Parity Conservation in Nuclear Reactions: Search for α Decay of the 8.88-Mev State in O^{16}

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A search has been carried out for the parity-nonconserving α decay of the 8.88-Mev (2^-) state in O^{16} by examining the alpha-particle spectrum following N^{16} β decay. An upper limit of $(\Gamma_\alpha/\Gamma_\gamma)<2\times10^{-6}$ was determined which is shown to lead to the estimate that $\mathfrak{F}^2\lesssim2\times10^{-12}$. The alpha-particle group corresponding to disintegration of the broad 9.58-Mev (1^-) state was observed and the log ft for the β decay to this state found to be 6.8 ± 0.1, the slow transition rate being in accord with a shell-model prediction that the 9.58-Mev state is due to a three-nucleon excitation. The shape of the alpha spectrum was fitted with a Breit-Wigner analysis.

INTRODUCTION

THE possibility of detecting a parity-nonconserving nuclear transition in the alpha-particle spectrum following N^{16} β decay has been pointed out by the present authors[1] and, independently, by Alburger *et al.*[2] The relevant energy-level diagram is shown in Fig. 1, which includes results from the present work. Preliminary results, published in a previous communication,[1] showed an alpha-particle group corresponding to a β decay to the broad 9.58-Mev state but did not show any evidence for alpha particles emanating from either the 8.88- or 9.84-Mev states. The 2^- 8.88-Mev state is known[3] to be fed by the β decay of N^{16} but its breakup into an alpha particle and a C^{12} nucleus is strictly forbidden on the basis of conservation of angular momentum and parity. The decay to the 2^+ 9.84-Mev state would represent a first-forbidden β transition.

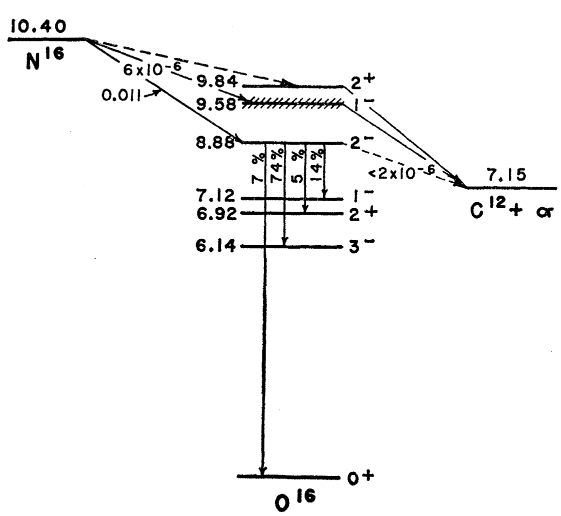

FIG. 1. Energy-level diagram showing the relevant states in the $N^{16}(\beta^-)O^{16*}(\alpha)C^{12}$ decay chain. The results of the present work are included; all other information was obtained from reference 3.

The experiment described previously has been refined considerably, particularly in regard to the sensitivity for detecting the parity forbidden transition, and the improved results are reported herein.

EXPERIMENTAL RESULTS

A schematic view of the target and counting chambers is shown in Fig. 2. Nitrogen gas, enriched to 96% N^{15}, was bombarded with 2-Mev deuterons. The beam entered and left the target chamber through thin (0.075×10^{-3} in.) nickel windows. Bombarding currents of about 1.5 μamp were used, and the gas target pressure was kept at about 3.5 in. Hg. The radioactive gas diffused into a small counting chamber which was viewed by a surface-barrier solid-state detector made of 70 ohm-cm, n-type silicon with a gold surface layer less than 0.1 μ thick.[4] The bias on the detector was kept sufficiently low (about 3.5 v) so that electrons would lose no more than about 500 kev in traversing the counter's depletion layer. The entire electronics system was frequently monitored for drifts by inserting pulses from a mercury pulser into the preamplifier input through a capacitor. The running cycle was to bombard (11 sec)–

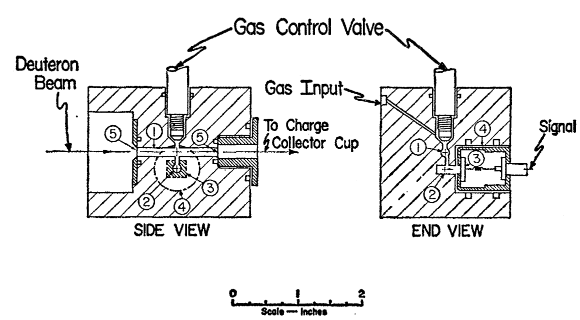

FIG. 2. Schematic diagram of target assembly. Components not labeled are designated by numbers as: (1) target volume; (2) counting volume; (3) silicon detector; (4) detector assembly; and (5) 0.075×10^{-3}-in. nickel foils.

[1] R. E. Segel, J. W. Olness, and E. L. Sprenkel, Phil. Mag. **6**, 163 (1961).

[2] D. E. Alburger, R. E. Pixley, D. H. Wilkinson, and P. Donovan, Phil. Mag. **6**, 171 (1961).

[3] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959). All information about N^{16} and O^{16} not otherwise referenced is taken from this compilation.

[4] The authors wish to thank Dr. G. Dearnaley of Atomic Energy Research Establishment, Harwell for the loan of this detector.

wait (5 sec)–count (13 sec). The accelerator was turned off by removing the spray voltage from the charging belt, and the waiting period was set to be long enough to allow the voltage to leak off the high-voltage terminal.

The detector was calibrated by scattering monoenergetic alpha particles, accelerated by the Van de Graaff generator, into the detector. A separate target chamber was used for these measurements in which the scatterer was a thin nickel foil. The absolute energy determined by this calibration was accurate to ± 30 kev in the energy region of interest (~ 1.5 Mev) and the energy scale (kev/channel) accurate to $\pm 3\%$. The main uncertainty in determining the energy calibration was due to an uncertainty in the thickness of the nickel scatterer.

The energy resolution of the detector was determined by inserting a known quantity of charge into the preamplifier (charge-sensitive) input with the detector in place. This noise spread was equivalent to about 65 kev and the spectra from monoenergetic alpha particles scattered into the detector confirmed that noise was the limiting factor in the detector energy resolution.

In determining the energy resolution of the entire system, the energy losses in the gaseous source had to be taken into account. An integration was performed over the source volume which showed that at the gas pressure used (3.5 in.) a monoenergetic alpha line would have appeared at the detector as a peak shifted downward by about 7 kev, of width 11 kev, plus a low-energy tail. Over 90% would appear within 60 kev of the true energy. The energy resolution of the entire system was therefore limited mainly by the detector and electronic noise.

The pulse-height spectrum from a run of some 6000 bombard-count cycles is shown in Fig. 3. It can be seen that, again,[1] only one alpha-particle group was observed, the group from the O^{16} 9.58-Mev state. The position and shape of this peak is discussed below. These data contain some 11 000 counts in this group. The rise at low pulse heights was due to electrons.

An upper limit for the number of alpha particles from the 8.88-Mev state was established with the aid of a computer calculation generously performed for us at Oxford University. In this computation, which used a computer program developed at Oxford, a sharp peak riding on a continuous spectrum is searched for by removing from the spectrum those channels which could be influenced by the sharp peak and then fitting the remainder of the spectrum with a polynomial. This polynomial is then used to predict the spectrum in the region of the sharp peak and the predicted spectrum compared to the observed one. Using this method, it was found that no more than 39 counts were present representing alpha particles from the 8.88-Mev state; the actual result being 7 ± 32, with the quoted error representing one standard deviation.

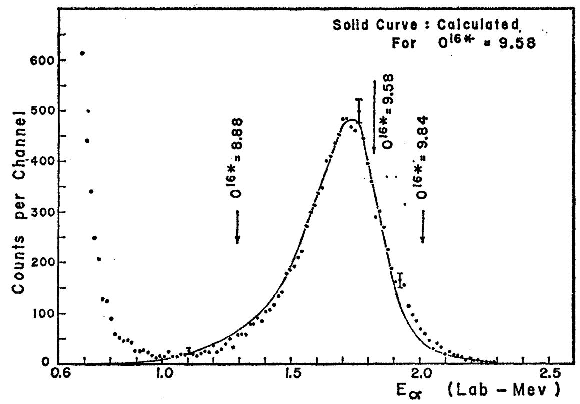

FIG. 3. Pulse-height spectrum from silicon detector viewing decaying N^{16} nuclei. The instrumental resolution was about 4 channels. The solid curve was calculated, as explained in the text, for the level parameters given by $E_\lambda'^0 = E_\lambda^0 + \Delta_\lambda^0 = 2.43$ Mev, $\Gamma_\lambda^0 = 0.65$ Mev. The values given here are in terms of the channel energies in the center-of-mass system. In terms of the energy of the emitted alpha-particle, as given by the scale in Fig. 3, the corresponding values are 1.822 and 0.440 Mev, respectively. The shift in the calculated peak to a lower energy, by about 80 kev, is due to the strong dependence on energy of the beta-transition probability.

In a similar manner, the number of alpha particles emanating from the 9.84-Mev state was found to be 16 ± 47.

The number of alpha particles per N^{16} disintegration was determined by measuring the activity in the small counting chamber. This activity was measured with a NaI(Tl) crystal behind a lead collimator such that only radiation from the counting chamber could reach the crystal. The average solid angle subtended by the silicon detector was computed by integrating over the gas volume. After making the appropriate corrections for gamma-ray absorption, gamma branching ratio, and NaI(Tl) efficiency, a branching ratio of $(6.1\pm 1.6)\times 10^{-6}$ to the 9.58-Mev state was determined. Taking the half-life of N^{16} to be 7.4 sec, and the β end-point energy as the energy corresponding to the observed peak in the alpha spectrum (see below), we find for the β transition to the 9.58-Mev state, log $ft = 6.8\pm 0.1$. This transition rate is somewhat higher than we reported previously and, as the present measurement was performed with more care and under better conditions, we consider its result to be the more accurate.

Combining our upper limit ($<2.2\times 10^{-8}$ alpha per N^{16} decay) for the number of alpha particles emanating from the 8.88-Mev state with the known branching ratio (1.1%) to this state, we find for the 8.88-Mev state: $\Gamma_\alpha/\Gamma_\gamma < 2.0\times 10^{-6}$.

The 800-ev width of the 9.84-Mev state assures that this state must decay largely by alpha emission. The upper limit for alpha particles observed emanating from this state therefore reflects an upper limit for the feeding of the state. Hence, from our data, we find for the 9.84-Mev state: log $ft > 8.1$.

UPPER LIMIT FOR PARITY NONCONSERVATION

As previously,[1] the absence of an alpha-particle group from the 8.88-Mev state can be used to estimate an upper limit to which parity is conserved in nuclear reactions. Taking our experimentally observed value of $\Gamma_\alpha/\Gamma_\gamma < 2.0\times10^{-6}$ and, as before, estimating $\Gamma_\gamma \cong 3\times10^{-3}$ ev, we find $\Gamma_\alpha < 6\times10^{-9}$ ev. Again, as previously, we estimate that a parity allowed transition could be expected to have a width of $\sim3\times10^3$ ev and we therefore conclude, using the usual notation: $\mathfrak{F}^2 \lesssim 2\times10^{-12}$.

As in all such experiments, it is necessary to point out that some rather crude estimates enter into the calculation of $\mathfrak{F}^2$ which can thus itself only be considered a rough estimate. However, we do note that the upper limit on $\mathfrak{F}^2$ given here is lower than any previously reported.

Blin-Stoyle[5] has discussed the degree of parity nonconservation to be expected because of the weak interaction component in the nucleon-nucleon potential and finds that $\mathfrak{F}^2 \sim 10^{-14}$ is to be expected. Blin-Stoyle implies that the theoretical estimate of $\mathfrak{F}^2$ due to this weak interaction term in the potential must be considered as uncertain to at least 2 orders of magnitude. The upper limit of $\mathfrak{F}^2$ derived from the present experiment is sufficiently close to Blin-Stoyle's estimate to imply that, pending further refinements in the theory, any parity nonconservation detected in a nuclear reaction would be ascribable to the weak-interaction component of the internucleon potential.

9.58-MEV STATE

The experimental data of Fig. 3 were fitted with a single-level expression to yield the level parameters of the 9.58-Mev state of O^{16}. The phase-shift analysis of $C^{12}(\alpha,\alpha)C^{12}$ by Hill[6] had resulted in the assignment, for this level, of spin and parity 1^-. The resonance behavior of the p-wave phase shift was fitted, in the single level approximation, for a resonance energy and total width given by $E_r = 2.43\pm0.01$ Mev, $\Gamma^0 = 0.645\pm0.010$ Mev. The interaction radius was chosen as $a = 1.40\ (A^{\frac{1}{3}}+4^{\frac{1}{3}})\times10^{-13}$ cm. Energies are given here in the center-of-mass system.

Since for this level $\Gamma = \Gamma_\alpha$ to within about $10^{-3}\%$, the relationship between the spectral intensity $W(E_\alpha)$ and the channel energy E_α may be written[7] (using the notation of Hill[6]) as

$$W(E_\alpha) \propto \frac{P(E_\beta)\Gamma_{\lambda\alpha}}{(E_\lambda+\Delta_\lambda-E_\alpha)^2+(\Gamma_\lambda/2)^2}, \qquad (1)$$

[5] R. J. Blin-Stoyle, Phys. Rev. **118**, 1605 (1960).

[6] R. W. Hill, Phys. Rev. **90**, 845 (1953).

[7] R. G. Sachs, *Nuclear Theory*, (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1953), p. 277 ff.

where

$$\Gamma_\lambda = \Gamma_{\lambda\alpha} = \left(\frac{2k_\alpha \gamma_{\lambda\alpha}^2}{A_l^2(\rho)}\right)_{\rho=k_\alpha a}, \qquad (2)$$

$$\Delta_\lambda = \Delta_{\lambda\alpha} = \frac{-\gamma_{\lambda\alpha}^2}{a}\left(\frac{d\ln A_l(\rho)}{d\ln\rho}+l\right)_{\rho=k_\alpha a}. \qquad (3)$$

In the above expressions the subscript λ is used to designate the particular intermediate state involved in the β, α transition, in this case the 9.58-Mev state of O^{16}; $\rho = k_\alpha r$, where k_α is the alpha-particle wave number and r is the radial coordinate describing the system $C^{12}+\alpha$; a is the "interaction radius". Values of $A_l^2(\rho) = F_l^2(\rho)+G_l^2(\rho)$ and $d\ln A_l(\rho)/d\ln\rho$ were taken from the curves of Sharp *et al.*[8] and from the tabulation of Coulomb functions by Block *et al.*[9] The probability $P(E_\beta)$ for the transition $N^{16}\rightarrow\beta^-+O^{16*}$ (9.58 Mev) was taken, as a function of beta end-point energy $E_\beta = 3.25-E_\alpha$, from the nomogram of Strominger *et al.*[10] Throughout the region of interest, the dependence is given very closely by $P(E_\beta)\propto(E_\beta)^4$.

The energy dependences of Γ_λ and Δ_λ were calculated from Eqs. (2) and (3) for the resonance values given by Hill: $E_\lambda'^0 = E_\lambda^0+\Delta_\lambda^0 = 2.43$ Mev, $\Gamma_\lambda^0 = 0.645$ Mev, and $a = 5.43\times10^{-13}$ cm. The spectral shape was then calculated from Eq. (1). The resultant curve, after being folded in with the energy distribution function describing the effects of the finite experimental resolution, is shown in Fig. 3. Since the energy spread defined by the experimental resolution was appreciably less than the peak width of Fig. 3, the resolution effects are small, and may be described approximately as a broadening of the spectral shape, in the peak region, to the extent of about 10 kev. (Note: The calculated curve shown in Fig. 3 has been shifted down by 5 kev in order to permit a direct comparison with the experimental data.)

The excellent fit observed in Fig. 3, especially within the region defined by $|E_\lambda'^0-E_\lambda|\lesssim\Gamma_\lambda/2$, may be taken as confirmation of the results of the $C^{12}(\alpha,\alpha)C^{12}$ analysis.

Alternatively, considering the present analysis only, we obtain the values $E'^0 = 2.43\pm0.04$ Mev, $\Gamma_\lambda^0 = 0.65\pm0.03$ Mev. The relatively large uncertainty in the value given for $E_\lambda'^0$ is due primarily to the uncertainty in the determination of the absolute energy scale of Fig. 3. In this respect the close agreement between the experimental and theoretical spectra (within 5 kev) just be considered largely fortuitous. The error limits for Γ_λ^0 are not so severely affected by this uncertainty in the *absolute* energy calibration, but represent more an estimate as to the insensitivity of the analysis to small variations in Γ_λ^0.

[8] W. T. Sharp, H. E. Gove, and E. B. Paul, Chalk River Project Report TPI-70, Atomic Energy of Canada, Ltd., Chalk River, Ontario, Canada (1955).

[9] I. Block, M. H. Hull, Jr., A. A. Broyles, W. G. Bouricius, B. E. Freeman, and G. Breit, Revs. Modern Phys. **23**, 147 (1951).

[10] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 597 (1958).

The full width at half-maximum of the calculated spectrum is 0.44 Mev, which matches the experimental value very closely. (In terms of the energy scale of Fig. 3, the corresponding value is 0.33 Mev.) The difference between this "peak width" of 0.44 Mev and the value $\Gamma_\lambda^0=0.65$ Mev is in a sense a measure of the effect of the level shift parameter Δ_λ. Since Δ_λ, and thus also Γ_λ^0, exhibits a strong dependence on the choice of interaction radius a, it is important to note that the calculated spectral width (and also, to a large extent, the spectral shape) can be related somewhat more directly to the results of the $C^{12}(\alpha,\alpha)C^{12}$ analysis. Since the potential scattering phase shifts φ_l vary rather slowly with channel energy, the resonance behavior of the $C^{12}(\alpha,\alpha)C^{12}$ cross section, in the region of the p-wave ($l=1$) resonance at $E_\alpha=2.43$ Mev is described quite well by the p-wave *resonance* phase-shift only[11]:

$$\beta_l=\arc\tan\frac{\Gamma_\lambda/2}{E_\lambda+\Delta_\lambda-E_\alpha}. \tag{4}$$

In terms of β_l, Eq. (1) can now be written as

$$W(E_\alpha)\propto P(E_\beta)(\Gamma_\lambda/2)^{-1}\sin^2\beta_l. \tag{5}$$

Therefore, insofar as one can neglect the distortion introduced in (5) through the energy dependences of $P(E_\beta)$ and Γ_λ (a good approximation for the region $|E_\lambda'^0-E_\alpha|\lesssim\Gamma_\lambda/2$) the spectral shape of Fig. 3 can be related directly to the $C^{12}(\alpha,\alpha)C^{12}$ cross section through β_l. To the extent that the approximations given here are valid, the above relationship is, in a practical sense, *not* dependent on a particular choice of interaction radius a.

As a check solely on the computational accuracy of the present analysis, Eqs. (2)–(4) were used to compute values of β_l vs E_α, which were then compared to those calculated by Hill for the $C^{12}(\alpha,\alpha)C^{12}$ analysis. The two sets of results were found to agree within the limits of arithmetical error involved in the calculations.

Accepting the 1^- assignment to the 9.58-Mev state, our log $ft=6.8$ indicates that this allowed transition is inhibited by a factor $\sim$ several hundred. This observation is in accord with the shell model description of O^{16} of Elliott and Flowers,[12] who were able to account for most of the negative parity states in O^{16} below 12 Mev as belonging to the $1p^{-1}(2s,1d)$ configuration but specifically deny the 9.58-Mev state as being of this prescription. Elliott and Flowers therefore assign the 9.58-Mev state to be of three-nucleon excitation (a two-nucleon excitation would not preserve the negative parity). As the 2^- N^{16} ground state would be expected to be mainly of the $1p^{-1}(2s,1d)$ configuration, the decay to a three-nucleon excitation state should be inhibited as, indeed, is the case. The high log ft for the transition to the 9.58-Mev state can therefore be taken as supporting evidence for the Elliott and Flowers model of O^{16}.

The β decay to the 9.84-Mev state is expected to be first forbidden on the basis of the N^{16} ground state being 2^- as indicated by its β spectrum and the 9.84-Mev state being 2^+ as determined by the ($C^{12}+\alpha$) scattering data. The value obtained here of log $ft>8.1$ is consistent with this transition being first forbidden though it does appear to be inhibited.

A slight anomaly does appear in the spectrum corresponding to $O^{16*}=9.7$ Mev, at which there is no known state in O^{16}. The energy is too low to correspond to the 9.84-Mev state and, as the deviation from a smooth curve is only about one standard deviation, we consider the anomaly not to be statistically significant.

ACKNOWLEDGMENTS

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[11] *Note added in proof*. A more complete discussion of a similar problem has been given in a recent publication: T. A. Griffy and L. C. Biedenharn, Nuclear Phys. **15**, No. 4, 636 (1960). In subsequent discussions, which the authors gratefully acknowledge, Dr. Biedenharn has pointed out that the desired relationship is given more exactly through the inclusion of the hard-sphere phase shift φ_l. In terms of Eq. (5), this requires that one replace β_l by the nuclear scattering phase shift $\delta_l=\beta_l+\varphi_l$. An extension of our analysis has shown that the inclusion of this modification does yield a better fit to the data, particularly in the region of low-energy tail of Fig. 2.

[12] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A242**, 57 (1957).