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Radiative Decay of the 1.472-MeV State of O^{19}†

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The mean lifetime of the 1.472-MeV level ($J^\pi = \frac{1}{2}^+$) in O^{19} has been measured using the Doppler-shift attenuation method and found to be $\tau_m = 1.22 \pm 0.36$ psec. The level decays $(1.4 \pm 0.2)\%$ to the ground state ($J^\pi = \frac{5}{2}^+$) and $(98.6 \pm 0.2)\%$ to the state at 96 keV ($J^\pi = \frac{3}{2}^+$). Energies of the first and second excited states of O^{19} were measured as 96.0 ± 0.5 and 1472 ± 1 keV, respectively. The experimental results are compared with a theoretical calculation.

I. INTRODUCTION

The mass-19 system has been of theoretical interest for many years. The independent-particle shell model was applied to this system first by Elliott and Flowers, and Redlich[1]: It has been treated by many authors[2,3] since then. For the $T=\frac{1}{2}$ system, especially F^{19}, a great deal of experimental information has been gathered and agreement between theory and experiment is in many cases most gratifying.[4] For the $T=\frac{3}{2}$ systems (O^{19}, Na^{19}) much less information has been obtained.[5-9] The theoretical interest of this system is, however, at least as great as that of the $T=\frac{1}{2}$ system: The low-lying levels should all belong to the ($2s$, $1d$) configuration, and radiative transitions between them should be largely $M1$ and $E2$. The lifetime of the $\frac{3}{2}^+$ state at 96 keV has been measured as 1.39 ± 0.05 nsec by McDonald *et al.*,[6] while recently the decay modes of several states have been reported by Fintz *et al.*[7,8] In the present work we describe the measurement of the lifetime of the 1.472-MeV level and its decay modes. These results are compared with transition rates calculated with the wave functions for O^{19} given by Inoue *et al.*[2] A preliminary report of this work has already appeared.[9]

II. EXPERIMENTAL PROCEDURE

An elaboration of the Doppler-shift attenuation method (DSAM) was used to measure the lifetime of the 1.472-MeV level in O^{19}. In this method the shape of the Doppler-shifted and broadened line corresponding to the transition $1.472 \rightarrow 0.096$ was examined. A schematic diagram of the target chamber and detectors is given in Fig. 1. The target was formed by allowing a small quantity of H_2O^{18} (>95% O^{18}) to condense on a copper surface, which was cooled to 77°K with liquid nitrogen. A deuteron beam of 2.68-MeV energy impinged on this target, and protons arising from the $O^{18}(d, p)O^{19}$ reaction ($Q = 1.73$ MeV) were detected in an annular silicon counter; the counter included angles between 164 and 176° with respect to the direction of the incoming beam. The spectrum observed with this detector allowed us to estimate the average deuteron energy as $\overline{E}_d = 2.45 \pm 0.15$ MeV for those deuterons exciting the 1.472-MeV level. Coincident γ rays were detected in a 25-cc Ge(Li) γ-ray spectrometer which could be placed at the angles $\theta_\gamma = 0$ and 90° with respect to the beam axis. The front face of this detector was 6 cm from the target.

III. RESULTS

The line shapes of the 1.376-MeV γ ray corresponding to the $1.472 \rightarrow 0.096$ transition are shown in Fig. 2 for $\theta_\gamma = 0$ and 90°. The full width at half maximum of the line at 90° was 4.5 keV. This was due mainly to the intrinsic resolution of the detector, with a small contribution due to kinematic broadening. The line shape for $\theta_\gamma = 0°$ was fitted using the method described by Warburton, Olness, and Poletti.[10] For the range of velocities ($v/v_0 \leq 1.28$, $v_0 = c/137$) of the recoiling O^{19} ions in the present experiment, the slowing-down time was represented by $-M_1(dv_z/dt) = K_e v_z/v_0 + K_n(v_z/v_0)^{-1}$. Here M_1 denotes the mass of the ion being stopped, v_z is its velocity in the z direction, and K_e and K_n are the proportionality constants for energy loss by electronic and nuclear collisions, respectively. As Ormrod, MacDonald, and Duckworth[11] and Fastrup, Hvelplund, and Sautter[12] have shown, experimentally determined values of K_e oscillate about the Lindhard-Scharff-Schiøtt (LSS) estimate[13] as a function of the nuclear charge of the ion being stopped. There appears to be only a slight dependence of this oscillatory behavior upon the atomic charge of the stopping material. Using the results for oxygen stopping in carbon[11,12] and in aluminum[11] we estimated that the LSS estimate should be increased

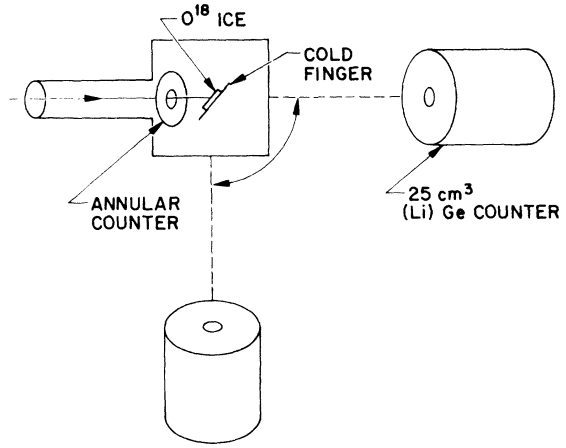

FIG. 1. Schematic diagram of apparatus used in the present experiment.

by $(30 \pm 15)\%$ for O^{19} ions stopping in H_2O^{18} ice, resulting in $K_e = 4.52 \pm 0.8$ keV cm$^2/\mu$g. We estimated K_n following the procedure outlined by Warburton, Olness, and Poletti[10] to give a value of $K_n = 0.249$ keV cm$^2/\mu$g (in the notation of Ref. 10, $\gamma_i^2 = 26.8$). With the above estimates, Eq. (B14) of Ref. 10 gives the dependence of the line shape observed at $\theta_\gamma = 0°$ on the lifetime of the excited nuclear state. In this manner the mean lifetime of the 1.472-MeV level in O^{19} was determined to be 1.22 ± 0.36 psec. This agrees very well with a recent Doppler-shift measurement of this mean lifetime using the $H^2(O^{18}, p)O^{19}$ reaction, $\tau_m = 1.27 \pm 0.2$ psec.[14]

Examination of the γ-ray spectrum in the vicinity of $E_\gamma = 1.47$ MeV, taking account of summing of the 96- to 1376-keV cascade γ rays, enabled us to estimate the decay modes of the 1.472-MeV level as $(98.6 \pm 0.2)\%$ to the first excited state and $(1.4 \pm 0.2)\%$ to the ground state. The measurement of Fintz *et al.*[8] is in good agreement with this result. Two earlier measurements[5,7] with somewhat larger errors show no essential disagreement. The energies of the first and second excited states of O^{19} were measured as 96.0 ± 0.5 and 1472 ± 1 keV, respectively. The γ-ray energy standards used were the γ rays from the $O^{19}(\beta^-)F^{19}$ decay, already present in the spectrum, as well as γ rays from a Co^{60} source and K x rays from a Pb flourescer deliberately included in the spectra used for energy determination.

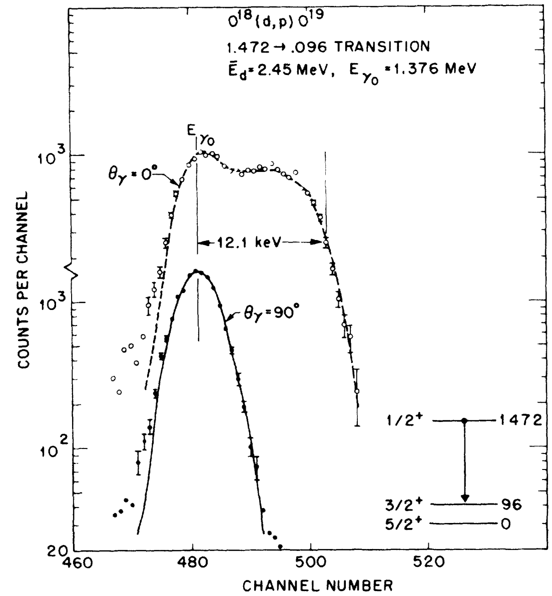

FIG. 2. The Doppler-shifted and broadened line shape for the γ ray arising from the transition from the 1472- to the 96-keV level in O^{19}. The line shape observed at $\theta_\gamma = 0°$ is shifted and broadened by comparison with the one observed at $\theta_\gamma = 90°$. The full energy shift, expected if all γ rays were emitted before any slowing down of the recoiling O^{19} ion, was 12.1 keV. The observed line shape is fitted best (dashed line) for a mean lifetime of 1.22 ± 0.36 psec for the 1.472-MeV level.

IV. DISCUSSION

It is of some interest to calculate the transition probabilities and associated partial lifetimes for the decay of the 1.472-MeV level to the ground state and to the level at 96 keV in O^{19}. Inoue *et al.*[2] have given a set of j-j coupling wave functions for these levels. If we neglect wave-function components with amplitudes of less than 0.10, we obtain from their work

$$|\tfrac{1}{2}\rangle = -0.960\,|d_{5/2}{}^2 s_{1/2}\rangle + 0.149\,|d_{5/2} d_{3/2} s_{1/2}\rangle + 0.221\,|d_{3/2}{}^2 s_{1/2}\rangle\,,$$

$$|\tfrac{3}{2}\rangle = +0.730\,|d_{5/2}{}^3\rangle - 0.645\,|d_{5/2}{}^2 s_{1/2}\rangle + 0.153\,|d_{5/2} d_{3/2} s_{1/2}\rangle + 0.123\,|d_{3/2}{}^2 d_{5/2}\rangle\,,$$

$$|\tfrac{5}{2}\rangle = -0.893\,|d_{5/2}{}^3\rangle + 0.366\,|s_{1/2}{}^2 d_{5/2}\rangle - 0.192\,|d_{3/2}{}^2 d_{5/2}\rangle - 0.102\,|d_{3/2}{}^2 d_{5/2}\rangle\,,$$

where we can associate the three expansions with the 1472- and 96-keV levels and the ground state, respectively. From an examination of this expansion, it is immediately obvious that there can be no $M1$ transitions between the largest components of each wave function, either because the $M1$ transition $s_{1/2} \to d_{5/2}$ is forbidden or because the $M1$ transition $(j^n) \to (j^n)$ is not allowed.[15] Transitions between a number of smaller components are also forbidden, since more particles than one are in different states. In view of this the $M1$ transitions between these states could be expected to be substantially hindered.

Neglecting the small components (amplitude <0.1), a calculation was carried out for both the $M1$ and $E2$ transition amplitudes: A fractional-parentage expansion for each component was made using the expression given by True[16] for the cases where all three spins are different or two of the three spins are the same. For the case where all three spins are identical we used the expression given by de-Shalit and Talmi[15] (Eq. 26.12). In this way we obtained, for instance

$$|d_{5/2}{}^3, \tfrac{5}{2}\rangle_a = +\tfrac{1}{3}\sqrt{2}\,|\tfrac{5}{2}{}^2 0)_a \tfrac{5}{2}, \tfrac{5}{2}\rangle - \tfrac{1}{6}\sqrt{10}\,|\tfrac{5}{2}{}^2 2)_a \tfrac{5}{2}, \tfrac{5}{2}\rangle - \tfrac{1}{2}\sqrt{2}\,|\tfrac{5}{2}{}^2 4)_a \tfrac{5}{2}, \tfrac{5}{2}\rangle,$$

$$|d_{5/2}{}^2 s_{1/2}, \tfrac{3}{2}\rangle_a = +\tfrac{1}{3}\sqrt{3}\,|\tfrac{5}{2}{}^2 2)_a \tfrac{1}{2}, \tfrac{3}{2}\rangle - (\tfrac{2}{3})\,|\tfrac{5}{2}\tfrac{1}{2}2)_a \tfrac{5}{2}, \tfrac{3}{2}\rangle - \tfrac{1}{3}\sqrt{2}\,|\tfrac{5}{2}\tfrac{1}{2}3)_a \tfrac{5}{2}, \tfrac{3}{2}\rangle,$$

and

$$|d_{5/2} d_{3/2} s_{1/2}, \tfrac{1}{2}\rangle_a = \tfrac{1}{3}\sqrt{3}\,|\tfrac{5}{2}\tfrac{3}{2}1)_a \tfrac{1}{2}, \tfrac{1}{2}\rangle - \tfrac{1}{3}\sqrt{3}\,|\tfrac{5}{2}\tfrac{1}{2}2)_a \tfrac{3}{2}, \tfrac{1}{2}\rangle + \tfrac{1}{3}\sqrt{3}\,|\tfrac{3}{2}\tfrac{1}{2}2)_a \tfrac{5}{2}, \tfrac{1}{2}\rangle.$$

By the use of the above and similar expressions, together with standard tensor algebra (see especially Ref. 15, p. 134) the reduced transition probabilities $\Lambda(M1)$ and $\Lambda(E2)$ were obtained where the Λ's are as defined by Warburton and Pinkston[17] and are given in terms of our reduced matrix elements by

$$\Lambda(M1) = (2J_i + 1)^{-1} |\langle J_i \| \sum_i (g_{l_i} \vec{l}_i + g_{s_i} \vec{s}_i) \| J_f \rangle|^2,$$

$$\Lambda(E2) = \tfrac{16}{5}\pi (2J_i + 1)^{-1} |\langle J_i \| \sum_i (g_{l_i} + \beta_i) r_i^2 (\vec{Y}_2)_i \| J_f \rangle|^2.$$

The radiative widths are given by

$$\Gamma(M1) = 2.76\times 10^{-3} E_\gamma^3 \Lambda(M1),$$

$$\Gamma(E2) = 8.02\times 10^{-8} E_\gamma^5 \Lambda(E2),$$

where $\Lambda(M1)$ is in units of nuclear magnetons, $\Lambda(E2)$ is in units of $e^2\,\mathrm{F}^4$, and Γ is in units of eV if E_γ is measured in MeV. For protons $g_l = 1$, while for neutrons $g_l = 0$. For this calculation we take the effective charge, $\beta = 0.5$ for the three neutrons involved.

In this way we calculated the following radiative widths (Weisskopf single-particle estimates[18] are in brackets),

$$\Gamma(M1, \tfrac{1}{2} \to \tfrac{3}{2}) = 5.19\times 10^{-4}\ \text{eV} \quad (5.47\times 10^{-2}\ \text{eV}),$$

$$\Gamma(E2, \tfrac{1}{2} \to \tfrac{3}{2}) = 3.4\times 10^{-6}\ \text{eV} \quad (12.3\times 10^{-6}\ \text{eV}),$$

$$\Gamma(E2, \tfrac{1}{2} \to \tfrac{5}{2}) = 4.1\times 10^{-6}\ \text{eV} \quad (17.2\times 10^{-6}\ \text{eV}).$$

Contributions to the $M1$ transition probability arose only from the following two transitions between components whose amplitude was greater than the arbitrary limit of 0.1:

$$|d_{5/2} d_{3/2} s_{1/2}, \tfrac{1}{2}\rangle \to |d_{5/2}{}^2 s_{1/2}, \tfrac{3}{2}\rangle,$$

and

$$|d_{5/2} d_{3/2} s_{1/2}, \tfrac{1}{2}\rangle \to |d_{5/2} d_{3/2} s_{1/2}, \tfrac{3}{2}\rangle.$$

The experimental transition strengths extracted from the measured mean lifetime $\tau_m = 1.22 \pm 0.36$ psec and decay branching are

$$\Gamma(M1, \tfrac{1}{2} \to \tfrac{3}{2}) + \Gamma(E2, \tfrac{1}{2} \to \tfrac{3}{2}) = (5.3^{+2.2}_{-1.2})\times 10^{-4}\ \text{eV},$$

and

$$\Gamma(E2, \tfrac{1}{2} \to \tfrac{5}{2}) = (7.6^{+2.9}_{-1.7})\times 10^{-6}\ \text{eV}.$$

The measured transition strengths may also be compared with predictions of the shell-model calculations by Halbert, McGrory, Wildenthal, and Pandya.[19] In these calculations the $d_{5/2}$, $d_{3/2}$, and $2s_{1/2}$ orbits are available to the valence nucleons, with the $(1s)^4(1p)^{12}$ core closed. Several model Hamiltonians were used; we shall compare our results with predictions based on the realistic effective Hamiltonian due to Kuo[20] and labeled in Ref. 19 as $\mathrm{K}+{}^{17}\mathrm{O}$. For this choice of Hamiltonians, Halbert *et al.*[19] report

$$\Gamma(M1, \tfrac{1}{2} \to \tfrac{3}{2}) + \Gamma(E2, \tfrac{1}{2} \to \tfrac{3}{2}) = 2.08\times 10^{-3}\ \text{eV},$$

and

$$\Gamma(E2, \tfrac{1}{2} \to \tfrac{5}{2}) = 1.47\times 10^{-5}\ \text{eV}.$$

Compared with experiment, these quantities are both too large by factors of 4 and 2, respectively.

The close agreement between the measured lifetime and the theoretical prediction based on the wave functions of Inoue *et al.*[2] is probably fortuitous in view of the neglect of small components in the wave functions and the expected inaccuracies in the amplitudes of the components which contribute to the $M1$ strength. However, both our calculation and that of Halbert *et al.* bear out the initial expectation of considerable inhibition of the $M1$ strength for the $\tfrac{1}{2}^+ \to \tfrac{3}{2}^+$ transition in O^{19} (106 times slower than the Weisskopf estimate).

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^{11}B States Observed in the Scattering of Neutrons from ^{10}B and in the ^{10}B$(n, \alpha)^7$Li Reaction*

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The polarization and the differential scattering cross section for neutrons scattered from ^{10}B have been measured for $0.075 \le E_n \le 2.2$ MeV. These results, together with those from the ^{10}B$(n,\alpha_0)^7$Li, ^{10}B$(n,\alpha_1)^7$Li*(0.48 MeV), ^{7}Li$(\alpha,\alpha)^7$Li, ^{7}Li$(\alpha,\alpha')^7$Li*(0.48 MeV), and other reactions leading to states in ^{11}B, have been simultaneously interpreted in one consistent R-matrix calculation. The calculated results are in good agreement with most of the data and give new information about states in ^{11}B. The level parameters obtained for these states and the calculated reaction cross sections are consistent with the corresponding quantities in the mirror nucleus ^{11}C. Quantitative explanations are given both for the well-known $1/v$ behavior of the cross section for the ^{10}B$(n,\alpha)^7$Li reaction and for the α_0/α_1 branching ratio.

I. INTRODUCTION

The energy level structure of ^{11}B above the α-particle threshold ($E_x = 8.664$ MeV) is quite complex. Experiments[1-6] with ^{7}Li$(\alpha, \alpha)^7$Li, ^{7}Li(α, α')-^{7}Li*, ^{7}Li$(\alpha, \gamma)^{11}$B*, ^{10}B$(d, p)^{11}$B, and ^{9}Be$(^3$He$, p)^{11}$B have yielded information on spins, parities, energies, and widths for several of the states below the neutron threshold ($E_x = 11.456$ MeV), but a number of anomalies in these observed reactions still remain unexplained. Above the neutron threshold, virtually no definitive information exists regarding J^π assignments, particle widths, and the like for the $T = \frac{1}{2}$ states in ^{11}B, although a number of broad resonances[1,3,7-16] in the neutron total cross section for ^{10}B as well as in the reactions ^{10}B$(n, n'\gamma)^{10}$B*, ^{10}B$(n, n)^{10}$B, ^{10}B(n, α_0)-^{7}Li, ^{10}B$(n, \alpha_1)^7$Li*, ^{7}Li$(\alpha, \alpha')^7$Li*, and ^{7}Li(α, n)-^{10}B have been observed in this region of excitation. ($T = \frac{3}{2}$ analogs of the two lowest states in ^{11}Be have