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Spectroscopy of ^{18}O: Radiative capture, ^{14}C(α,γ)^{18}O

M. Gai, R. Keddy,* and D. A. Bromley
A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06511

J. W. Olness and E. K. Warburton
Brookhaven National Laboratory, Upton, New York 11973
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The electromagnetic deexcitation of the six known ^{14}C+α resonances in the range $E_\alpha=1.7-2.7$ MeV was observed with a Ge(Li) detector. Results for the branching ratios of the 7.62-, 8.04-, and 8.13-MeV ^{18}O levels were found to be in agreement with previous measurements. Deexcitation of the 7.86-, 8.21-, and 8.28-MeV levels was observed for the first time. The radiative widths of these three (α,γ) resonances were determined. Electromagnetic transition strengths were derived for all the resonances from the gamma-ray branching ratios and the total radiative widths. A selective and enhanced $E1$ decay ($\sim 10^{-2}$ W.u.) of the 3_3^- state is observed; among the available 2^+ states lower in excitation, this 3_3^- state is observed to deexcite only to the 2_3^+ state. The 2_3^+ state is well understood to involve excitations of the ^{16}O core, whereas the 2_2^+ and 2_1^+ states arise mainly from simple two neutron (*sd*-shell) configurations. The relevance of the $\alpha+{}^{14}$C radiative capture reactions for nucleosynthesis of heavier elements, at the hadronization phase of the big bang, is discussed.

I. INTRODUCTION

Radiative alpha particle capture on even-even nuclei is a powerful spectroscopic tool. For the (α,γ) reaction mechanism, the obtained yield is directly related to the gamma width (Γ_γ), and is therefore very useful in determining reduced matrix elements of electromagnetic decay rates of quasibound states. In addition, because of the spin zero entrance channel, only natural parity [i.e., $\pi=(-1)^J$] resonances are formed, and these resonances are formed with complete alignment, i.e., population of $m=0$ substates only, along the beam axis. Thus, the gamma-radiation angular distributions are unusually informative. Offsetting these advantages, there are severe technical problems with all (α,γ) reactions. All derive from the fact that the cross section is typically small, $\approx 10^3$ reduced below those characteristic of particle in-particle out reactions. Background problems from neutrons arising from the (α,n) reaction on target contaminants, beam-defining slits, etc. are always present; however, neutron-induced gamma radiation becomes especially troublesome above the (α,n) threshold(s) on the target material(s). Thus, the ^{14}C(α,γ)^{18}O reaction has been rather well studied[1-6] below the ^{14}C(α,n)^{17}O threshold[4] at $E_\alpha^{\rm lab}=2.336$ MeV; above this energy the neutron-induced background becomes overwhelming if the gamma radiation is detected with NaI scintillators.

The present study was initiated because of interest in the first two resonances above the neutron threshold, especially the 3^- state at $E_\alpha^{\rm lab}=2643$ keV ($E_x=8283$ keV).[5] It was believed that the neutron background would be tolerable if gamma radiation were observed with a Ge(Li) detector; this was indeed the case. Preliminary results of this study have been published elsewhere.[7-9]

Recently, there has been a great deal of interest in the primordial nucleosynthesis of heavier ($A>11$) elements, during the hadronization phase of the quark-gluon plasma. Synthesis of ^{12}C (Refs. 10–12) and therefore ^{14}C (Ref. 13) is predicted. In such a situation the capture rate of $\alpha+{}^{14}$C to form ^{18}O is crucial for understanding the nucleosynthesis of neutron rich heavier light nuclei. This rate is of particular interest at relatively higher energies, on an astrophysical scale,[14] $E_\alpha\approx 2-5$ MeV.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A. General

The alpha beams were provided by the Brookhaven National Laboratory (BNL) 3.5-MeV Van de Graaff accelerator. The ion source available at this accelerator was not solely dedicated to ^{4}He and, consequently, the beam was significantly contaminated with isotopes of molecular hydrogen; in the initial stages of this work both ^{3}H^{1}H and ^{2}H^{2}H were present. The ^{3}H beam had its most noticeable effect in producing the 1982-keV radiation from the ^{16}O(t,p)^{18}O(2_1^+) reaction. The most noticeable effect of the deuterium came from the 4439-keV transition from the ^{14}N(d,α)^{12}C(2_1^+) reaction. The deuterium was also responsible for a large fraction of the neutron-induced background, especially at alpha-particle energies below the ^{14}C(α,n) threshold.

The target consisted of a nominal 3-μg/cm^2, 96% enriched ^{14}C film evaporated onto a 0.05-cm Ta beam stop. The Ta backing was heat-treated in vacuum prior to evaporation to remove oxides and was cooled during bombardment by an air-water spray on its rear surface. Beam intensities up to 40 μA were used, with the target oriented at 45° to the beam direction. Clear evidence of

^{14}C target deterioration was found with these beam currents; hence, a special experiment was designed to investigate relative resonance strengths, as will be discussed below.

The reaction gamma rays were detected in a 90-cm^3 coaxial Ge(Li) detector placed at distances of 2.5–9.4 cm from the target, where it subtended half-angles of 35°–15°. Excitation functions and gamma-ray branching ratios were extracted from data taken with the detector at 90° to the beam. Angular distributions were obtained from observations at angles of 30°, 50°, 70°, and 90°. All spectra were recorded using a 4096-channel analyzer. The relative γ-ray efficiencies were determined in the range $846 \le E_\gamma \le 3450$ keV from measurements on ^{56}Co spectra. In this energy range the efficiency was well reproduced by a function of the form aE_γ^{-k}, with $k=0.833$. Subsequent to initial reports of this work, however, it was recognized[15,16] that the efficiency of Ge detectors falls off considerably more rapidly for $E_\gamma > 3.5$ MeV than is predicted by the function aE_γ^{-k}. The efficiency curve for $3.5 < E_\gamma < 8.5$ MeV was therefore constructed from previous calibration data obtained both at BNL and elsewhere,[17] since it appears reasonable to assume that our detector shows the same observed behavior as in Ref. 17. We also note that the efficiency curves of Refs. 15 and 17 are essentially identical. The uncertainty in the relative efficiency is estimated to be 2% for $700 \le E_\gamma \le 3450$ keV and to vary linearly from 2% at 3450 keV to 10% at 10 000 keV. The absolute γ-ray efficiency was determined using calibrated sources of ^{228}Th, ^{22}Na, and ^{60}Co.

B. Excitation function

The first measurements related in an excitation function comprising 4096-channel spectra taken in $2 \le \delta E_\alpha^{\text{lab}} \le 8$ keV steps over the range $1.77 < E_\alpha^{\text{lab}} < 2.7$ MeV. The results are displayed in Fig. 1, showing relative yields in the vicinities of the resonances studied. All spectra were carefully examined for resonant behavior and only at the six resonances shown and at the $E_\alpha^{\text{lab}}=1140$ keV resonance were resonant gamma transitions observed. The relative yields were constructed from all the observed resonant gamma transitions and

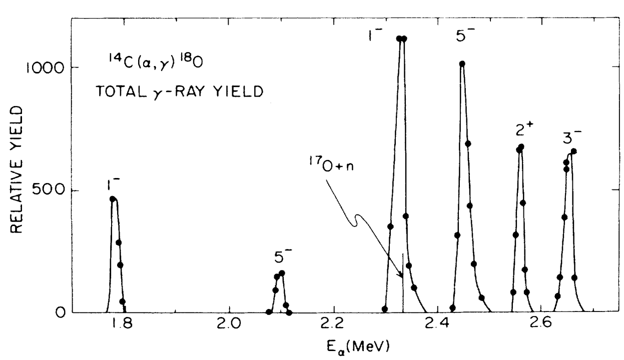

FIG. 1. Yield curves for $^{14}C(\alpha,\gamma)^{18}O$. The heights of the resonances have been adjusted so as to correspond to our final adopted resonance yields as discussed in Sec. II F.

have been corrected for efficiency and angular distribution effects. The heights of the resonances in Fig. 1 have been scaled to our final adopted peak yields as discussed in Sec. II F. The $^{14}C(\alpha,\gamma)^{18}O$ resonances having $J^\pi=4^+$, 1^-, 1^-, and 5^-, at $E_\alpha^{\text{lab}}=1140$, 1790, 2330, and 2440 keV (all ± 2 keV), were reported previously by Lee *et al.*[3] A level was known[4,18] at 7859(5) keV [corresponding to $E_\alpha^{\text{lab}}=2098(5)$ keV]; this is the first observation of it in the (α,γ) reaction. The 2554(3)- and 2643(3)-keV resonances had been observed previously as anomalies in ^{14}C(α,n) and $^{14}C(\alpha,\alpha)$ interactions;[5] this is their first observation via radiative capture. Assignments of $J^\pi=2^+$ and 3^- were made previously to these latter two resonances.[4] The resonance energies extracted from the observed resonances had large uncertainties (7–10 keV) because of target deterioration. The excitation energies thus extracted agreed within errors with those (± 5–10 keV) obtained from summing the measured energies of deexcitation gamma transitions, and with the excitation energies cited in the literature.[4,5] We emphasize that in this paper level energies are used only as a label, and we therefore use the values cited in the literature.

C. Gamma-ray branching ratios

Spectra recorded for ≈ 0.1 C of beam charge, taken at 90° to the beam direction at the $E_\alpha^{\text{lab}}=1790$ and 2330 keV resonances are shown in Figs. 2 and 3. The neutron induced background is clearly evident in the case of the higher energy, 2330-keV 1^- resonance. These spectra also illustrate the background caused by deuterons, which principally involves the Doppler broadened 4.44-MeV line from $^{14}N(d,\alpha)^{12}C(2_1^+)$ reaction. Spectra recorded for ≈ 0.4 C at 90° to the beam at the $E_\alpha^{\text{lab}}=2098$ and 2440 keV resonances are shown in Fig. 4. For the $E_\alpha^{\text{lab}}=2440$ keV resonance we show a net spectrum constructed by subtracting a spectrum taken just off resonance, while for the 2098-keV resonance the original on-resonance spectrum is shown. The $E_\alpha^{\text{lab}}=2098$ keV spectrum illustrates the background caused by deuterons and neutrons. The neutrons give rise to the ^{27}Al γ transitions via (n,n′) reactions on the Al beam line. For both these resonances only one decay mode could be definitely established. In the inset we show the unsubtracted and background spectra at the region of the possible $5_R^- \to 3_1^-$ and $3_1^- \to 2_1^+$ decays discussed below.

Portions of 90° spectra taken at the 3^-, $E_\alpha^{\text{lab}}=2643$ keV and 2^+, $E_\alpha^{\text{lab}}=2554$ keV resonances are shown in Fig. 5. A spectrum taken at $E_\alpha^L=2584$ keV is also shown to illustrate the nonresonant yield. The spectra were taken for accumulated charges of (a) 0.91 C, (b) 0.35 C, and (c) 0.29 C, respectively. In addition to these spectra, an additional one was taken at the 3^- resonance energy with 6 cm of Pb between target and detector. This latter spectrum was useful in identifying neutron-induced activities, which are also resonant due to the ^{14}C(α,n) channel. The portions of spectra shown in Fig. 5 were selected to most clearly indicate the evidence for the γ branches found at these two resonances. For this

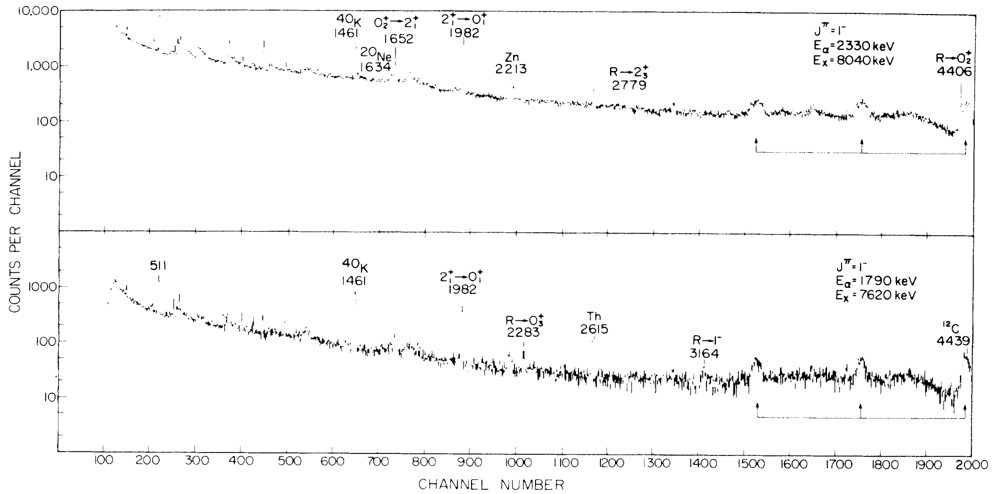

FIG. 2. Spectra illustrating low-energy gamma decays of the 1^- states at $E_\alpha = 2330$ and 1790 keV. Primary and secondary transitions are identified as well as background lines. All transitions are labeled by their energies in keV. Contaminant transitions are labeled by the nucleus in which they occur. Transitions in ^{18}O are labeled by $J_n^\pi \rightarrow J_n^\pi$, where n denotes the nth level of a particular J^π or by $R \rightarrow J_n^\pi$, where R denotes the resonance state.

spectrum we also label the expected but not observed $3_R^- \rightarrow 2_1^+$ transition, to be discussed later.

Branching ratios were extracted from the data of Figs. 2–5 for all six resonances shown in Fig. 1. Data were also obtained from the angular distribution measurements (see Sec. II D), which represented about 4 h of beam exposure at each resonance. A careful internal energy calibration was made for each spectrum using known background gamma-ray energies; for example, 511-keV annihilation radiation, ^{40}K 1461 keV, ^{228}Th 2615 keV, and ^{27}Al and ^{56}Fe transitions. The ^{56}Fe(n,γ) reaction, in particular, provided convenient reference lines at 7631.33(17) and 7645.77(17) keV.[19] Intensities or intensity limits were extracted for all possible deexcitation transitions into and out of all the bound ^{18}O levels.[4] Because γ-γ coincidence data were not taken, the energy E_γ of the transitions was the only available signature for each transition. Two criteria were imposed before a gamma-ray branch was assigned to a particular resonance decay: (1) the observed decay exhibited the expected resonance behavior, and (2) the total fluxes into, I_γ(in), and out of, I_γ(out), a particular bound level were equal. If the fluxes were not equal within counting statistics, the uncertainties assigned to the intensities were increased to encompass the discrepancy, e.g., if evidence for one of I_γ(out) or I_γ(in) was not definite, a limit was assigned to the branching ratio. This procedure and the extraction of branching ratios from the 90° data re-

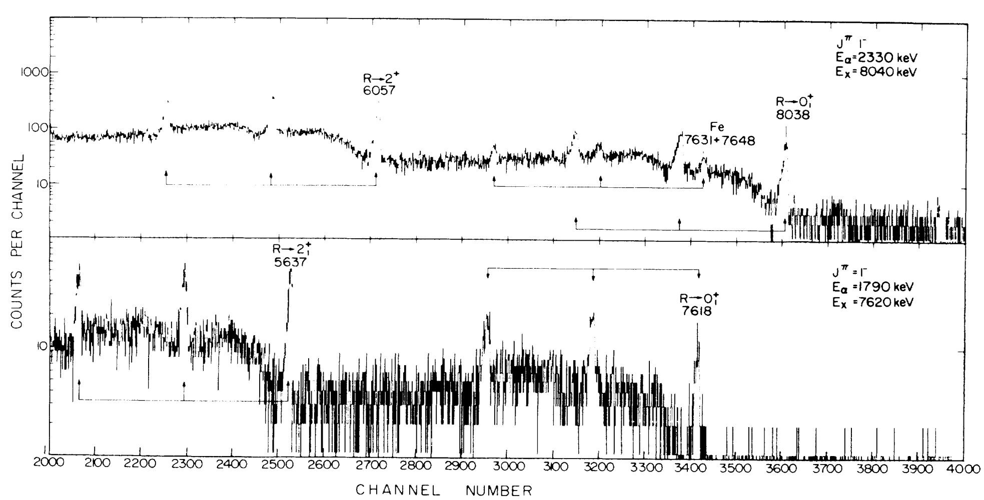

FIG. 3. Spectra illustrating high-energy gamma decay of the 1^- states. Clear evidence for radiation damage of the Ge(Li) detector is observed as a low-energy tail of the gamma lines. For further details, see the caption of Fig. 2.

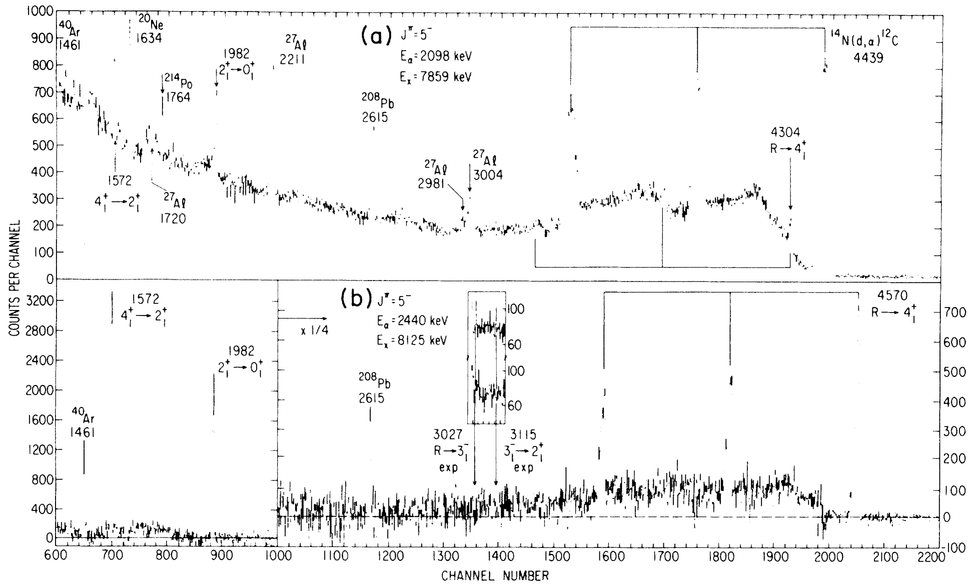

FIG. 4. Partial spectra illustrating gamma-decay at (a) the $E_\alpha=2098$ keV resonance and (b) the $E_\alpha=2440$ keV resonance with off-resonance background subtracted. In the inset of the spectrum taken for the $J^\pi=5^-$ resonance at $E_\alpha=2440$ keV, we show the region around the expected $5_R^- \to 3^-$ transition and the expected subsequent decay of the 3^- state. The top spectrum in the inset is taken on resonance at 2440 keV, and the bottom spectrum off resonance. For further details, see the caption of Fig. 2.

quired correction for angular distribution effects and a careful appraisal of the effective solid angle subtended by the Ge(Li) detector. For an angular distribution expressible as

$$W(\theta)=I_\gamma[1+A_2Q_2P_2(\theta)+A_4Q_4P_4(\theta)]\ , \tag{1}$$

the 90° yield is

$$W(90°)=I_\gamma(1-0.5Q_2A_2+0.375Q_4A_4)\ , \tag{2}$$

where the A_k are the angular distribution coefficients for complete alignment[20] and the Q_k are the attenuation coefficients corresponding to the solid angle subtended

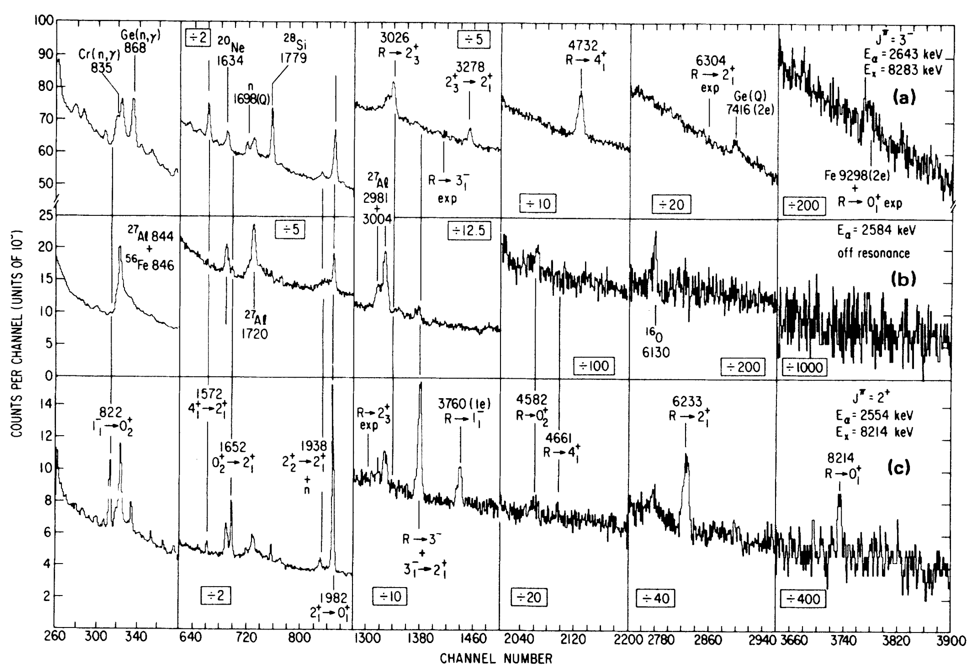

FIG. 5. Selected portions of 90° spectra taken at (a) the $E_\alpha=2643$ keV resonance, (b) off resonance, i.e., $E_\alpha=2584$ keV, and (c) the $E_\alpha=2554$ keV resonance. The energy regions were chosen to display the evidence for observed branching ratios and for some limits on branching ratios. Q denotes an uncertain or unknown assignment. One- and two-escape peaks are labeled (1e) and (2e), respectively. For further details, see the caption of Fig. 2.

by the detector. We took the Q_k from information in the literature (see, e.g., Ref. 21) and assigned to them an uncertainty of 5%. The resulting branching ratio results are given in Table I. All limits correspond to two standard deviations. For four of the levels, branching ratios had been reported previously. We find our results in satisfactory agreement with those of Lee *et al.*,[3] and we therefore adopt the arithmetic average of the two deter-

TABLE I. Gamma-ray branching ratios of six $^{14}C(\alpha,\gamma)^{18}O$ resonances. For convenience, the transition strengths, $B(L)$, in Weisskopf units, are given in the last column.

J_i^π	E_i (keV)	J_f^π	E_f (keV)	E_γ (keV)	Multi-polarity	Branching ratio (%) Ref. 3	Present	Adopted	$B(L)^a$ (W.u.)
1^-	7620(2)	0^+	0	7618	$E1$	24(2)	23(2)	23(2)	4.6(10)[−4]
	$E_\alpha^{lab}=1790(2)$	2^+	1982	5637	$E1$	62(3)	62(3)	62(3)	3.0(6)[−3]
					$M2$	$\delta=-0.027(8)$			0.33(20)
		0^+	3634	3986	$E1$		<1	<1	<1.7[−4]
		2^+	3920	3699	$E1$	<15	<3	<3	<6.3[−4]
		1^-	4456	3164	$M1$	8(1)	8(2)	8(1)	4.8(12)[−2]
					$E2$	$\delta=-0.21(3)$			1.9(7)
		2^+	5260	2359	$E1$		<3	<3	<2.4[−3]
		0^+	5336	2283	$E1$	6(1)	6(1)	6(1)	4.4(12)[−3]
		2^-	5530	2090	$M1,E2$		<5	<5	<0.13
		1^-	6198	1422	$M1,E2$	<2	1(1)	1(1)	0.07
5^-	7859(5)	4^+	3555	4304	$E1$		>75	>75[b]	1.2(2)[−3]
	$E_\alpha^{lab}=2098(5)$								
1^-	8040(2)	0^+	0	8038	$E1$	16(1)	17(1)	16(1)	7.2(15)[−4]
	$E_\alpha^{lab}=2330(2)$	2^+	1982	6057	$E1$	68(3)	71(2)	70(2)	7.3(15)[−3]
		0^+	3634	4406	$E1$	11(1)	9(1)	10(1)	2.7(6)[−3]
		2^+	3920	4119	$E1$	<15	<1	<1	<4.0[−4]
		1^-	4456	3584	$M1$		<1.5	<1.5	<0.02
		3^-	5098	2942	$E2$		<1	<1	<26
		2^+	5260	2779	$E1$	5(1)	3.2(9)	4(1)	4.3(14)[−3]
		0^+	5336	2703	$E1$		<1	<1	<1.4[−3]
		2^-	5530	2510	$M1,E2$		<2	<2	<0.08
		1^-	6198	1842	$M1,E2$		<2	<2	<0.20
5^-	8125(2)	4^+	3554	4570	$E1$	>95	99(1)	99(1)	5.9(12)[−3]
	$E_\alpha^{lab}=2440(2)$	3^-	5098	3027	$E2$		1(1)	1(1)	5.0(5)
		4^+	7117	1008	$E1$		<2	<2	<1.3[−2]
2^+	8214(4)	0^+	0	8213	$E2$		19(4)	19(4)	0.9(3)
	$E_\alpha^{lab}=2554(4)$	2^+	1982	6232	$M1,E2$		29(3)	29(3)	2.5(6)[−2]
		4^+	3554	4660	$E2$		3(1)	3(1)	2.5(10)
		0^+	3634	4581	$E2$		<3	<3	<3.3
		2^+	3920	4294	$M1,E2$		3(1)	3(1)	7.5(31)[−3]
		1^-	4456	3759	$E1$		29(3)	29(3)	4.8(12)[−3]
		3^-	5098	3117	$E1$		17(1)	17(1)	5.0(12)[−3]
		2^+	5260	2954	$M1,E2$		<3	<3	
			5336–6351				<1	<1	
3^-	8283(3)	0^+	8281		$E3$		<7	<7	<22
	$E_\alpha^{lab}=2643(3)$	2^+	1982	6300	$E1$		<3	<3	<1.6[−4]
		4^+	3554	4728	$E1$		61(3)	61(3)	6.1(15)[−3]
		2^+	3920	4362	$E1$		<3	<3	<4.7[−4]
		1^-	4456	3827	$E2$		3(3)	3(3)	8(8)
		3^-	5098	3185	$M1,E2$		<8	<8	<7.3[−2]
		2^+	5260	3022	$E1$		36(3)	36(3)	1.4(3)[−2]
		3^+	5378	2905	$E1$		<4	<4	<2.2[−3]
		2^-	4420	2753	$M1,E2$		<8	<8	<0.12
		3^-	6404	1878	$M1,E2$		<5	<5	<0.22

[a]The first number in parentheses is the uncertainty in the least significant figure. The number in square brackets is the multiplicative power of 10 (i.e., 2.5(6)[−2] means $2.5(6)\times 10^{-2}$). No uncertainty is given for limits which correspond to 2 standard deviations in the branching ratio and 1 standard deviation in the total radiative width. In two cases an $L, L+1$ mixing ratio was given (Ref. 3) and two transition strengths are listed. For all other cases the transition is assumed to proceed by the lowest allowed multipolarity.

[b]And >85 for 1 standard deviation. Assumed 100% in calculating $B(E1)$.

minations. The adopted branching ratios are summarized in Fig. 6.

In the following we expand on points relevant to the decay branching ratios of the particular states.

The $J^{\pi}=4^{+}$ resonance at 1140 keV. A detailed study of the deexcitation of this state, using the ^{14}C(^{7}Li,tγ)^{18}O reaction, has been carried out.[9,22] In the present work we observed the two major decay modes to the 2_1^+ and 4_1^+ states, corresponding to 97% of the decay modes of this state.[22] We also measured the absolute radiative widths as described in Sec. II F.

The $J^{\pi}=1^{-}$ resonance at 1790 keV. The quality of the data shown in Figs. 2 and 3 for this state is good, allowing us to improve on previously published upper limits for some weak decay modes. All other branching ratios, given in Table I, are in good agreement with previously published data.

The $J^{\pi}=5^{-}$ resonance at 2098 keV. Only one deexcitation transition with $E_\gamma=4304$ keV corresponding to deexcitation to the first excited 4^+ state was observed, as shown in Fig. 4. The limit on the sum of branching ratios to other states was obtained from the balance of $J_R^{\pi}\rightarrow 4_1^+$ and $2_1^+\rightarrow 0_1^+$ transition intensities, assuming that all other branches cascade into the 2_1^+ state. This is

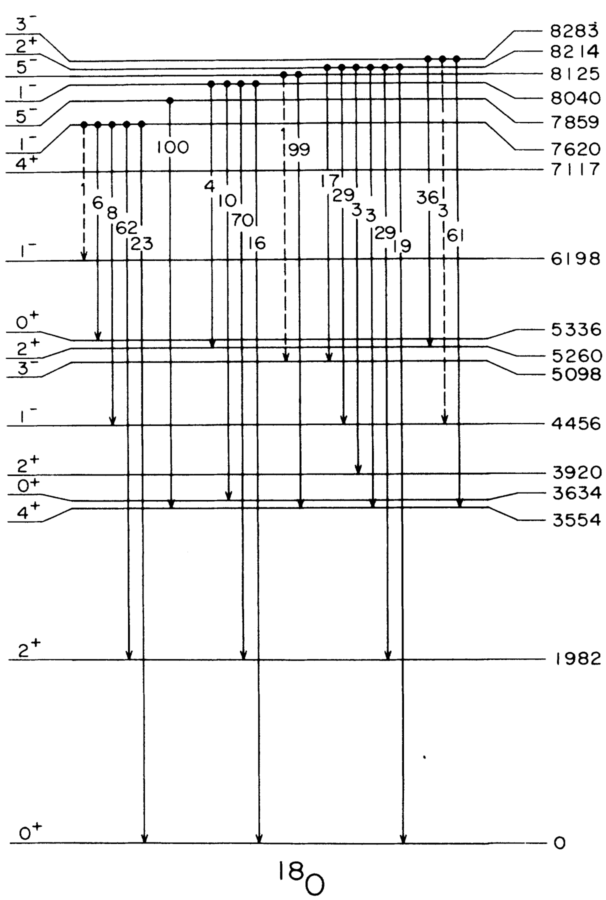

FIG. 6. Gamma-ray branching ratios (in percent) for the six ^{14}C(α,γ)^{18}O resonances studied in the present work. Excitation energies are given in keV.

the first reported observation of electromagnetic deexcitation of this state, and, as discussed below, it allowed us to establish a J^{π} assignment for the state.

The $J^{\pi}=1^{-}$ resonance at 2330 keV. At this energy neutron induced backgrounds from target contaminants are becoming more noticeable, as shown in Figs. 2 and 3. However, accurate determination of branching ratios, including that for the $1_R^-\rightarrow 0_2^+$ transition (a doublet with the 4439-keV transition of ^{12}C), was possible. The branching ratios are in good agreement with previously published results.

The $J^{\pi}=5^{-}$ resonance at 2440 keV. As shown in Fig. 4, we observe a strong transition at $E_\gamma=4570$ keV, corresponding to deexcitation of the 5^- resonant state to the first excited 4^+ state, as well as transitions corresponding to the subsequent deexcitation of the 4_1^+ and 2_1^+ states. A very weak transition was possibly observed at $E_\gamma=3027$ keV, corresponding to the $5_R^-\rightarrow 3_1^-$ transition, as shown in the inset of Fig. 4. Since only an upper limit was established on the subsequent $3_1^-\rightarrow 2_1^+$ deexcitation and the transition could not be definitely established as resonant, we were unable to satisfy our criterion given above, and, consequently, we quote this branching ratio with a 100% uncertainty.

The $J^{\pi}=2^{+}$ resonance at 2554 keV. The observation of the gamma decay of this state with a Ge(Li) detector is reported here for the first time. The complex detailed spectrum shown in Fig. 5 clearly demands the use of Ge(Li) detectors. Note that the 3116-keV line is a doublet composed of the $R\rightarrow 3_1^-$ transition and the subsequent $3_1^-\rightarrow 2_1^+$ decay. The 8214-keV transition shows a large anisotropy, as expected for a completely aligned ($m=0$ substate only) $2^+\rightarrow 0^+$ transition.

The $J^{\pi}=3^{-}$ resonance at 2643 keV. This state has a large neutron decay width with results that are clearly evident in the spectrum shown in Fig. 5. In order to identify gamma rays resulting from (n,γ) reactions on material other than the target and its immediate vicinity, a spectrum was taken on resonance, but with a lead filter 6 cm thick interposed between the target and the detector. The lines corresponding to the deexcitation of the 3^- resonance, and all cascade deexcitation lines, are clearly evident in the on-resonance unfiltered spectrum but not in the filtered one. A possible observation of a very weak line at $E_\gamma=3832$ keV is noted. This energy is that expected for the $3_R^-\rightarrow 1^-$ transition. However, the background level in this spectrum at $E_\gamma=822$ keV did not permit identification of the subsequent $1^-\rightarrow 0_2^+$ transition, and the transition could not be established as resonant. Thus we quote this branching ratio with a 100% uncertainty. The high level of background in this spectrum did not allow extraction of upper limits on transition strengths below the 3% level as compared to $\approx 1\%$ for lower energy resonances. Even under these conditions, however, it should be noted that we find no evidence for either the $3_R^-\rightarrow 2_2^+$ or $3_R^-\rightarrow 2_1^+$ transitions as shown in Fig. 5. Our upper limit on the reduced matrix elements for these transitions is still a factor of 100 smaller than that for the enhanced $3_3^-\rightarrow 2_3^+$ $E1$ decay as shown in Table I. The apparent selective $E1$ decay of this resonance to the 2_3^+ state was discussed in Ref. 9.

We refer the reader to Refs. 9 and 22 for a general discussion of selective $E1$ decay modes in ^{18}O.

D. Gamma-ray angular distributions

Gamma-ray angular distributions were measured at the four highest energy resonances reported herein. The electromagnetic deexcitation of all four are dominated by $E1$ transitions of sufficient strength that competing $M2$ radiations are expected to have negligible effects on the angular distributions. All observed distributions were in agreement with expectations based on the known spins of the initial and final states and the assumption of the lowest allowed multipolarity in each case, i.e., $L=\Delta J$. Only for a single case (the 8214$\rightarrow$1982, $2^+\rightarrow 2^+$ transition) was the branching ratio large enough to obtain information on the $E2/M1$ mixing ratio. For this transition we find $\delta(E2/M1)<0.27$, where the limit corresponds to two standard deviations.

E. J^π for the 7859-keV level

Our successful matching of I_γ(in) and I_γ(out) for the transitions involving the resonances with known spin studied in this work demonstrated that our evaluation of angular distribution effects was done correctly. This is especially noteworthy because the angular distributions for the ^{14}C$(\alpha,\gamma)^{18}$O reaction are quite anisotropic and these corrections are correspondingly large. Conversely, it is possible to obtain some meaningful information on angular distributions from the 90° yield data alone. We have exploited this fact to set limits on the spin of the 7859-keV level. The only observed deexcitation of this level is $J_R^\pi\rightarrow 4^+\rightarrow 2^+\rightarrow 0^+$. The angular distributions of all three members of this cascade are functions of two parameters, namely J_R and the $(L+1)/L$ mixing ratio for the $J_R^\pi\rightarrow 4^+$ transition; moreover, the $4^+\rightarrow 2^+$ and $2^+\rightarrow 0^+$ transitions have identical angular distributions. Thus the intensity ratio

$$R(J_R)=\frac{0.5[I_\gamma(4^+\rightarrow 2^+)+I_\gamma(2^+\rightarrow 0^+)]}{I_\gamma(J_R\rightarrow 4^+)} \tag{3}$$

was calculated as a function of the mixing ratio for assumed J_R^π values of 3^-, 4^+, and 5^-, and for pure $E2$ radiation for $J_R^\pi=2^+$ and 6^+. The restrictions are to natural parity and the assumption that $M3$ admixtures in $E2$ transitions are negligible. Experimentally, we find $R(J)=0.620(46)$. This value is compared to the calculated values in Fig. 7; only $J^\pi=3^-$ and 5^- provide satisfactory agreement with experiment. $J^\pi=4^+$ is ruled out at ≈ 3.3 standard deviations (96% confidence limit). From these data we conclude that $J^\pi=3^-$ or 5^- for this level.

Other information on this spin comes from comparison of an empirical $2J+1$ proportionality[18] to the measured ^{12}C(^{7}Li,p)^{18}O reaction cross sections. From the systematic behavior of these cross sections, Fortune *et al.*[18] conclude that the 7859-keV level has most probably $J=4$ or 5. The 7859-keV level was also excited in the ^{18}O(e,e$'$)^{18}O reaction by Norum *et al.*,[23] who assumed a 4^+ assignment for this level. However, analysis

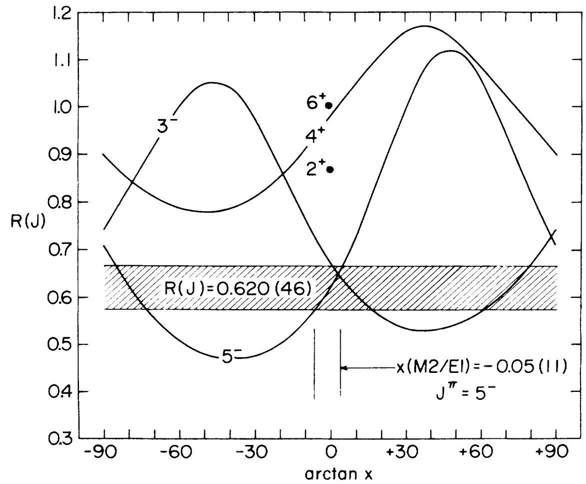

FIG. 7. The ratio of the 90° intensities, $I_\gamma(90°)$, of the $3555(4_1^+)\rightarrow 1982(2_1^+)$ and $1982\rightarrow 0$ transitions (mean value) to $I_\gamma(90°)$ for the $7859\rightarrow 3555$ transition. The experimental value is compared to theoretical predictions for various assumed spin parities for the 7859-keV level.

shows that their measured form factor fits a 5^- assignment just as well as a 4^+ assignment.[24] Systematics, such as the results of the ^{16}O(e,e$'$)^{16}O reaction[25] would appear to favor 4^+ and 5^- over 3^-, although this preference is certainly model dependent. From analysis of double-differential cross sections in the sequential breakup reaction ^{12}C(^{18}O,^{18}O*$\rightarrow$^{14}C+α), Rae and Bhowmik[26] gave a definite 5^- assignment to the 7859-keV level. We note that $J^\pi=3^-$ appears to be excluded with a higher degree of confidence than a $J^\pi=4^+$ assignment. We conclude that $J^\pi=3^-$ can be excluded on the basis of these previous results and that we can assign $J^\pi=5^-$ to the 7859-keV level with 96% confidence.

F. Total radiative widths

Our conclusions with respect to the total radiative widths for the levels studied are implicit in the gamma-ray yield curve data shown in Fig. 1. These data were accumulated over ≈ 2 weeks of measurement, using a ^{14}C target with a nominal thickness of 3 μg/cm^2, and beam currents of 30–40 μA. As we have noted previously, even with the air/water spray cooling, it was evident that target deterioration reduced the peak yield by a factor of 3–4 over the period of the measurements, and it was therefore necessary to make appropriate corrections for it.

In order to do so, and also to obtain an independent measure of $\omega\gamma$, two additional sets of measurements were undertaken at reduced beam currents of 5 μA and also 0.2 μA, using fresh ^{14}C targets. Since the power dissipation in the targets were in these cases some 10–200 times less than when measuring the data of Fig. 1, it was expected that the rate of target deterioration would be correspondingly reduced.

Figure 8 shows a portion of the data obtained at the $E_\alpha^{\rm lab}=1140$ keV resonance with a beam current of 5 μA. We choose to present these data in some detail as an il-

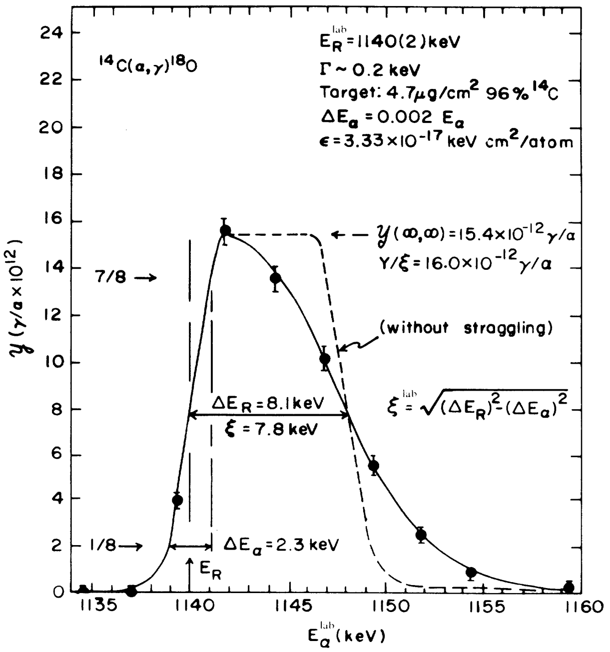

FIG. 8. Yield curve for the 4^+ $E_\alpha^{\rm lab}=1140$ keV resonance in ^{14}C$(\alpha,\gamma)^{18}$O, illustrating the data and parameters which enter into a determination of the quantity $\omega\Gamma_\alpha\Gamma_\gamma/\Gamma$. All measured quantities displayed are in the laboratory system, even though calculations are carried out in the center of mass system.

lustration of our general method of analysis, inasmuch as it represents a careful attempt to obtain an absolute measure of the quantity $\omega\gamma$ for direct comparison with previous results.[1-3]

The necessary formalism is set forth in the review article by Gove,[27] from which we select key sections using essentially his notation. The total cross section for the ^{14}C$(\alpha,\gamma)^{18}$O reaction leading to a resonance state of spin J at center of mass (c.m.) energy $E_\alpha^{\rm c.m.}=E_R$ is

$$\sigma(E)=\pi\lambda\!\!\!^{-2}\omega\frac{\Gamma_\alpha\Gamma_\gamma}{(E-E_R)^2+(\Gamma/2)^2} \tag{4a}$$

with

$$\lambda\!\!\!^{-}=\hbar/\mu v\ , \tag{4b}$$

$$\Gamma=\Gamma_n+\Gamma_\alpha+\Gamma_\gamma+\cdots,\quad \Gamma_\gamma=\sum\Gamma_{\gamma i} \tag{4c}$$

$$\omega=2J+1 \text{ for spinless target and projectile}\ , \tag{4d}$$

$$\gamma=\Gamma_\gamma\Gamma_\alpha/\Gamma\ . \tag{4e}$$

Here, μ and v are the reduced mass and relative velocity for the $\alpha+{}^{14}$C system.

In an ideal experimental case where the c.m. beam energy spread (ΔE_α) and c.m. target thickness (ξ) are much less than the c.m. resonance width (Γ), the peak yield is easily determined as $\sigma(E_R)=4\pi\lambda\!\!\!^{-2}\omega\gamma/\Gamma$, thus determining $\omega\gamma$ as well as Γ. The analysis procedure appropriate to the present case, where ξ and $\Delta E_\alpha\geq\Gamma$, has been treated in detail by Gove[27] and depends on the observation that the experimental data can be used to define the resonance integral

$$\int_{-\infty}^{+\infty}\sigma(E)dE=2\pi^2\lambda\!\!\!^{-2}\omega\gamma\ . \tag{5}$$

Two extreme cases are distinguished:

$$\omega\gamma\equiv\omega\Gamma_\alpha\Gamma_\gamma/\Gamma=\frac{2\epsilon}{\lambda\!\!\!^{-2}}y(\infty,\infty)\ \text{(thick target)} \tag{6a}$$

$$=\frac{2\epsilon}{\lambda\!\!\!^{-2}}\frac{Y}{\xi}\ \text{(thin target)}\ . \tag{6b}$$

Here, ϵ is the c.m. stopping power (in keV cm^2/atom) appropriate to alpha particles traversing the (assumed) ^{14}C target layer, and ξ is the c.m. target energy thickness (in keV); $y(\infty,\infty)$ is the peak yield for the "thick target" case, corresponding to $\xi\gg\Gamma$ and also $\xi\gg\Delta E_\alpha$, in which case the energy integral of Eq. (5) follows directly. For the thin target case, it becomes necessary to construct the energy integral Y [see Eq. (6b)] by integrating over the experimental resonance curve.

Figure 8 summarizes key parameters for the $E_R^{\rm lab}=1140$ keV resonance level, as taken from Ref. 5. We note that while all our calculations are carried out in the center of mass (c.m.) system, we use merely as a label the laboratory resonant energies. The yield curve shown in this figure was constructed as the sum of the intensities of the strong resonant transitions observed at $\theta_\gamma=90°$, recorded at a beam current of 5 μA for an integrated charge of 1250 μC/point. The absolute efficiency of the Ge(Li) detector, as well as the angular distribution corrections, were determined as described in Sec. II C, and result in the absolute abscissal scale shown; we estimate an associated error of $\approx 5\%$. The solid curve represents our estimate of what the true shape is, while the dashed curve illustrates what would be expected in the absence of straggling of the alpha particles in the target material.

Measurements at several resonances in the range $1.14\leq E_\alpha^{\rm lab}\leq 2.44$ MeV demonstrated that our beam energy spread could be expressed as $\Delta E_\alpha=0.002E_\alpha$, which is $\approx\frac{2}{3}$ of the spread expected from the geometry of the Van de Graaff control slits settings. (We note that the low-energy rise from $\frac{1}{8}$ to $\frac{7}{8}$ of maximum yield defines ΔE_α for either a Gaussian or triangular shape for the beam energy profile.) The specific energy loss for alpha particles in ^{14}C was taken from Ziegler[28] and in the range $1\leq E_\alpha^{\rm c.m.}\leq 3$ MeV can be empirically parametrized as

$$\epsilon=(4.59-E_\alpha)7.1\times10^{-18}\ \text{keV cm}^2/\text{atom}\ , \tag{7}$$

with E_α the c.m. energy in MeV and ϵ in the c.m. system. These values are some 13–19 % lower than those given in the earlier tabulations of Northcliff and Schilling[29] and of Allison and Warshaw.[30]

The measured c.m. full width at half maximum (FWHM) of the resonance is $\Delta E_R=6.3$ keV. The true target thickness can then be estimated quite accurately as

$$\xi=[(\Delta E_R)^2-(\Delta E_\alpha)^2-\Gamma^2]^{1/2}\ , \tag{8}$$

to provide the result indicated in Fig. 8, namely $\xi=6.1$ keV. This corresponds to an effective target thickness (when oriented at 45° to the incident beam) of 4.7 μg/cm^2, or a ^{14}C layer of thickness 3.3 μg/cm^2. The latter value is in good agreement with the nominal design thickness of 3 μg/cm^2, which was also verified by measuring the radioactivity of the ^{14}C target material.

Having thus defined all the necessary factors, we finally compute the experimental values for $y(\infty,\infty)$ and Y/ξ, as given in Fig. 8. The two results are in excellent agreement, and lead directly to an estimate of $\Gamma_\alpha\Gamma_\gamma/\Gamma=33(5)$ eV for this target, where we quote only the statistical uncertainty propagated though our analysis.

The measurement depicted in Fig. 8 was later repeated, using the same geometry and target, and yielded a result for $\Gamma_\alpha\Gamma_\gamma/\Gamma$ some 25% lower, thus providing a semiquantitative measure of the rate at which the assumed target deterioration occurred. Conversely, a measurement using a thicker fresh target ($\xi=9$ keV) reproduced the first set of results, yielding $\Gamma_\alpha\Gamma_\gamma/\Gamma=40$ meV. However, we emphasize that since there is no way of assessing quantitatively the extent of any initial target damage, it is safer, in our judgment, to take the results obtained above as establishing a firm lower limit on the actual value of $\Gamma_\alpha\Gamma_\gamma/\Gamma$.

Finally, in order to significantly reduce the rate of target deterioration under bombardment, a third set of measurements was undertaken, at a beam current of 0.2 μA, to determine the peak yield of primary γ rays from the resonances at 2643, 2554, 2440, 2330, and 1140 keV. The data were taken in the order given above, using a fresh ^{14}C target similar to that used for the data of Fig. 8. Analysis of the results for the 1140-keV resonance yields in this case the value $\Gamma_\alpha\Gamma_\gamma/\Gamma=47(8)$ meV. The fact that this result is larger than the value obtained with the 5-μA beam, and since the data were obtained at the end of the sequence, this indicates that target deterioration was significantly reduced at this lower current. (Note that the power dissipation in the target is, in fact, some 25 times less.)

Values of $\omega\gamma$ for the 2330-, 2440-, and 2554-keV resonances were subsequently obtained from these data, although here it was necessary to account for the fact that the necessary inequalities of Eq. (6a) were not entirely satisfied (i.e., we have in this case $\xi\leq\Delta E_\alpha$). For an overall fit to these data, we take as best values $\Delta E_\alpha=2.8(5)\times10^{-3}E_\alpha$, and a target thickness of 3.0(5) μg/cm^2. For the 1140-keV resonance, this gives $\Delta E_\alpha^{\text{c.m.}}=2.5$ keV and $\xi^{\text{c.m.}}=5.5$ keV. For $E_R^{\text{lab}}=2554$ keV, we have $\Delta E_\alpha^{\text{c.m.}}=5.6$ keV, whereas $\xi^{\text{c.m.}}=3.9$ keV. However, it can be easily shown that in the latter case (i.e., beam width larger than target width), for the circumstance of a Gaussian (or triangular) beam spread, the measured value of $y(\infty,\infty)$, which we define as $y_m(\infty,\infty)$, can be related to the desired value as

$$y(\infty,\infty)=y_m(\infty,\infty)[x(2-x)]^{-1}\ , \tag{9}$$

for values $x<1$, where $x\equiv\xi/(2\Delta E_\alpha)$.

Using this approach we find the following values of $\omega\gamma$, given in meV, for the indicated resonance levels (E_R^{lab} in keV); 2750±600 (2330), 2310±520 (2440), 2110±600 (2554), and 4080±1690 (2643). The value given for the 2643-keV resonance has also been corrected for the $\Gamma^{\text{c.m.}}=7.8$ keV width of this state, following the procedure described in detail below.

We now wish to compare the results summarized above, representing an independent set of conclusions on radiative widths based completely on the present measurements, to those given previously in Refs. 1–3.

In 1959 Gove and Litherland[2] reported a study of the ^{14}C$(\alpha,\gamma)^{18}$O resonances at $E_\alpha^{\text{lab}}=1140$ and 1790 keV. They obtained values of $\omega\gamma$ relative to that for the $E_{\text{p}}^{\text{lab}}=527$ keV resonance level[6] in ^{14}C(p,γ)^{15}N. Somewhat later, in 1967, Lee, Krone, and Prosser[3] produced a careful study of the four resonance levels observed at $E_\alpha^{\text{lab}}=1140$, 1790, 2330, and 2440 keV. Their determination of $\omega\gamma$ for these resonances utilized the earlier result of Gove and Litherland[2] for the 1790-keV level, yielding the conclusion $\Gamma_\alpha\Gamma_\gamma/\Gamma=42$, 340, 890, and 220 meV, respectively, for the four levels in question. These results form the basis for the absolute widths quoted in the 1978 and 1983 survey articles.[4,5] (Somehow, the 1959 results reported by Phillips[1] seem to have been ignored.)

In the intervening years three independent measurements[31–33] of $\omega\gamma$ for the $E_{\text{p}}^{\text{lab}}=527$ keV resonance in the ^{14}C(p,γ)^{15}N, reaction have been published, resulting in an upward revision of its value by some 50%.

The status of these measurements is reviewed in Appendix A. Our conclusion is that the values of $\Gamma_\alpha\Gamma_\gamma/\Gamma$ reported in Refs. 2 and 3 should be increased by a factor of 1.20. We now adopt these renormalized values. Specifically, we take as the best measure of γ for the resonances at $E_\alpha^{\text{lab}}=1140$, 1790, 2330, and 2440 keV the values $\gamma=\Gamma_\alpha\Gamma_\gamma/\Gamma=50$, 410, 1073, and 265 meV, respectively, as listed in Table II. Uncertainties were not assigned explicitly to these widths by either Gove and Litherland[2] or Lee *et al.*[3] From our experience and a careful consideration of their experiments (Appendix A), we would, however, estimate an overall uncertainty of 20% as appropriate for their results. We emphasize that these results for the absolute widths hinge on the data of Ref. 2.

These revised previous results are in very good agreement with the best absolute values obtained independently in the present experiment discussed below. For the 1140-keV resonance the result for $\Gamma_\gamma\Gamma_\alpha/\Gamma$ is 47(8) meV (present) as compared to 50(13) (revised previous result). For the higher excitation resonances we observe that the present results are somewhat smaller, with progressively large uncertainties. This might well have been expected, since our results are strongly dependent on the ratio $\xi/\Delta E_\alpha$, which is known to only limited precision. On the other hand, the previous measurements employed thicker targets, such that this was not such a large problem. Therefore, in view of the satisfactory agreement, we adopt the revised previous results for (specifically) the 1140-, 1790-, 2330-, and 2440-keV levels. The yield curve data of Fig. 1 were accordingly normalized to give relative peak yields for these four resonances consistent with the quoted values for γ. The peak yields for the 2098-, 2554-, and 2643-keV resonances were then determined relative to the strong $J^\pi=5^-$ resonance level at $E_\alpha^{\text{lab}}=2440$ keV. (This procedure is justified, since ξ and

TABLE II. Peak yields and radiative widths for the seven known ^{14}C(α,γ)^{18}O resonances.

$E_\alpha^{\rm lab}$ (keV)	J^π	$y_m(\infty,\infty)$[a] (relative)	$\omega\gamma$[b] (meV)	Γ_γ[b] (meV)
1140	4^+	230	454	95(20)
1790	1^-	470	1229	410(82)
2098	5^-	170(17)	470	43(9)
2330	1^-	1116	3220	1073(215)
2440	5^-	1000	2917	265(53)
2554	2^+	680(68)	2041	412(93)
2643	3^-	644(64)	3049	488(129)

[a]Relative to 1000 for the 2240-keV resonance. The values without uncertainties are the revised values of Ref. 3 and have an assumed uncertainty of 20%. The other three values are from the present work and have an additional uncertainty of 10%.

[b]Extracted from $y_m(\infty,\infty)$ using Eq. (6a). For the 3^- resonance, the additional multiplicative factors discussed in Appendix B were applied.

ΔE_α change little over such a limited interval.) The main advantage to this approach was that it allowed us to use the extensive data obtained at higher bombarding currents, which had appreciably better statistics.

In order to establish radiative widths Γ_γ from the peak yields $y_m(\infty,\infty)$, it is, of course, necessary to have some knowledge of the total and alpha widths of the resonances. In Table III we list the available experimental information. We also list the Wigner sum-rule limit for Γ_α, labeled as Γ_α(max), which we define as[34,35]

$$\Gamma_\alpha(\max)=2P_L\theta^2=1287P_L \ (\text{keV}) \quad [\text{assuming } R=1.4(4^{1/3}+14^{1/3}) \text{ fm}]\,, \tag{10}$$

where $\theta^2=\frac{3}{2}\hbar^2/\mu R^2$. This limit is of use in estimating an upper limit on the possible alpha particle widths of the two 5^- resonances for which there is no direct experimental information.

With the single exception of the 3^- resonance state at $E_\alpha^{\rm lab}=2643$ keV, for which $\Gamma^{\rm c.m.}=7.8$ keV (Ref. 5), the resonance widths (Γ) can all be taken as appreciably less than the target thickness (ξ) and hence the simple relationship given in Eq. (6a) was used to determine the values of $\Gamma_\alpha\Gamma_\gamma/\Gamma$. Our results are presented in Table II, where they are compared to our revision of the results of Ref. 3.

For the 2643-keV resonance the level width is of the same order as the target thickness, $\xi^{\rm c.m.}=14$ keV, at the time of the measurements, and the measured peak yield is thus smaller than would have been obtained for $\xi\gg\Gamma$. There are several ways of estimating the necessary correction; a simple procedure is given in Appendix B. Based on these considerations, we conclude that the correct value for $y(\infty,\infty)$ for the 3^- resonance is 1.56(15) times $y_m(\infty,\infty)$. The data of Table II include this adjustment. In the extraction of Γ_γ from $\Gamma_\gamma\Gamma_\alpha/\Gamma$, we have assumed for all levels, except that corresponding to the 4^+ resonance, that $\Gamma_\gamma\ll\Gamma_\alpha$, as listed in Table III.

III. SUMMARY

The previously unreported electromagnetic deexcitation of three ^{14}C+α radiative capture resonances has been studied via Ge(Li) spectroscopy. Gamma-ray branching ratios were obtained for these three resonances and for three others in the range $1.7<E_\alpha<2.7$ MeV. The results for the latter three are in good agree-

TABLE III. Available experimental information on Γ and Γ_α and the calculated penetrability, P_L, sum-rule limit on Γ_α, $\Gamma_{2\alpha}$(max), and the sum-rule limit on the alpha spectroscopic factor, θ, for the seven ^{14}C(α,γ)^{18}O resonances.

$E_\alpha^{\rm lab}$ (keV)	J^π	Γ(lab)[a] (keV)	Γ_α/Γ	P_L[b,c]	Γ_α(max)[b] (keV)	θ_α^2[d] (%)
1140	4^+	0.26(6)[−3]	0.53(3)[a]	1.02[−6]	13.1[−4]	11
1790	1^-	<3		2.80[−2]	36.1[+0]	<9
2098	5^-			4.77[−5]	61.3[−3]	
2330	1^-	<3		1.55[−1]	19.9[+1]	<15
2440	5^-			2.07[−4]	26.2[−2]	
2554	2^+	1.6(10)	0.99(1)[e]	9.81[−2]	12.6[+1]	1.2
2643	3^-	10(1)	0.89(6)[e]	2.90[−2]	37.4[+0]	24

[a]Reference 5.

[b]The number in square brackets gives the power of 10 by which the given number must be multiplied.

[c]Calculated from Eq. (10) for a radius of $R=1.4(4^{1/3}+14^{1/3})$ fm and the E_α of column 1.

[d]Defined as $100[\Gamma_\alpha/\Gamma_\alpha(\max)]$, see Eq. (10).

[e]Reference 30.

ment with previously reported data. The extraction of absolute radiative widths for the six resonances was thwarted by target deterioration problems. Thus we report peak cross sections, and radiative widths, relative to previous measurements. The accuracy of these previous absolute radiative width determinations and of our own data is discussed in detail. It is clear that more accurate widths could be obtained without too much difficulty. Our experience indicates that beam currents as low as $\approx 0.2\ \mu$A could be used and that such measurements could still be made to yield quite accurate results in a reasonable time. Such an effort is still worthwhile because there is more than the usual possibility of significant systematic errors in both our cross-section measurements and the earlier ones.

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APPENDIX A: ABSOLUTE WIDTHS FROM THE ^{14}C(α,γ)^{18}O REACTION

The absolute gamma-ray widths quoted in the most recent summary report on ^{18}O are those published in 1967 by Lee *et al.*,[3] which, in turn, are normalized to earlier (1959) results published by Gove and Litherland.[2] These, in turn, were normalized to an even earlier[6] absolute measurement (1955) of resonance gamma rays from the ^{14}C(p,γ)^{15}N reaction. All three sets of measurements were carefully and fully described, and since no others have been reported in the intervening years, it is useful to reexamine the reported analyses in the light of such additional information as has been acquired during the past three decades. As it happens, a crucial piece of evidence bears on the absolute gamma ray width observed in ^{14}C(p,γ)^{15}N, which has been revised upward by a factor ≈ 1.5 during this time period.

We begin with the original measurement of Gove and Litherland,[2] who studied the $E_\alpha^{\rm lab}=1140$ and 1790 keV resonances in the ^{14}C(α,γ)^{18}O reaction. They used a 20-μg/cm^2 carbon target enriched to 25% in ^{14}C and detected gamma radiation with a 10×12.7-cm NaI(Tl) detector. The absolute gamma-ray width Γ_γ for the ground-state transition from the $E_\alpha^{\rm lab}=1790$ keV resonance was determined from a comparison measurement with the known ground-state transition from the $E_{\rm p}^{\rm lab}=527$ keV resonance in ^{14}C(p,γ)^{15}N. The comparison used the same target and detector geometry, and thus eliminated the need for detailed knowledge of the ^{14}C enrichment of the target, or indeed of its exact constitution. Only three parameters were required: (1) the relative NaI(Tl) efficiency for detection of the ground-state transitions from the two resonances, (2) the relative stopping powers for alpha particles and protons at the specified resonance energies, and (3) the absolute width factor $\omega\Gamma_{\gamma_0}$ for the ^{14}C(p,γ)^{15}N reaction ground state transitions.

Since the key considerations are discussed in some detail in the earlier papers, points (1) and (2) are easily checked. The smoothly varying energy dependence of the relative γ-ray efficiency curve used is in satisfactory agreement with more recent data[33] for comparison of the 7.63- and 10.70-MeV ground-state transitions in ^{18}O and ^{15}N, respectively. Also, since the first-excited states of ^{18}O and ^{15}N are at 1.982 and 5.270 MeV, respectively, there was no problem in cleanly resolving the ground-state transitions from possible cascade transitions. Thus, we assign no corrections based on (1).

For the relative stopping powers, Gove and Litherland[2] took their data from Allison and Warshaw,[30] whereas the recent more accurate data of Zeigler[28] gives values of $\epsilon_\alpha \approx 15\%$ lower. A more serious correction arises from their use (mistakenly) of laboratory values for ϵ, when what is required in Eqs. (4)–(6) is the c.m. value. The two are related by the mass factor

$$\epsilon(\mathrm{c.m.})=\frac{m_1}{m_1+m_2}\epsilon(\mathrm{lab}) \tag{A1}$$

where m_1 and m_2 are the masses of the projectile and target, respectively. [This point is referenced explicitly in the review article of Rolfs and Litherland,[36] and also in the 1976 thesis of Beukens[33] (p. 21).] Thus with respect to point (2) we deduce a correction factor of 0.77, which should be applied to account properly for the stopping power dependence.

With respect to point (3) it is useful to note that what was actually compared in Ref. 2 was the experimental measure of the quantity

$$\omega\gamma_0=\frac{2J+1}{(2I+1)(2i+1)}\frac{\Gamma_i\Gamma_{\gamma_0}}{\Gamma}$$

for the resonance states observed in the (α,γ_0) and (p,γ_0) reactions. Here the subscript i denotes the entrance channel particle (α or p) and the subscript 0 signifies that we are dealing only with the ground-state deexcitation of the resonances. The value of $\omega\gamma_0$ for ^{14}C(p,γ_0)^{15}N had been determined previously[6] to be $\omega\gamma_0=240$ meV; based on this, the value for the ^{14}C(α,γ)^{18}O $E_\alpha^{\rm lab}=1790$ keV resonance was deduced[2] to be $\omega\gamma_0=240$ meV.

Somewhat later (1959) Hebbard and Dunbar[31] reported the value $\omega\gamma_0=360$ meV for the $E_{\rm p}^{\rm lab}=527$ keV resonance in ^{14}C(p,γ_0)^{15}N. Reference 8 of that paper[31] refers to a private communication from Gove revising upward the earlier value of Bartholomew *et al.*[6] to give $\omega\gamma_0=350$ meV. In a more recent study, Beukens[33] reports the value $\omega\gamma_0=395(74)$ meV. These three separate measurements are in quite good agreement, and we adopt a central value $\omega\gamma_0=375(60)$ meV, where the quoted uncertainty is given as a fair estimate based on the earlier work.

The conclusion from these considerations is that the value taken by Gove and Litherland[2] for the strength of the ^{14}C(p,γ)^{15}N calibration resonance should be revised upward by a factor $\frac{375}{240}=1.56$. Combining this information with that bearing on points (1) and (2), we deduce a net correction factor of 1.20, which should be applied to the previously quoted value $\omega\gamma_0$ for the 1790-keV resonance level. Since in this case $\omega=3$, and the previous value was $\Gamma_\alpha\Gamma_{\gamma_0}/\Gamma=79$ meV, we conclude that $\Gamma_\alpha\Gamma_{\gamma_0}/\Gamma=95$ meV, or $\omega\gamma_0=283$ meV, and for branching ratio 23% this yields $\omega\gamma=1229$, as listed in Table II.

The value reported by Phillips[1] for the width of the ground-state transition from the $E_\alpha^{\rm lab}=1790$ keV resonance is $\Gamma_{\gamma_0}=120(20)$ meV, which is in agreement with this revised value from Ref. 2. However, Phillips's results for the $E_\alpha=2330$ keV resonance are low, by a factor ≈ 2.3, compared to either the renormalized results of Lee *et al.*[3] or of the present study. Finally, we note that the results of Refs. 2 and 3 are also in excellent agreement with respect to the strength of the 7117$\rightarrow$1982 transition in ^{18}O.

APPENDIX B: EXTRACTION OF $\omega\gamma$ FROM $y_m(\infty,\infty)$ FOR THE 3^- RESONANCE

For the 3^- resonance in the ^{14}C(α,γ)^{18}O reaction the extraction of $\omega\gamma$ from the peak yield requires a correction for the effect of the large width of this resonance $\Gamma_{\rm lab}=10(1)$ keV (Ref. 4). This is the only one of the seven resonances studied for which such a correction is significant. The correction (R) can be estimated in several ways. An instructive one is to calculate the overlap of the Breit-Wigner expression with a target of simple composition, either uniform or triangular in profile. These assumptions are incorporated in

$$R=\frac{2}{\pi}\left[\tan^{-1}y-\frac{\delta_+}{2y}\ln(1+y^2)\right], \qquad \text{(B1)}$$

where $\delta_+=0$ for a uniform target and 1 for a triangular target profile, and $y=2\Delta/\Gamma$. Equation (B1), properly interpreted, gives the ratio of the peak yield for finite Γ to that for $\Gamma \ll 2\Delta$, where 2Δ is the target thickness at the base, i.e., the FWHM is Δ for a triangle and 2Δ for a uniform effective target deposition profile. By effective, we mean that other phenomena, such as beam spread and energy-loss straggling, have been incorporated. It bears noting that, from the excitation function measured for the 5^- 2440-keV resonance, we find that our actual effective target deposition has a FWHM of 18 keV with a profile somewhere between triangular and uniform. For a FWHM of 18 keV and $\Gamma=10$ keV we obtain R(triangular)$=0.60$ and R(uniform)$=0.68$ with 7% uncertainty corresponding to 20% uncertainty in Δ/Γ. We adopt $R=0.64(6)$.

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*Permanent address: Nuclear Physics Research Unit, University of the Witwatersrand, Johannesburg, South Africa.

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