LETTERS TO THE EDITOR

On the Spin of the Neutron

The intrinsic angular momenta of the proton and the deuteron imply a neutron spin (in units of $\hbar$) of either $\frac{1}{2}$ or $\frac{3}{2}$. The usual assumption of $\frac{1}{2}$ for the neutron spin is based entirely upon arguments of simplicity, since either of these two possible values is consistent with data on nuclear spins. In view of the importance of the neutron spin in nuclear theory, it would be desirable to determine this quantity by direct experiment. It has recently been shown[1] that experiments on the scattering of neutrons by ortho- and parahydrogen would enable one to obtain information about the spin dependence and the range of the neutron-proton interaction. It is the purpose of this note to point out that such experiments also permit the determination of the neutron spin.

A system composed of a proton and a neutron with S_n units of spin may have a resultant spin angular momentum of either $S_n+\frac{1}{2}$ or $S_n-\frac{1}{2}$. If the neutron spin is $\frac{3}{2}$, the excited state of the deuteron is a quintet state, as compared with a singlet excited state for $S_n=\frac{1}{2}$. In either case, the position of the excited level is determined by the requirement that σ_0, the cross section for the scattering of slow neutrons by free protons, equal the experimental value of 14×10^{-24} cm^2. For both possible values of the neutron spin, we may write

$$\sigma_0=4\pi\left(\frac{S_n+1}{2S_n+1}a^2{}_{S_n+\frac{1}{2}}+\frac{S_n}{2S_n+1}a^2{}_{S_n-\frac{1}{2}}\right), \tag{1}$$

where the a's denote the amplitudes of the waves scattered in the states of corresponding resultant spin angular momenta. The triplet state amplitude was determined by an integral equation method from the interaction potential $-Be^{-(r/b)^2}$, with $B=36.8$ Mev and $b=2.25\times10^{-13}$ cm. The resultant value of $a_1=-5.73\times10^{-13}$ cm corresponds to a triplet scattering cross section of 4.13×10^{-24} cm^2. The values of a_0 and a_2 for the respective spins of $S_n=\frac{1}{2}$ and $S_n=\frac{3}{2}$ may then be calculated, with the results $a_0/a_1=\pm3.31$ and $a_2/a_1=\pm2.22$. For both spins, a plus sign indicates a real excited state, and a minus sign a virtual excited state.

The appropriate extension of Fermi's theorem[2] to the situation under consideration states that

$$-\frac{4\pi\hbar^2}{M}\left(\frac{S_n+1}{2S_n+1}a_{S_n+\frac{1}{2}}+\frac{S_n}{2S_n+1}a_{S_n-\frac{1}{2}}\right.$$
$$\left.+\frac{1}{2S_n+1}(a_{S_n+\frac{1}{2}}-a_{S_n-\frac{1}{2}})\boldsymbol{\sigma}_p\cdot\mathbf{S}_n\right)\delta(\mathbf{r}_n-\mathbf{r}_p), \tag{2}$$

where $\mathbf{S}_n$ and $\frac{1}{2}\boldsymbol{\sigma}_p$ are the spin operators of the neutron and the proton, is the effective neutron-proton interaction to be inserted in the Born approximation formula. By utilizing methods almost identical with those employed in reference 1, we may calculate the cross sections for the various transitions excited in molecular hydrogen by neutron impact. The cross sections thus obtained for *para→para*, *para→ortho*, *ortho→para*, and *ortho→ortho* transitions are, respectively, proportional to

$$\left(\frac{S_n+1}{2S_n+1}a_{S_n+\frac{1}{2}}+\frac{S_n}{2S_n+1}a_{S_n-\frac{1}{2}}\right)^2,$$
$$3\frac{S_n(S_n+1)}{(2S_n+1)^2}(a_{S_n+\frac{1}{2}}-a_{S_n-\frac{1}{2}})^2,$$
$$\frac{S_n(S_n+1)}{(2S_n+1)^2}(a_{S_n+\frac{1}{2}}-a_{S_n-\frac{1}{2}})^2,$$

and

$$\left(\frac{S_n+1}{2S_n+1}a_{S_n+\frac{1}{2}}+\frac{S_n}{2S_n+1}a_{S_n-\frac{1}{2}}\right)^2+\frac{2}{3}\frac{S_n(S_n+1)}{(2S_n+1)^2}(a_{S_n+\frac{1}{2}}-a_{S_n-\frac{1}{2}})^2.$$

The actual cross sections are these quantities multiplied by functions of the neutron energy which involve only properties of the hydrogen molecule.

The experiments of both Dunning[3] and Stern[4] and their collaborators show that the scattering cross section of *ortho*-H$_2$ at liquid-air neutron temperatures ($T=100$°K) is much larger than the corresponding *para*-H$_2$ cross section. It has already been pointed out[1] that this result is in agreement with the theoretical expectations for a virtual singlet state. Assuming a neutron spin of $\frac{3}{2}$, the theoretical value of the ratio $\sigma_{ortho}/\sigma_{para}$, at an energy of $3kT/2=0.012$ ev, is 3.11 for a virtual quintet state and 1.09 for a real quintet state. In either case, the two cross sections are quite comparable in magnitude, in contradiction with experiment. On the basis of these experiments the conclusion must be drawn that the intrinsic angular momentum of the neutron is, in reality, $\frac{1}{2}\hbar$.

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[1] J. Schwinger and E. Teller, Phys. Rev. **52**, 286 (1937).

[2] E. Fermi, Ricerca Scient. **7**, 13 (1936).

[3] J. R. Dunning, F. G. Brickwedde, J. H. Manley and H. J. Hoge, to be published shortly.

[4] J. Halpern, I. Estermann, O. C. Simpson and O. Stern, Phys. Rev. **52**, 142 (1937).