Lifetimes of the N^{14} 5.83-MeV and 6.44-MeV Levels*

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The lifetimes of the N^{14} 5.83- and 6.44-MeV levels were studied by the Doppler shift attenuation method using the $C^{12}(He^3,p)N^{14}$ reaction to populate the levels. The shifts in energy of the 0.73-MeV $5.83 \rightarrow 5.10$ transition and the 1.33-MeV $6.44 \rightarrow 5.10$ transition were observed between two angles to the beam by recording gamma-ray spectra in coincidence with the N^{14} $5.10 \rightarrow 0$ transition. From these measurements the mean lifetime of the N^{14} 5.83-MeV level was found to be greater than 2.3×10^{-12} sec, while the mean lifetime of the N^{14} 6.44-MeV level was found to be $(5.9\pm1.2)\times10^{-13}$ sec.

I. INTRODUCTION

THE lifetime of the N^{14} 5.83-MeV level was previously measured[1] from observations on the $5.83 \rightarrow 5.10$ transition using the $C^{13}(p,\gamma)N^{14}$ reaction to produce the cascade $8.90 \rightarrow 5.83 \rightarrow 5.10$. It was consequently shown[2] that a result of this measurement was either that the parities of the N^{14} 5.83- and 5.10-MeV levels were not the same, or that both levels contained $\sim5\%$ $T=1$ impurities in their predominantly $T=0$ wave functions. Since that time, it has been found that both levels have odd parity.[3–5] Thus, the lifetime measurement would seem to demand a quite severe breakdown of isotopic-spin purity in both the N^{14} 5.83- and 5.10-MeV levels. For this reason it seemed worthwhile to make an independent measurement of the lifetime of the N^{14} 5.83-MeV level.

Recently the gamma-ray decay of the N^{14} 6.44-MeV level has been studied[6] and it was found that this level has branches to the 1^+ ground state, 1^+ 3.95-MeV level, and 2^- 5.10-MeV level of $(65\pm3)\%$, $(21\pm2)\%$, and $(14\pm3)\%$, respectively. Since the 6.44-MeV level has $J^\pi=3^+$ [6,7] the first two of these decay modes are expected to be $E2$ and there is evidence to this effect.[6,7] The Weisskopf estimates[8] for the mean lifetimes of these two $E2$ transitions (using a radius constant $r_0=1.2$ F) are 3.6×10^{-14} sec and 4.2×10^{-12} sec, respectively. Both of these lifetime estimates are in the range which is accessible to measurement by the Doppler shift attenuation method, accordingly such a measurement was undertaken.

II. EXPERIMENTAL PROCEDURE

Carbon targets with a surface density of about 0.5 mg/cm² were prepared from a colloidal dispersion of carbon and alcohol. The mass density of the target material was measured using larger quantities of the material and found to be 1.53 ± 0.02 gm/cm³. During the course of the experiment, two sets of data were taken. For the first set, a self-supporting carbon foil was loosely mounted on a 10-mil Ta backing. For the second set of data, the carbon target was prepared directly on a 5-mil Ni backing. The difference in target mounting was the only major difference between the two runs. The targets were bombarded with 3.3-MeV He^3 ions accelerated by the BNL Van de Graaff accelerator; the incident beam current was about 0.3 μA. The incident energy was chosen after taking a rough excitation function for the N^{14} $6.44 \rightarrow 0$ transition. The incident bombarding energy was such that the resonance[7] for $C^{12}(He^3,p\gamma_{6.44})$ was at the front of the target, with the result that the recoil N^{14} nuclei from the $C^{12}(He^3,p)N^{14*}$ (6.44-MeV level) reaction were stopped in the target. Resulting gamma radiation was detected with two NaI(Tl) crystals optically coupled to 3-in. photomultiplier tubes. Both scintillators were located in the horizontal plane. One of these crystals was 5 in. in diam by 5 in. thick, and was located in a fixed position 90° to the beam axis. The front face of this detector was 5.5 cm from the target. The second of the two detectors was 3 in. in diam by 3 in. thick and was mounted on a platform which rotated about the target. The front face of this detector was 15 cm from the target. Both detectors were shielded from stray radiations with at least 2 in. of lead.

To observe the 0.73-MeV $5.83 \rightarrow 5.10$ transition and the 1.33-MeV $6.44 \rightarrow 5.10$ transition, fast-slow coincidence techniques were employed. The plate currents from the two photomultiplier tubes were first preamplified and subsequently amplified with transistor double-delay line clipping amplifiers. Fast (35 nsec)-slow (2 μsec) coincidence conditions were imposed on the amplified pulses; trailing edge timing was used for the fast coincidence condition, and the slow coincidence condition included pulse-height selection. Events were selected in the 5×5-in. crystal, whose pulse amplitudes corresponded in the pulse-height distribution to the full

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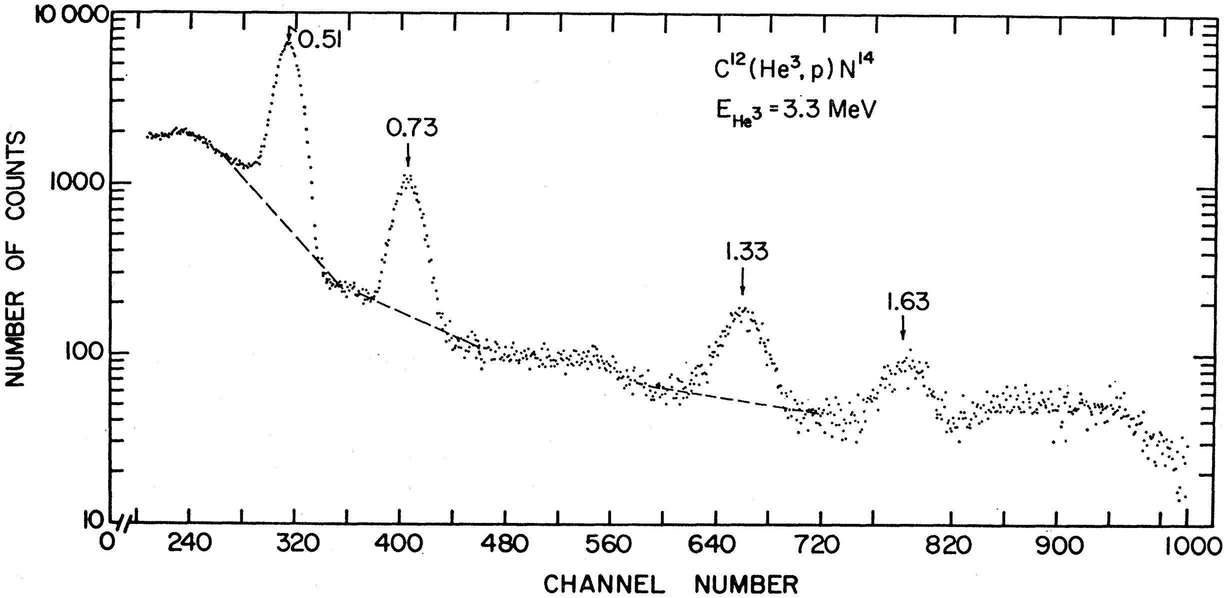

FIG. 1. Pulse-height distribution of the low-energy gamma radiation in coincidence with the N^{14} 5.10 → 0 transition. The photopeaks labeled in the figure correspond to annihilation radiation, the 0.73-MeV 5.83 → 5.10 transition, the 1.33-MeV 6.44 → 5.10 transition, and the 1.63-MeV 3.95 → 2.31 transition. The low-energy radiation was detected with a 3×3-in. NaI(Tl) scintillator at 165° to the He^3 beam and sorted and stored in a 1024-channel analyzer. The 5.10-MeV gamma radiation was detected with a 5×5-in. NaI(Tl) detector.

energy and the first and second escape peaks of the 5.10 → 0 transition. Pulse-height selection on the amplified output of the 3×3-in. crystal included pulse heights corresponding to the energy region from approximately 0.3 to 1.9 MeV. When coincidence conditions were satisfied, the pulse-height distribution of events in the 3×3-in. crystal was sorted and stored in a multichannel pulse-height analyzer. The pulse-height analyzer consisted of a 64 by 64-channel analyzer[9] coupled to a 4096-channel linear converter.[10]

To observe the shift in energy of the 0.73-MeV 5.83 → 5.10 transition and the 1.33-MeV 6.44 → 5.10 transition, when detected at two different angles to the beam, it is important that the detection system gain and the multichannel analyzer be stable despite changing counting rates and rotation of the photomultiplier tube, etc. Furthermore, since the gamma radiation of interest was selected by coincidence conditions, the counting times were rather long ($\sim 2\frac{1}{2}$ hours per spectrum) and the system had to be stable for the duration of the data collection.

The gain of the detection system was stabilized by employing a "spectrostat"[11,12] for the high-voltage supply of the photomultiplier which viewed the 3×3-in. crystal. This device stabilized the gain of the system up to and including the amplified pulses by examining the pulse height at the photopeak of the 0.51-MeV radiation with a single-channel analyzer and adjusting the photomultiplier high voltage to correct for gain changes.

Data were collected by recording pulse-height distributions in coincidence with the 5.10 → 0 transition in successive fashion at two angles to the beam axis. As mentioned above, two sets of data were collected. For the first run, the self-supporting carbon foil was bombarded and 5 pulse-height distributions were recorded with the 3×3-in. crystal at 15 and 135°. These data indicated a small shift in energy for the 0.73-MeV 5.83 → 5.10 transition. Since this shift could be due to some of the N^{14*} recoils from the $C^{12}(He^3,p)N^{14}$ (5.83-MeV level) reaction slowing down in the region (2–3 mm) between the carbon foil and the Ta backing, a second set of data was collected bombarding the carbon target prepared directly on the Ni backing. In this case, the N^{14*} recoils from the $C^{12}(He^3,p)N^{14}$ (5.83-MeV level) reaction were stopped either in the carbon target or the Ni backing. Seven pulse-height distributions were recorded at angles of 20 and 165°. Accordingly, the results for the 0.73-MeV transition are based on the second set of data, while both sets were used for the 1.33-MeV 6.44 → 5.10 transition.

III. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 1 illustrates a pulse-height distribution. Four photopeaks are labeled in the figure. A large amount of annihilation radiation and the 1.63-MeV gamma ray from the N^{14} 3.95 → 2.31 transition are present besides the two transitions of interest. The 1.63-MeV gamma

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rays are due to real coincidences resulting from summing of the 2.49 and the 2.31-MeV gamma rays from the $6.44 \rightarrow 3.95 \rightarrow 2.31 \rightarrow 0$ cascade in the 5×5-in. crystal and to accidental coincidences. The contribution of accidentals to the coincidence spectra was about 5%. However, since the relative accidental rate did not vary much the presence of the accidental coincidences had negligible effect upon the final result. For each recorded pulse-height distribution, the peak channels of the 0.51-, 0.73-, and the 1.33-MeV photopeaks identified in Fig. 1 were located using a Gaussian least-squares fit computer program.[13] The three photopeaks were fitted individually, assuming an exponential background (the dashed curves of Fig. 1). The average peak position was determined at each angle for all three photopeaks and the Doppler shift between the two angles of observation calculated; the channel shift was converted to keV using the known energies of the photopeaks to provide an energy calibration. The pulse-height versus energy curve was found to be linear within the errors of the measurement. No base line bias was used on the analyzer. The effect of the background subtraction was examined by finding the average peak positions for several different assumed shapes of the background under the peaks. It was found that the error introduced by the uncertainty in the assumed background was small compared with the statistical uncertainty in the peak positions.

For the first set of data, when the detector angles were 15 and 135°, the 0.73-MeV transition was found to shift 1.55±0.30 channels or 3.32±0.64 keV; the corresponding shift for the 1.33-MeV transition was 4.21±0.72 channels or 9.01±1.54 keV. In the second set of data, where the detector angles were 20 and 165°, the 0.73-MeV transition shifted by 0.10±0.11 channels or 0.24±0.26 keV; the corresponding shift for the 1.33-MeV transition was 4.50±0.66 channels or 10.7±1.6 keV.

From these data and the angular distribution of the outgoing protons, we evaluate the Doppler shift attenuation factor F', given by[16]

$$F'=\frac{\Delta E}{E_0\beta(0)(\cos\theta_1-\cos\theta_2)}, \qquad (1)$$

where $c\beta(t)$ is the average velocity of the recoil ions formed at $t=0$, E_0 is the gamma-ray energy for the nuclei at rest, and ΔE is the difference in gamma-ray energy measured at the angles θ_1 and θ_2. For the method we have used, the validity of Eq. (1) relies strictly on the isotropy of the p-γ-γ correlation. However, the effects of any proton-gamma anisotropies were estimated for the geometries of the measurements and found to be negligible.

The angular distribution of the outgoing protons for the $C^{12}(He^3,p)N^{14*}$ (5.83-MeV level) has not been reported in the He^3 energy region of interest. Therefore, to evaluate $\beta(0)$ we have assumed the average outgoing proton is at 45° (center of mass), and that the reaction takes place at the incident bombarding energy of 3.0 MeV. The assumed He^3 energy of 3.0 MeV is arrived at by averaging $\beta(0)$ over a roughly determined excitation function for the formation of the 5.83-MeV level from $E_{He^3}=2.8$ MeV, where the 0.73-MeV gamma ray is beginning to be discernable, to $E_{He^3}=3.3$ MeV. The yield appears to increase smoothly between these energies. The assumed proton angle of 45° is estimated to be a conservative lower limit to the average angle of the outgoing protons to the incident beam direction. With these assumptions, we are able to place an upper limit for F' for the 0.73-MeV transition, $F'<0.1$. The angular distribution for the outgoing protons for the $C^{12}(He^3,p)N^{14*}$ (6.44-MeV level) reaction at the 3.0-MeV resonance has recently been measured and determined to be isotropic.[7] For an isotropic distribution of the protons in the center-of-mass system, the average recoil velocity of the N^{14} ions is just equal to the velocity of the center of mass, which we evaluate at the 3.0-MeV resonance. (There is no appreciable formation of the 6.44-MeV level below this resonance.[7]) Thus, we calculate F' for the 1.33-MeV radiation to be 0.45±0.05. The range-velocity relationship for N^{14} ions stopping in C^{12} can be obtained from the stopping power data of Porat and Ramavataram[14] and the range-energy data of Powers and Whaling.[15] We find that these data are represented quite well by the expression[16]

$$R(\text{c.m.})=\alpha[v-(2/\pi)v_n\tan^{-1}(\pi/2\, v/v_n)], \qquad (2)$$

with the empirical constants v_n and α given by $v_n=0.47v_0$, where $v_0=c/137$, and $\alpha=(9.1\pm0.4)\rho^{-1}\times10^{-13}$ sec, where ρ is the density of the C^{12} target in gm/cm^3. For N^{14} ions stopping in these C^{12} targets ($\rho=1.53\pm0.02$ gm/cm^3), $\alpha=(5.95\pm0.26)\times10^{-13}$ sec, and for N^{14} ions stopping in Ni, we find $\alpha=(2.55\pm0.13)\times10^{-13}$ sec.

The range-velocity relationship used above implies a relationship for the Doppler shift attenuation factor of the form[16]

$$F'=[\lambda\alpha/(1+\lambda\alpha)][1-\delta(v_i/v_n)], \qquad (3)$$

where $\tau(=\lambda^{-1})$ is the mean lifetime of the radiation, and v_i is the initial velocity of the moving ion; the correction factor $\delta(\gamma_i)$ is given by

$$\delta(\gamma_i)=\frac{1}{\gamma_i(1+\gamma_i^2)^{\lambda\alpha/2}}\int_0^{\tan^{-1}\gamma_i}\frac{d\theta}{(\cos\theta)^{\lambda\alpha}}, \qquad (4)$$

with $\gamma_i=(\pi/2)(v_i/v_n)$. Using the iteration procedure

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described by Warburton *et al.*,[16] we find $\delta(\gamma_i)=0.11\pm0.01$ and $F=0.50\pm0.05$ for the 1.33-MeV radiation, with $F=\lambda\alpha/1+\lambda\alpha$. Using the value of α for the carbon targets, we have for the mean life of the 6.44-MeV level $\tau=(5.9\pm1.2)\times10^{-13}$ sec.

For the purpose of obtaining a lifetime limit for the 5.83-MeV level from the value obtained for the attenuation factor, i.e., $F'<0.1$, we can assume $F'=F=\lambda\alpha/1+\lambda\alpha$, and taking $\alpha=(2.55\pm0.13)\times10^{-13}$ sec (the value for Ni, we obtain $\tau>9\alpha$ or $\tau>2.3\times10^{-12}$ sec for the N^{14} 5.83-MeV level, where the limit corresponds to one standard deviation.

IV. DISCUSSION

We have set a limit for the mean lifetime of the 5.83-MeV level, $\tau>2.3\times10^{-12}$ sec. This limit is in disagreement with the previous measurement of the lifetime of this level by Warburton, Rose, and Hatch[1] who found $6.5\times10^{-13}>\tau>5\times10^{-14}$ sec for the mean lifetime. Furthermore, as mentioned in the introduction and emphasized by Warburton and Pinkston,[2] the previous value apparently demands large isotopic spin impurities ($\approx5\%$) in both the 5.83- and 5.10-MeV levels. The limit set here does not require the isotopic spin mixing as it corresponds to a radiative width for the 5.83-MeV state of $\Gamma_\gamma<2.9\times10^{-4}$ eV. This limit is less than the model-independent limit for the radiative width of the $5.83\rightarrow5.10$-MeV transition calculated by Warburton and Pinkston, $\Gamma(M1)<10^{-3}$ eV.

We find that the N^{14} 6.44-MeV state has a mean lifetime, $\tau=(5.9\pm1.2)\times10^{-13}$ sec, corresponding to a radiative width, $\Gamma_\gamma(6.44)=1.1\times10^{-3}$ eV. As mentioned in the introduction the $6.44\rightarrow0$ and the $6.44\rightarrow3.95$ transitions are predominantly $E2$.[6,7] If we use the branching ratios[6] and Weisskopf estimates[8] for these transitions quoted in the introduction, we find $|M|^2$, the ratio of the radiative width to the Weisskopf estimate, for these transitions are 4.0×10^{-2} and 1.5, respectively (assuming pure $E2$ radiations).

The N^{14} ground state and 3.95-MeV level are both states which belong predominantly to the shell-model configuration s^4p^{10} (or p^{-2}),[17,18] while the N^{14} 6.44-MeV level has recently been assigned[19] to the configuration $s^4p^8(2s,1d)$. Since $E2$ radiation between two states whose shell-model configurations differ by rearrangement of more than one nucleon is forbidden, the $E2$ transitions N^{14} $6.44\rightarrow0$ and $6.44\rightarrow3.95$ would seem to be due to admixtures of p^{-2} in the 6.44-MeV level and $s^4p^8(2s,1d)$ in the N^{14} ground state and 3.95-MeV level. The quite strong $6.44\rightarrow3.95$ transition, i.e., $|M^2|=1.5$, would seem to indicate large admixtures of p^{-2} in the 6.44-MeV level and/or $(2s,1d)$ in the 3.95-MeV level. A possible explanation for the quite different strengths of the $6.44\rightarrow0$ and $6.44\rightarrow3.95$ transitions is that the 6.44-MeV level contains a large admixture of p^{-2}, which would be $p_{3/2}^{-2}$ since the 6.44-MeV level has $J^\pi=3^+$. Then the $E2$ matrix element due to this admixture for the $6.44\rightarrow0$ transition would most likely be relatively smaller than that for the $6.44\rightarrow3.95$ transition since the N^{14} ground state is mostly $p_{1/2}^{-2}$, while the 3.95-MeV level is predominantly $(p_{1/2}^{-1},p_{3/2}^{-1})$.[17] The $J^\pi=3^+$ $T=0$ level of p^{-2} is predicted to be at an excitation energy of 9–13 MeV.[17,18]

Combining the experimental values for the radiative width of the N^{14} 6.44-MeV level and the branching ratio for the $6.44\rightarrow5.10$ transition, we obtain 1.54×10^{-4} eV for this $3^+\rightarrow2^-$ transition. Assuming that this transition is $E1$, we find $|M^2|=1.6\times10^{-4}$. This is a reasonable value for an $E1$ transition, which is forbidden because it is a $\Delta T=0$ transition in a self-conjugate nucleus.[8]

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