

In writing the second member of (24) use is made of the fact that $U^a(t)$ is hermitian. The third member re-expresses the first with the aid of (19r) and its adjoint. The transition to the fourth involves (15). The fifth is reached with the aid of (19a) and its adjoint. Exploiting again Eq. (19r) we get to the sixth member of (24). Since $U^a(\infty)$ has always a reciprocal, we infer from (24) that

$$U^a(t)\bar{U}^a(t) = 1. \quad (25a)$$

Applying the same identities in a somewhat different order and using (22) one similarly arrives at

$$U^r(t)\bar{U}^r(t) = 1. \quad (25r)$$

Equations (25) and (8) imply the statement made at the beginning of the paragraph.

The author has enjoyed several instructive conversations with Dr. Hartland Snyder regarding the question discussed in this note.

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¹ Equation (13) rather than (3) is essentially the definition adopted by Yang and Feldman for their "Heisenberg S-matrix." (Phys. Rev. **79**, 972, 1950.) The expressions

$$F(x) = U^r(t)F^{\text{in}}(x)\bar{U}^r(t) = F^{\text{in}}(x) - i \int_{-\infty}^t dt' U^r(t') [H(t'), F^{\text{in}}(x)] \bar{U}^r(t')$$

$$F(x) = U^a(t)F^{\text{out}}(x)\bar{U}^a(t) = F^{\text{out}}(x) - i \int_{+\infty}^t dt' U^a(t') [H(t'), F^{\text{out}}(x)] \bar{U}^a(t')$$

for the various Heisenberg field operators are equivalent to the integral equations employed by these authors. This may be seen by evaluating the commutator brackets explicitly for the various fields. The relation between $F^{\text{out}}(x)$ and $F^{\text{in}}(x)$ is then $F^{\text{out}}(x) = \bar{U}^a(t)U^r(t)F^{\text{in}}(x)\bar{U}^r(t)U^a(t)$.

² J. Schwinger, Phys. Rev. **74**, 1439 (1948).

³ Equations (19) may be regarded as the definitions of the "Heisenberg reaction operator" in the same sense as (13) is taken to define the "Heisenberg collision operator." See reference 1.

The Mechanism of nD Capture

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THE thermal neutron-deuteron capture cross section has long been known to be very small (0.46×10^{-27} cm² for neutrons of velocity 2200 m/sec.¹ Several attempts at its calculation have been published, and the values obtained are: 3×10^{-27} cm² by Schiff,² 0.17×10^{-27} cm² by Höcker,³ 0.73×10^{-27} cm² by Burhop and Massey,⁴ while Verde⁵ indicates that the cross section is very small but declines to give any numerical value.

It is generally considered that the H^3 wave function is mostly of 2S character, and that capture from the continuum 2S and 4S states proceeds by the emission of a magnetic dipole gamma-ray. There are strong selection rules on this process. Two types of 2S wave function must be distinguished, "symmetric," in which the neutrons are in a relative singlet state, and "antisymmetric," in which the neutrons are in a relative triplet state. Now if the radiation interaction involves only the spin magnetic moments of the nucleons then the transition can only link wave functions having the same neutron spin symmetry. Further, since 2S wave functions of different energies are orthogonal, the magnetic transition must take place from the continuum 4S state. Only the antisymmetric 2S part of the ground-state wave function then has the neutron spin symmetry of the quartet state and can contribute to the matrix element of the transition. As this part of the ground state is believed to be very small, the capture cross section is correspondingly small. The above-mentioned authors all based their calculations on estimates of the amount of admixture. It is the purpose of the present note to indicate that their interpretation of the capture process is not a unique one.

Two additional mechanisms seem important: Magnetic dipole capture via the interaction moment⁶ does not obey the selection rules which limited the possible transitions via the spin moments; electric quadrupole capture can occur from the continuum 4S state to ground state 4D terms.⁷

The capture cross section produced by the spin-antisymmetric interaction moment was computed for the present communication on the assumption that the ground state is a pure symmetric 2S state. The matrix element for a transition between this state and the 2S continuum state can be compared with the corresponding matrix element which appears in the calculation of the three-body magnetic moment anomaly. Then the numerical value of the capture matrix element follows from the known value of the three-body magnetic moment anomaly simply by renormalizing one wave function to an amplitude appropriate in the continuum. This method of approximation avoids any detailed assumptions about the interaction moment operator. The necessary renormalization was effected by comparison of the continuum and ground-state wave functions at the point of zero particle separation, a criterion which is reasonable because of the short-range nature of the interaction moment. In this manner a capture cross section was computed which was found to have about one-quarter of the experimental value. The transition involving the continuum 4S state seems to contribute as much again, although its estimation is less reliable. Thus, in a first estimate, interaction moment magnetic dipole transitions to the main part of the H^3 wave function seem to yield about half the observed nD capture cross section.

The electric quadrupole capture cross section has been estimated very crudely, using the Gerjuoy-Schwinger value of 4 percent 4D function. It is found nearly to equal the magnetic cross section, so that adding the two just gives the experimentally observed cross section. While this is certainly fortuitous, it does indicate that it is unnecessary to postulate an antisymmetric 2S term in the ground state as the explanation of the capture process.

Accurate calculation of the quadrupole cross section would show what upper bound the small empirical value can set on the amount of ground-state 4D function. It may be rather low. It is interesting that the interaction moment model of the three-body magnetic anomaly does not lead to any contradiction with the known small capture cross section.

This investigation was carried out as a direct consequence of conversations with Professor R. G. Sachs.

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¹ Sargent, Booker, Cavanagh, Hereward, and Niemi, Can. J. Research **A25**, 134 (1947).

² L. I. Schiff, Phys. Rev. **52**, 242 (1937).

³ G. Höcker, Physik. Z. **43**, 236 (1942).

⁴ Burhop and Massey, Proc. Roy. Soc. (London) **A192**, 156 (1947).

⁵ Verde, Helv. Phys. Acta **XXIII**, 453 (1950); Nuovo cimento **7**, 283 (1950); **8**, 152 (1951).

⁶ N. Austern and R. G. Sachs, Phys. Rev. **81**, 710 (1951); N. Austern, Phys. Rev. **81**, 307(A) (1951).

⁷ The existence of such terms is known theoretically. Gerjuoy and J. Schwinger, Phys. Rev. **61**, 138 (1942); Pease and Feshbach, Phys. Rev. **81**, 142(L) (1951), also private communications from Dr. Pease.

Nuclear Magnetic Resonance Measurements on Be⁹, Al²⁷, and Si²⁹ in Beryl

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MEASUREMENTS have been made of nuclear magnetic resonance absorption in a single crystal of beryl (Be₃Al₂Si₆O₁₈) at a frequency of 2.3 Mc/sec and a temperature of 20°K.

The five lines due to electric quadrupole splitting of the Al²⁷ resonance were clearly observed. With the hexagonal axis of the crystal parallel to the magnetic field, the separation between adjacent lines was 0.45 Mc/sec. Three lines due to Be⁹ have been found. With the axis parallel to the field, the separation between the lines was 0.13 Mc/sec. A search was made for other lines in the regions where they would be expected to appear, if present, but nothing was observed. Since the signal-to-noise ratio for the outer lines of the triplet was greater than thirty to one, it seems certain that there were no other lines. This result is in agreement with the recent measurements of Schuster and Pake¹ and confirms the value $I = \frac{3}{2}$ for the spin of Be⁹.