Letters to the Editor

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Velocity Dependent Nuclear Interactions*

C. H. BLANCHARD, R. AVERY, AND R. G. SACHS
University of Wisconsin, Madison, Wisconsin
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RECENT consideration of the relationship between nuclear shell structure and a j-j coupling scheme[1] suggests the investigation of nucleon-nucleon interactions which give spin-orbit coupling directly. Invariance requirements, in non-relativistic theory, limit the possible interactions linear in the nucleon momenta to the forms[2]

$$J(|\mathbf{r}_j-\mathbf{r}_k|)[(\mathbf{r}_j-\mathbf{r}_k)\times(\mathbf{p}_j-\mathbf{p}_k)]\cdot\begin{cases}(\boldsymbol{\sigma}_j+\boldsymbol{\sigma}_k)\begin{cases}\frac{1}{2}(\tau_{j3}+\tau_{k3}) & (1)\\ \frac{1}{2}(1+\tau_{j3}\tau_{k3}) & (2)\\ \frac{1}{4}(3+\boldsymbol{\tau}_j\cdot\boldsymbol{\tau}_k) & (3)\\ \frac{1}{2}(1-\tau_{j3}\tau_{k3}) & (4)\end{cases}\\ (\boldsymbol{\sigma}_j-\boldsymbol{\sigma}_k)\quad \frac{1}{2}(\tau_{j3}-\tau_{k3}) & (5)\\ [\boldsymbol{\sigma}_j\times\boldsymbol{\sigma}_k]\quad \frac{1}{2}[\boldsymbol{\tau}_j\times\boldsymbol{\tau}_k]_3. & (6)\end{cases}$$

Each of these interactions evidently gives spin-orbit coupling directly. The purpose of this letter is to report the results of a brief preliminary investigation of the effects of these forces in the nuclei H^2, H^3, and He^3.

None of the interactions can affect low energy nucleon-nucleon scattering since each transforms like a P function and each conserves relative orbital angular momentum. Hence none of them can couple an incoming S wave either to an S wave or to a wave of higher L. Appreciable effects on high energy scattering are to be expected, however, with possible differences between $N-P$ and $P-P$ scattering resulting from the isotopic spin dependence of the interactions. Because they transform like P functions, none of the interactions can contribute to the binding energy of a nucleus in an S state or in an $S-D$ cross term. Only (4) can contribute to the binding energy of H^2 (and this only in the $D-D$ term), and hence affect the wave function; (1) and (2) cannot because they vanish between unlike nucleons; (3) vanishes in a singlet isotopic spin state; (5) and (6) give no contribution since an antisymmetric spin operator must have a zero average value in a symmetric spin state. Thus the D state contribution of (4) remains as the only possible effect of any of the interactions (1) to (6) on the deuteron. In H^3 and He^3, the first four interactions can contribute to D state binding; (5) and (6) cannot, because of the spin symmetry of a quartet state. Any of the six interactions can introduce P state in H^3 and He^3 through direct coupling with the S state. Kinetic energy considerations, however, suggest that even if these forces are comparable in strength to the central and tensor forces, the wave functions will still be mostly S state.

Owing to their velocity dependence, each of the interactions introduces contributions to nuclear magnetic moments which are additional to the spin and orbital moments of the individual nucleons. These "interaction moments" arise because, on the introduction of an external magnetic field, the operator corresponding to the momentum of the kth nucleon is modified by the substitution $\mathbf{p}_k\rightarrow\mathbf{p}_k-(e/c)\frac{1}{2}(1-\tau_{k3})\mathbf{A}(\mathbf{r}_k)$. Thus the average of the energy of interaction between nucleons contains a term, U, linear in the field, which gives the interaction of an additional moment, $\mathbf{M}_I$, with the field: $U=-(\mathbf{M}_I\cdot\mathbf{H})$.

The H^2 moment is well accounted for by spin and orbital moments, so we assume that no large interaction moment in this nucleus can be tolerated. In H^3 and He^3 there are equal and opposite anomalies[3] of the order of 0.27 n.m. We have estimated the S state interaction moments in these three nuclei for each of the interactions (1) to (6), when introduced with a strength and range comparable to those of the usually assumed forces. The interaction moments of (1), (2), and (3) vanish for the S states of all three nuclei. The interaction moments arising from (5) and (6) can account for the observed anomalies of H^3 and He^3 while giving no contribution to the H^2 moment. The contributions of (4) to the H^3 and He^3 moments, while of the order of the anomalies, are of the *same* sign for the two nuclei and thus incapable of accounting for the anomalies; (4) also gives an appreciable contribution ($\approx$0.25 n.m.) in H^2.

These results may be used to discard interaction (4) as a possibility. As has been shown, the remaining interactions cannot affect the H^2 wave function. The interactions (5) and (6), which can account for the moment anomalies, both vanish between like particles; they differ only in a space exchange factor, since on eliminating the isotopic spin notation they may be written

$$J(|\mathbf{r}_N-\mathbf{r}_P|)[(\mathbf{r}_N-\mathbf{r}_P)\times(\mathbf{p}_N-\mathbf{p}_P)]\cdot(\boldsymbol{\sigma}_N-\boldsymbol{\sigma}_P)\begin{cases}1. & (5')\\ P_{NP}{}^x. & (6')\end{cases}$$

From these considerations one can conclude that velocity dependent interactions are worthy of serious consideration in phenomeneological studies of nuclear processes. The introduction of one or more of them may aid in understanding: (1) the strong spin-orbit coupling indicated by nuclear shell structure, (2) nuclear magnetic moment anomalies, (3) high energy $N-P$ scattering data,[4] (4) the differences between high energy $N-P$ and $P-P$ scattering.[5]

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Deuteron-Proton Scattering at 10 Mev*

K. B. MATHER,† H. J. KARR,‡ AND R. O. BONDELID
Physics Department, Washington University, St. Louis, Missouri
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THE coincidence scattering chamber referred to in an earlier communication[1] has been applied to the determination of absolute differential cross sections for the elastic scattering of deuterons by protons. Deuterons were accelerated to 10.0±0.2 Mev by the Washington University cyclotron. The scattering media were Nylon and polythylene-terephthalate foils.

In view of the present interest in the d-p interaction, a preliminary report is being made here for angles from 45° to 155° in the center of mass system. Complete publication covering a wider range of angles will be made shortly. Further work, with a photographic scattering chamber in which protons are scattered from deuterium gas is nearing completion.

Table I lists absolute cross sections $\sigma(\theta)$ in the c.m. system as a

TABLE I. Absolute cross sections in c.m. coordinates for deuteron-proton scattering.

θ	$\sigma(\theta)\times10^{25}$ cm^2 sterad.$^{-1}$
45°	1.78
55	1.55
65	1.32
75	1.10
85	0.89
95	0.71
105	0.59
115	0.57
125	0.68
135	0.97
145	1.46
155	2.09