Antineutrino Disintegration of the Deuteron*

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The cross section for the antineutrino disintegration of the deuteron, $\bar{\nu}+d\rightarrow n+n+e^+$, is considered. The only important contribution to the cross section arises from a ^1S final nucleon state, and only the tensor part of the beta-interaction is effective. The matrix element can be evaluated by the effective-range formulation well known from calculations of the photomagnetic disintegration of the deuteron. The cross section is evaluated for three antineutrino energies: 5.5, 8.5, 13.5 Mev. The results for this process would be the same if the neutrino were a Majorana particle.

INTRODUCTION

IN the preceding paper, Muehlhause and Oleksa[1] study the feasibility of antineutrino detection by observing the disintegration of the deuteron. The process they consider is:

$$\bar{\nu}+d\rightarrow n+n+e^+,$$

the production by an antineutrino on deuterium of two neutrons and a positron.‡ This paper briefly describes the theoretical calculation of the cross section for this process for the energy range of antineutrinos of interest, from about 15 Mev down to threshold. The calculation is straightforward and the results very largely independent of special assumptions about the structure of the deuteron or of nuclear forces. The interaction between the antineutrinos and nuclear matter is described by the usual beta interaction of nuclear physics; the results are uncertain only to the extent that the coupling constants are undetermined. It should be remarked that the cross section is the same for a Dirac antineutrino and for a Majorana particle, so that this process by itself does not indicate anything of the particle or antiparticle nature of the neutrino.

FORMULATION

The disintegration takes place by the interaction of the incoming antineutrino with the bound proton, the proton and neutrino transforming into a neutron and positron. There are, then, three final particles: two heavy (neutrons) and one light (positron). An important question is that of the division of energy among the three final products. The greatest fraction of the energy is carried off by the light particle. In the simpler process in hydrogen,

$$\bar{\nu}+p\rightarrow n+e^+,$$

the recoil energy is less than half a Mev for a 15-Mev antineutrino, and less for less energetic antineutrinos. Since in the deuteron process the proton is in a bound state with a kinetic energy of several Mev, the final neutrons can have substantially higher energies. However, even for a 15-Mev incoming antineutrino the important contributions to the cross section come from neutron energies of less than 2 Mev. The fact that we are concerned with low-energy nucleons will greatly simplify the calculation and insure that it is independent of detailed assumptions about deuteron structure.

The discussion is greatly facilitated by a suitable choice of canonical coordinates and momenta. The initial state is defined by giving the momentum of the antineutrino, $\mathbf{p}_\nu$, and of the deuteron, which we can take as zero. The final state of the three outgoing particles is completely defined by just two momenta. It is very convenient to choose these as the positron momentum, $\mathbf{p}_e$, and the relative momentum of the two neutrons, $\mathbf{p}_n$. The $\mathbf{p}_n$ is defined in the usual way, as half the difference of the two neutron momenta. The total energy is, then, given by

$$E=c(m_e^2c^2+p_e^2)^{\frac{1}{2}}+\frac{p_n^2}{M}+\frac{(\mathbf{p}_\nu-\mathbf{p}_e)^2}{4M},$$

where M is the neutron mass and m_e the electron mass. In the region of interest, the last term, corresponding to the recoil of the nucleon center of mass, can always be neglected—to within 1% in the final result. There remains, then, a very simple kinematics:

$$E=c(m_e^2c^2+p_e^2)^{\frac{1}{2}}+\frac{p_n^2}{M}=E_e+E_n,$$

with $\mathbf{p}_e$ and $\mathbf{p}_n$ the otherwise independent momenta.

The interaction, too, is simple and requires only

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[1] C. O. Muehlhause and S. Oleksa, preceding paper [Phys. Rev. **105**, 1332 (1957)].
‡ *Note added in proof.*—My attention has been called to a very recent article by A. V. Govorkov [Zhur. Eksptl. i Teort. Fiz. **30**, 974 (1956)], dealing with neutrino-induced disintegration of deuterons. The qualitative conclusions of that paper are the same as here: that the final neutrons are emitted in the ^1S state and that only the tensor interaction contributes appreciably. In fact, it is suggested that this experiment be used to measure the tensor interaction. The numerical evaluations differ; Govorkov makes an estimate based on use of plane-wave final state wave functions, and thus neglects interaction between final state neutrons. The difference between Govorkov's results, extended to the energies considered here, and the results of this paper can be readily attributed to the approximation.

TABLE I. Values of $\sigma/3g_T^2$ for three antineutrino energies.

Antineutrino energy E_ν in Mev	$\sigma/3g_T^2$ in cm^2
13.5	4.2×10^{-20}
8.5	8.5×10^{-21}
5.5	8.5×10^{-22}

brief discussion. The beta-interaction assumed here is that determined from nuclear transitions: a combination of scalar, tensor, and pseudoscalar with comparable coupling constants.[2] Since the final nucleons are of low energy, it is sufficient to take the lowest order nonrelativistic forms:

$$H_{\text{int}}=G_S(\psi_\nu^*\beta\psi_e)(\psi_f^*\psi_i)+G_T(\psi_\nu^*\beta\boldsymbol{\sigma}\psi_e)(\psi_f^*\boldsymbol{\sigma}\psi_i),$$

where ψ_i, ψ_f are the initial and final nucleon wave functions, and ψ_e, ψ_ν are the positron and neutrino free-particle wave functions. The coupling constants G_S, G_T have to be taken from the nuclear beta-decay data, and are known only approximately. The quantity $(3G_S^2+G_T^2)$ is known to 10%, but the ratio G_S/G_T is known only to 50% ($G_S/G_T\sim1\pm0.5$). The interaction has been written as for a Dirac neutrino, but it should be emphasized again that these results would be the same for a Majorana particle.

MATRIX ELEMENT

Finally the computation rests on the evaluation of the interaction matrix element. The part dependent on the nuclear variables is of the form

$$\int\psi_f^*(\mathbf{r}_1,\zeta_1;\mathbf{r}_2\zeta_2)\mathbf{O}_1\exp\left[\frac{i(\mathbf{p}_e-\mathbf{p}_\nu)\cdot\mathbf{r}_1}{h}\right]\times\psi_i(\mathbf{r}_1,\zeta_1;\mathbf{r}_2\zeta_2)d\tau_1d\tau_2,$$

where $\mathbf{r}_i$, ζ_i are the nucleon space and spin coordinates, and $\mathbf{O}_i$ is either 1 for the scalar interaction or $\boldsymbol{\sigma}_i$ for the tensor. After separation of the trivial integrations over the center-of-mass coordinates, there remains:

$$\int\phi_f^*(\mathbf{r},\zeta_1,\zeta_2)\exp\left[\frac{i(\mathbf{p}_e-\mathbf{p}_\nu)\cdot\mathbf{r}}{2h}\right]\phi_i(\mathbf{r},\zeta_1,\zeta_2)d\tau,$$

where $\mathbf{r}$ is the relative coordinate. There is possibie the very great simplification of the "dipole approximation"—the recoil factor, $\exp[i(\mathbf{p}_e-\mathbf{p}_\nu)\cdot\mathbf{r}/2\hbar]$, is replaced by 1. Then, since ϕ_i is the deuteron ground state wave function, consisting of mainly ^3S, only S final states contribute appreciably; because ^3S is excluded for the identical neutrons, only ^1S final states need be considered. Then, only the tensor interaction contributes, the scalar not permitting the necessary spin-flip. The error involved in the approximation can be seen from an evaluation of the leading discarded term—the P-state contribution. An explicit evaluation, assuming zero P-state forces and a Hulthén ground state function, results in a 1% P-state contribution relative to the leading ^1S. The validity of the approximation stems from two facts. First, even for 15-Mev antineutrinos the exponent in the recoil factor is small; when $|\mathbf{r}|$ is taken as 4×10^{-13} cm (the deuteron radius), $(p_\nu r/\hbar)^2$ is less than 1/20. Second, since the final nucleon energies, E_n, are low, the final states of higher angular momentum are small in the region where the deuteron function is considerable.

We have, finally, to evaluate:

$$\int\chi_S\chi_g dr,$$

where χ_S/r is the radial part of the ^1S final state wave function, corresponding to energy E_n, and χ_g/r is the radial part of the ^3S portion of the deuteron ground state function. This is very similar to the matrix element appearing in the low-energy photomagnetic disintegration of the deuteron. In fact, under the assumption of charge independence of nuclear forces, it is of identical form. It is, then, possible to take over the effective-range formulation of the photomagnetic effect.[3] The calculation has been carried through in just this way. The results depend only on a singlet neutron-neutron effective range and scattering length, the neutron-proton "triplet" effective range, and the binding energy of the deuteron. The neutron-neutron parameters are assumed to be the same as the neutron-proton singlet values.[4]

By means of the effective-range formulation the matrix element is given as a function of the neutron energy, E_n, or, for a fixed neutrino energy, of the positron energy, E_e. The cross section is, then given by:

$$\sigma=\int\int\int dE_e\frac{2\pi}{hc}\cdot\frac{cp_eE_ed\Omega_e}{(2\pi\hbar c)^3}\cdot\frac{1}{2}\frac{cp_nMc^2}{(2\pi\hbar c)^3}d\Omega_n\times4\pi G_T^2\left(1+\frac{1}{3}\frac{c\mathbf{p}_e\cdot c\mathbf{p}_\nu}{E_eE_\nu}\right)\left|\int\chi_S\chi_g dr\right|^2,$$

and a numerical integration over the positron spectrum completes the evaluation. The results of the computations are given in Table I. In using these results, the accuracy of the calculation should be kept in mind. The kinematic simplification is an approximation good to within 1%; the nonrelativistic approximation to the

[2] E. J. Konopinski and L. M. Langer, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 3, p. 261.

[3] H. Bethe and C. Longmire, Phys. Rev. **77**, 647 (1950); H. Feshbach and J. Schwinger, Phys. Rev. **84**, 194 (1951).

[4] The values of the parameters used are: $a_s=-2.38\times10^{-12}$ cm, $r_s=2.40\times10^{-13}$ cm, $r_t=1.70\times10^{-13}$ cm, $\gamma=(ME_D/\hbar^2)^{\frac{1}{2}}=2.31\times10^{12}$ cm^{-1}. For a discussion of the determination of these quantities from experiment, see, in addition to the papers of reference 3: Hafner, Hornyak, Falk, Snow, and Coor, Phys. Rev. **89**, 204 (1953); C. Storrs and D. Frisch, Phys. Rev. **95**, 1252 (1954). These papers contain references to previous work.

beta-interaction, the neglect of other than ^1S final states, and the "dipole approximation" are all related and of the same order, altogether good to about 2%; the effective-range approximation can be taken only within several percent. Further, there are the uncertainties in the parameters used in the evaluation of the effective-range result; the principal error comes from the uncertainty in the singlet effective range, r_s. The results are, then accurate only to within about 10 to 15%. The cross section for various antineutrino energies is given in terms of three times the reduced tensor coupling constant,[5] $g_T^2=(G_T/m_ec^2)^2(m_ec/\hbar)^6$. The range of energies is from near threshold, 4.0 Mev, to the upper range of the pile spectrum. As an aid to interpolation, it should be noted that $\sigma/(E_\nu-4.0)^2$ is a fairly smooth function.

[5] Konopinski and Langer give $3g_T^2\cong 4\times 10^{-23}$, within about 30%.

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New Radioisotope of Platinum—Pt^{200}†

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A new radioisotope of platinum, Pt^{200}, with an 11.5-hr half-life has been produced by successive neutron capture in Pt^{198}. It was identified by milking its daughter, Au^{200}. The activation cross section for the reaction $Pt^{199}(n,\gamma)Pt^{200}$ is approximately 15 barns.

INTRODUCTION

An 11.5-hr activity, identified as Pt^{200}, has been produced by successive neutron capture in Pt^{198} by irradiating platinum metal in the NRX reactor at Chalk River. Recently Warren and Fink,[1] in an attempt to form Pt^{200} by the same method, failed to observe such an activity. From their results they set limits for its half-life as less than 4 days or greater than 2 yr.

Pt^{198} (7.2% of natural platinum) by neutron capture leads to the following nuclear reactions:

$$\begin{array}{lllll} Pt^{198} & & & & \\ (n,\gamma) & & & & \\ 4 \text{ barns} & & & & \\ \downarrow & & & & \\ Pt^{199} & \xrightarrow{\beta^-} & Au^{199} & \xrightarrow{\beta^-} & \\ (n,\gamma) & & (n,\gamma) & & Hg^{199} \text{ (stable)} \\ \sim 15 \text{ barns} & 30 \text{ min} & 30 \text{ barns} & 3.17 \text{ days} & \\ \downarrow & & \downarrow & & \\ Pt^{200} & \xrightarrow[11.5 \text{ hr}]{\beta^-} & Au^{200} & \xrightarrow[48 \text{ min}]{\beta^-} & Hg^{200} \text{ (stable)}. \end{array}$$

Since the presence of the other radioisotopes formed by neutron capture in the stable isotopes of platinum made the direct detection of Pt^{200} very difficult, the method of daughter extraction was applied. The 48-min Au^{200} daughter of Pt^{200} is easily identifiable. It decays with a maximum β-particle energy of 2.2 Mev and its γ-ray spectrum has been studied. Although few investigations of Au^{200} have been made[2-4] Butement and Shillito have definitely shown by cross bombardments that the mass assignment of the 48-min gold activity is 200.

EXPERIMENTAL

Samples of spectroscopically pure and thermocouple grade platinum metal were irradiated in the NRX reactor in two different fluxes. The details of the irradiation conditions are given in Table I.

Au^{200} is formed in large amounts by neutron capture in Au^{199} as seen from the nuclear reactions above. This contribution of Au^{200} and part of the Au^{199} activity from the decay of Pt^{199} were eliminated by allowing a decay period of 15 hours or more after the irradiation, followed

TABLE I. Details of irradiation conditions.

Irradiation	Pt^{198} (atoms)	Flux (n/cm² sec)	Length of irradiation (hours)
1	4.0×10^{19}	6.8×10^{13}	8
2	20.0×10^{19}	1.4×10^{13}	21
3	21.0×10^{19}	1.5×10^{13}	24

TABLE II. Summary of the results.

Irradiation	Half-life of Pt^{200} (hours)	Yields of Pt^{200} at the end of irradiation (atoms)
1	10.9	5.5×10^{8}
2	11.9	2.4×10^{8}
3	11.8	2.7×10^{8}

† Contribution from the Research Chemistry Branch, Atomic Energy of Canada Limited, Chalk River, Ontario.

[1] G. W. Warren and R. W. Fink, Bull. Am. Phys. Soc. Ser. II, 1, 171 (1956).

[2] Sherr, Bainbridge, Anderson, Phys. Rev. **60**, 473 (1941).

[3] W. Maurer and W. Ramm, Z. Physik **119**, 602 (1942).

[4] F. D. S. Butement and R. S. Shillito, Proc. Phys. Soc. (London) **A65**, 945 (1952).