 1$ components account respectively for approximately 37 per cent, 12 per cent and 30 per cent of the total D-state probability. Of the remaining higher components only the $l = 1$, $\lambda = 3$ is relevant with a probability of about 13 per cent. The others have very small amplitudes.

We can now investigate which channels have been actually tested experimentally so far. To our knowledge, the first unambiguous experimental information on the D-state components in $A = 3$ nuclei has been obtained by measuring the tensor analyzing powers for $(\vec{d}, t)$ reactions at sub-Coulomb energies⁴⁾. These quantities have been shown⁸⁾ to depend on one single parameter D_2 , related to the S and D channels:

$$D_2 = \frac{1}{15} \frac{\int_0^\infty u_2(y) y^4 dy}{\int_0^\infty u_0(y) y^2 dy} \quad (13)$$

In this expression, $u_0(y)$ and $u_2(y)$ are the radial wave functions defined by the overlap integral

$$R(\vec{y}) = \langle X_{\frac{1}{2}m_n}^{(n)} \varphi_{1m_d}^{(d)} | \psi_{\frac{1}{2}m_t}^{(t)}(\vec{x}, \vec{y}) \rangle$$

$$= \sum_{\substack{\lambda=0,2 \\ \mu, m}} \langle 1m_d \frac{1}{2}m_n | S m \rangle \langle \lambda \mu S m | \frac{1}{2}m_t \rangle Y_{\lambda\mu}(\vec{y}) u_{\lambda}(y), \quad (14)$$

where $s = \frac{1}{2}$ for $\lambda = 0$ and $s = 3/2$ for $\lambda = 2$ and the n, d and t labels refer to neutron, deuteron and triton, respectively. The values of D_2 extracted from the data⁴⁾ are in the range $-0.30 \lesssim D_2 \lesssim -0.24 \text{ fm}^2$. The D_2 parameter tests only the $\lambda = 2, l = 0$ component. The overlap integral in fact involves an integration with respect to the proton-neutron co-ordinate $\vec{x}$ of the deuteron, which contains the $l_d = 0$ and $l_d = 2$ components. The main contribution to $R(\vec{y})$ comes obviously from the $\lambda = 1, l = 0$ component of the $A = 3$ wave function. This term defines $u_0(y)$. The component $u_2(y)$ is defined by the overlap of the deuteron D-wave with the $\lambda = 2, l = 0$ component. The contributions from other channels either vanish or are proportional to the product of the deuteron and triton D-wave amplitudes and can therefore be neglected.

A more complete test of the D-state in $A = 3$ is provided by a recent experiment⁵⁾ which inspired the present comments. The authors of Ref. 5) measured the tensor analyzing power $A_{yy}(\theta)$ of the reaction $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ at $\theta_{\text{lab}} = 90^\circ$. They analyzed their results in the light of an exact Faddeev calculation for both continuum and bound states using the Reid soft-core potential. The main conclusions can be summarized as follows.

- i) At the angle chosen ($\theta_{\text{lab}} = 90^\circ$), the reaction from the continuum proton-deuteron state to the ^3He ground state proceeds almost entirely through E1 radiation. The E2 and M1 as well as higher multipole contributions to A_{yy} are negligible at $\theta = 90^\circ$ and become important only in the forward and backward directions, more precisely outside the region $40^\circ \lesssim \theta \lesssim 150^\circ$.

- ii) The most important component of the continuum wave function is a proton-deuteron P-wave with channel spin $s_0 = 3/2$.
- iii) The tensor analyzing power $A_{yy}(\theta)$ depends entirely on the D-components of the ^3He ground state: it vanishes when the tensor force (i.e., the D-state) is absent. On the other hand, it is nearly insensitive to the deuteron D-state in the initial p-d state.
- iv) The dominant contribution to A_{yy} , about 89 per cent, is due to transitions into D-state components with $l = \lambda = 1$. The $l = 0, \lambda = 2$ component contributes about 9 per cent while the $l = 2, \lambda = 0$ channel does not contribute at all.

Let us try to explain these results in our simplified scheme. The E1 operator has the form

$$M(E1) = \frac{e}{2} \sum_i (1 - \tau_3^{(i)}) \vec{r}_i. \quad (15)$$

In the new co-ordinates $\vec{x}$ and $\vec{y}$ this operator becomes

$$M(E1) = \frac{e}{2} \left[\frac{\tau_3^{(1)} - \tau_3^{(2)}}{2} \vec{x} + \frac{\tau_3^{(1)} + \tau_3^{(2)} + 2\tau_3^{(3)}}{3} \vec{y} \right]. \quad (16)$$

The structure of the components in the entrance channel is approximately

$$\psi_{\lambda_0 l_d s_0}^{(-)} \approx \varphi_{\lambda_0}(\vec{y}) \psi_{l_d}(\vec{x}) \chi^{s_0} \xi([12]-), \quad (17)$$

where $\psi^{(-)}$ [or $\psi^{(+)}$] refer to the symmetry properties of the isospinors $\xi([12]-)$ [or $\xi([12]+)$] with respect to particles 1 and 2.

The E1 operator (15) acting on $\psi_{\lambda_0 l_d s_0}^{(-)}$ gives

$$M(E1) \psi_{\lambda_0 l_d s_0}^{(-)} \approx -\frac{e}{2} \vec{x} \psi_{\lambda_0 l_d s_0}^{(+)} - \frac{e}{3} \vec{y} \psi_{\lambda_0 l_d s_0}^{(-)}. \quad (18)$$

One should note that the action of the $M(E1)$ term linear in $\vec{x}$ has turned $\psi^{(-)}$ into $\psi^{(+)}$. It follows from parity and spin conservation that only the components with odd λ_0 and $s_0 = 3/2$ in the entrance channel are coupled by the E1 operator to the D-component of the ^3He ground state. A comparison with expression (12) for ϕ_D shows that the terms linear in $\vec{x}$ and $\vec{y}$ couple the $\lambda_0 = 1, l_d = 0, s_0 = 3/2$ entrance channel to the $\lambda = 1, l = 1$ and $\lambda = 2, l = 0$ D-state

components respectively. The resulting contribution to $A_{yy}(\theta)$ is proportional to these large amplitudes and is therefore sizeable. The contribution from other couplings is either vanishing or small. For instance, the entrance channel $\lambda_0 = 1, l_d = 2$ is coupled to the D-state by both the $\vec{x}$ and $\vec{y}$ terms of the E1 operator. The contribution to $A_{yy}(\theta)$, however, is proportional to the product of deuteron and the ^3He D-state amplitudes, which makes this term quite small. This explains why $A_{yy}(\theta)$ is insensitive to the deuteron D-state in the entrance channel. These simple considerations lead to the conclusion, supported by detailed calculations⁵⁾, that the tensor analyzing power $A_{yy}(\theta)$ at $\theta = 90^\circ$ tests the important $\lambda = 1, l = 1$ component, as well as the relatively small $\lambda = 2, l = 0$ one, which has already been tested by other experiments. Its recent determination represents therefore a major progress toward the experimental knowledge of the D-state in ^3He and ^3H .

The most important component which has $\lambda = 0, l = 2$ remains unexplored, however. Can the determination of the tensor analyzing powers at forward and backward angles, where other multipoles contribute, provide information on this channel?

Consider first the M1 transition. In the impulse approximation this transition is suppressed because of the quasi-orthogonality of the $A = 3$ S-state to the unbound states in the entrance channel. The transition is therefore dominated by meson exchange currents^{5),9)}, which makes it of little use for our purpose.

More relevant to the $\lambda = 0, l = 2$ D-state is the E2 contribution. In fact, the E2 operator, expressed in $\vec{x}$ and $\vec{y}$ coordinates, contains terms in $Y_2(x)$, $[Y_1(x) Y_1(y)]_2$ and $Y_2(y)$ and therefore couples all three D-state components to the $\lambda_0 = l_d = 0, s_0 = 3/2$ entrance channel.

We recall, however, that the E2 contribution is non-negligible only in the regions $\theta \lesssim 40^\circ$ and $\theta \gtrsim 150^\circ$, where also the M1 and higher multipole transitions as well as the E1 term contribute⁵⁾. The complexity of this situation requires a very careful theoretical study with very good wave functions. In addition the meson exchange currents, which dominate the M1 transition must be treated properly. So far only an approximate calculation has been performed¹⁰⁾. The interference between the E1 and E2 contributions to the tensor analyzing powers at forward and backward angles determines an angular distribution of $T_{21}(\theta)$ quite different from that of $A_{yy}(\theta)$. This result is interesting but far from

conclusive, because many serious approximations are involved. The M1 and higher multipole transitions were ignored. The relative motion between the deuteron and the other nucleon in the continuum was described only in the plane wave approximation. This has been shown inadequate⁵⁾: the distortion of the proton-deuteron wave function reduces $A_{yy}(\theta)$ by 40 to 60 per cent.

We conclude that a complete and sophisticated theoretical analysis is necessary in order to use $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ radiative capture as a test of the full D-state.

It was suggested recently¹¹⁾ that information on the D-state can be provided by the asymmetry in $^3\text{He}(\vec{e}, e')X$ quasi-elastic electron scattering with longitudinally polarized electrons. This asymmetry is defined as

$$A = \frac{\sigma(\theta, \beta, +) - \sigma(\theta, \beta, -)}{\sigma(\theta, \beta, +) + \sigma(\theta, \beta, -)}, \quad (19)$$

where θ is the scattering angle, β the angle between the polarization vector of ^3He and the beam direction and + or - denote the helicity of the incoming polarized electron.

We believe such a determination to be difficult for the following reason. Near the peak, the quasi-elastic process corresponds to a scattering primarily from S-wave nucleons. Since in such a channel the two protons have mainly opposite spins, the polarized electron sees mainly the spin asymmetry from the neutron. In principle there is also a contribution to A from the spatial proton asymmetry in the $\lambda = 0, l = 2$ channel, the one of interest to us. This contribution, however, is necessarily much smaller and therefore difficult to disentangle from the rest. The D-state effects are more appreciable at high momentum transfer corresponding to the tails of the quasi-elastic peak. Only the $\lambda = 2, l = 0$ D-state component, however, contributes significantly¹¹⁾.

A promising tool for testing the different D-state components, including the $\lambda = 0, l = 2$ term, is provided by the ^3He and ^3H M1 elastic form factors in electron scattering. The part of the M1 operator of interest to us has the following form in the impulse approximation⁷⁾:

$$T_{10}^{(m)} = -\frac{e}{2m} \frac{i\gamma}{\sqrt{3}} \sum_i j_2(qr_i) \left(Y_2(\hat{r}_i) \otimes \vec{\sigma}_i \right)_{10}, \quad (20)$$

where $j_2(qr)$ is a spherical Bessel function.

Expressed in the coordinates $\vec{x}$ and $\vec{y}$, the operator (20) contains terms in $(Y_2(\hat{y}) \otimes \vec{\sigma})_{10}$, $[(Y_1(\hat{x}) \otimes Y_1(\hat{y}))_2 \otimes \vec{\sigma}]_{10}$ and $(Y_2(\hat{x}) \otimes \vec{\sigma})_{10}$. Each of these terms couples the S to the D-state with a contribution proportional to the D-state amplitude. In particular the term in $(Y_2(\hat{x}) \otimes \vec{\sigma})_{10}$ couples the $\lambda = 1 = 0$ S-state to the $\lambda = 0, 1 = 2$ component. The contribution of the S-D coupling is known^{7),12)} to push the diffraction minimum to considerably lower q values (from $q \sim 4 \text{ fm}^{-1}$ to less than $\sim 3 \text{ fm}^{-1}$). Such a shift, however, is not directly observable because of the competing contribution from meson exchange that restores the minimum to its previous position in agreement with experiments¹³⁾.

The test of the D-state components rests therefore upon the possibility of separating the impulse approximation from the meson-exchange contribution. In such a case one could easily estimate separately the contribution of each D-channel. This information, together with the knowledge of the D-state component from the other experiments discussed here, especially the $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ reaction, should allow a reasonably accurate estimate of the $\lambda = 0, 1 = 2$ component. No such analysis is presently available.

In a very recent experiment¹⁴⁾ the Saclay group separated the isoscalar from the isovector part of the trinucleon magnetic form factor. In the non-relativistic limit the contribution to the isoscalar part comes nearly entirely from the M1 operator in the impulse approximation, which is of order $1/m$ in the nucleon mass. In this case the meson-exchange contribution appears as a relativistic correction of order $1/m^3$ ¹⁵⁾. It would be useful to check explicitly if the contribution to the isoscalar part due to the S-D coupling is observable and if it comes mainly from the operator in the impulse approximation, at least up to moderately high q values. One must otherwise rely on the accuracy to which the meson-exchange contributions can be estimated.

We therefore conclude that, as long as the meson-exchange contribution can be either eliminated or accurately evaluated, the analysis of the magnetic form factors together with that of the tensor analyzing powers of the $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ and sub-Coulomb $(\vec{d}, t)$ reactions suffice for a detailed test of the various D-state components in ^3He and ^3H . This information would allow one to understand the precise role played by the tensor force in these light nuclei.

TABLE

	λ	l	L	s	σ - τ Symmetry	Probability (%)
S	0	0	0	1/2	A	87.8
	2	2	0	1/2	A	1.4
	0	0	0	1/2	-	0.8
	1	1	0	1/2	+	0.8
D	0	2	2	3/2	-	3.3
	2	0	2	3/2	-	1.1
	1	1	2	3/2	+	2.7
	3	1	2	3/2	+	1.2
	1	3	2	3/2	+	0.4
	2	2	2	3/2	-	0.2

TABLE CAPTION

Calculated probabilities of S- and D-state components in ^3He ground state taken from Ref. 2). The components with weight less than 0.1 per cent are not shown. The total D-state probability is 9 per cent. A refers to completely antisymmetric spin-isospin states, + and - to mixed-symmetry states respectively symmetric and antisymmetric in particles 1 and 2.

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Fig. 1