The Collision of Neutrons with Deuterons and the Reality of Exchange Forces

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March 20, 1947

A DECISION regarding the reality of exchange forces between a neutron and a proton is not easily arrived at from a study of the collisions of neutrons with protons. The reason for this is the short range of the forces. For a marked difference between exchange and ordinary forces to show up, collisions in which the relative angular momentum is greater than zero must take place with appreciable probability. With a short range force this will be the case only if the neutron energy is high. On the other hand, owing to the relatively diffuse structure of the deuteron, its interaction with a neutron has a much longer range than that of a proton. As a result, collisions of neutrons with deuterons, in which the neutrons possess a relative angular momentum greater than zero, occur with appreciable probability at much lower energies than with protons. A study of these collisions should therefore assist in establishing the reality or otherwise of exchange forces. In 1941 we published a detailed theoretical study of the scattering of neutrons,[1] with energies ranging from 0.1 to 11.5 Mev, by deuterons. The fundamental interaction energy V between nucleons was taken of the form

$$V(r)=A(mM+hH+bMH+\omega)e^{-2r/a},$$

where M is the Majorana operator interchanging position but not spin coordinates, and H the Heisenberg operator interchanging all coordinates. The constants A and a were taken to be those derived by Present and Rarita[2] from a study of the binding energies of the light nuclei. Calculations were carried out for three separate sets of assumptions regarding the constants m, h, b, ω:

I. Ordinary type forces
$$m=h=0,\qquad \omega=\tfrac{1}{2}(1+x),\qquad b=\tfrac{1}{2}(1-x)$$

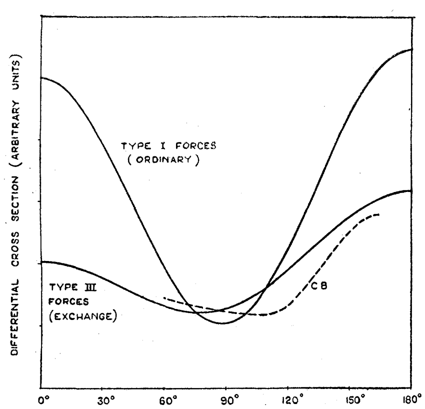

FIG. 1. Comparison of observed and calculated angular distributions, in the center of mass system, of 2.53-Mev neutrons scattered by deuterons.
The full line curves are according to the theory on the respective assumption of ordinary and exchange forces. The dashed curve gives observations of Coon and Barschall. The scale is adjusted to give agreement between theory and experiment near 90°.

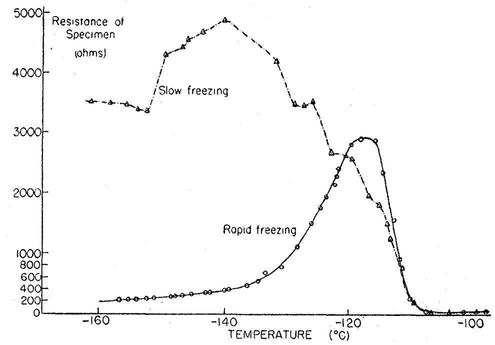

FIG. 2. Comparison of the observed and calculated total cross sections for collisions of neutrons with deuterons. The upper and lower curves are derived theoretically on the respective assumption of ordinary and of exchange forces. The vertical lines indicate values observed by Ageno, Amaldi, Bocciarelli, and Trabacchi, including range of error.

II. Exchange type forces
$$\omega=b=0,\qquad m=\tfrac{1}{2}(1+x),\qquad h=\tfrac{1}{2}(1-x)$$
III. Exchange type forces
$$m=2b=\tfrac{1}{3}(1+3x),\qquad h=2\omega=\tfrac{1}{3}(1-3x).$$

All three of these are consistent with the binding energy of the ^1S as well as ^3S state of the deuteron, if x is taken to be 0.6.

It was found that, whereas the two exchange type forces II and III did not give substantially different results, they gave quite markedly different results from the ordinary type forces I for neutrons with energies greater than 2 Mev. At the time of writing of the paper there was little experimental information available to decide which assumption gave the best results. Recently two sets of measurements have been published, those of Coon and Barschall[3] on the angular distribution of 2.53-Mev neutrons scattered by deuterons, and those of Ageno, Amaldi, Bocciarelli, and Trabacchi[4] of the cross sections for elastic collisions of 4.1, 12.5, and 14-Mev neutrons with deuterons. Comparison of the theoretical predictions with these observations, as illustrated in Figs. 1 and 2, is interesting. On the whole, the evidence is decidedly in favor of exchange (Type III) forces. It is true that the observed cross sections for the higher energy neutrons are somewhat larger than predicted on the assumption of these forces, but this is to be expected as the additional contribution to the cross section from neutrons with two units of relative angular momentum has been ignored in the theory and it must be appreciable at these energies. The theory is being extended to allow for these contributions.

In our previously published theoretical work,[1] two forms of wave function for the doublet state of the three particle systems were used, referred to as doublet (a) and doublet (b) respectively. The second only of these has the correct form for a true doublet wave function, and it has been used in obtaining the theoretical results illustrated in Figs. 1 and 2.

[1] R. A. Buckingham and H. S. W. Massey, Proc. Roy. Soc. [A] **179**, 123 (1941).
[2] R. Present and W. Rarita, Phys. Rev. **51**, 788 (1937).
[3] J. H. Coon and H. H. Barschall, Phys. Rev. **70**, 592 (1946).
[4] M. Ageno, E. Amaldi, D. Bocciarelli, and G. C. Trabacchi, Il. Nuov. Cimento **9**, i 1943; Phys. Rev. **71**, 20 (1947).