A Study of Isospin Mixing in $^{16}$O Near 18 MeV Excitation Energy

Li-yun Kuo

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A STUDY OF ISOSPIN MIXING IN $^{16}$O
NEAR 16 MEV EXCITATION ENERGY

by

Li-yun Kuo

a Thesis
 Submitted to the
Faculty of the Graduate College
in partial fulfillment
of the
Degree of Master of Arts

Western Michigan University
Kalamazoo, Michigan
December, 1971
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Li-yun Kuo
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INTRODUCTION

The concept of isospin was introduced in 1932 by Heisenberg, who used the formalism of Pauli spin matrices to distinguish mathematically between neutrons and protons. For his calculations, the neutron and proton were considered two alternative states of the same particle which we now call the nucleon. The name "isotopic spin" (now isospin) was suggested by Wigner in 1937. In this same paper Wigner emphasized the importance of charge independence and pointed out the usefulness of the isospin quantum number for the purpose of labelling nuclear states. The existence of a conservation law for isospin in a nuclear reaction was first postulated by Oppenheimer and Serber in 1938 and was rediscovered by Adair in 1952. Since the work of Adair, isospin has been studied vigorously both experimentally and theoretically.

Conservation of isospin requires equality for the proton and neutron reduced widths of states in self-conjugate nuclei. An indication of isospin mixing in $^{14}_N$ was obtained by Shire and Edge who studied the mirror reactions $^{10}_B(\alpha,p_0)^{13}_C$ and $^{10}_B(\alpha,n_0)^{13}_N$ and found that the neutron reduced width for the 12.69-MeV state was about 5.7 times as large as the proton reduced width.
More recent measurements of these same reactions have been reported. Calculations by Barker and Mann show that even small amounts of isospin mixing can lead to large differences in the reduced widths for neutron and proton emission in mirror reactions.

The best known example of isospin mixing is that of the doublet states (16.63 and 16.93 MeV) of $^8\text{Be}$. These states are $J^\pi = 2^+$ and include both $T = 0$ and $T = 1$ components. Most of the information concerning this case has been obtained from reaction studies in which these levels occur in the final state. Direct observation of the neutron and proton is not possible since these levels are stable with respect to their decay process, i.e., the threshold energies of neutron and proton decay are higher than these levels.

We are interested here in neutron and proton emission from the self-conjugate nucleus, $^{16}_0$, at excitation energies near 18 MeV. Differential cross section measurements have been made for the mirror reactions $^{12}_C(\alpha,n_0)^{15}_0$ and $^{12}_C(\alpha,p_0)^{15}_N$ over a large angular range in the energy range from 13 to 16 MeV. Previous investigations of $^{16}_0$ by studying the $^{12}_C(\alpha,n_0)^{15}_0$ reaction in the energy range of interest were limited to measurements of the total cross section by the observation of $^{15}_0$ positron activity. The previous $^{12}_C(\alpha,p_0)^{15}_N$ measurements made with good energy resolution...
were limited to scattering angles larger than 90°.
THEORETICAL CONSIDERATIONS

Cross Section For A Nuclear Reaction

When a target nucleus is bombarded with an incident particle, a long-lived system which consists of the target nucleus and the incident particle may be formed. This system is called the compound nucleus. States of the compound nucleus formed by an incident particle "a" and a target nucleus "X" may be studied by measuring the cross section for the reaction $X(a,b)Y$ as a function of the energy of the incident particle. Here "b" is the particle emitted from the reaction and "Y" is the residual nucleus. The cross section data will exhibit anomalies, or "resonances", at energies which correspond to states of the compound nucleus. The width in energy of each resonance is related to the mean life of the corresponding state of the compound nucleus by the Heisenberg uncertainty relation.

The theoretical expression for the cross section of a reaction $X(a,b)Y$ has a particularly simple form if a resonance is narrow and isolated. For this case the cross section in the vicinity of a resonance is given by the well-known Breit-Wigner formula: \(^\text{(1)}\)

$$
\sigma_{ab}(E) = \frac{\pi}{k_a^2} \frac{(2J + 1)}{(2J+1)(2J'+1)} \frac{\Gamma_a \Gamma_b}{(E-E_R)^2 + (\Gamma/2)^2}
$$
where

\[ \sigma_{ab}(\bar{s}) = \text{reaction cross section summed over } 4\pi \text{ steradians}, \]

\[ k_a = \text{wave number of the incident particle in the c.m. system}, \]

\[ J = \text{angular momentum of the state of the compound nucleus}, \]

\[ j = \text{spin angular momentum of the incident particle}, \]

\[ j^* = \text{spin angular momentum of the target nucleus}, \]

\[ \Gamma_{a,b} = \text{partial widths for the emission particles} \]

\[ \Gamma = \text{total width}, \]

\[ E_R = \text{energy of the resonance}. \]

The total width \( \Gamma = \Sigma \Gamma_s \), where \( \Gamma_s \) is the partial width for decay by the emission of particle s. Each partial width \( \Gamma_s \) can be decomposed into components \( \Gamma_{s1} \) according to the orbital angular momentum of the decay process, i.e., \( \Gamma_s = \Sigma \Gamma_{s1} \). Here \( l \) is the orbital angular momentum quantum number. Finally, each \( l \) component of the partial width may be written

\[ \Gamma_{s1} = 2 P_l \gamma_{s1}^2 \]

where

\[ P_l = \text{the penetrability for the orbital quantum number} \ l, \]

\[ \gamma_{s1}^2 = \text{reduced width of the particle} \ s \ \text{for the orbital quantum number} \ l. \]

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The $P_1$ are obtained from the regular and irregular solutions of the wave equation with the Coulomb potential and can be found in the literature. The reduced width $\delta_{s1}^2$ is an energy independent parameter which, along with the resonance energy, $E_R$, and the angular momentum of the state $J$, characterizes the compound nucleus state of interest.

The penetrabilities for neutron emission and for proton emission are listed in Table I for two states of particular interest here, the 17.63-MeV and 18.10- MeV states of $^{16}O$. These penetrabilities were determined using the graphs and tables published by Marion and Young.

The theoretical expression for the differential cross section of a reaction is considerably more complicated than equation (1). Additional complications arise if the resonance is not narrow. Nevertheless, at certain angles the energy dependence of the differential cross section for a reaction may have a form very similar to equation (1).

Isospin

The course of a nuclear reaction depends on a number of conservation laws. Physical quantities which are conserved in a nuclear reaction include charge, mass number, angular momentum, parity, and energy. In addition, it is convenient to consider the conservation of a phy-
### PENETRABILITIES
FOR PROTON AND NEUTRON EMISSION

<table>
<thead>
<tr>
<th>( \ell )</th>
<th>( \rho/A_\ell^2 ) (proton)</th>
<th>( \rho/A_\ell^2 ) (neutron)</th>
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<tr>
<td><strong>( E_\alpha = 14.0 \text{ MeV} )</strong></td>
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<tr>
<td>0</td>
<td>1.9</td>
<td>1.3</td>
</tr>
<tr>
<td>1</td>
<td>1.3</td>
<td>1.0</td>
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<tr>
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<tr>
<td><strong>( E_\alpha = 14.6 \text{ MeV} )</strong></td>
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<tr>
<td>0</td>
<td>2.0</td>
<td>1.5</td>
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<td>4</td>
<td>0.052</td>
<td>0.0043</td>
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Table I
sical quantity, called isobaric spin (or isospin), which is a consequence of the hypothesis of the charge independent of nuclear forces. According to this hypothesis, the nuclear interactions are equal between two neutrons, two protons, and a neutron and a proton.\textsuperscript{20} Wigner was the first to point out that if the Coulomb interaction between protons can be neglected, then a new quantum number, now called the total isospin quantum number, can be associated with nuclear states.\textsuperscript{2}

In terms of the isospin formalism, the neutron and the proton are considered to be two different states of the same particle, called the nucleon. The mathematical apparatus of isospin theory is identical to that used for spin angular momentum for a particle of intrinsic spin \( s = \frac{1}{2} \). Thus the neutron and proton are formally identified as two states of the same particle, the nucleon, which has a total isospin, \( t \), of \( \frac{1}{2} \). The neutron is defined as the "spin-up" state, i.e., \( t_z = +\frac{1}{2} \), and the proton is defined as the "spin-down" state, i.e., \( t_z = -\frac{1}{2} \). The quantum number \( t_z \) is called the isospin projection. The total isospin projection of a system of particles is given by \( T_z = \frac{1}{2}(N-Z) \), where \( N \) and \( Z \) are the number of neutrons and protons of the system, respectively. The isospin formalism for a system of particles can be illustrated effectively by considering the two nucleon system.\textsuperscript{21} This system has one bound state, the deuteron.
which has a spin (angular momentum) of 1 and three unbound states nearby in energy, each with a spin (angular momentum) of 0. These three unbound states are the neutron-neutron (n-n) system, the proton-proton (p-p) system, and the neutron-proton (n-p) system, respectively. The last mentioned state is the singlet state of the deuteron. The isospin projections, $T_z$, for the n-n, n-p and p-p systems are +1, 0 and -1, respectively. The three unbound systems (n-n, n-p, p-p) are considered the three members of a $T = 1$ multiplet. The one bound system, the ground state of the deuteron, can be described as the sole member of a $T = 0$ singlet. Thus the ground state of the deuteron can be assigned the isospin quantum numbers $(T, T_z) = (0, 0)$, and the unbound excited state of the deuteron, the quantum numbers $(T, T_z) = (1, 0)$.

The total wave function of two nucleons may be factored into the product of a function of space and spin and a function of isospin. The isospin eigenfunctions $\Psi(T, T_z)$ for two nucleons are:

\begin{align*}
\Psi(1, 1) &= \Psi_\alpha(\frac{1}{2}) \Psi_\beta(\frac{1}{2}) \\
\Psi(1, 0) &= \frac{1}{\sqrt{2}} \left[ \Psi_\alpha(\frac{1}{2}) \Psi_\beta(-\frac{1}{2}) + \Psi_\alpha(-\frac{1}{2}) \Psi_\beta(\frac{1}{2}) \right] \\
\Psi(1, -1) &= \Psi_\alpha(-\frac{1}{2}) \Psi_\beta(\frac{1}{2}) \\
\Psi(0, 0) &= \frac{1}{\sqrt{2}} \left[ \Psi_\alpha(\frac{1}{2}) \Psi_\beta(-\frac{1}{2}) - \Psi_\alpha(-\frac{1}{2}) \Psi_\beta(\frac{1}{2}) \right]
\end{align*}
where
$$\Psi(\frac{1}{2}) = \text{Pauli spin eigenfunction for spin up},$$
$$\Psi(-\frac{1}{2}) = \text{Pauli spin eigenfunction for spin down}.$$  

Thus the similarity in formalism between ordinary spin and isospin is obvious.

### Isospin Mixing

Unlike the case for such quantities as angular momentum and energy, isospin is not expected to be strictly conserved during a nuclear reaction. A rigorous conservation of isospin would require that the n-n, n-p and p-p forces be identical. Clearly the p-p force is different because of the presence of the Coulomb interaction. Thus, nuclear states which have no definite value of T may exist. These "mixed" states consist of a combination of states which have different T values. In a nuclear reaction, this mixing of states may occur in the initial state, the compound nuclear state, and or the final state.

Of particular interest here is the isospin mixing which occurs in the compound nucleus. The best known example of strong isospin mixing in the compound nucleus is the pair of states of $^8\text{Be}$ at 16.63 MeV and 16.93 MeV which are discussed in Chapter I.

Barker and Mann have pointed out that mixing in the compound nucleus has a particularly strong effect on the
ratio of neutron reduced width to the proton reduced width for the decay of a self-conjugate nucleus. This ratio can be determined in the following way.

The isospin wave function for a state of the compound nucleus may be described in terms of a core coupled to a single nucleon. Let $\Phi_{\alpha}(T, T_z)$ represent the core state with quantum numbers $\alpha$, $T$, and $T_z$, and $\Psi_{\beta}(t_z)$ represent the nucleon with quantum numbers $\beta$ and $t_z$. The wave function of the $(\alpha, \beta)$ configuration for $(T, T_z) = (1, 0)$ will be (see Equation (3) and (5))

$$\Psi_{\alpha\beta}(1, 0) = \frac{1}{\sqrt{2}} \left[ \Phi_{\alpha} \left( \frac{1}{2}, -\frac{1}{2} \right) \Psi_{\beta} \left( \frac{1}{2} \right) + \Phi_{\alpha} \left( \frac{1}{2}, \frac{1}{2} \right) \Psi_{\beta} \left( -\frac{1}{2} \right) \right].$$ \hspace{1cm} (6)

And the wave function of the same configuration for $(T, T_z) = (0, 0)$ will be

$$\Psi_{\alpha\beta}(0, 0) = \frac{1}{\sqrt{2}} \left[ \Phi_{\alpha} \left( \frac{1}{2}, -\frac{1}{2} \right) \Psi_{\beta} \left( \frac{1}{2} \right) - \Phi_{\alpha} \left( \frac{1}{2}, \frac{1}{2} \right) \Psi_{\beta} \left( -\frac{1}{2} \right) \right].$$ \hspace{1cm} (7)

The wave function for the self-conjugate nucleus in a state of energy $E = \lambda$ may contain both $T = 0$ and $T = 1$ components and is given by

$$\Psi(\lambda, T_z = 0) = \sum_{\alpha, \beta} a_{\alpha\beta} \Psi_{\alpha\beta}(1, 0) + \sum_{\alpha, \beta} b_{\alpha\beta} \Psi_{\alpha\beta}(0, 0)$$ \hspace{1cm} (8)

where $a_{\alpha\beta}$ and $b_{\alpha\beta}$ are constants.

If there is one dominant configuration for each component and the neutron and proton single particle width for this configuration are assumed to be equal, this ratio is given by

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Or, if there are many configurations which contribute and the neutron and proton single particle widths for all these configurations are assumed to be equal, then

$$R = \frac{\delta_{\text{n}}^2(\lambda, 0)}{\delta_{\text{p}}^2(\lambda, 0)} = \frac{(a_{\alpha\beta}^\lambda + b_{\alpha\beta}^\lambda)^2}{(a_{\alpha\beta}^\lambda - b_{\alpha\beta}^\lambda)^2} = \frac{(A + B)^2}{(A - B)^2}. \quad (9)$$

It can be shown that the technique of observing neutron and proton emission from a self-conjugate nucleus is a particularly sensitive method for identifying an isospin doublet, that is, two strongly mixed states which arise from the mixing of two nearly degenerate states with the same spin and parity but different value of $T$.

The wave functions for two degenerate states, one with

$$\sum_{\alpha\beta} a_{\alpha\beta}^\lambda$$

and

$$\sum_{\alpha\beta} b_{\alpha\beta}^\lambda.$$

It should be noted that this ratio depends on the sum and difference of $A$ and $B$, and not of $A^2$ and $B^2$. Thus, a small amount of isospin mixing can cause a large difference in the neutron and proton emission from that state.

It can be shown that the technique of observing neutron and proton emission from a self-conjugate nucleus is a particularly sensitive method for identifying an isospin doublet, that is, two strongly mixed states which arise from the mixing of two nearly degenerate states with the same spin and parity but different value of $T$. The wave functions for two degenerate states, one with

$$e_{\alpha\beta} = a_{\alpha\beta}^\lambda$$

and

$$e_{\alpha\beta} = b_{\alpha\beta}^\lambda.$$
(T,T_z) = (1,0) and the other with (T,T_z) = (0,0), can be written as:

\[ \Psi_{\lambda}(1,0) = \sum_{\alpha,\beta} a_{\alpha,\beta}^{\lambda} \Psi_{\alpha,\beta}(1,0), \]  
\[ \Psi_{\lambda}(0,0) = \sum_{\alpha,\beta} b_{\alpha,\beta}^{\lambda} \Psi_{\alpha,\beta}(0,0). \]  

From perturbation theory we have

\[ \lambda_1 = \lambda + \Delta, \]  
\[ \lambda_2 = \lambda - \Delta, \]  
\[ \Delta = \langle \Psi_{\lambda}(0,0) | V | \Psi_{\lambda}(1,0) \rangle. \]

where \( V \) is the perturbing potential, e.g., the Coulomb potential. The perturbed wave functions which correspond to the two separated energies \( \lambda_1 \) and \( \lambda_2 \) are

\[ \Psi_{\lambda_1} = \frac{1}{\sqrt{2}} \left[ \Psi_{\lambda}(1,0) + \Psi_{\lambda}(0,0) \right], \]  
\[ \Psi_{\lambda_2} = \frac{1}{\sqrt{2}} \left[ \Psi_{\lambda}(1,0) - \Psi_{\lambda}(0,0) \right], \]

where \( \lambda_1 > \lambda_2 \) if \( \Delta > 0 \).

Substituting equations (6), (7), (11) and (12) into (16) and (17) we have

\[ \Psi_{\lambda_1} = \frac{1}{2} \sum_{\alpha,\beta} \left[ (a_{\alpha,\beta}^{\lambda} + b_{\alpha,\beta}^{\lambda}) \phi_{\alpha}^{\lambda}(\frac{1}{2}, -\frac{1}{2}) \psi_{\beta}(\frac{1}{2}) + (a_{\alpha,\beta}^{\lambda} - b_{\alpha,\beta}^{\lambda}) \phi_{\alpha}^{\lambda}(\frac{1}{2}, \frac{1}{2}) \psi_{\beta}(\frac{1}{2}) \right] \]  
\[ + (a_{\alpha,\beta}^{\lambda} - b_{\alpha,\beta}^{\lambda}) \phi_{\alpha}^{\lambda}(\frac{1}{2}, \frac{1}{2}) \psi_{\beta}(\frac{1}{2}). \]
\[ \Psi_{\lambda_2} = \frac{1}{2} \sum_{\alpha, \beta} \left[ (a_{\alpha \beta}^\lambda - b_{\alpha \beta}^\lambda) \phi_\alpha(\frac{1}{2}, -\frac{1}{2}) \psi_\beta(\frac{1}{2}) + (a_{\alpha \beta}^\lambda + b_{\alpha \beta}^\lambda) \phi_\alpha(\frac{1}{2}, \frac{1}{2}) \psi_\beta(-\frac{1}{2}) \right]. \] (19)

Both of the two perturbed states include terms involving neutron wave functions and proton wave functions. If the constants \( a_{\alpha \beta}^\lambda \) and \( b_{\alpha \beta}^\lambda \) are both positive, one can see that the state with higher energy, \( \lambda_1 \), has constructive interference for the neutron functions and destructive interference for the proton functions. Thus for this state, neutron emission may be enhanced and proton emission may be suppressed. For the state with lower energy, \( \lambda_2 \), the converse is true.
EXPERIMENTAL METHOD

The $^{12}$C($\alpha,n)^{15}$O Reaction

A beam of 13 to 16 MeV alpha particles was obtained from the Western Michigan University Model EN Tandem Van de Graaff accelerator. The beam was energetically analyzed by a Varian Model 1058 90° analyzing magnet. The analyzing magnet was calibrated by determining the threshold of the Al(p,n) reaction. The beam was collimated by a 3/16-inch diameter tantalum collimator and stopped by a 0.01-inch thick tantalum foil.

The natural carbon targets used in the experiment were prepared at The University of Texas by Terrell. Each carbon foil was mounted on a tantalum backing which also served as the beam stop. One target, of thickness 460 $\mu$g/cm$^2$, was used to determine angular distributions in the vicinity of 14.5 MeV alpha-particle energy. Another target, of thickness 218 $\mu$g/cm$^2$, was used for excitation functions over the energy range 13 to 16.5 MeV at laboratory angles of 42° and 145°. The energy loss to the center of the thick target at 14.5 MeV was approximately 40 keV for the thinner target and 80 keV for the thicker target. The number of the incident particles was determined by integrating the beam current with a Brookhaven Model 1000 current integrator. The beam current
ranged from about 0.03 to 0.1 microampere.

The neutrons were detected by a shielded long counter. The distance from the target to the front of the long counter was 12 inches. At this distance the effective half-angle subtended by the detector was 16°. Pulses from the long counter were amplified by a Tennelec Model 100c preamplifier and by an Ortec Model 485 amplifier and recorded by an Ortec Model 484 scaler. In order to ascertain the effect of the finite angular resolution, measurements at a number of energies between 14 and 15 MeV were repeated with the angular spread reduced by a factor of two. These measurements with higher angular resolution were made at angles where the angular distribution had a maximum, a minimum or a relatively steep slope. The two sets of data agreed within the statistical errors. All data were obtained as excitation functions at the laboratory angles 0°, 15°, 30°, 42°, 57°, 72°, 84°, 107°, 120°, 135° and 148°.

Background measurements were performed to determine the number of counts from the collimating system and beam-stop and from the 13C present in the natural carbon target. Measurements made using a shadow cone indicated that the number of room-scattered neutrons was negligible. The number of neutrons due to the 13C was determined with a carbon target enriched to 42 percent in 13C. This background changed slowly with energy and angle and
ranged between 10 and 30 percent. The background from the beam stop and collimator was measured by removing the carbon target. The tantalum backing was left in exactly the same position as during data taking. This background for the thinner target was usually less than 10 percent over the energy range of interest.

The absolute efficiency of the counter was determined with the aid of a Pu-Be neutron source. The efficiency was found to be about 0.45 percent. A small correction was made for the variation of neutron efficiency as a function of neutron energy. This correction factor ranged between 1.05 and 0.95.

For the angular distribution data at a laboratory angle of 148° some of the neutrons were scattered by the flanges of the target support. This effect was about 10 percent.

The $^{12}\text{C}(\alpha,\text{p})^{15}\text{O}$ Reaction

The proton measurements were performed by scattering alpha particles from a self-supporting natural carbon target placed inside an Ortec Series 600 scattering chamber. The target used for these measurements was 218 $\mu\text{g/cm}^2$ thick and was taken from the same carbon foil used for the thin-target neutron measurements. This target was oriented at an angle of 30° to the incident particle beam. At 14.5 MeV its thickness produced an energy loss
of approximately 45 keV to the center of the target. The beam was collimated to a 0.107-inch tantalum collimator and stopped by an Ortec Model 6103 shielded single beam stop and it was integrated with a Brookhaven Model 1000 current integrator. The emitted protons were detected by an Ortec Model 200-300 silicon surface barrier detector. Polyethylene foils between 0.003 and 0.013 inches thick, were placed in front of the detector to stop the scattered alpha particles. At the most forward angle, 36°, a 0.001 inch nickel foil was added to a 0.003 polyethylene foil. The distance between the target and the detector was 4 inches. The half angle subtended by the proton detector was 3.1°. Pulses from the detector were amplified by an Ortec Model 190A preamplifier and an Ortec Model 485 amplifier, and recorded by a Nuclear Data Model 2200 multichannel analyzer.

All angular distribution data were obtained as excitation functions at the laboratory angles 36°, 62.3°, 78.3°, 90.5°, 96.8°, 110.7°, 126.8° and 170° over the energy range 13 to 15 MeV. Most of these angles correspond to the same center of mass angles used for the (α, n) measurements at 14.5 MeV alpha-particle energy. Moreover, two excitation functions were taken at 46° and 152.4° laboratory angle from 13 to 16.5 MeV. Due to the presence of hydrogen nuclei in the target, measurements at angles less than 36° were not possible.
The number of protons detected was determined by integrating the counts over the proton peak and then subtracting a suitable background. The background was obtained by adding up the counts over a similar number of channels spread out on both side of the proton peak. At 36° in the laboratory system, the proton group from the $^{12}$C(α,p) reaction was not completely resolved from the proton group due to the hydrogen nuclei. Here the counts for the proton peak was determined by assuming that the overlap tails of these groups were about the same.
RESULTS

Excitation Functions

Differential cross section curves from 13 to 16 MeV are shown in Figure 1 for the $^{12}\text{C}(\alpha,p)^{15}\text{N}$ and $^{12}\text{C}(\alpha,n)^{15}\text{O}$ reactions at about 55° c.m. and at about 158° c.m.. The data were taken in energy steps of about 65 keV except over the 14 MeV and 14.6 MeV resonances where smaller energy steps were taken. The errors for the $(\alpha,p)$ curves are about the size of the data points or smaller unless shown otherwise. For the $(\alpha,n)$ curves, only a few typical error bars are given. The errors shown include the statistical uncertainty and the uncertainty in the background subtraction. The curves are drawn by eye through the data points. An $(\alpha,p)$ excitation curve from about 13 to 15 MeV for a laboratory angle of 111° is shown in Figure 2. At this angle the effect of nearby resonances on the shape of the 14.0 MeV resonance is small.

For a fixed laboratory angle the center of mass angle of the reaction is a function of the incident alpha-particle energy. For the excitation functions shown here the change in the c.m. angle is about 1° for the $(\alpha,p)$ reaction and 5° for the $(\alpha,n)$ reaction.
Figure 1. Differential cross section excitation functions for the $^{12}$C($\alpha$,p$_0$)$^{15}$N and $^{12}$C($\alpha$,n$_0$)$^{15}$O reactions at a backward angle. The laboratory angles were chosen such that the center of mass angles are nearly equal. The angles in the center of mass system are $\sim 55^0$ and $\sim 158^0$. Statistical errors are smaller than the size of the points unless otherwise indicated. The lines are drawn through the experimental points.
Figure 2. Differential cross section excitation functions for the $^{12}\text{C}(\alpha,p_0)^{15}\text{N}$ at the center of mass angle $\sim 122^0$. Statistical errors are smaller than the size of the points unless otherwise indicated. The line is drawn through the experimental points.
$^{12}\text{C}(\alpha,p)^{15}\text{N}$

$\theta_{\text{LAB}} = 110^\circ$

$E_\alpha$(MeV)

$\sigma_{\text{cm}}$(mb/sr)
Angular Distributions

In Figure 3 and Figure 4 are shown angular distributions over the resonance at 14.0 MeV in the (α, p) reaction (17.63 MeV excitation energy in $^{16}$O) and the resonance at 14.6 MeV in the (α, n) reaction (18.10 MeV excitation energy in $^{16}$O), respectively. Again, the curves are drawn by eye through the data points. The actual ordinate of each curve is obtained by subtracting the number in parenthesis following the energy from the plotted ordinate. Figure 5 compares the angular distributions for the outgoing protons near the peak of the 14.0 MeV resonance and for the outgoing neutrons at the peak of the 14.6 MeV resonance. The angular distributions for the outgoing protons at the peaks of the other (α, p) resonances, 13.26, 13.71, 14.82 and 15.29 MeV, are shown in Figure 6. In Figure 7 is shown the angular distribution of the outgoing protons at 14.6 MeV, i.e., the energy of the strong (α, n) resonance. Also shown in this figure are (α, p) and (α, n) angular distributions near 15.1 MeV.

Uncertainties

The factors which contribute substantially to the error in the absolute value of the (α, n) cross section are the target thickness, the long counter efficiency,
Figure 3. Angular distributions of the $^{12}\text{C}(\alpha,p)^{15}\text{N}$ reaction over the resonance of 17.63 MeV state in $^{16}\text{O}$. The ordinate of each curve is obtained by subtracting the number in parenthesis following the energy. Statistical errors are smaller than the size of points unless otherwise indicated. The curves are drawn through the experimental points.
Figure 4. Angular distributions of the $^{12}\text{C}(\alpha,n)^{15}\text{O}$ reaction over the resonance of 18.10 MeV state in $^{16}\text{O}$. The ordinate of each curve is obtained by subtracting the number in parenthesis following the energy. Statistical errors are shown on some typical points only. The curves are drawn through the experimental points.
Figure 5. Angular distributions of the $^{12}\text{C} (\alpha, p_0)^{15}\text{N}_d$ reaction near the center of the 17.63-MeV state in $^{16}\text{O}$, and the $^{12}\text{C} (\alpha, n_0)^{15}\text{O}$ reaction near the center of the 18.10-MeV state in $^{16}\text{O}$. Statistical errors are shown. The curves are drawn through the experimental points.
Figure 6. Angular distributions of $^{12}{C}(\alpha,p_{\alpha})^{15}{N}$ reaction at the peaks of other proton resonances of 13.26, 13.71, 14.82 and 15.29-MeV alpha particle energies. Statistical errors are smaller than the size of the points unless otherwise indicated. The lines are drawn through the experimental points.
Figure 7. Angular distributions of $^{12}\text{C}(\alpha,p_0)^{15}\text{N}$ reaction at 14.62 MeV alpha particle energy and of $^{12}\text{C}(\alpha,p_0)^{15}\text{N}$ and $^{12}\text{C}(\alpha,n_0)^{15}0$ reactions near 15.1-keV alpha particle energy. Statistical errors are smaller than the size of the points unless otherwise indicated. The curves are drawn through the experimental points.
$^{12}\text{C} \ (\alpha, p) \ ^{15}\text{N}$

$E_\alpha = 15.09 \text{ MeV (3)}$

$^{12}\text{C} \ (\alpha, n) \ ^{15}\text{O}$

$E_\alpha = 15.05 \text{ MeV}$

$^{12}\text{C} \ (\alpha, p) \ ^{15}\text{N}$

$E_\alpha = 14.62 \text{ MeV}$

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and the background correction. The uncertainty of each of these factors was about 15 percent, about 10 percent, and about 20 percent, respectively. Since the background correction usually was less than 20 percent, this correction contributed at most 4 percent to the final error. Thus the total error in the absolute value of the \((\alpha,n)\) cross section is believed to be about \(\pm 20\) percent.

Only the uncertainty in the target thickness contributes appreciably to the error of the \((\alpha,p)\) cross section. Thus the error in the absolute value of the \((\alpha,p)\) cross section is estimated to be about \(\pm 15\) percent.

The relative error of the two reaction cross sections, that is, the \((\alpha,p)\) cross section relative to the \((\alpha,n)\) cross section, is expected to be about \(\pm 15\) percent. Only the long counter efficiency and background correction uncertainties of the \((\alpha,n)\) measurements contribute substantially to this relative error. Since the targets used for both the \((\alpha,p)\) and the \((\alpha,n)\) measurements were obtained from the same carbon foil, the contribution of the foil thickness to this relative error is assumed to be negligible.

The uncertainty in the energy of the incident alpha particles is due mainly to the uncertainty in the target thickness and in the calibration of the analyzing magnet. The former uncertainty contributes about \(\pm 7\) keV to the error of the energy. The energies presented here were
determined using a calibration constant for the analyzing magnet obtained by measuring the Al(p, n) threshold. More recent measurements using the $^{12}$C(α, n) threshold indicate that these energies are low by about 15 keV, that is, each of the energies presented in this work should be corrected by adding 15 keV. After this correction is made, then the uncertainty in the magnet calibration at 14.5 MeV is believed to be less than 15 keV. Therefore the total error in the alpha-particle energy—after the 15 keV correction is made—is about ±15 keV.
DISCUSSION

In the absence of isospin mixing, excitation functions for the mirror reactions at the same center of mass angles should show the same structure when the penetrabilities for the outgoing nucleons are taken into account. In the present case, because the proton energy in the center of mass system is larger than the neutron energy, the penetrabilities for the outgoing protons are larger than those for the outgoing neutrons (See Table I). Therefore, for equal reduced widths for proton and neutron emission, the cross sections should be larger for the \((\alpha, p)\) reaction than the \((\alpha, n)\) reaction. The actual ratio of the penetrabilities depends on the particular value (or values) of orbital angular momentum involved.

Figure 1 shows a strong resonance in the \((\alpha, p)\) reaction near 13.97 MeV (17.63 MeV excitation energy in \(^{16}O\)) which does not appear in the \((\alpha, n)\) reaction at both of 55° and 158° c.m. Also, the strong resonance near 14.6 MeV (18.10 MeV excitation energy in \(^{16}O\)) in the \((\alpha, n)\) reaction does not appear in the \((\alpha, p)\) reaction. In fact, the \((\alpha, p)\) cross section has a minimum near 14.6 MeV at both of these angles. Measurements at five additional angles are in accord with the data shown. Clearly the behavior of the 13.97 and 14.6-MeV states is not
consistent with conservation of isospin.

As discussed in Chapter II, a pair of states with the properties shown in Figure 1 can be produced by strong mixing of a \( T = 0 \) state with a \( T = 1 \) state which has the same spin and parity. This strong mixing could result from a relatively weak isospin non-conserving interaction, e.g., the Coulomb interaction, if the unperturbed states were nearly degenerate. The mixing, of course, would result in a considerable increase in the energy spacing of the isospin mixed doublet. If the amplitudes of the \( T = 0 \) and \( T = 1 \) components of the two mixed states are nearly equal, which appears to be the case here, it is possible for one state to have constructive interference for proton emission and nearly total destructive interference for neutron emission. The other state would then have constructive interference for neutron emission and nearly total destructive interference for proton emission.

Such an explanation would require both the widths of the two states to be comparable and the angular distributions for the outgoing nucleons to be similar. A quantitative determination of these properties in the present case is complicated by the high density of levels in this energy region. The 17.63 and 18.10-MeV states are superimposed on different background states.
In addition, interference effects may be present and these would probably be different for the two levels.

Nevertheless, qualitative agreement is obtained for the widths of the two levels. The width of the 18.10-MeV level is seen to be \( \approx 250 \text{ keV} \) from Figure 1. The width of the 17.63-MeV level can best be obtained from the excitation function at 111° shown in Figure 2 and is seen to be about 180 keV.

Also, qualitative agreement is obtained for the angular distributions. Figure 5 compares the angular distributions for the outgoing protons from the 17.63-MeV level and the outgoing neutrons from the 18.10-MeV level. Figure 3 and 4 show that these two curves, which are near the centers of the resonances, are representative of the shapes over the resonances. It can be seen from Figure 5 that the shapes are very similar. Furthermore, there is evidence that the quantitative differences, e.g., the higher (\( \alpha, p \)) cross sections at forward angles and the higher (\( \alpha, n \)) cross sections near 100°, are produced by the background contributions. The proton angular distribution shown in Figure 5 is influenced strongly at forward angles by the high energy tail of the resonance near 13.71 MeV. This resonance has an angular distribution which increases markedly as one goes from 120° to 45°, as shown in Figure 6. The higher minimum in the (\( \alpha, n \)) cross section shown in Figure 5 may re-
sult from background due to the presence of one or more nearby resonances which have not been resolved from the 14.6-MeV resonance. One might expect to observe this background in the (α,p) reaction near 14.6 MeV. It can be seen from Figure 7 that such a background is indeed present.

It should be noted that the shapes of the angular distributions at the other resonances in the energy range investigated, shown in Figure 6, are different from each other and those shown in Figure 5. Therefore, it appears highly improbable that the similarity in shape for the angular distributions shown in Figure 5 is accidental.

Finally, one might expect the isospin mixing to be small at energies away from the 13.97-MeV and 14.6-MeV resonances. The (α,p) and (α,n) angular distribution at a given energy would then be similar. Figure 7 shows that this is in fact the case at about 15.1 MeV.

Additional information about the properties of the 17.63 and 18.10-MeV 16O states may be obtained by considering the excited states of 16N, the T = +1 analogue of 16O. If these 16O states do indeed arise from the mixing of a T = 0 and a T = 1 state, the analogue T = 1 state should occur in 16N (and 16F). This 16N analogue state and the doublet members of 16O would of course have the same spin and parity. The excitation energy of
this $^{16}_N$ state should be equal to the excitation energy of the $T = 1$ unperturbed $^{16}_0$ state minus 12.83 ± 0.02 MeV, the isobaric mass difference between $^{16}_0$ and $^{16}_N$. It is reasonable to assume that the total width of this $^{16}_N$ state should be comparable to the total width of the unperturbed $T = 1$ state of $^{16}_0$ and therefore to the total width of each of the doublet members.

If it is assumed that the two unperturbed $^{16}_0$ states are degenerate, the energy of the $T = 1$ unperturbed $^{16}_0$ state would be 17.86 MeV (See Question (11)). Thus the expected state of $^{16}_N$ should occur at an excitation energy of about 5.03 MeV and should have a width of about 200 keV.

Three levels of $^{16}_N$ which have approximately the correct energy and width are known. Each will be discussed in turn.

1. 4.725-MeV excitation energy: This state has a width of 290 ± 30 keV and has been assigned a spin and parity of 1" by Hewka et. al. However, an assignment of $J^\pi = 1^-$ for the 17.63 and 18.10-MeV levels of $^{16}_0$ does not appear to be compatible with existing $^{16}_0(\gamma,n)^{15}_0$

\[^{+}\] The arguments that follow are based on the assumption the $\Gamma_\alpha < \Gamma_n$ (or $\Gamma_p$) and thus the neutron width (proton width) has approximately the same magnitude as total width. This assumption seems reasonable since there is no clear evidence for either member of the doublet in the $^{12}_C(\alpha,\alpha)$ reaction.
and $^{15}\text{N}(p,\gamma)^{16}\text{O}$ data. The selection rules for electric dipole transitions are $\Delta T = 1$ and $\Delta J = 1$ with a change of parity. Thus, the $^{16}\text{O}(\gamma,n)^{15}\text{O}$ reaction should resonate at 18.10-MeV state where the neutron partial width is large, and the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction should resonate at the 17.63-MeV state where the proton width is large. Neither resonance is shown by the existing data. If the spin and parity of this $^{16}\text{N}$ level are indeed $1^-$, it seems unlikely that this state is the desired one.

2. 4.774-MeV excitation energy: This state has a width of 59 $\pm$ 8 keV and tentative spin and parity assignments of $(1,2,3)^+$ by Hewka et al. and $(1,2)^+$ by Sikkema. Since only natural parity states can be observed in the present work, this state could be the desired $^{16}\text{N}$ analogue state only if $J^\pi = 2^+$. 

3. 5.305-MeV excitation energy: This state has a width of 260 $\pm$ 30 keV and tentative spin and parity assignments of $2^-$ by Hewka et al. and of $(2,3)^+$ by Sikkema. The former assignment is based in part on model dependent arguments. This state would be the one searched for only if $J^\pi = 2^+$. 

Thus, either the 4.774-MeV or 5.305-MeV state of $^{16}\text{N}$ may be the expected analogue of $T = 1$ unperturbed $^{16}\text{O}$ state. If the $J^\pi$ of the 5.305-MeV state proves to be $2^-$.
as suggested by Hewka et. al. then, of these two states, the 4.774-MeV $^{16}_N$ state is the only possible candidate.

It should be noted that a $J^\pi$ of $2^+$ for the unperturbed $T = 1$ state of $^{16}_O$ is consistent with the available data on the $^{16}_O(^{14}_N, n)^{15}_O$ and $^{15}_N(p, y)^{16}_O$ reactions and the existing data regarding excited states of $^{16}_N$. 

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34. C.P. Sikkema, Nucl. Phys. 32, 470 (1962).