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Resonant alpha capture by ^{7}Be and ^{7}Li

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Resonances at $E_\alpha=401$, 814, and 953 keV were observed in the ^{7}Li(α,γ) reaction. From the thick target yields the corresponding states in ^{11}B at 8920, 9185, and 9274 keV were found to have center-of-mass resonance strengths of 0.0088 ± 0.0014, 0.317 ± 0.047, and 1.72 ± 0.17 eV, respectively. The radiative widths deduced for the latter two states are $0.17^{+0.06}_{-0.03}$ and 1.15 ± 0.16 eV, respectively. Using a 40 mCi ^{7}Be target, α-capture resonances were observed at $E_\alpha=884$ (^{11}C$^*=8105$ keV) and 1376 (^{11}C$^*=8421$ keV) keV with center-of-mass resonance strengths of 0.331 ± 0.041 and 3.80 ± 0.57 eV, respectively. The radiative widths deduced for these states are 0.350 ± 0.056 and 3.1 ± 1.3 eV, respectively. The observed decay rates are compared with theoretical calculations.

I. INTRODUCTION

Spectroscopic measurements of the light nuclei (Li-O) provide an important test of the extensive theoretical work that has been carried out in this mass region. In addition, low-energy capture data are an important input to the calculation of astrophysical reaction rates.

We have investigated the ^{7}Be$(\alpha,\gamma)^{11}$C reaction with a radioactive ^{7}Be target. This reaction has never been studied, and the levels in ^{11}C between the thresholds for α decay and p decay are of particular interest.[1,2] The states at excitation energies of 8105 and 8421 keV were populated in the present work. Some information about these levels has been reported from investigations employing the ^{12}C(^{3}He,α) (Ref. 3), ^{10}B(p,γ) (Ref. 4), and ^{9}Be(^{3}He,n) (Refs. 2, 5, and 6) reactions, but accurate measurements of the radiative widths have not been published.

For the investigation of states in the mirror nucleus, ^{11}B, the reaction ^{7}Li$(\alpha,\gamma)^{11}$B was studied. The strengths of the known low-lying resonances populating the states at 8920, 9185, and 9274 keV had only been roughly determined before.[7,8,9] The ^{11}B state at 8920 keV is the analog of the state in ^{11}C at 8421 keV.

In Sec. II a brief description of the experimental procedure is given. The method of analysis and the resonant energies, branching ratios, and resonance strengths are presented in Sec. III. In Sec. IV the radiative widths are discussed and the results compared with the theoretical calculations. A summary is given in Sec. V.

II. EXPERIMENTAL PROCEDURE

A. ^{7}Li$(\alpha,\gamma)^{11}$B

A beam of singly-charged ^{4}He ions was accelerated in the 4.5 MV Dynamitron accelerator at the Argonne National Laboratory. Beam currents were typically 1 to 5 μA. Most of the measurements were performed with LiF targets enriched to $>99.9\%$ ^{7}Li. In addition, some data were taken with enriched ^{7}Li-metal targets. The targets were ≈60 μg/cm^2 thick and were made by evaporation onto the inside of a Ta cup. The cup is part of a chamber which permits the target to be wobbled, thus facilitating heat dissipation. In addition, an air cooling jet was directed onto the back of the Ta cup. An 80 cm^3 active volume Ge(Li) detector and a 25.4 cm long by 25.4 cm diam NaI(Tl) crystal were used to observe the γ rays. The Ge(Li) detector was placed at an angle of 55°, and the NaI(Tl) detector at an angle of 125°, with respect to the beam direction. These angles were chosen to minimize corrections for the angular distributions of the γ rays. The Ge(Li) detector was about 4.5 cm, and the NaI(Tl) crystal about 19 cm, from the beam spot on the target.

In order to determine the detector efficiencies, an aluminum target was prepared by evaporation, and the thick target yield from the 992-keV ^{27}Al(p,γ)^{28}Si resonance was measured. Since the decay scheme of the state populated by this resonance has been carefully studied,[10] and since the resonance strength is known[11] to be 1.91 ± 0.11 eV, the efficiency of the detectors could be determined for γ-ray energies up to 10.8 MeV.

Standard electronics arrangements were used, with provision being made to determine the dead time. The outputs of the analog-to-digital converters were routed to a PDP 11/45 computer and the resulting spectra were stored on magnetic tape.

For weak resonances, long counting times were necessary in order to achieve satisfactory statistical accuracy. Because of carbon buildup on the target, there was the possibility that during the run the energy of the beam after penetrating the carbon layer might be below the resonance. In order to check that the carbon layer did not degrade the beam energy to below resonance, spectra were transferred to tape periodically during the run and the yield monitored.

B. $^{7}Be(\alpha,\gamma)^{11}C$

The ^{7}Be for the target was produced by the $^{7}Li(p,n)^{7}Be$ reaction. After chemical separation,[12] about 80 mCi of ^{7}Be was electrodeposited onto a Pt disc in a 5 mm diam circle. It should be pointed out in this connection that the ^{7}Be was separated, by chemical means, from the ^{7}Li target material such that at the time of electrodeposition the ratio of ^{7}Li to ^{7}Be was less than 0.5%. The method used to prepare the target did introduce about 7 μg of solids, mostly of light elements.[13] Because ^{7}Be decays by electron capture, ^{7}Li builds up in the target. About one-half of the original ^{7}Be had decayed to ^{7}Li when the present experiment was performed.

Because the number of ^{7}Be atoms in the target was small (about 1×10^{16}), and because the resonances are not particularly strong, beam currents as high as 15 μA were used. The Pt disc was cemented onto a thin Ta disc and placed in a chamber which permitted water to circulate immediately behind the Ta. The chamber was isolated from the ground and acted as the Faraday cup. In front of the target was a long cylindrical Cu tube maintained at liquid nitrogen temperature to reduce the buildup of carbon. A dc voltage of -300 V was placed on the cold finger in order to reduce the loss of secondary electrons from the target.

The detectors were the same as described in Sec. II A and the 992-keV $^{27}Al(p,\gamma)$ resonance was again used for the efficiency calibrations. The Ge(Li) detector was placed at 55°, and the NaI(Tl) detector at 90°, to the beam direction. The Ge(Li) detector was situated about 7 cm, and the NaI(Tl) crystal about 23 cm, from the location of the beam spot on the target. Lead was placed between the target and the detectors in order to filter out the 478 keV radiation from the ^{7}Be decay. Calibration of the detectors was done with the filters in place. The electronics arrangement was similar to that used to study the $^{7}Li(\alpha,\gamma)^{11}B$ reaction.

III. ANALYSIS AND RESULTS

A. $^{7}Li(\alpha,\gamma)^{11}B$

Resonances at incident α-particle energies (laboratory) of 953, 814, and 401 keV were investigated. The thick target γ-ray yields for each of these resonances are shown in Fig. 1 as a function of the Dynamitron voltage. The resonance energies, which are taken to be the half-heights of the leading edges of the resonance curves, are in good agreement with the values determined using the energies of the levels in ^{11}B measured in other reactions.[14] The thick-target yield (Y) is taken as the height above background of the resonance-curve plateau. This yield is corrected for dead time and for the angular distribution[9] of the observed γ ray. The resonance strength (ω_γ) is calculated by use of the expression:

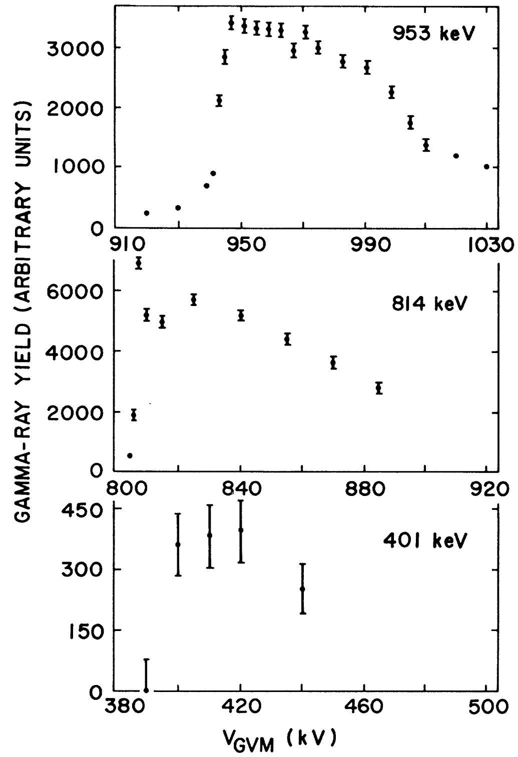

FIG. 1. Resonance curves for the $^{7}Li(\alpha,\gamma)$ reaction. The symbol V_{GVM} represents the generating-voltmeter reading of the Dynamitron. The α-particle energy (laboratory) is given next to each resonance curve. The three resonances were not all taken with the same target. For the 953- and 814-keV resonances the yields of the γ rays resulting from the transitions to the 4445 keV level in ^{11}B are plotted, while for the 401-keV resonance it is the ground state transition.

$$\omega_\gamma=(2/\pi\lambdabar^2)(1/\epsilon\Omega)\xi[M_T/M_I+M_T)(Y/\delta)(e/Q)\ . \qquad (1)$$

The masses M_i and M_T refer to the incident particle and target nucleus, respectively, and their inclusion in the expression is necessary if the resonance strength is to be in the center-of-mass frame. (This factor has sometimes been omitted in papers, textbooks, and review articles.) The wavelength (in cm) of the incident particle in the center of mass is given by

$$\lambdabar=4.572\times10^{-13}[(M_I+M_T)/M_T](M_iE_L)^{-1/2}\ ,$$

in which M_T and M_I are in u and E_L is the projectile energy in MeV in the laboratory system. The product of the efficiency and solid angle of the detector is represented by $\epsilon\Omega$ with the solid angle in sr. The branching ratio for the particular transition studied is represented by δ and (Q/e) gives the number of incident α particles. The symbol ξ represents the stopping power (laboratory system) of the target atoms (in eV per active atom/cm^2) for the incident α particles and was obtained from the compilation of Ziegler.[15]

To obtain ξ in this manner the composition of the target must be known. Because ^{7}LiF targets of the desired thickness are easier to make and store than ^{7}Li-metal targets, the former were usually used. However, the reliabili-

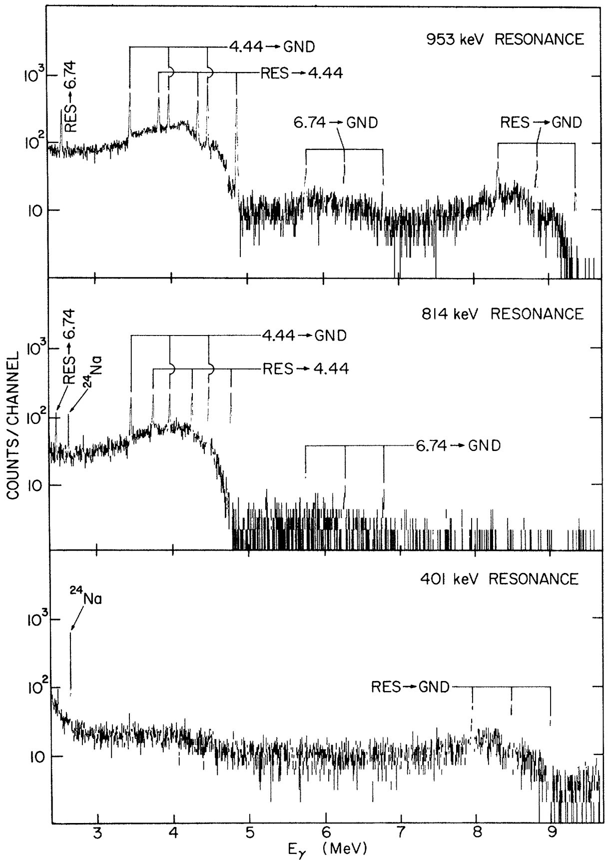

FIG. 2. Spectra obtained with the Ge(Li) detector on the ^{7}Li$(\alpha,\gamma)^{11}$B resonances.

ty of resonance strength measurements is open to question when targets are made by evaporating compounds because of possible deviations from stoichiometry. Resonance strengths were therefore checked by making measurements with a target prepared by evaporating ^{7}Li metal. The ratio of the resonance strengths (which should be unity) obtained with the two targets can be calculated from Eq. (1) to be

$$(\omega_\gamma)_{\rm Li}/(\omega_\gamma)_{\rm LiF}=[(Y/Q)_{\rm Li}/(Y/Q)_{\rm LiF}](\xi_{\rm Li}/\xi_{\rm LiF}) .$$

In calculating this ratio from the yields obtained for a particular transition, stoichiometry is assumed. This check was made at the 953-keV resonance. For the strongest transition, the above ratio was 1.11 ± 0.08 from data collected with the Ge(Li) detector. An analysis of the ratio for several transitions indicated that the results were consistent, within the uncertainties of about 10%, with a stoichiometry of $^7\mathrm{Li}_1\mathrm{F}_1$.

Although overall stoichiometry is preserved in the target, some redistribution of the constituents may take place. Evidence that this may occur can be observed in the shape of the 814-keV resonance near the leading edge (see Fig. 1). Similar resonance shapes have been observed by Spear *et al.*[16] with sintered LiF targets. The processes in the target which result in such shapes are not yet completely clear, but the degree to which they occur depends, among other things, on the total charge placed on the target. Hence the resonance shape obtained will depend on how long the target has been exposed to the beam. A discussion of possible mechanisms, with relevant references, is given by Spear *et al.*[16]

Spectra obtained on the three resonances with the

TABLE I. Branching ratios and resonance strengths of states in ^{11}B obtained using the ^{7}Li$(\alpha,\gamma)^{11}$B reaction. In each case the transition is from the state populated by the α capture to the final state indicated. The earlier results of Bennett *et al.* (Ref. 7) are not included in the table.

E_α (keV)	Initial state (keV)	Final state (keV)	Branching ratios %		ω_γ (eV)		
			Previous[a]	Present	Present	Jones[b]	Green[c]
953	9274	0000	19.7±1.0	17.1±1.0	0.345±0.057		
		4445	67.5±2.0	71.7±1.8	1.18±0.15		
		6743	12.8±0.7	11.2±0.6	0.198±0.036		
					1.72 ±0.17	3.4	4.5
814	9185	0000	0.9±0.3[d]	<1			
		4445	82.8±2.0	91.6±4.5	0.281±0.046		
		6743	12.8±0.4	8.4±1.0	0.0293±0.0060		
					0.310±0.047	0.63	0.50
401	8920	0000	95 ±1	>90	0.0084±0.0013		
		4445	4.5±0.5				
					0.0088±0.0014	0.025	0.045

[a]See compilation by Ajzenberg-Selove and Busch (Ref. 14).
[b]Reference 8.
[c]Reference 9.
[d]Several observed weak transitions are not included.

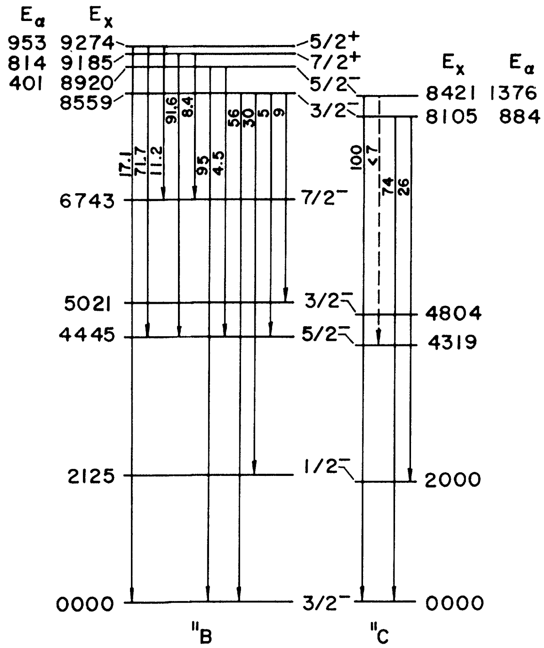

FIG. 3. The γ decay of some states in ^{11}B and ^{11}C. All energies are in keV. The branching ratios (in percent) are placed to the left of the lines indicating the transitions. The branching ratios for ^{11}C are from the present work as are those for the 9274- and 9185-keV states in ^{11}B. The other branching ratios are from the compilation by Ajzenberg-Selove and Busch (Ref. 14). The value of 8421 keV for energy of the second $\frac{5}{2}^-$ state in ^{11}C is from the present work (see Sec. III B).

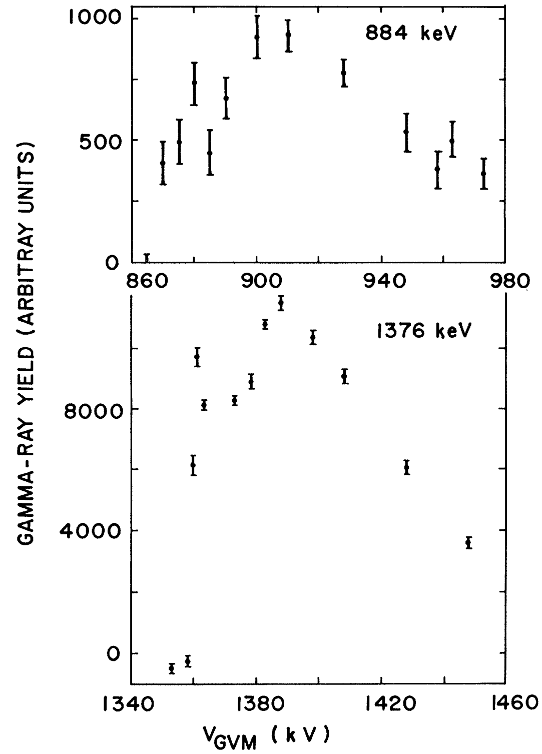

FIG. 4. Resonance curves for the $^7Be(\alpha,\gamma)$ reaction. For both resonances the yield of γ rays to the ground-state transition is plotted.

Ge(Li) detector are shown in Fig. 2. The spectra that were taken with the NaI(Tl) crystal were consistent with those from the Ge(Li) detector. On the 953 keV resonance, the same lines were seen with the two spectrometers. On the 401 keV resonance the NaI(Tl) crystal could not resolve the 4475 and the 4445 keV lines. In all cases where the same gamma ray was seen in both spectra the intensities, corrected for efficiency, agreed to within the experimental error.

Table I gives a comparison of the present values for the branching ratios and resonance strengths with those of other workers. The present values are weighted averages from the two detectors and both systematic and statistical uncertainties have been included. The results from the two detectors are in good agreement. For the 401-keV resonance, the total strength was obtained by assuming a $95\pm1\%$ branch[14] from the resonance level to the ground state. Figure 3 shows the γ-ray decay of the resonances.

B. $^7Be(\alpha,\gamma)^{11}C$

Resonances at α-particle energies (laboratory) of 884 and 1376 keV were studied. The yield curves over each resonance are shown in Fig. 4. Several factors influence the shapes of the resonance curves. There was a 5 to 10% inhomogeneity in the distribution of ^7Be over the target.[17] Under the prolonged bombardment of the target with high beam currents, some thermal diffusion of the ^7Be may have taken place leading to distortions of the resonance shapes similar to that discussed in Sec. III A and Ref. 16. There was, furthermore, some buildup of carbon on the target from the previous experiment. The area of the target struck by the beam in the present experiment was somewhat larger than the area of the carbon spot, which caused an uneven plateau.

Values for the resonance energies obtained here, 1376 ± 3 and 884 ± 8 keV, agree well with those of 1380 ± 13 and 878 ± 3 keV obtained using the accepted values[14] of 8424 ± 8 and 8104.5 ± 1.7 keV for the energies of the excited states populated. Our value of 1376 ± 3 keV results in an excitation energy of 8421 ± 2 keV for the second $\frac{5}{2}^-$ state in ^{11}C.

The resonance strengths were calculated in two ways. The first was to simply use Eq. (1); this will be called the absolute method. A second technique makes use of the ^7Li in the target to determine the ^7Be resonance strengths relative to a resonance in $^7Li(\alpha,\gamma)$ (relative method). Using Eq. (1) and $\xi=\Delta/n$, discussed below, we obtain

$$[\delta(\omega_\gamma)]_{Be}/[\delta(\omega_\gamma)]_{Li}=(\lambdabar_{Li}^2/\lambdabar_{Be}^2)(\Delta_{Be}/\Delta_{Li})(n_{Li}/n_{Be})(Q_{Li}/Q_{Be})[(Y/\epsilon\Omega)_{Be}/(Y/\epsilon\Omega)_{Li}] .$$

Advantages of this method are that the ratio (n_{Li}/n_{Be}) is known more accurately than n_{Be} alone and the ratio of the efficiencies is known more accurately than the absolute efficiencies. The disadvantage is that the uncertainty in the

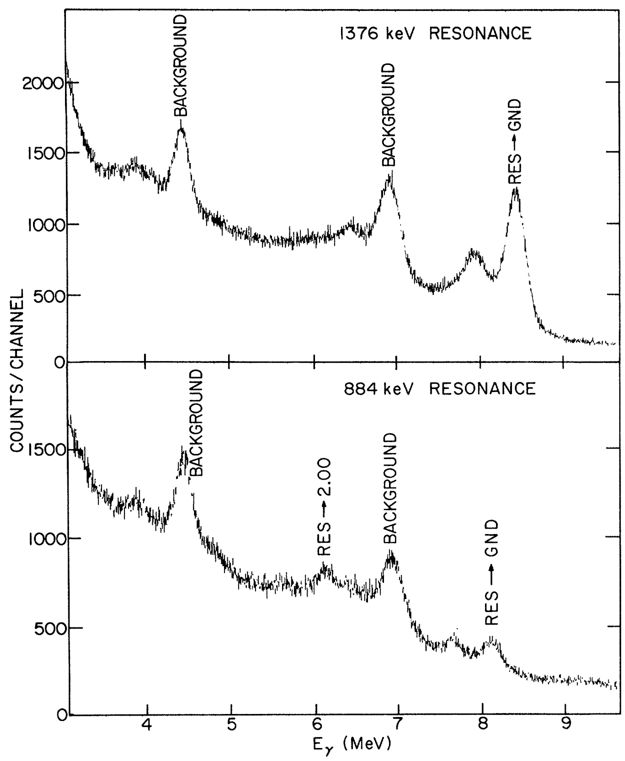

FIG. 5. Spectra obtained with the NaI(Tl) detector on the ^{7}Be(α,γ)^{11}C resonances. The background lines were also present off resonance and are believed to be the 4.43 MeV γ ray from ^{12}C and the 6.92 MeV γ ray from ^{16}O.

^{7}Li 953-keV resonance strength used for normalization must be included in the determination of the ^{7}Be resonance strength.

In order to use these methods the stopping power ξ must be known. Although the amount of ^{7}Be in the target was less than 0.12 μg it was dispersed throughout about 7 μg of other material.[13] Thus a "thick target" resonance shape was obtained with a full-width at half maximum of Δ. The measured Δ and the known number of ^{7}Be atoms/cm^2 ($n = 5.13 \pm 0.51 \times 10^{16}$ atoms/cm^2 determined in a separate experiment[13]) were used to calculate the stopping power $\xi (\xi = \Delta / n)$ required in Eq. (1). The widths of the yield curves, Δ, are in agreement with expected energy losses from previous experiments with this target.[13] For the determination of the resonance strength, a 2.4% correction was made to the NaI(Tl) yield for the γ-ray angular distribution at the 1376-keV resonance by using the analogous transition in ^{11}B; for the 884-keV resonance, no angular distribution correction was made.

Spectra obtained on the two resonances with the NaI(Tl) detector are shown in Fig. 5. Both show a ground state transition as well as background lines at 4.43 and 6.92 MeV. The background lines were present off resonance as well and are believed to be due to ^{12}C and ^{16}O, respectively. On the 884-keV resonance, a transition to the first excited state is also apparent. It should be noted that because of a weak background line at about 7.7 MeV, the first escape peak for the ground-state transition is about twice what would be expected.

On the 1376-keV resonance, the spectrum from the Ge(Li) detector showed only the ground state transition. The 884-keV resonance was too weak to be observed with the Ge(Li) detector. As can be seen from Table II, the relative and absolute resonance strengths are in excellent agreement. The adopted values are weighted averages of the relative and absolute results. However, the two sets of results are not completely independent. In particular, both rely on the same energy dependence of the efficiency curves and, therefore, the uncertainties for the accepted values are somewhat larger than would be obtained assuming independence. The branching ratios and adopted resonance strengths are also given in Table II (see also Fig. 3).

IV. DISCUSSION

A. ^{7}Li(α,γ)^{11}B

The resonance strength can be written in the form

$$\omega_\gamma = [(2J+1)/(2J_i+1)(2J_T+1)](\Gamma_i \Gamma_\gamma / \Gamma) ,$$

in which Γ_i represents the width for decay back to the entrance channel, Γ_γ is the total radiative width, Γ is the total width of the level, and J, J_i, and J_T are the spins of the resonance level, the incident particle, and the target nucleus, respectively. If the radiative width (Γ_γ) and the α-particle width (Γ_α) are the only significant widths, as is the case here, then $\Gamma = \Gamma_\alpha + \Gamma_\gamma$.

For the 9274-keV level (populated at the 953-keV reso-

TABLE II. Branching ratios and resonance strengths of states in ^{11}C obtained using the ^{7}Be(α,γ)^{11}C reaction. The (ω_γ) (relative) were obtained by using the known strength of the 953-keV resonance in the ^{7}Li(α,γ) reaction (see Sec. III B).

E_α (keV)	Initial state (keV)	Final state (keV)	Branching ratio (%)	ω_γ (relative) (eV)	ω_γ (absolute) (eV)	ω_γ (adopted)[a] (eV)
1376±3	8421	0000	100	4.01 ±0.74	3.66 ±0.60	3.80 ±0.57
		4319	<7			
				4.01 ±0.74	3.66 ±0.60	3.80 ±0.57
884 ±8	8105	0000	74±12	0.238±0.040	0.289±0.081	0.248±0.038
		2000	26±5	0.082±0.016	0.086±0.027	0.083±0.015
				0.320±0.043	0.375±0.086	0.331±0.041

[a]See Sec. III B.

TABLE III. Partial widths, in the center-of-mass system, of the levels studied in the present work. E_x represents the excitation energy of the state. The last column gives the α widths calculated using the α-structure amplitudes of Kurath (Ref. 23).

Nucleus	E_x (keV)	J^π	Γ_γ (eV)	Γ_α (eV) Experimental	Γ_α (eV) Calculated
^{11}B	9274	$\frac{5}{2}^+$	1.15 ± 0.16	4×10^3	
^{11}B	9185	$\frac{7}{2}^+$	$0.17^{+0.06}_{-0.03}$	$1.6^{+1.5}_{-1.1}$	
^{11}B	8920	$\frac{5}{2}^-$	4.368 ± 0.021[a]	0.0059 ± 0.0009	0.0072
^{11}C	8421	$\frac{5}{2}^-$	3.1 ± 1.3	12.6 ± 3.8	11
^{11}C	8105	$\frac{3}{2}^-$	0.350 ± 0.056	$4\rightarrow18$	53

[a]Reference 19.

nance) Γ is about[8] 4 keV in the center-of-mass system (in Ref. 14 a value of 7 keV is given, apparently a misprint), indicating that Γ_α/Γ is very close to unity. The value $\Gamma_\gamma=1.15\pm0.16$ eV is obtained from the measured resonance strength. Using this value and our branching ratios (Table I), one obtains transition strengths to the ground, 4445 keV, and 6743-keV states of about 7×10^{-4}, 2×10^{-2}, and 2×10^{-2} W.u., respectively, assuming all the transitions are predominantly $E1$. For the 9185-keV level (814-keV resonance) Olness *et al.*[1] measured $\Gamma_\gamma/\Gamma=0.1^{+0.2}_{-0.05}$. Our value for ω_γ gives

$$(\Gamma_\alpha/\Gamma_\gamma)/\Gamma=0.155\pm0.024 \text{ eV} .$$

Combining these two results yields $\Gamma_\gamma=0.17^{+0.06}_{-0.03}$ eV and $\Gamma_\alpha=1.6^{+1.5}_{-1.1}$ eV. For $\Gamma_\gamma=0.17$ eV and the present branching ratios (see Fig. 2) we obtain about 4×10^{-3} and 3×10^{-3} W.u. for the strengths of the $E1$ transition to the 4445- and 6743-keV states, respectively. A weak branch has been reported (see Table I) to the ground state, which is a mixed transition[9] with 53% $M2$ and 47% $E3$. The resulting transition strengths are 43 W.u. for the $E3$ component and 0.17 W.u. for the $M2$ component. As discussed by Olness *et al.*,[1] the $E3$ strength seems too large.

Our value of

$$\omega_\gamma=0.0088\pm0.0014 \text{ eV}$$

for the 8920-keV level (401-keV resonance) is considerably smaller than most other measurements[7,8,9] which average to 0.04 eV, although it should be noted that the other measurements do not agree well with each other (see also Ref. 18). In the present experiment this strength was measured several times with different targets and with both NaI(Tl) and Ge(Li) detectors and all results were in good agreement. Since the earlier workers[8,9] used only NaI(Tl) detectors it may be that contaminant γ rays made a significant contribution.

Millener *et al.*[19] compiled a value of $\Gamma_\gamma=4.368\pm0.021$ eV for the 8920-keV level. Combining this with our value of $(5.9\pm0.9)\times10^{-3}$ eV for $(\Gamma_\alpha\Gamma_\gamma/\Gamma)$ gives

$$\Gamma_\alpha=(5.9\pm0.9)\times10^{-3} \text{ eV} .$$

These values give $(\Gamma_\gamma/\Gamma)\approx1$ which is in agreement with the lower limit of 0.84 given by Olness *et al.*[1] The ground state transition from this level is predominantly $M1$ with a 0.6% admixture[9] of $E2$, which leads to transition strengths of 0.32 and 0.42 W.u. for the $M1$ and $E2$ components, respectively. For the 4.5% branch to the 4445-keV state (see Fig. 3) the $M1$ transition strength is 0.11

TABLE IV. A comparison of shell-model calculations (Refs. 19 and 20) and the experimental results for two positive-parity states in ^{11}B. The energies are in keV. The radiative widths are in the center-of-mass system and given in Weisskopf units (W.u.). All transitions are $E1$ unless noted otherwise.

Transition	Branching ratios (%) Calculated[a]		Branching ratios (%) Present	Γ_γ (W.u.) Calculated[a]		Γ_γ (W.u.) Present
9185→g.s.		0.4	<1		0.31 ($M2$)	0.17[b]
					6.4 ($E3$)	43[b]
→4445	94	92.5	89.3	6.7×10^{-3}	11×10^{-3}	$4.2^{+1.2}_{-.03}\times10^{-3}$
→6743	6	7.1	8.2	2.0×10^{-3}	6.2×10^{-3}	$2.8^{+0.9}_{-0.3}\times10^{-3}$
9274→g.s.	95	94	17.1	37×10^{-3}	18×10^{-3}	$7.3\pm1.1\times10^{-4}$
→4445	2	3	71.7	8.4×10^{-3}	4.0×10^{-3}	$22\pm3\times10^{-3}$
→5021	1	1		4.2×10^{-3}	2.4×10^{-3}	
→6743	2	2	11.2	38×10^{-3}	23×10^{-3}	$23\pm3\times10^{-3}$

[a]The left and right columns are from the results of Teeters and Kurath (Ref. 20) and Millener *et al.* (Ref. 19), respectively.

[b]Calculated using the branching ratio and the mixing ratio given in Ref. 9.

W.u. The information available for the partial widths of the levels studied in ^{11}B is summarized in Table III.

Shell-model calculations of states in ^{11}B have been carried out using a weak-coupling basis by Teeters and Kurath[20] and, more recently, on an SU(3) basis by Millener *et al.*[19] Although these latter calculations are equivalent to the former ones, somewhat different results are obtained because of the selection of slightly different two-body matrix elements and single-particle energies. Millener *et al.*[19] include $2\hbar\omega$ configurations in addition to those of $0\hbar\omega$ considered by Teeters and Kurath,[20] but these additional terms give only small contributions to the negative-parity wave functions. A comparison between these calculations and the present experimental results is given in Table IV. Both theoretical results[19,20] agree well with the measured decay properties of the major branches of the $\frac{7}{2}^{+}$ state at 9185 keV. For the weak ground-state transition, the measured $E3$ component has a much greater enhancement than predicted. For the $\frac{5}{2}^{+}$ state at 9274 keV, both calculations predict a much stronger transition to the ground state than is observed. The present experiment, as well as earlier work,[8,9] shows that this state decays predominantly to the $\frac{5}{2}^{-}$ state at 4445 keV (see Fig. 3). The calculated radiative widths to the 4445- and 6743-keV states are in reasonable agreement with the experimental results.

B. ^{7}Be$(\alpha,\gamma)^{11}$C

The two levels investigated in ^{11}C were thought[1] to have negligible γ widths compared to α-particle widths since γ rays from them were not observed in studies using the ^{9}Be(^{3}He,n) and ^{10}B(d,n) reactions. Indeed, a study[21] of ^{11}C using the ^{12}C(^{3}He,$\alpha\gamma$) reaction yielded $(\Gamma_\gamma/\Gamma) < 0.04$ for the 8105-keV state, and a recent investigation[2] using the ^{9}Be(^{3}He,nγ) reaction yielded a preliminary result of

$$(\Gamma_\gamma/\Gamma)=0.055\pm0.035 \; .$$

Combining the preliminary value with our measured

$$\omega_\gamma=0.331\pm0.041 \text{ eV}$$

yields

$$\Gamma_\gamma=0.350\pm0.056 \text{ eV}$$

and $4 \text{ eV} \le \Gamma_\alpha \le 18$ eV with a most probable value of 6 eV.

The situation is less clear for the 8421-keV level. One study,[4] using the ^{10}B(p,γ) reaction, yielded $(\Gamma_\gamma/\Gamma)=0.8\pm0.2$, while another,[21] using the ^{12}C(^{3}He,$\alpha\gamma$) reaction, yielded $(\Gamma_\gamma/\Gamma)=0.2\pm0.1$. A recent investigation by Wiescher *et al.*[22] of the ^{10}B(p,γ) reaction found that interference effects between several levels can account for the value of 0.8 obtained by Anttila *et al.*[4] and yielded $(\Gamma_\gamma/\Gamma)=0.20\pm0.05$. As the latest study[22] had the best counting statistics, was the most extensive, and agreed with one of the earlier studies,[21] the value obtained from it will be used here. Combining our measured value for ω_γ ($=3.80\pm0.57$ eV) with the most accurate value for Γ_γ/Γ yields $\Gamma_\gamma=3.1\pm1.3$ eV and $\Gamma_\alpha=12.6\pm3.8$ eV.

Kurath[23] has calculated α-structure amplitudes for 1p-shell nuclei. These can be combined with calculated penetrabilities to obtain Γ_α. In determining the necessary penetrability factors, the radius parameter was taken to be $R_0=1.36$ fm. The measured values for Γ_α are compared in Table III with those calculated using the α-structure amplitudes. This table also includes a state in ^{11}B discussed above (see Sec. IV A). The agreement between measured and calculated α widths is excellent for the two $\frac{5}{2}^{-}$ states, but for the $\frac{3}{2}^{-}$ state the predicted Γ_α is somewhat larger than the upper limit determined by experiment.

V. SUMMARY

Resonance strengths from previous studies[7,8,9] of the ^{7}Li$(\alpha,\gamma)^{11}$B resonances at 401, 814, and 953 keV were not in agreement. In the present work, measurements were done carefully using both a Ge(Li) and a NaI(Tl) detector. Results from these detectors were in close agreement and yielded final total resonance strengths with uncertainties of less than 17% (see Table II). The radiative and α widths that could be extracted are presented in Table III. The present results for the positive parity states are compared with calculations[20] using the weak coupling model. Branching ratios and the radiative width are predicted satisfactorily for the $\frac{7}{2}^{+}$ state (9185 keV), but the calculations do not agree with the experimental results for the $\frac{5}{2}^{+}$ state (9274 keV) (see Table IV).

The present study is the first to report resonant α capture on ^{7}Be. Resonance strengths were obtained for levels populated at $E_\alpha=884$ and 1376 keV. Again, both a Ge(Li) and a NaI(Tl) detector were used and the results from the two detectors were in excellent agreement. The radiative and α widths extracted are given in Table III. The α widths obtained for the negative-parity states in both ^{11}C and ^{11}B are compared in this table with those calculated using the α-structure amplitudes given by Kurath.[23] Agreement between the experimentally determined and theoretically calculated α widths is good for the two $\frac{5}{2}^{-}$ states, but poor for the $\frac{3}{2}^{-}$ state.

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