Search for Parity Nonconservation in the Force Between Nucleons*

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An experiment to search for the parity-forbidden α decay of the 8.87-MeV state in ^{16}O has been performed. No evidence of this decay was observed. Assuming a laboratory radiation width of 3.43×10^{-3} eV for the 8.87-MeV state, we find the laboratory α-decay width to be less than 2.1×10^{-9} eV with a 95% confidence limit.

INTRODUCTION

This paper describes an experiment designed to observe a possible violation of parity conservation in the force between nucleons. This search was motivated specifically by the expectation that a weak interaction between nucleons would manifest itself as a violation of parity in the total nucleon-nucleon force, and in a more general way, by basic interest in the violation of fundamental symmetries. The experiment performed was a search for parity-forbidden α decay from the 2^- state at 8.87 MeV in ^{16}O.

The self-interacting-current hypothesis suggested to explain the weak interaction[1] assumes a current consisting of terms depending upon hadrons (nucleons in our case) and leptons separately. The interaction energy is found by taking the product of the current with its adjoint, and cross terms correspond to known phenomena such as β decay. In addition, there are terms corresponding to physical processes which have not yet been directly observed. In particular, the product of one term with its adjoint predicts parity nonconservation in the total nuclear force due to the weak interaction. General estimates of the magnitude of this effect by Blin-Stoyle[2] and Michel[3] indicate that the amplitude of the part of the wave function with irregular parity, F,[4,5] is probably of the order of 10^{-7} to 10^{-6}.

A number of experiments in which the effect should be proportional to F have been reported[6] and several of these did in fact give a positive result. However, these experiments involve γ decay and thus the electromagnetic interaction as well as the strong interaction. Effects proportional to F^2 (see Bonar *et al.*[7]) might also be observed involving only the strong and weak interactions, and an observed violation could be interpreted without the complication of the electromagnetic interaction. Among these, α decay of the 8.87-MeV level in ^{16}O has received the greatest attention in the past.[8-12]

All studies of this decay, including the present one, have proceeded in the same basic way. A nuclear reaction is used to produce the radioactive nucleus ^{16}N, which subsequently undergoes β decay to ^{16}O with a half-life of 7.10 sec.[13] Only two α-unstable levels in ^{16}O have a significant branching ratio for this decay: the 8.87 MeV 2^- with a branching ratio of 0.011 and the 9.6-MeV 1^- state with a branching ratio of 1.20×10^{-5}.[10] The experimentally observed quantity is the α spectrum following the β decay, and a violation of parity conservation would be indicated by the existence of a peak in this spectrum corresponding to the 8.87-MeV 2^- state. Since α decay of the 9.6-MeV 1^- state is not inhibited, the principal contribution to the observed α spectrum is from this state. Let $\Gamma_{\alpha\,\mathrm{ob}}$ and Γ_γ be the observed laboratory α-decay width and the laboratory radiation width of the 8.87-MeV state. Since γ decay is the only allowed decay mode of the 8.87-MeV state, its total width will be very closely equal to Γ_γ. Since α decay of the 9.6-MeV state is allowed, its total width will be very nearly equal to its α width,[14] and from the known β branching ratios we may write

$$\frac{\Gamma_{\alpha\,\mathrm{ob}}}{\Gamma_\gamma}=1.09\times10^{-3}\frac{n_\alpha(8.87)}{n_\alpha(9.6)},$$

where n_α denotes the number of observed α particles. Thus, the observed α width may be expressed in terms of the known γ width, and the quantity F^2 may be expressed as[10]

$$F^2=\frac{\Gamma_{\alpha\,\mathrm{ob}}}{\Gamma_\alpha}=\frac{\Gamma_{\alpha\,\mathrm{ob}}}{\Gamma_\gamma}\times\frac{\Gamma_\gamma}{\Gamma_\alpha},$$

where Γ_α is the α-decay width which the 8.87-MeV state would have if it were a 2^+ state.

The experimentally determined quantity in the above expression for F^2 is the ratio $n_\alpha(8.87)/n_\alpha(9.6)$, and it is this ratio which should be compared with the results of other measurements. At the time the present experiment was started, the most sensitive limit on this ratio was 0.05%[11] (with an unstated confidence limit). Since the completion of the present experiment, a much more sensitive limit of 0.004% (unstated confidence limit) has been published by Hättig *et al.*[12] This result represents a substantial improvement over previous measurements and also over the present experiment. In spite of this, we have published the present result because, as noted for example by Okun,[15] this is a measurement which is of great importance to the theory of the weak interaction and all information relevant to the result is of some importance.

The ratio $\Gamma_\gamma/\Gamma_\alpha$ in the expression for F^2 depends upon a theoretical estimate of the width Γ_α. This estimate will differ depending on the assumptions made concerning nuclear systematics. In the present paper we adopt the value of $\Gamma_\alpha = 6.7\times10^3$ eV chosen by Donovan, Alburger, and Wilkinson.[8] The radiation width Γ_γ of the 8.87-MeV level was taken to be 3.43×10^{-3} eV based on the lifetime measurements of Pixley and Benenson.[16]

Very recently, two theoretical estimates of $\Gamma_{\alpha\,\mathrm{ob}}$ based on the conserved-vector-current theory of the weak interaction have been reported. The first, by Gari and Kümmel,[17] gave $\Gamma_{\alpha\,\mathrm{ob}} = (1.2 \text{ to } 1.8)\times10^{-10}$ eV with an estimated uncertainty of ±20%. The second, by Henley, Keliher, and Yu,[18] gave $\Gamma_{\alpha\,\mathrm{ob}} = (1.3 \text{ to } 2.1)\times10^{-10}$ eV with an estimated uncertainty of ± a factor of 2.

EXPERIMENTAL METHOD

In the present experiment ^{16}N was produced by the reaction $^{15}\mathrm{N}(d,p)^{16}\mathrm{N}$. The target gas, enriched to 99% ^{15}N, was contained within a gas cell equipped with double-foil beam entrance and exit windows cooled with helium gas. An approximately 20-μA 2.4-MeV deuteron beam was passed through the cell causing a small fraction of the ^{15}N to be converted to ^{16}N. The gas was allowed to flow continuously through a 60-in.-long 0.019-in.-diam tube to a counting cell. After passing through the counting cell, the gas was collected in a tube cooled to liquid-helium temperature for reuse as feed gas for the beam cell.

The counting cell, shown in Fig. 1, has basic cylindrical symmetry. The radioactive ^{15}N-^{16}N mixture was contained within a region bounded on either side by thin plastic foils. On each side of this region a fully depleted surface-barrier detector of nominal thickness 25 μ was mounted. By separating the radioactive gas and detector we reduced the number of electrons entering the detector tangentially to its face, and thus the electron-induced background in the spectral region of interest. The use of two detectors not only increased the count

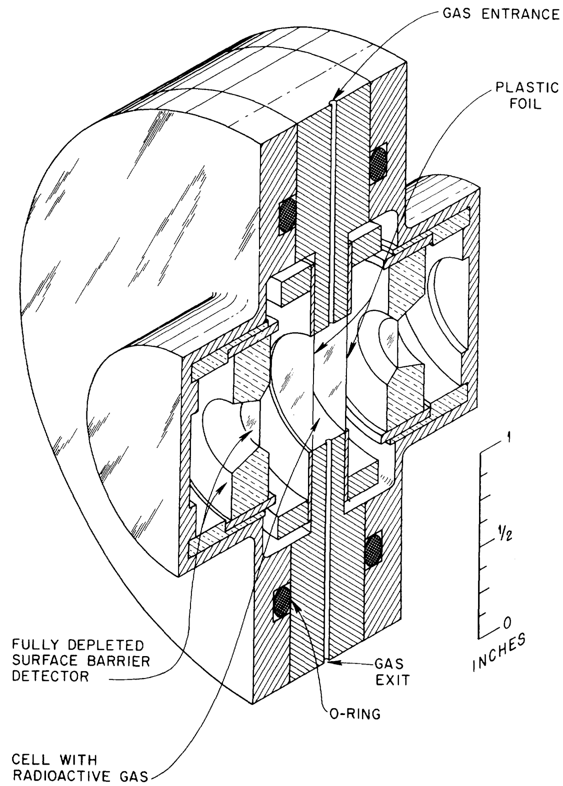

FIG. 1. A simplified view of the counting cell. Bolts, bolt holes, detector electrical connections, interconnecting passages, and other details are not shown.

rate by a factor of 2, but also provided checks on internal consistency. In order to minimize the plastic-foil thickness, equal pressure was maintained on both sides of the foils. This was done by connecting the sample and detector regions with tubes in which the traversal time of the gas was long in comparison with the ^{16}N half-life. Neutron-induced background was minimized by heavily shielding the counting cell with paraffin and by immersing the counting cell in an ice-water bath. This bath also cooled the detectors to 0°C, improving their resolution. The cell was designed so that an ^{241}Am source could be inserted into the sample region without breaking the vacuum.

A total of six α spectra were measured for the present experiment in three separate "runs." Because of foil breakage and β-induced radiation damage in the detectors, it was necessary to use five foils and four detectors to accumulate these spectra, and they may be thought of as semiindependent. The total number of α particles attributed to the 9.6-MeV state in these six spectra is 949 730. A typical spectrum is shown in Fig. 2.

In the last phase of the experiment we discovered that a small amount of radioactive gas may have been present in the counting-cell-detector regions.

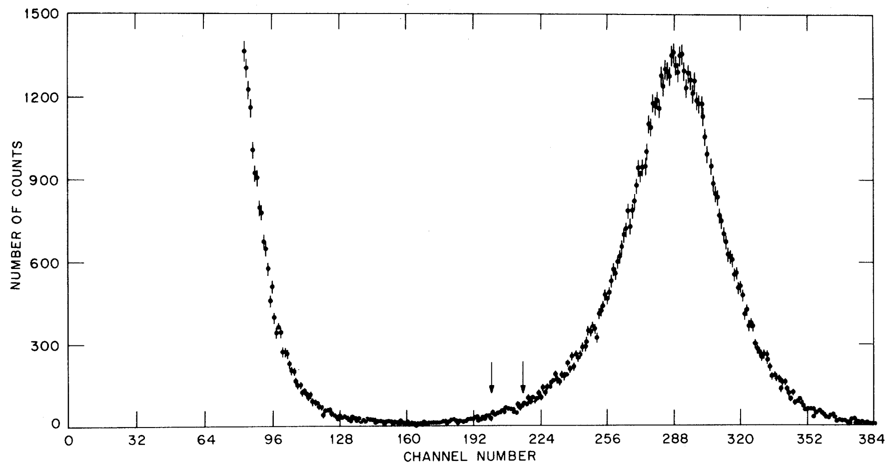

FIG. 2. A typical α-particle spectrum. The large peak, containing 79 023 counts, is due to the 9.6-MeV state. Vertical arrows indicate the expected positions of peaks due to the 8.87-MeV state.

Consequently, there may be a substantial contribution to some of the observed spectra from ^{16}N in the detector regions. α particles originating in the detector regions will be shifted slightly in energy relative to those originating in the sample region. Thus, there are two possible peaks in the observed spectra corresponding to the 8.87-MeV state. The most probable positions of these two peaks are indicated in Fig. 2 by vertical arrows. Since we did not have experimental information on the relative concentrations in the sample and detector regions, we analyzed the spectra under the assumption that two peaks of unknown relative intensity were present.

In order to analyze these spectra, it was necessary to predict the location and shape of peaks arising from the 8.87-MeV state. This prediction has two aspects. One is the calculation of effects related to the finite counting-cell geometry. This was done using standard Monte Carlo techniques and will not be discussed further. The other aspect was the determination of the input parameters for this calculation. For example, it was necessary to measure the response of the detectors for α particles with the energy expected in the peak (1.3 MeV), the straggling and energy loss caused by the plastic foils, and the line broadening caused by the background β flux. Two types of calibration measurements were made. Periodically, during the course of the experiment, pulser and ^{241}Am α-source calibrations were recorded. This allowed us to monitor electronic stability, radiation damage, and β-induced line broadening. In addition, we made auxiliary measurements with the accelerator α-particle beam. The beam was allowed to scatter from a thin gold target producing a monoenergetic source of 1.3-MeV α particles. Thus, we were able to make direct measurements of detector resolution, straggling, inhomogenity, and energy loss associated with the foils. For the spectrum shown in Fig. 2, the Monte Carlo calculations showed that the expected peaks would be well approximated by normal distributions with most probable standard deviations of approximately 21 and 26 keV for the lower and upper peaks, respectively. In Fig. 2 these values correspond to most probable standard deviations of 3.6 and 4.5 channels, respectively, and are typical of all the spectra. The expected positions of the peaks were based on the ^{241}Am α-source calibrations. For use in the analysis described below we shall denote our estimated probability distributions for the peak positions C_j and widths S_j by $D_j^C(C_j)$ and $D_j^S(S_j)$, where $j=1$, 2 refer to the lower and upper peaks, respectively. We assumed these functions to be normal distributions. Since the six spectra were measured under different conditions, it was not possible to add them for analysis. Thus, they were analyzed separately and the results combined for the final experimental result.

ANALYSIS

The analysis of the spectra was based primarily on the likelihood-function technique.[19] The essential idea of this method is as follows: Let x_i be the observed number of counts in channel i. We associate with x_i a probability distribution $f(x_i, \bar{x}_i)$ representing the probability that $\bar{x}_i$ is the "true" value of x_i. The function $f(x_i, \bar{x}_i)$ was assumed to be a normal distribution centered at x_i with standard deviation $\sqrt{x_i}$. The joint probability for any set of $\bar{x}_i$ is called the likelihood function,

$$L(x_i, \bar{x}_i,\ i=n,m)=\prod_{i=n}^{m} f(x_i, \bar{x}_i).$$

$L(x_i, \bar{x}_i,\ i=n,m)$ is then the relative probability that a given set of $\bar{x}_i$ are the true values of the measured variables x_i. For this analysis we defined $\bar{x}_i$ by the function

$$\bar{x}_i = B_i + P_i^j(A_j, C_j, S_j), \quad j=1 \text{ or } 2$$

or

$$\bar{x}_i = B_i + P_i^1(A_1, C_1, S_1) + P_i^2(A_2, C_2, S_2),$$

where B_i is a background function and P^1 and P^2 are normal distributions centered at C_1 and C_2, with areas A_1 and A_2 and standard deviations S_1 and S_2, respectively, representing the two possible 8.87-MeV-state peaks. These definitions yield the likelihood functions $L(A_j, C_j, S_j)$ and $L(A_1, A_2, C_1, C_2, S_1, S_2)$, respectively. In this notation, the dependence of L on B_i is implicit.

Consider, for example, the function $L(A_1, C_1, S_1)$. We interpret this as the relative probability that a peak of area A_1 and width S_1 is situated at channel C_1 on a background defined by B_i. In this sense, $L(A_1, C_1, S_1)$ represents the information contained in that part of the α spectrum defined by $n \leq i \leq m$. In addition to this spectral information, we have information concerning the position and shape of the peaks. This is contained in the probability distributions $D_1^C(C_1)$ and $D_1^S(S_1)$ determined from our auxiliary measurements. We interpret the product function

$$L(A_1, C_1, S_1) \times D_1^C(C_1) \times D_1^S(S_1)$$

as the relative probability for the variables A_1, C_1, S_1, B_i based on all the information contained in our measurements.

Now, in general, we are only interested in a probability distribution for A_1. This may be obtained in principle by integration over all values of the other variables.

$$L(A_1) = \iiint \cdots \int L(A_1, C_1, S_1) D_1^C(C_1) \times D_1^S(S_1) dC_1 dS_1 dB_n \cdots dB_m .$$

Unfortunately, we were not able to successfully perform integrations over the background variables. In order to perform integrations of this type, we found it necessary to fix the background by an auxiliary procedure and then to integrate only with respect to C_1 and S_1.

In an analysis of this type there are two possibilities: One can or cannot "see" peaks in the spectra. Recognition of peaks in the spectra represents additional information which may be more accurate than the auxiliary determination represented by $D_j^C(C_j)$. We examined our data for this possibility in the following way. A background B_i was generated by making a least-mean-squares fit for a fourth-degree polynomial to each spectrum in the region of interest. We examined the difference between this background and the data and assigned positions C_j^0 to channels in the center of regions where peaks appeared to exist. We then calculated likelihood functions for a fixed peak position of the form

$$L(A_j, C_j^0) = \int L(A_j, C_j^0, S_j) D_j^S(S_j) dS_j, \quad j=1 \text{ or } 2 .$$

In no case was there statistically significant evidence for a peak. Therefore, we used the distributions $D_j^C(C_j)$ in our final calculations described below.

In order to calculate a value for $n_\alpha(8.87)/n_\alpha(9.6)$ we performed the following analysis on each spectrum. Backgrounds were calculated by fitting polynomials of degree three through seven to portions of the spectrum adjacent to the regions where we expected to find peaks. In general, the level of significance (in terms of χ^2 and the number of variables) of these fits was not a strong function of the degree of the polynomial. Three criteria were used to choose a background B_i for subsequent calculations from these fits: a small number of parameters (low degree), a high level of significance, and an average area in the region of the peaks which was consistent with the average of all fits to a given spectrum. The backgrounds chosen were either fourth- or fifth-degree polynomials.

Let $A_T = A_1 + A_2$ be the total area in the two peaks. The probability distribution for A_T for a given background is then

$$L(A_T) = \iiiint\!\!\int L(A_1, A_T - A_1, C_1, C_2, S_1, S_2) \times D_1^C(C_1) D_2^C(C_2) D_1^S(S_1) D_2^S(S_2) dA_1 dC_1 dC_2 dS_1 dS_2 .$$

By algebraic substitution it can be shown that $L(A_T)$ can be closely approximated by

$$L(A_T) = \int L^1(A_1) L^2(A_T - A_1) dA_1 ,$$

where

$$L^1(A_1) = \iint L(A_1, C_1, S_1) D_1^C(C_1) D_1^S(S_1) dC_1 dS_1$$

and

$$L^2(A_2) = \iint L(A_2, C_2, S_2) D_2^C(C_2) D_2^S(S_2) dC_2 dS_2 ,$$

under the assumption that the two expected peaks do not overlap. This assumption is satisfied in our case. $L^1(A_1)$ and $L^2(A_2)$ were evaluated using Monte Carlo techniques and also several Newton-Cotes methods, i.e., Newton's method, Simpson's rule, and the trapizoidal rule. All of these techniques gave the same results, but we found the Newton-Cotes techniques to be significantly more efficient. It should be noted that the calculation of

$L^1(A_1)$ and $L^2(A_2)$ also provide a check on the internal consistency of the data and procedure. The final result for the experiment is a likelihood function generated by taking the product of individual $L(A_T)$ obtained from each spectra. From this function we concluded that there was no positive evidence for peaks in these spectra, and we placed the following limits on $n_\alpha(8.87)/n_\alpha(9.6)$: 0.057% (95% confidence limit), 0.069% (99% confidence limit). Using the values of Γ_γ and Γ_α quoted above, we calculate the following corresponding limits on $\Gamma_{\alpha\,\mathrm{ob}}$ and F^2: $\Gamma_{\alpha\,\mathrm{ob}} < 2.1\times10^{-9}$ eV (95% confidence limit), $\Gamma_{\alpha\,\mathrm{ob}} < 2.6\times10^{-9}$ eV (99% confidence limit), $F^2 < 3.2\times10^{-13}$ (95% confidence limit), $F^2 < 3.8\times10^{-13}$ (99% confidence limit). These values are consistent with the results presented in Refs. 11 and 12 and are lower than other previous experiments. They are also compatible with the recent estimates given by Gari and Kümmel[17] and Henley, Keliher, and Yu.[18]

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Note added in proof: The experimental data reported in Ref. 12 has been reanalyzed. This analysis, which gives a positive result, has been recently reported by Hättig, Hünchen, and Wäffler.[20]

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[1]R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958).

[2]R. J. Blin-Stoyle, Phys. Rev. 118, 1605 (1960); 120, 181 (1960).

[3]F. C. Michel, Phys. Rev. 133, B329 (1964).

[4]D. H. Wilkinson, Phys. Rev. 109, 1603 (1958).

[5]T. D. Lee and C. N. Yang, Phys. Rev. 104, 254 (1956).

[6]The experimental situation prior to about 1968 is reviewed by W. D. Hamilton, *Progress in Nuclear Physics* (Pergamon Press, Oxford, England, 1969), Vol. 10, p. 3. Later references include Y. G. Abou *et al.*, Phys. Letters 27B, 16 (1968); F. Boehm and E. Kankeleit, Nucl. Phys. A109, 457 (1968); V. M. Lobashov *et al.*, Phys. Letters 30B, 39 (1969).

[7]D. C. Bonar, C. W. Drake, R. D. Headrick, and V. W. Hughes, Phys. Rev. 174, 1200 (1968). A review of previous work is given in this reference.

[8]P. F. Donovan, D. E. Alburger, and D. H. Wilkinson, in *Proceedings of the Rutherford Jubilee International Conference, Manchester, 1961* (Heywood and Company, London, England, 1961), p. 827.

[9]R. E. Segal, J. W. Olness, and E. L. Sprenkel, Phys. Rev. 123, 1382 (1961).

[10]W. Kaufmann and H. Wäffler, Nucl. Phys. 24, 62 (1961).

[11]D. P. Boyd, P. F. Donovan, B. Marsh, D. E. Alburger, D. H. Wilkinson, P. Assimakopoulos, and E. Beardsworth, Bull. Am. Phys. Soc. 13, 1424 (1968).

[12]H. Hättig, K. Hüchen, P. Roth, and H. Wäffler, Nucl. Phys. A137, 144 (1969).

[13]S. A. Scott and A. Notea, Nucl. Phys. 77, 641 (1966).

[14]J. D. Larson and R. H. Spear, Nucl. Phys. 56, 497 (1964).

[15]L. B. Okun, Comments Nucl. Particle Phys. 1, 181 (1967).

[16]R. E. Pixley and W. Benenson, Nucl. Phys. A91, 177 (1967).

[17]M. Gari and H. Kümmel, Phys. Rev. Letters 23, 26 (1969).

[18]E. M. Henley, T. E. Keliher, and D. U. L. Yu, Phys. Rev. Lettters 23, 941 (1969).

[19]J. Orear, University of California Radiation Laboratory Report No. UCRL-8417, 1958 (unpublished).

[20]H. Hättig, K. Hünchen, and H. Wäffler, Phys. Rev. Letters 25, 941 (1970).