Parity Conservation in the Reaction $T(d,n)He^4$ †*

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An experimental test for parity conservation in the strong nuclear reaction $T(d,n)He^4$ has been made using an incident accelerated beam of polarized deuterons. The deuterons, incident with 140-keV energy on a thick target of tritiated titanium, were vector-polarized transverse to the beam direction. The experiment measured the ratio in numbers of neutrons emitted parallel and antiparallel to the direction of the initial polarization vector, using opposed neutron counters. Periodic reversal of the polarization vector was used to eliminate instrumental asymmetries. The magnitude of the real part of the relative parity-violating amplitude, $|\mathrm{Re}\mathfrak{F}|$, was found to be $\lesssim 3.8\times10^{-3}$, consistent with the conservation of parity.

I. INTRODUCTION

Although it appears that the law of conservation of parity in the strong interactions has firm status apart from probable small violations, which may be manifestations of the weak interactions, it is desirable to explore the generality of this law by testing it under many different experimental conditions.

Such a test may be performed by the experimental establishment of an upper limit for the relative amplitude $\mathfrak{F}$ for a parity-violating transition. The quantity $\mathfrak{F}$ may be expressed by expanding the state function Φ of the final state of a particular isolated system as follows:

$$\Phi = |[1-|\mathfrak{R}\mathfrak{F}|^2]^{1/2}|\Psi_{\mathrm{regular}} + \mathfrak{R}\mathfrak{F}\Psi_{\mathrm{irregular}},$$

where Ψ_{regular} is a component which arises with relative amplitude $|[1-|\mathfrak{R}\mathfrak{F}|^2]^{1/2}|$ via a parity-conserving interaction in the isolated system, and $\Psi_{\mathrm{irregular}}$ is the component which arises with relative amplitude $\mathfrak{R}\mathfrak{F}$ via a parity-violating interaction. Of course neither component necessarily has a definite parity but if the initial state were prepared with a definite parity then the final regular component would have that parity and the irregular component would have the opposite parity. If the process which leads to the formation of the final irregular component proceeds through separable stages, as in compound-nucleus formation and decay, then the amplitude $\mathfrak{R}\mathfrak{F}$ may be factorized into the amplitude $\mathfrak{R}$ for proceeding via parity-conserving stages and the amplitude $\mathfrak{F}$ for proceeding through an intermediate parity-nonconserving transition. For example, as discussed later, $\mathfrak{R}$ may be the amplitude for an electromagnetic transition of one parity relative to an electromagnetic transition of opposite parity occurring for the regular component. In a process not separable into stages, or where detailed knowledge is not available, $\mathfrak{R}$ is often set equal to 1.

Although both of these factors, $\mathfrak{R}$ and $\mathfrak{F}$, are complex numbers, a measurement of $\mathrm{Re}\mathfrak{F}$, for instance, is often reported in the literature as a measurement of $\mathfrak{F}$, so in this paper such informality is retained when discussing experiments other than that reported here.

Following the classification of Wilkinson,[1] experiments to measure $\mathfrak{F}$ can be divided into three classes as follows:

Class I: Experiments which violate "absolute" selection rules through parity mixing. These experiments measure $\mathfrak{F}^2$.

Class II: Experiments which measure observables such as a polarization or angular distribution which depends on interference between opposite-parity components of the wave function. These effects are proportional to $\mathfrak{F}$.

Class III: Experiments that observe interference effects as in class II but where the effect is proportional to $\mathfrak{F}^2$.

Experiments have been completed in all classes. The most precise in each are discussed below.

Segal, Olness, and Sprenkel[2] searched for the parity-forbidden α decay of the 8.88-MeV $(2-)$ state in O^{16} to the $(0+)$ C^{12} ground state. The reaction $(I(-)^{I+1})\rightarrow(0+)+\alpha$ is absolutely forbidden by parity considerations. The result was $|\mathfrak{F}|^2\leq 2\times10^{-12}$ and involved an estimate of the ratio of the reduced widths of the α decay and competing γ decays. Similar results have been obtained by others.[3]

Several very sensitive experiments have been done in class II. They all consisted of observing interference effects in the electromagnetic decay of excited nuclei. Two of these experiments, following a method suggested by Wilkinson,[4] measure the circular polarization of the de-excitation γ rays of unpolarized initial states.[5,6]

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[6] V. M. Lobashov *et al.*, Phys. Letters **25B**, 104 (1967).

Others[7–9] have followed the method of Haas, Leipuner, and Adair,[10] wherein parity conservation implies that γ rays, emitted by the polarized nucleus that is formed upon slow polarized neutron capture by unpolarized nuclei, should be symmetric in intensity parallel and antiparallel to the initial neutron polarization vector. Both types measure the effect of interference between the opposite-parity E-1 and M-1 modes of electromagnetic decay. Although these experiments are somewhat ambiguous at a level where effects of the weak interactions[11] should appear, they set an upper limit of parity nonconservation in strong interactions of about $\mathfrak{F}=10^{-6}$ for electromagnetic decay of a nuclear state. Less precise results have been obtained for the class-III experiments, the most precise[1] giving a measure of $\mathfrak{F}^2 \lesssim 10^{-4}$.

The experiments described above derive their great sensitivity from the choice of a reaction such that the parity-nonconserving channel (α emission, E-1 radiation) would have much greater amplitude than the parity-conserving channel on the basis of the presumably known nuclear interaction properties. In such cases the actually observed effect is proportional to $\mathfrak{R}\mathfrak{F}$ or $\mathfrak{R}\mathfrak{F}^2$, where $\mathfrak{R}$, as previously discussed, is a nuclear factor such as the ratio of nuclear matrix elements (or partial widths). $\mathfrak{R}$ may usually be estimated for an appropriate nuclear model.

It should be noted that the sensitive class-II type experiments consisted of observing interference effects of the electromagnetic transitions to determine the nature of the initial nuclear state with respect to parity. Class-II processes not involving electromagnetic interactions have not set limits on effects due to parity nonconservation to any great degree.[12] In particular the nucleon-nucleon scattering data allow the parity-nonconserving terms to be as much as the order of 10% of the value possible without parity restrictions. Speculation[13] concerning the conserved quantities in the nuclear electromagnetic interaction makes it desirable to test the conservation properties of these interactions.

The present experiment examines the validity of the parity invariance of strong interactions by observing the angular distribution of particles emitted from polarized nuclei. As in the well-known weak-interaction experiments,[14] a violation of parity conservation is indicated by a term in the angular distribution proportional to $\mathbf{P}\cdot\mathbf{k}_2$, where $\mathbf{P}$ is the vector polarization and $\mathbf{k}_2$ is the momentum of the emitted particle. In this case the polarized nucleus is formed by using a nuclear reaction having a definite intermediate angular momentum with a polarized incoming s-wave beam. The reaction will be discussed in more detail in Sec. II.

The question of invariance under parity P is related to that of invariance under time reversal T and charge conjugation C by the TCP theorem,[15] which concludes that a Hamiltonian satisfying its assumptions[16] will commute with any of the six operations which can be formed by the products of TCP and its permutations. It follows that a Hamiltonian that does not commute with P will not commute with at least one of the transformations T and C.

A second and related theorem[17] states that it is impossible to observe interference effects due to parity nonconservation if the interaction is invariant under C, if there are no final-state interactions, provided one is looking for terms of the type $\mathbf{P}\cdot\mathbf{k}_2$ and if first-order perturbation theory holds.

If this second theorem were to apply in our experiment then it might be concluded that an upper limit on parity nonconservation would imply a corresponding upper limit on C noninvariance and that any P violation in conjunction with T violation would not be detected. However, strong interactions are involved in this experiment so that first-order treatment of the reaction matrix is not valid, and the second theorem need not apply, regardless of the validity of the other conditions listed above.

On the other hand, this experiment only measures terms of the type $\mathrm{Re}R_cR_v^*$, where R_c and R_v are parity-conserving and parity-nonconserving reaction matrix elements (a fact that is related to the proof of the second theorem). A thorough search for parity nonconservation in strong interactions might include examples where the imaginary part of $R_cR_v^*$ would be measured.

II. THEORY OF THE EXPERIMENT

The $\mathrm{T}(d,n)\mathrm{He}^4$ reaction was first suggested as a test reaction for the measurement of deuteron tensor polarization by Galonsky, Willard, and Welton[18] (it had previously been noted by Goldfarb that a nonisotropic distribution could result even with incoming s waves

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[15] G. Luders, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **28**, No. 5 (1954).

[16] J. J. Sakurai, *Invariance Principles and Elementary Particles* (Princeton University Press, Princeton, N.J., 1964), p. 142.

[17] T. D. Lee, R. Oehme, and C. N. Yang, Phys. Rev. **106**, 340 (1957); F. Coester, *ibid.* **107**, 299 (1957).

[18] A. Galonsky, H. B. Willard, and J. A. Welton, Phys. Rev. Letters **2**, 349 (1959).

if polarization had rank-2, or tensor, components). Galonsky, Willard, and Welton also pointed out that symmetry with respect to the polarization axis is obtained as a result of parity invariance in the nuclear interaction. The $T(d,n)He^4$ reaction has a maximum cross section of $\sim$5b at 107 keV with a resonance width of 140 keV. At low energies, the reaction is considered to be primarily initiated by s waves and to proceed via the $J=\frac{3}{2}^+$ intermediate state. The parity-conserving part of the reaction produces a d-wave final state with 14-MeV neutrons. The question of parity conservation is applied to such a reaction in the following way. By parity conservation is meant that the interaction Hamiltonian of the reaction is invariant with respect to a parity transformation. It may be shown[19] that if the interaction Hamiltonian is invariant under a parity transformation then the corresponding scattering matrix S is so invariant, a consequence of the unitary nature of the parity operator. Such a conclusion would, of course, apply to the reaction matrix R, where $R=S-1$.

Hence, in the reaction of this experiment, where there are only two particles in the initial incoming state and two particles in the final outgoing state, all of the same relative intrinsic parity, parity conservation will imply that the reaction matrix only connects initial and final states of the same parity as described by $(-)^{l_1}$ and $(-)^{l_2}$, where l_1 and l_2 are the respective relative orbital angular momentum quantum numbers for the initial and final states.

The angular distribution of neutrons in this reaction, for incident polarized deuterons, may be obtained using the formulation of Goldfarb,[20] in particular Eqs. 2.14(a) and 2.14(b) of Ref. 20. However, these equations were derived assuming parity conservation. A rederivation without this assumption results in the following change in Eqs. 2.14:

In Eq. 2.14(b), change

$$\text{“}\cdots\text{even } k_s\text{” to “}\cdots\text{even } k_s+k_l+k\text{”},$$
$$\text{“}\cdots\text{odd } k_s\text{” to “}\cdots\text{odd } k_s+k_l+k\text{”}.$$

This change, which is valid for beams of arbitrary spin, has been applied in the case of a spin-1 beam, and the resulting angular distribution is given in the Appendix to this article.

The above symbols are defined by

$$\mathbf{k}_l=\mathbf{l}_1-\mathbf{l}_1',\ \mathbf{k}_s=\mathbf{s}_1-\mathbf{s}_1',\ \mathbf{k}=\mathbf{k}_l+\mathbf{k}_s,$$

where $\mathbf{s}_1$ refers to the spin vector of the incident beam particle and $\mathbf{l}_1$ to the initial orbital angular momentum vector. The primes refer to the same or different reaction matrix elements,

$$R\equiv\langle cL_2l_2s_2b|R|aL_1l_1s_1b\rangle,$$
$$R'\equiv\langle cL_2'l_2's_2b'|R|aL_1'l_1's_1b'\rangle,$$

with a the spin of the target particle, b the angular momentum quantum number of the intermediate state, s_1 the spin of the beam particle, c the spin of the residual nucleus, s_2 the spin of the outgoing particle, and $\mathbf{L}_1=\mathbf{l}_1+\mathbf{s}_1$, $\mathbf{L}_2=\mathbf{l}_2+\mathbf{s}_2$.

The coordinate system for the reaction is defined with initial and final unit momentum vectors $\mathbf{k}_1$ and $\mathbf{k}_2$. The z axis is taken to be along $\mathbf{k}_1$. The x axis, perpendicular to the z axis, will be chosen for this experiment to be in the direction of the magnetic field in the ion source, so that the vector polarization will be parallel or antiparallel to the x axis. θ is the angle between $\mathbf{k}_1$ and $\mathbf{k}_2$, i.e., $\cos\theta=\mathbf{k}_1\cdot\mathbf{k}_2$, and φ is the angle between the projection of k_2 on the x-y plane and the x axis.

The angular distribution W may be expressed as $W=W_0+W_1+W_2+W_3+W_4$, where the information given in Table I applies.

The "Reflection sign change" refers to whether the term changes sign under a parity transformation. "The Polarization rank dependences" 0, 1, 2 refer in turn to polarization, vector polarization, and tensor polarization of the beam. The "Interference types" entries refer to the matrix-element combinations which can appear in the distribution; subscripts v and c refer to parity violation or conservation. A sign reversal of rank-1 polarization reverses the signs of W_1 and W_3; a tensor sign change reverses signs of W_2 and W_4.

W_0 is the angular distribution for an unpolarized beam, W_1 exhibits the well-known "left-right"asymmetry, W_2 provides the tensor polarization analysis of the reaction, and W_3 is the term which would be detected in this experiment. W_4, although not looked for in this experiment, is a term which might bear consideration in further searches for parity nonconservation.

These terms may be expanded further; in particular, W_3 contains a term proportional to $\mathbf{P}\cdot\mathbf{k}_2\times(\mathbf{k}_1\times\mathbf{k}_2)$, and a term proportional to $\mathbf{P}\cdot\mathbf{k}_2$. This experiment measured the term proportional to $\mathbf{P}\cdot\mathbf{k}_2$. In this experiment where two counters are placed symmetrically on the x axis, one corresponding to a reflection of the other in the y-z plane, the only possible detectable effect of a sign change of vector polarization would be of term W_3.

The reaction at low energies is ordinarily considered to be specified by only one matrix element:

$$\langle cL_2l_2s_2b|R|aL_1l_1s_1b\rangle=\langle 0\ \tfrac{3}{2}\ 2\ \tfrac{1}{2}\ \tfrac{3}{2}|R|\tfrac{1}{2}\ 1\ 0\ 1\ \tfrac{3}{2}\rangle\equiv R_0.$$

All other parity-conserving elements are known to be small or zero because of the isotropy of the unpolarized angular distribution in the case of elements with nonzero l_1, and because of previous tensor polarization measurements in the case of zero l_1.

The counter positions and polarization directions of this experiment are such that terms W_1 and W_4 would not be detected. Misalignments of the counter position and polarization could in principle cause misleading data because of the effects of the term W_1, but this term requires existence of nonzero l_1 elements which, as

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TABLE I. Breakdown of the total angular distribution W into terms W_0 through W_4 according to their reflection and polarization dependencies. This experiment measured that part of W_3 which is proportional to $\mathbf{P}\cdot\mathbf{k}_2$.

Dependence	W_0	W_1	W_2	W_3	W_4
Rank of polarization dependence	0	1	2	1	2
Interference types	$\mathrm{Re}R_vR_v'^*$ and $\mathrm{Re}R_cR_c'^*$	$\mathrm{Im}R_vR_v'^*$ and $\mathrm{Im}R_cR_c'^*$	$\mathrm{Re}R_vR_v'^*$ and $\mathrm{Re}R_cR_c'^*$	$\mathrm{Re}R_cR_v'^*$	$\mathrm{Im}R_cR_v'^*$
Reflection sign change	No	No	No	Yes	Yes

mentioned, would be small, so that such misalignments would have to be of the order of a radian to obtain a false result. Such a large misalignment would be out of the question in this experiment.

The angular dependence in W is such that with counters at $\theta=\frac{1}{2}\pi$ and the polarization vector perpendicular to $\mathbf{k}_1$ as in this experiment, then parity violations with incident odd l_1 will not de detected in interference with R_0. Such elements, e.g., with incident p wave, could be detected with this experimental arrangement if there were a large parity-conserving incident p-wave element, which is not the case with this reaction. In any case, one could expect the parity-violating elements with incident s wave to be the largest because of the low incident energy in the experiment.

In further discussion of the angular distribution we neglect all elements not in interference with R_0 and all parity-conserving elements except R_0. With these considerations the angular distribution may be expressed as

$$\begin{aligned} W/W_0 = 1 &- \tfrac{1}{12}\{6P_2(\cos\theta)P_{zz}+4P_2{}^1(\cos\theta) \\ &\times[P_{xz}\cos\varphi+P_{yz}\sin\varphi] \\ &+P_2{}^2(\cos\theta)[(P_{xx}-P_{yy})\cos 2\varphi+2P_{xy}\sin 2\varphi]\} \\ &-\mathrm{Re}\{R_1/R_0+R_2/R_0\}\{P_1(\cos\theta)P_z \\ &+P_1{}^1(\cos\theta)[P_x\cos\varphi+P_y\sin\varphi]\} \\ &+(\text{parity-violating terms involving } l_1\geq 1). \end{aligned}$$

It may be seen that the term containing R_1 and R_2 is proportional to $\mathbf{P}\cdot\mathbf{k}_2$. In this equation, R_0 is as defined before and

$$R_1\equiv\langle 0\,\tfrac{3}{2}\,1\,\tfrac{1}{2}\,\tfrac{3}{2}|R|\tfrac{1}{2}\,1\,0\,1\,\tfrac{3}{2}\rangle,\quad R_2\equiv\langle 0\,\tfrac{1}{2}\,1\,\tfrac{1}{2}\,\tfrac{1}{2}|R|\tfrac{1}{2}\,1\,0\,1\,\tfrac{1}{2}\rangle.$$

The general conclusion, therefore, is that a measure of the $\mathbf{P}\cdot\mathbf{k}_2$ term allows a measure of the parity-nonconserving ratio $\mathrm{Re}(R_1/R_0)$ assuming a knowledge of the vector polarization of the deuteron beam. The vector polarization may be deduced from a knowledge of the polarized ion source characteristics plus a measure of the tensor polarization components which are obtained from the terms in the angular distribution. The ratio of magnitude of the matrix elements R_1 and R_0 neglecting parity considerations is about 1 for the energies involved in the $T(d,n)He^4$ reaction considering[21] only the decay probability of a $He^5(I=\frac{3}{2}, E\sim 18\text{ MeV})$ state into a final p or d state.

III. EXPERIMENTAL METHODS AND APPARATUS

A. Production of Atomic Polarization

The polarized deuteron beam was produced by an atomic-beam magnetic-resonance polarized deuteron source, of which preliminary descriptions have been given.[22,23] This source makes use of the atomic-beam magnetic-resonance method to select deuterium atoms in a particular Zeeman hyperfine substate, or combination of such substates. These polarized atoms are then ionized to produce polarized nuclei, which are then electrostatically accelerated.

A schematic of the apparatus is shown in Fig. 1. The first step in the operation of the ion source is the dissociation of molecular deuterium by a radio-frequency discharge in a Pyrex bulb. A slit in the bulb permits effusion of the thermal-energy atomic deuterium into a vacuum. The discharge-bulb source slit and a collimating slit that is placed in the vacuum together define a beam of atoms. The atoms of the beam pass in turn through an inhomogeneous magnetic deflecting field

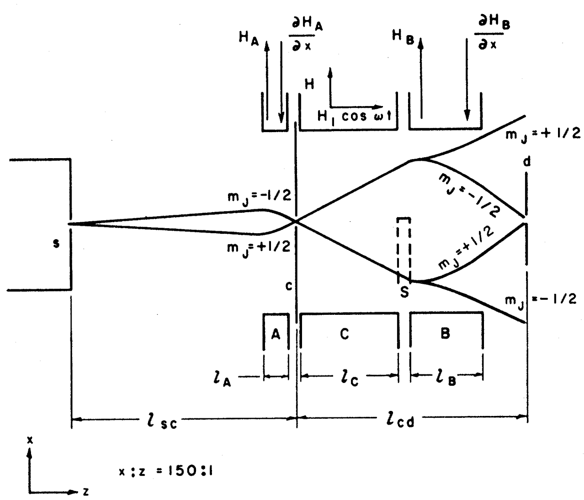

FIG. 1. Schematic diagram of the atomic-beam magnetic-resonance spectrometer. s is the source chamber with source slit. c is the collimator slit. The A and B regions are regions of inhomogeneous magnetic field. The C region contains the oscillating electromagnetic field and in addition a constant homogeneous field. d is the detector slit. S is a wire stop. Trajectories of atoms in different m_J states are shown. $l_{sc}=19.7$ cm, $l_{cd}=16.3$ cm, $l_A=2.0$ cm, $l_C=8.0$ cm, and $l_B=6.0$ cm. The source, collimator, and detector slits are 1 cm high, with respective widths of 0.13, 0.13, and 0.15 mm.

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(A field), the collimating slit, a homogeneous magnetic field (C field), and a second inhomogeneous magnetic deflecting field (B field). During passage through the C field, which is constant in time, beam atoms also pass through a loop where they may be subjected to a radio-frequency oscillating magnetic field superposed on the C field.

The A and B deflecting fields have field gradients transverse to the direction of atomic-beam propagation so that the atoms may be deflected from a straight path by the interaction of the atomic dipole moment with the inhomogeneous magnetic field. The direction of deflection of atoms in these regions is determined by the direction of the field gradient, which is the same in both A and B regions, and also by the sign of the atomic magnetic dipole moment, which is the same as the sign of the electronic magnetic projection quantum number m_J because of the high field strength in these regions. Thus atoms having magnetic moments of opposite signs are spatially separated in the A region, and are further separated in the B region provided each atom in the B region retains the same sign of m_J possessed in the A region. However, m_J may be reversed in the C region by a radio-frequency transition between two substates designated by opposite m_J ($m_J=\frac{1}{2}\leftrightarrow m_J=-\frac{1}{2}$), resulting in a corresponding reversal of the effective magnetic moment that the atom has on arrival in the high field of the B region. An atom which has undergone such a transition is then redeflected, or refocussed, in the B region. The deflecting fields are designed so that the redeflected atom crosses the straight path it would have had if there had been no deflection at all.

The atoms have a modified Boltzmann distribution of velocities,[24] however the location of the crossing point is independent of the velocity of the atoms. Thus all atoms that undergo a reversal of magnetic moment in the C region are refocussed, forming an image of the source slit. This image is formed in the plane marked d on Fig. 1. Atoms that retain the same m_J in the A and B regions are deflected away from the image. Thus an aperture placed at the image position passes only atoms which have undergone a change in m_J. The result is that only atoms in the pair of substates involved in the transition are passed through the aperture. Such polarized atoms, after passage through the aperture, are ionized by electron bombardment, resulting in a beam of polarized deuterons.

If desired, further state selection may be effected by a wire stop between the B and C regions, which blocks the unwanted substate, permitting selection of a single substate. The wire stop was not used in this experiment.

B. Determination of Deuteron Polarization

A Breit-Rabi diagram of the ground state of deuterium is shown in Fig. 2, indicating three transitions, A, B, and C, which may be induced in deuterium. As described in the previous section, only those atoms which have undergone a transition will reach the ionizer region. For example, when the 444-Mc/sec field was applied, only those substates designated in the (F,m_F) representation as $(\frac{3}{2},\frac{1}{2})$ and $(\frac{1}{2},\frac{1}{2})$ were ionized. Polarization may be calculated in each case by writing the density matrix for the beam of state-selected atoms in the uncoupled or (m_J,m_I) representation. This may be done by expressing the hyperfine substates as an expansion in terms of the uncoupled electronic and nuclear states designated by (m_J,m_I). The density matrix is then composed by appropriately combining the expansion coefficients. Such expansion coefficients are functions of magnetic field, and are evaluated at the field in the ionizer. The ionization process is represented by contracting the density matrix with respect to the electronic quantum numbers m_J. This corresponds physically to the excellent approximation that no change in nuclear quantum number can take place during the ionization time since it is so short compared to the characteristic interaction time of the nucleus with the electronic fields. If the quantization axis is defined to be along the magnetic field direction in the ionizer, the density matrix of the ionized deuteron beam is diagonal with elements equal to N_1, N_0, and N_{-1}, which are the fractional numbers of deuterons in the $m_I=1$, 0, -1 states, respectively. With the x axis taken to be in the quantization direction, the polarization in this system may be expressed in terms of P_x and P_{xx}, with $P_y=P_z=P_{xy}=P_{yz}=P_{xz}=0$, and $P_{yy}=P_{zz}=-\frac{1}{2}P_{xx}$. Consider, for example, transition C of Fig. 2 connecting the substates designated by $(F,m_F)=(\frac{3}{2},\frac{1}{2})$ and $(F,m_F)=(\frac{1}{2},\frac{1}{2})$. Under ideal conditions a deuteron beam characterized by $P_x=0.50$, $P_{xx}=-0.50$ is produced. The small but finite field necessary to maintain polarization in the ionizer reduces these polarization values a few percent. It should be noted that the transition probabilities do not affect the polarization but only the intensity of the polarized beam. In addition to the polarized deuteron beam, which is obtained only when the radio frequency is applied, there is the unpolarized background beam of D_2^+ and D^+ ions, present whether or not the radio frequency (rf) is applied. This background originates from background gas containing deuterium, principally in the form of D_2. This background consisting of the rf-off beam must be subtracted from the rf-on beam to obtain the polarization as stated. The background was typically five times the polarized beam intensity.

The vector polarization was deduced from a knowledge of the tensor polarization, which was gained from a measure of the 0°-90° asymmetry with respect to the x axis of the 14-MeV neutrons from $T(d,n)He^4$. This tensor polarization dependence has been experimentally confirmed.[23,25]

[24] N. H. Ramsey, *Molecular Beams* (Oxford University Press, London, 1956).

[25] E. Baumgartner, L. Brown, P. Huber, H. Rudin, and H. R. Striebel, Phys. Rev. Letters **5**, 154 (1960); H. Rudin *et al.*, Helv. Phys. Acta **34**, 58 (1961).

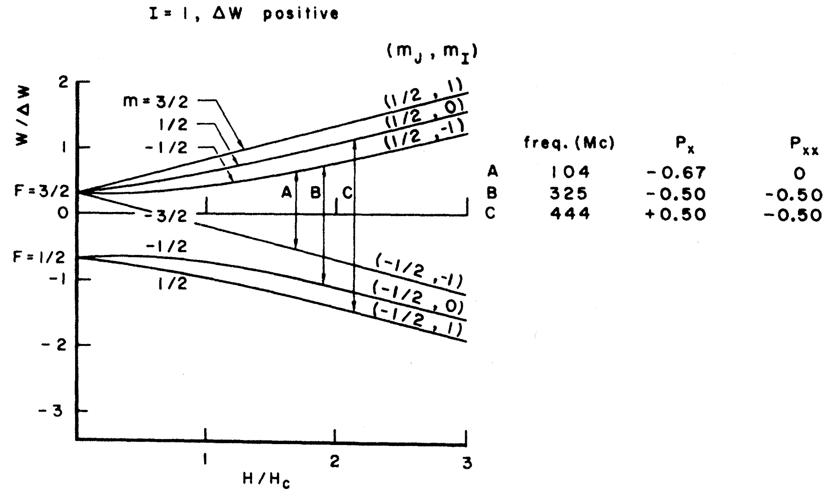

FIG. 2. Shown schematically on the Breit-Rabi diagram for deuterium are the three transitions together with frequencies and polarizations. They are shown at different values of H/H_c only for clarity. H_c is a characteristic field given by $H_c \equiv (g_J - g_I)\mu_0/\Delta W$. The values given for P_x and P_{xx} are for equal ionization of the two refocused states in a low field, $H/H_c \ll 1$. g_J and g_I are the electronic and nuclear g values in atomic units, μ_0 is the Bohr magneton, H is the magnetic field, and ΔW is the zero-field hyperfine separation.

C. Ionization of the Atomic Beam

To obtain deuterons, the deuterium atomic beam was ionized by electron bombardment in an electrostatic electron gun. A schematic of the ionizer is given in Fig. 3. A 4-G field transverse to the atomic and ion beams maintained polarization. The filament was carburized thoriated wolfram. The electrons, upon emission from the Ohmically heated filament, were accelerated by electrodes of roughly Pierce-type configuration, further accelerated by focusing plates, and then steered so as to intersect the atomic beam. The ions were extracted electrostatically by the electrode stack shown. The 650-eV electron beam was typically 0.5 mm wide with a current density of 100 mA/cm^2. Ionization efficiency of the gun for deuterium atoms was of the order of 2×10^{-4}, and the polarized deuteron current was of the order of 10^{-10} A. A difficulty of ionization by this method is that the electron beam should be steered and focused to precisely intersect the atomic beam for maximum intensity. However, it was possible to unequally ionize the two spatially diverging atomic states if the electron beam were too narrow; monitoring of the tensor polarization by means of the reaction angular distribution provided corrections to the polarization from this effect.

D. Measurement of the Angular Distribution

The polarized deuteron beam was accelerated to 140 keV and focused on a thick tritiated-titanium stationary target. Neutron counters (plastic scintillators) were placed at $\theta=90°$, $\varphi=0°$, 180°, and 270°. The resulting recoil proton spectrum was biased to count about 70% of the neutrons. The electronics were modified to improve stability, especially against changes in temperature and humidity. Bias settings and gains were periodically monitored.

E. Data and Results

Data were recorded simultaneously for the three neutron counters. The three different radio frequencies were applied to the atomic transition region in sequence for a period of an hour per frequency. However, during each 1-h period the radio frequency was turned on and off for equal time intervals of 50 msec. Two scalers were provided for each counter, one recording neutron counts with the radio frequency off and the other recording counts while the radio frequency was on. This provision enabled subtraction of counts due to cosmic radiation and neutrons arising from the unpolarized background component in the deuteron beam. The equality of the on and off times was periodically checked. Thus the rapid on-off rf modulation and the simultaneous recording of neutron counts from all counters obviated false results due to fluctuations in polarized beam intensities.

The repeated alternation of the three frequencies was to ensure against drifts in time of instrumental asym-

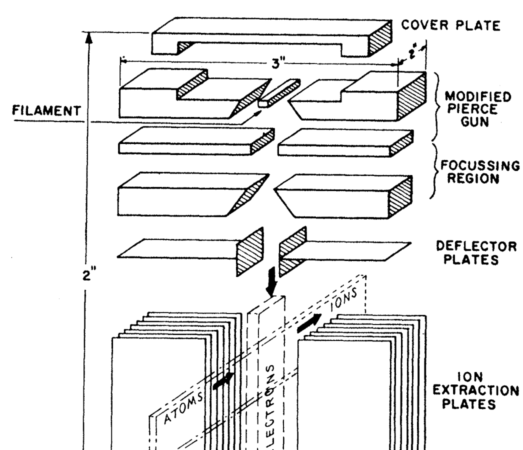

FIG. 3. Schematic of the electron gun which ionized the atomic beam. The filament and cathode are at -650 V. The electrons are thermionically emitted, accelerated electrostatically through the series of slits shown, and arrive at the ionization region which is maintained at an average of 0 V but which has an electrostatic field imposed by the ion extraction plates.

metries. The alternation of the three frequencies was rather slow, but the runs were long enough that there were many such alternations, and the electronics were stabilized for this reason. Ratios of counts from different counters with the radio frequency off furnished a direct and adequate monitor on the instrumental asymmetry drifts, and proved these to be of no significant effect on the final data.

As noted in Fig. 2, the vector polarization is equal and opposite for the transitions B (325 Mc/sec) and C (444 Mc/sec). Therefore the 0° to 180° asymmetry (which would occur only as a result of a parity violation) should reverse and become an equal and opposite asymmetry on changing the frequency from B to C. A major factor in the choice of these transitions is that they both produce the same tensor polarization, except for a negligible second-order difference because of the combined effect of small magnetic field in the ionizer plus unequal ionization of states. Since the angular distribution in this reaction is so strongly dependent upon tensor polarization, a changing tensor polarization coupled with any asymmetry in the counter positions could give false results. However, because the tensor polarization was the same in both transitions, large solid angle counters could be used with confidence.

The ratio measured was

$$\left(\frac{\mathrm{I_{on}}-\mathrm{I_{off}}}{\mathrm{III_{on}}-\mathrm{III_{off}}}\right)_C\left(\frac{\mathrm{III_{on}}-\mathrm{III_{off}}}{\mathrm{I_{on}}-\mathrm{I_{off}}}\right)_B\equiv 1+\epsilon,$$

where I and III refer to counters at 180° and 0°, respectively, with respect to the x axis; the subscript indicates the state of the radio-frequency power, and C and B refer to the transitions as noted. This quantity ϵ is a measure of any $\mathbf{P}\cdot\mathbf{k}_2$ angular dependence and is independent of first-order counter asymmetries. The 104-Mc/sec transition and a third counter centered at $\theta=90°$, $\varphi=270°$ provided a continuous monitor of the tensor polarization and therefore a check of the behavior of the apparatus. The precision in the measured value of ϵ set an upper limit on $\mathfrak{F}$ or the parity-nonconserving part of the reaction.

The statistical uncertainty in ϵ was calculated from the number of counts in the usual manner. The variation in ϵ measured during the different runs was studied for statistical consistency. A run is defined as a period of 12 data hours (4 complete 3-h cycles), which was chosen from experience as a length of time during which the asymmetry of the counters could be expected to remain constant. The distribution of runs over a total of 189 data hours gave a χ^2 probability of 0.5.

Checks were made of possible systematic errors. The constancy of the detector efficiency was determined by comparing the rf-off ratios for each run. Deviations were within statistical expectations.

Other possible errors lie in the measurement of the average counter angles. Solid-angle corrections were made and errors can arise in these corrections.

Second-order asymmetries in the 0° to 180° measurements can arise from combinations of polarization-dependent $\cos\theta$ or $\sin\varphi$ distributions combined with imperfect positioning of the counters.

Since the counted neutrons are polarized, the counter efficiency must be independent of, or symmetrical with respect to, neutron polarization.

These possible errors were estimated and/or measured by varying the experimental parameters and in each case determined to be small compared to counting statistics. The final result for the experimental limit of the ratio of the parity-violating to the parity-conserving amplitude in this reaction can be derived from the standard deviation of the experimental value for ϵ. The result is

$$|\mathrm{Re}\mathfrak{F}|\lesssim 3.8\times 10^{-3}.$$

This limit includes the nuclear factor $\mathfrak{R}$, in our case ~ 1, which is quite insensitive to nuclear-model assumptions and which does not include any assumptions about electromagnetic effects. At most previously measured limits this factor $\mathfrak{R}$ was large, typically 10^3 to 10^4 for the electromagnetic decays.

APPENDIX

The general angular distribution for a reaction with polarized deuterons incident on an unpolarized target, with two particles in the final state, with polarization-insensitive detectors, and with a relaxation of the parity-conservation rule, is as follows. The derivation of this formula is discussed in the main text of this article.

$$W(\theta,\varphi)=W_0(\theta)+\frac{\lambda\!\!\!^{-2}}{4\hat{a}^2}\sum_{bb'L_1L_1'L_2L_2'l_1l_1'l_2l_2'k}\hat{b}^2\hat{b}^{2\prime}\hat{L}_1\hat{L}_1'\hat{L}_2\hat{L}_2'\hat{l}_1\hat{l}_1'\hat{l}'\hat{l}_2'(-)^{a-2b'+c-s_2+k-L_1+l_1'}W(bb'L_1L_1';ka)W(l_2l_2'L_2L_2';ks_2)$$
$$\times W(bb'L_2L_2';kc)(l_20,l_2'0|k0)q(bb';L_1L_1',L_2L_2',l_1l_1',l_2l_2')\sum_{k_l}\sum_{k_s=1}^{2}(l_10,l_1'0|k_l0)\hat{k}_l\hat{k}_s$$
$$\times\begin{Bmatrix} l_1 & l_1' & k_l \\ 1 & 1 & k_s \\ L_1 & L_1' & k \end{Bmatrix}B_1(k_lk_sk;RR'^*).$$

For even (k_l+k), parity is conserved in *both* R and R', or parity is violated in *both* R and R', and

case (1):

$$B_1(k_l,k_s=1,k;RR'^*)=\mathrm{Im}(RR'^*)\left(\frac{(k-1)!}{(k+1)!}\right)^{1/2}(k_l0,11|k1)P_k^1(\cos\theta)[P_y\cos\varphi-P_x\sin\varphi],$$

case (2):

$$B_1(k_l,k_s=2,k;RR'^*)=\mathrm{Re}(RR'^*)\left\{\frac{1}{\sqrt{2}\sqrt{3}}(k_l0,20|k0)P_k(\cos\theta)P_{zz}+\frac{2}{3}\left(\frac{(k-1)!}{(k+1)!}\right)^{1/2}(k_l0,21|k1)\right.$$
$$\left.\times P_k^1(\cos\theta)[P_{xz}\cos\varphi+P_{yz}\sin\varphi]+\frac{1}{3}\left(\frac{(k-2)!}{(k+2)!}\right)^{1/2}(k_l0,22|k2)P_k^2(\cos\theta)[(P_{xx}-P_{yy})\cos2\varphi+2P_{xy}\sin2\varphi]\right\}.$$

For odd (k_l+k), parity is conserved in only one of the elements R or R', and parity is violated in the other element, and

case (3):

$$B_1(k_l,k_s=1,k;RR'^*)=\mathrm{Re}(RR'^*)\left\{\frac{1}{\sqrt{2}}(k_l0,10|k0)P_k(\cos\theta)P_z\right.$$
$$\left.+\left(\frac{(k-1)!}{(k+1)!}\right)^{1/2}(k_l0,11|k1)P_k^1(\cos\theta)[P_x\cos\varphi+P_y\sin\varphi]\right\},$$

case (4):

$$B_1(k_l,k_s=2,k;RR'^*)=\mathrm{Im}(RR'^*)\left\{\frac{2}{3}\left(\frac{(k-1)!}{(k+1)!}\right)^{1/2}(k_l0,21|k1)P_k^1(\cos\theta)[-P_{xz}\sin\varphi+P_{yz}\cos\varphi]\right.$$
$$\left.+\frac{1}{3}\left(\frac{(k-2)!}{(k+2)!}\right)^{1/2}(k_l0,22|k2)P_k^2(\cos\theta)[-(P_{xx}-P_{yy})\sin2\varphi+2P_{xy}\cos2\varphi]\right\}.$$

The quantity $\lambda\!\!\!^{-}$ is the reduced wavelength in the initial center-of-mass system. The contraction factor q is inserted to avoid duplication in the summation and is defined as follows:

$q(bb';L_1L_1',L_2L_2',l_1l_1',l_2l_2')=0$

when $b<b'$; or

when $b=b'$ and $L_1<L_1'$; or

when $b=b'$, $L_1=L_1'$, and $L_2<L_2'$; or

when $b=b'$, $L_1=L_1'$, $L_2=L_2'$, and $l_1<l_1'$; or

when $b=b'$, $L_1=L_1'$, $L_2=L_2'$, $l_1=l_1'$, and $l_2<l_2'$.

Also, $q(bb';L_1L_1',L_2L_2',l_1l_1',l_2l_2')=2$

when $b>b'$; or

when $b=b'$ and $L_1>L_1'$; or

when $b=b'$, $L_1=L_1'$, and $L_2>L_2'$; or

when $b=b'$, $L_1=L_1'$, $L_2=L_2'$, and $l_1>l_1'$; or

when $b=b'$, $L_1=L_1'$, $L_2=L_2'$, $l_1=l_1'$, and $l_2>l_2'$.

Also, $q(bb;L_1L_1,L_2L_2,l_1l_1,l_2l_2)=1$.

The symbols $(\,, | \,)$, $W(\,; \,)$, and $\{ \; \}$ denote the usual vector coupling coefficients, Racah coefficients, and the 9-j symbol, respectively. The caret symbol means, for example, $\hat{a}=(2a+1)^{1/2}$.

In expressing the angular distribution as $W=W_0+W_1+W_2+W_3+W_4$, as discussed previously in this article, cases (1), (2), (3), and (4) for B_1 result in terms W_1, W_2, W_3, and W_4, respectively. W_0 is given by Eq. (2.12) in Ref. 20.

The notation is consistent with that of Goldfarb, but see the text of this article for definitions of x, y, z, θ, φ.