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Excitation Energy and Lifetime of the O^{15} 7276-keV State*

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An accurate determination of the energy of the sixth excited state in O^{15} has been carried out because of the proximity of this level to the proton binding energy and the resulting possibility of its importance in the stellar formation of O^{15}. Gamma rays from this state occurring in the $N^{14}(d,n)O^{15}$ reaction at $E_d=3.2$ MeV were measured by means of a Ge(Li) detector at 90° to the beam. The transition leading to the (5241.3 ± 0.5)-keV level of O^{15} is found to have an energy of 2034.7 ± 0.3 keV. Thus the O^{15} level in question has an energy of 7276.0 ± 0.6 keV, which is 16.8 ± 1.3 keV below the proton binding energy of 7292.8 ± 1.2 keV. From a measurement at 0° to the beam the 0°–90° Doppler shift of the 2035-keV gamma ray is found to be 2.3 ± 0.4 keV. For a very short lifetime the expected Doppler shift is 14.4 ± 1.3 keV. The observed shift corresponds to a mean lifetime of $(1.25\pm0.3)\times10^{-12}$ sec for the 7276-keV state of O^{15}.

I. INTRODUCTION

In a previous study[1] of electromagnetic transitions in N^{15} and O^{15} a new O^{15} level was located at an excitation energy of 7284 ± 7 keV and thus interestingly close to the proton binding energy[2] of 7292.8 ± 1.2 keV. From a recent investigation of the $O^{16}(p,d)O^{15}$ reaction Marion *et al.*[3] obtained an energy value of 7285 ± 10 keV for this state. Because of the possible role of this level in the stellar formation of O^{15} via the $N^{14}(p,\gamma)O^{15}$ reaction, it was evident that an accurate measurement of the energy of this state would be desirable. During the course of the present work Hensley[4] determined by means of magnetic-spectrometer measurements on the $O^{16}(He^3,\alpha)O^{15}$ reaction that the energy of this state is 21.6 ± 2 keV below the $N^{14}+p$ threshold.

We have made an energy measurement on the gamma rays emitted from this state and have found that the O^{15} level is 16.8 ± 1.3 keV below the proton binding energy.

The previous work[1] on levels in N^{15} and O^{15} suggested that the N^{15} 7563-keV and O^{15} 7276-keV levels form a mirror pair and if so both have $J^\pi=\frac{7}{2}^+$, which is the spin-parity of the former. Recent results of Hensley[4] show that, indeed, the O^{15} 7276-keV level has $J=\frac{7}{2}$. Recently Lieb[5] has obtained a mean lifetime of $(1.5\pm0.5)\times10^{-13}$ sec for the N^{15} 7563-keV level. Thus if the O^{15} 7276-keV state is its mirror level its lifetime might be observable. We have carried out Doppler-shift measurements which result in a determination of the mean lifetime of the O^{15} 7276-keV state.

II. EXPERIMENTAL METHODS AND RESULTS

A target of ZrN several mg/cm² thick was bombarded with a beam of 3.2-MeV deuterons in order to study the gamma radiation from the $N^{14}(d,n)O^{15}$ reaction. High-resolution gamma-ray measurements were made with a Ge(Li) detector having a sensitive volume of 4 cm³. Some of the data were recorded in a 2048-channel pulse-height analyzer. For the precision energy measurements the data were recorded in a 1600-channel pulse-height analyzer in which the overall gain of the amplifier-analyzer system[6] was servo-stabilized by using two constant-temperature-controlled precision pulsers connected to the input of the preamplifier.

In the singles pulse-height spectrum from the Ge(Li) detector at 90° to the beam one of the lines that was observed had an energy of about 1013 keV. If this were to be assigned as the two-escape peak of a 2035-keV gamma ray the corresponding full-energy-loss peak could not have been seen in the singles spectrum because of the strong two-escape peak due to the 3085-keV gamma-ray from C^{13} formed in the $C^{12}(d,p)C^{13}$ contaminant reaction. Hence neither the nature nor the origin of the 1013-keV line could be determined from the Ge(Li) singles spectrum alone.

In order to establish the identity of the 1013-keV line the Ge(Li) detector output was recorded in coincidence with a 5×5-in. NaI(Tl) detector placed on the opposite side of the target. A pulse-height window was set on the NaI(Tl) detector output so as to include the full-energy-loss and one-escape peaks of the strong 5.3-MeV gamma rays. Figure 1 shows the resulting coincidence spectrum. All of the lines in this spectrum can be assigned (as indicated in the figure) as either full-energy-loss or two-escape peaks of transitions (occurring in the $N^{14}+d$ reactions) which arise from the known cascade decays[1] of states in N^{15} and O^{15} through the various states in the region of 5.3 MeV. These assignments are based on the measured energies of the peaks, on the consistency of the intensity ratios of the various two-escape peaks to the corresponding full-energy-loss peaks, and on the observed widths of the peaks. Thus the 1013-keV line, which occurs at about channel 800 in Fig. 1, has its matching peak at channel 1624. The energies, relative intensities, and approximately equal widths of these two lines are all consistent with their assignments as the full-energy-loss and two-

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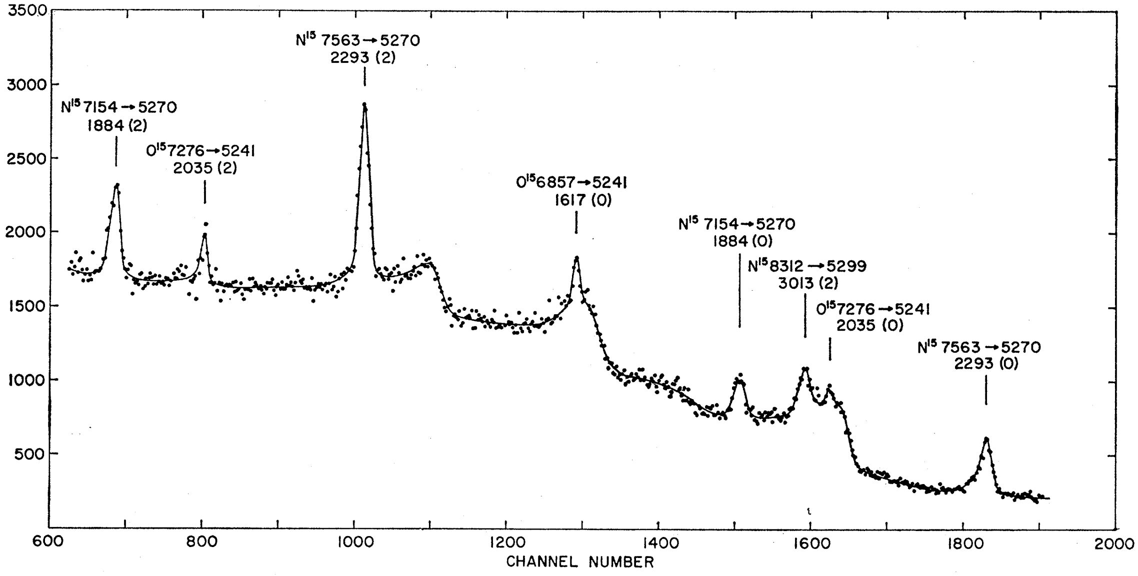

FIG. 1. Coincidence measurement of gamma rays from a ZrN target bombarded with 3.2-MeV deuterons. The pulse-height spectrum from a 4 cm³ Ge(Li) detector is shown in coincidence with a 5×5-in. NaI(Tl) detector when the latter was channeled on the full-energy-loss and one-escape peaks of the 5.3-MeV gamma rays. The run was of 23-h duration at a beam current of 0.0025 μA. The peak assignments indicate the nucleus, the energies of the initial and final states in keV, and the transition energy in keV. Numbers in parentheses indicate whether the line is a two-escape peak (2) or a full-energy-loss peak (0).

escape peaks of gamma rays of 2035 keV that are in coincidence with gamma rays of ~5.3 MeV. It may be noted that the 2035-keV lines are noticeably narrower than those pairs of lines belonging to the 1884-keV transition (N^{15} 7154→5270) and to the 2293-keV transition (N^{15} 7563→5270). A comparison of Fig. 1 with the singles spectrum showed that the relative intensities of the 1884-, 2035-, and 2293-keV two-escape peaks were the same in the singles and coincidence spectra. All of the evidence is therefore consistent with the assignment of the 2035-keV gamma ray to the O^{15} 7276→5241-keV transition.

In order to measure the energy of the two-escape peak of the 2035-keV gamma ray a source of Bi^{207} was superposed while recording the Ge(Li) singles spectrum from the $N^{14}+d$ reactions. Bi^{207} emits gamma rays of 569.62 ± 0.06 keV and 1063.44 ± 0.09 keV.[7] Two additional reference lines in the spectrum were those of annihilation radiation, 511.00 keV, and the (870.81 ± 0.22)-keV line[8] from the $O^{16}(d,p)O^{17}$ reaction due to oxygen contamination in the target. By means of a post-bias amplifier the energy region from 400 to 1400 keV was recorded in the 1600-channel pulse-height analyzer (0.57 keV per channel dispersion). The Ge(Li) detector was placed 15 cm from the target and it was positioned accurately at 90° to the incident beam. A run of 34-h duration was made under these conditions.

Computer Gaussian fits were made to the 1013-keV line and to the 1063.44-keV line of Bi^{207} from this long run in order to establish their peak positions and associated errors in position. The peak positions of the other calibration lines at 511.00, 569.62, and 870.81 keV were determined from hand plots and their respective errors in position were estimated. A least-squares computer fit was then made to the peak channel numbers of the four reference lines of the form

$$E_\gamma=\sum_{n=0}^{m} a_n x^n$$

where x is the channel number and m was varied from 1 to 3.[8] From this fit the energy of the 1013-keV line was found to be 1012.60 ± 0.20 keV. The corresponding gamma-ray energy is 2034.6 ± 0.3 where the over-all error allows for a possible error of about ±0.2 keV resulting from Doppler shift if the detector was not exactly at 90° to the beam. (This possible error was estimated after determining the 0°–90° Doppler shift as described below.)

By adding the appropriate second-order Doppler recoil energy correction to the gamma-ray energy, an O^{15} transition energy of 2034.7 ± 0.3 keV is obtained. Since the state to which the decay takes place has an energy of 5241.3 ± 0.5 keV[9] then the upper level has an energy of 7276.0 ± 0.6 keV. Thus the O^{15} level in question is 16.8 ± 1.3 keV below the proton binding energy of 7292.8 ± 1.2 keV.

From a similar analysis of a run taken at 0° to the beam it was found that the 0°–90° Doppler shift of the

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2035-keV gamma ray is 2.34±0.38 keV. The calculated 0°–90° Doppler shift for the reaction used and for a mean lifetime negligibly short compared to the stopping time of the O^{15} recoils is (14.4±1.3) keV where we have assumed that the O^{15} recoils have an average center-of-mass angle $\theta_{\text{c.m.}}$ to the deuteron beam corresponding to $\cos\theta_{\text{c.m.}}=(0\pm0.33)$. Thus the attenuation coefficient[10] F' is given by $F'=(2.34\pm0.38)/(14.4\pm1.3)=0.16\pm0.03$. In order to obtain a mean lifetime for the O^{15} 7276-keV level from this result we need to know the energy loss for O^{15} ions in ZrN as a function of ion energy. This information was obtained by interpolation of data[11] for the stopping of O^{16} ions in carbon, aluminum, nickel, silver and gold. This procedure yields a dE/dx curve which is characterized by a slowing down time[10] α of $(2.9\pm0.4)\times10^{-13}$ sec for O^{15} ions in ZrN. A full analysis, including the effects of slowing down and scattering of the O^{15} ions by nuclear collisions yields a mean lifetime of (1.25±0.3) psec for the O^{15} 7276-keV level.

III. DISCUSSION

Our present result for the energy of the O^{15} 7276-keV level indicates that the previous measurement[1] from this laboratory of 2044±7 keV for the energy of the cascade gamma ray is high by about 1.3 standard deviations. Our result, 16.8±1.3 keV, for the energy separation between this state and the $N^{14}+p$ threshold is not in very good agreement with the separation 21.6±2 keV derived by Hensley,[4] but in either case the O^{15} level is established as lying well below the $N^{14}+p$ threshold.

As discussed by Hensley,[4] the excitation energy and spin of the O^{15} 7276-keV level are such that the state will have a negligible effect on the stellar production rate of O^{15}. The effect of this state on the rate of the $N^{14}+p\rightarrow\gamma+O^{15}$ reaction is also dependent on the radiative width of the level. The quite small radiative width in the present work leads to an even smaller contribution of this state to the stellar production of O^{15} than that estimated by Hensley.

In our previous[1] study of the gamma rays from $N^{14}+d$, a weak (unresolved) peak with an energy of 2045±6 keV and a Doppler width of 15±5 keV was observed in a Ge(Li) singles spectrum. This peak was ascribed to the O^{15} 7276 → 5241 transition because of its agreement in energy with the NaI(Tl) measurement[1] of 2044±7 keV for this transition. We now know, however, that the energy of this peak is too high and its Doppler width too large to be associated with the 7276 → 5241 transition and it must have arisen from some other (unknown) source. Thus, the previous[1] conclusion (based on the observed Doppler widths) that the O^{15} 7276-keV level has a mean lifetime less than 5×10^{-13} sec is in error.

The $E2/M1$ mixing ratios of the N^{15} 7563 → 5270 and O^{15} 7276 → 5241 mirror transitions have both been measured.[12,13] Both are predominantly $M1$ transitions. Assuming that other branches from the $J=\frac{7}{2}$ states are negligible, the mean lifetimes of (0.15±0.05) [5] and (1.25±0.3) psec for the N^{15} 7563 → 5270 and O^{15} 7276 → 5241 transitions, respectively, lead to $M1$ transition strengths of $(1.8\pm0.6)\times10^{-2}$ and $(0.30\pm0.07)\times10^{-2}$ Weisskopf units, respectively. It is seen that both transitions are quite weak compared to the average[14] $M1$ strength of ~0.15 Weisskopf units. An explanation for the weakness of the N^{15} 7563 → 5270 transition has been offered by Lieb.[5]

At first sight it might appear that the difference by a factor of about 6 between the N^{15} and O^{15} transition strengths violates Morpurgo's[15] rule for the near equality of $M1$ transition strengths in mirror nuclei. However, this rule is only expected to hold on the average. It is based on the fact that matrix elements for $\Delta T=0$ transitions can be written in the form: $M=M_0+M_1T_3$, where M_0 and M_1 are independent of T_3 and, *on the average* M_1 is ~10 times larger (in magnitude) than M_0 for $M1$ transitions. Applying this formalism to the present case, we have $(M_0+\frac{1}{2}M_1)^2$ and $(M_0-\frac{1}{2}M_1)^2$ for the N^{15} and O^{15} transition strengths, respectively. If now we take $M_1\simeq5M_0$ we can explain the difference in the two $M1$ rates. This appears reasonable since the values quoted above for the transition strengths show that M_1 is considerably weaker than usual.

Note added in proof. By means of techniques similar to those described in this paper recent information has been obtained on the O^{15} 6.86-MeV level and the N^{15} 7.15- and 7.56-MeV levels, the latter two being the mirrors of the O^{15} 6.86- and 7.28-MeV levels. Measurements at $\theta=90°$ to the beam on the gamma rays corresponding to the O^{15} 6.86 → 5.24, N^{15} 7.15 → 5.27 and 7.56 → 5.27 cascade transitions gave 1618.4±0.6, 1884.0±1.5, and 2295.5±0.6 keV respectively for their energies. By adding the corresponding transition energies to the energies[9] of the N^{15} 5.27- and O^{15} 5.24-MeV levels (after correcting the gamma-ray energies for the second-order Doppler recoil energy) the excitation energies obtained are 6859.8±1.0 keV in O^{15} and 7155.5±1.7 and 7567.1±1.0 keV in N^{15}. The 0°–90° Doppler shifts of the 1618.4- and 1884.0-keV lines were observed to be 8.7±0.5 and 11.4±1 keV as compared to shifts (calculated as described in the text) of 11.7 ±1.5 and 13.6±3.8 keV. These results indicate that these lifetimes may be measurable by a more refined version of the Doppler-shift attenuation method. The Doppler shift results for the N^{15} 7.15-MeV level are

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consistent with the results of Lieb,[5] while those for the O^{15} 6.86-MeV level give a rough estimate of the mean lifetime: $\tau=0.10\pm0.06$ psec. It was also determined that the intensities of the gamma-ray branches from the N^{15} 7.15- and 7.56-MeV levels to the $\frac{1}{2}^+$ 5.30-MeV level were both less than 4% of their respective branches to the $\frac{5}{2}^+$ 5.27-MeV level.

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Effective Interactions in C^{14}

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Conventional shell-model calculations on the assumption of *jj* coupling have been made for the level spectrum of C^{14} considering C^{12} as the core. The three different choices of the exchange mixture considered are (a) *s*-state interaction only, (b) singlet-even interaction only, and (c) singlet-even and triplet-odd interaction. The configuration-mixing effects are also studied and are found to be insignificant. The energy levels are satisfactorily explained with an attractive but weak singlet-even (Serber-type) interaction operating only in *s* and *d* states, and of a fairly long Gaussian range. The importance of the *d*-state forces is pointed out and the configuration assignments to various levels are made.

1. INTRODUCTION

The calculation of energy levels in *p*-shell nuclei has generally been carried out within the framework of the *LS*-coupling or the intermediate-coupling models. It was even remarked[1] that conventional shell-model calculations are not likely to be made for mass-14 nuclei. However, such calculations were made for N^{14} by True[2] using a central two-body interaction of the Gaussian type. The odd-parity states of C^{14} have been discussed on the basis of the usual *jj*-coupling model by several authors.[3–8] Nagarajan[9] suggested an intermediate-coupling configuration calculation for the nuclear spectrum of C^{14}. However, no detailed shell-model calculations are available so far for this nucleus. The aim of the present study is to calculate the level spectrum of C^{14} using a central two-body interaction of the Gaussian type in an effort to determine the nature (exchange character) and the parameters of the effective interaction.

The calculations are made using the method of relative coordinates outlined in Sec. 2. The experimental information available on the level scheme is presented in Sec. 3, followed by a discussion of the relevant shell-model configurations. The results of our calculations for various types of assumed interaction are given in Sec. 5 and a discussion of these results is presented.

2. METHOD OF CALCULATIONS

The most general form for the central two-body interaction can be written as

$$H_{12}=[A_0+A_1M+A_2B+A_3MB]V(r_{12})\,, \qquad (1)$$

where M and B are, respectively, space and spin-exchange operators, (Majorana and Bartlett), and the A_k's are constants. The constants are so normalized that

$$A_0+A_1+A_2+A_3=1\,. \qquad (2)$$

The radial dependence has been chosen to be of Gaussian shape $V_0\exp[-(r/r_0)^2]$ as a matter of convenience in computations; V_0 and r_0 being the strength and range of the potential. Since in the evaluation of the Hamiltonian matrix in a given configuration space, we shall consider states with definite isotopic spin T,

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