PHYSICAL REVIEW C VOLUME 12, NUMBER 3 SEPTEMBER 1975

γ-ray decay of the 9.042 and 9.806 MeV states in ^{23}Na†

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(Received 28 April 1975)

The ^{12}C(^{12}C,$p\gamma$)^{23}Na reaction, at an incident energy of $E_{c.m.} = 19.3$ MeV, has been used to study the γ-ray decay of the 9.042 and 9.806 MeV levels in ^{23}Na, which are resonantly excited at this energy. Doppler shift attenuation measurements have yielded lifetime limits of $\tau < 10$ fs for the 9.042 MeV level and $\tau < 20$ fs for the 9.806 MeV level. Angular distributions of the γ rays deexciting these two levels have been measured, and the results are consistent with the assumption of $J = \frac{15}{2}$ and $J = \frac{17}{2}$, respectively. The measurements indicate that these two levels are likely candidates for the $\frac{15}{2}^+$ and $\frac{17}{2}^+$ members of the ground state rotational band in ^{23}Na.

[NUCLEAR REACTIONS ^{12}C(^{12}C, $p\gamma$), $E_{c.m.} = 19.3$ MeV, measured $\sigma(E_\gamma, \theta_\gamma)$, p-γ coin. Natural target. Deduced ^{23}Na levels, J^π, δ, $T_{1/2}$.]

I. INTRODUCTION

In a recent paper Van Bibber *et al.*[1] reported a resonance structure in the ^{12}C(^{12}C,p)^{23}Na reaction, at a center-of-mass energy of 19.3 MeV, for several levels in ^{23}Na above $E_x \sim 9$ MeV. The resonance structure was especially pronounced for two levels at excitation energies of about 9.07 and 9.84 MeV. In an earlier experiment, using the same reaction at a center-of-mass energy of 14 MeV, Frank *et al.*[2] observed the γ-ray decay of a level at 9.04 MeV and suggested that this was the $\frac{15}{2}^+$ member of the $K^\pi = \frac{3}{2}^+$ ground state rotational band of ^{23}Na. It is likely that this level and the lower level observed by Van Bibber *et al.* are the same and that this level and the one near 9.8 MeV are the $\frac{15}{2}^+$ and $\frac{17}{2}^+$ members of the ground state roational band of ^{23}Na. If these two levels are in fact high spin members of the ground state band of ^{23}Na, it is expected that they will decay primarily through the $\frac{11}{2}^+$ and $\frac{13}{2}^+$ members of the band at $E_x = 5.534$ MeV and $E_x = 6.235$ MeV, respectively. A recent γ-ray linear polarization measurement has confirmed the spin and parity assignment to the former level.[3] The measurements reported in this paper of the γ-ray decay schemes, correlations, and lifetimes give some information on the spins of the levels at 9.042 and 9.806 MeV and multipole mixing ratios of the transitions and are consistent with these two levels being members of the ground state rotational band in ^{23}Na.

II. PARTICLE SPECTRA

Due to the fortunate circumstance that the two levels of interest in this study are fed much more strongly than other nearby levels at the resonance energy of 19.3 MeV center-of-mass, it was possible to use a particle-detection system with relatively poor resolution but large solid angle in the particle-γ coincidence studies discussed in the following sections. This fact is illustrated by the two particle spectra contained in Fig. 1. On the left is the spectrum measured with a 1 mm thick annular detector centered at 180° and covering an angular range of 162 to 176°. The target in this case was an 80 μg/cm^2 carbon film mounted on a 0.125 mm gold backing. A 0.25 mm thick aluminum absorber foil was used in front of the detector to stop the high counting rate one would otherwise have from the ^{12}C(^{12}C, α)^{20}Ne reaction. With this configuration an over-all resolution of ≈ 300 keV in excitation energy was obtained for a lab solid angle of ≈ 300 msr. The spectrum on the right was obtained using an Enge split-pole spectrograph with a position-sensitive proportional counter on the focal plane. A 5 μg/cm^2 self-supporting carbon target was used and in this case an over-all resolution of 50 keV was obtained for a lab solid angle of ≈ 2 msr. It should be pointed out that for the angle chosen for the spectrograph measurement, 15° lab, the relative yields of the levels in ^{23}Na are approximately the same as for the annular detector configuration since the ^{12}C + ^{12}C reaction must necessarily be symmetric about 90° in the center-of-mass system. It is apparent that at this beam energy only two levels of ^{23}Na are strongly populated and one is justified in sacrificing resolution in order to obtain a larger solid angle. The excitation energies quoted in this work, obtained from our measurements of the γ-ray energies plus the previously measured energies of the

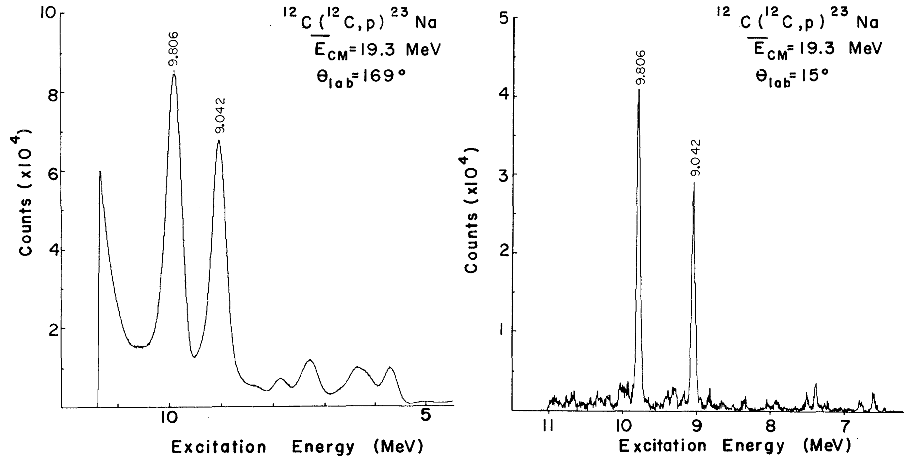

FIG. 1. Particle spectra of protons from the $^{12}C(^{12}C, p)^{23}Na$ reaction at $E_{c.m.} = 19.3$ MeV. The spectrum on the left was obtained with a 1 mm annular detector near $\theta = 180°$. This spectrum is "folded over" because the detector-foil combination used was not thick enough to stop protons from lower excited states of ^{23}Na. The spectrum on the right was obtained with a position-sensitive proportional counter on the focal plane of a magnetic spectrograph.

5.534 and 6.235 MeV levels,[2] are 9.042 ± 0.006 and 9.806 ± 0.006 MeV for the levels of interest.

III. γ-RAY BRANCHING RATIOS

For the particle-γ coincidence measurements the annular detector system described in the last section was used and γ-rays were detected using two Ge(Li) detectors with nominal volumes of 45 and 65 cm^3. These were mounted on opposite sides of the beam and could be rotated in the angular ranges of 0–90° and 0–135°, respectively. In order to obtain reasonable coincidence rates the detectors were placed fairly close to

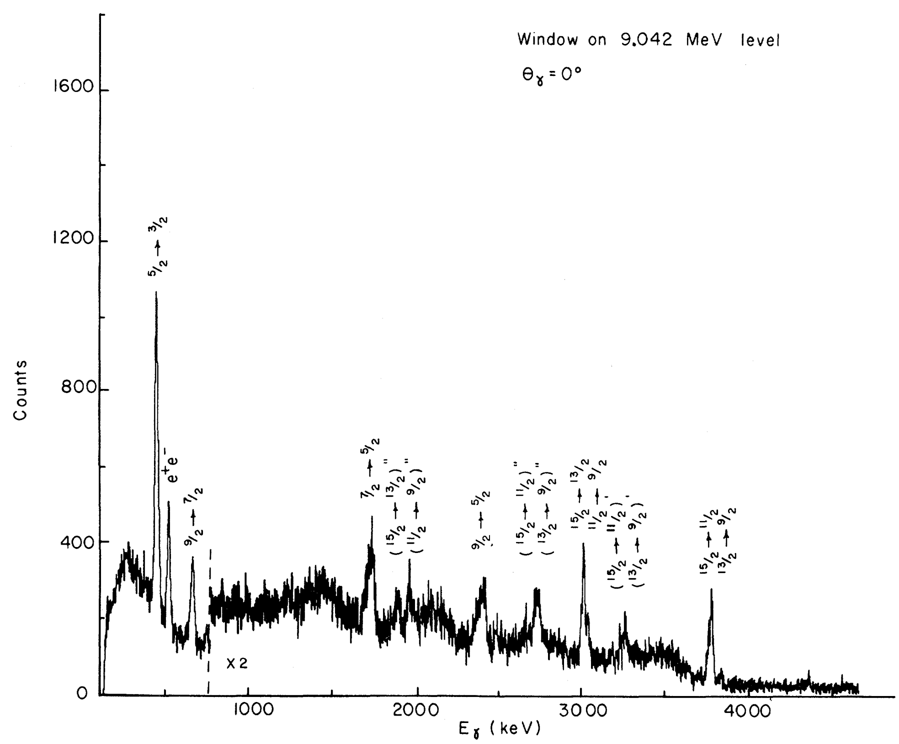

FIG. 2. γ-ray coincidence spectrum showing transitions in coincidence with particles feeding the 9.042 MeV level.

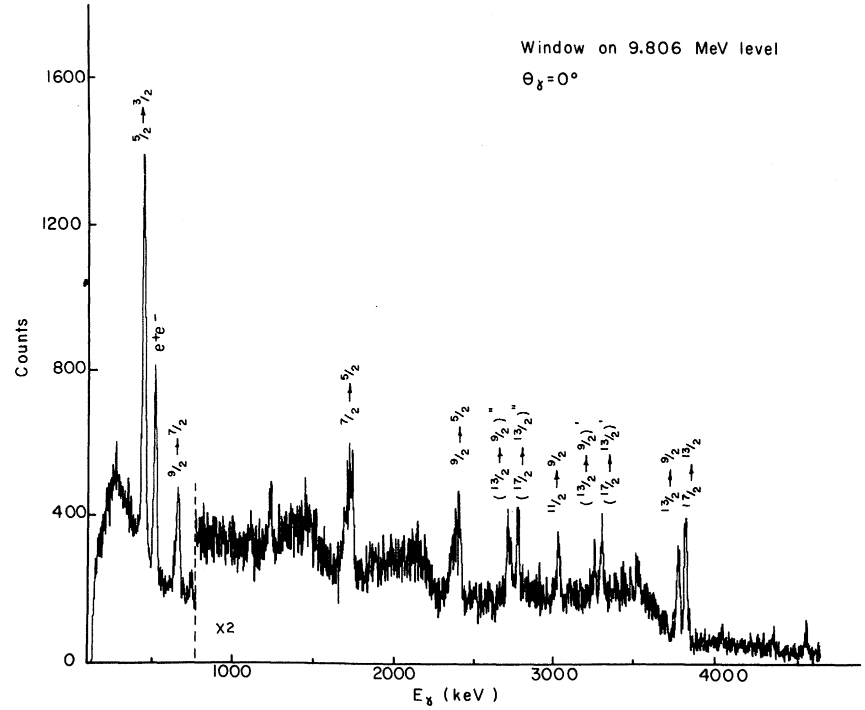

FIG. 3. γ-ray coincidence spectrum showing transitions in coincidence with particles feeding the 9.806 MeV level. The peak near 1.2 MeV in this spectrum has not been identified, but may be due to the decay of one of the more weakly excited levels in this energy region (see Fig. 1).

the target, at a distance of about 9 cm. For this geometry, the resolution of the γ rays of interest was limited by Doppler broadening and in several cases it was not possible to resolve peaks for angles near 90°. Figure 2 is a coincidence γ-ray spectrum measured at 0° for a window on the 9.042 MeV level proton group. Figure 3 is a similar spectrum corresponding to a window on the 9.806 MeV level.

For the level at $E_x = 9.806$ MeV, the only γ decay observed was to the (probable) $J=\frac{13}{2}$ level at an excitation energy of 6.235 MeV. No evidence was seen for a decay to the 9.042 MeV level and it is estimated that this branch is, at most, 5% of the total decay for this level.

The 9.042 MeV level was observed to decay both to the $J=(\frac{13}{2})$ state at 6.235 MeV and the $J=\frac{11}{2}$ state at 5.534 MeV. Both of these γ rays could be resolved from nearby transitions only at $\theta = 0°$ (Fig. 2) and it was necessary to resort to indirect methods to calculate the branching ratio. The first method consisted of correcting the yields at $\theta = 0°$ for angular correlation effects assuming $J=\frac{15}{2}$ for the 9.042 MeV level. The second method used was to assume that the yields at $\theta = 60°$ for both unresolved doublets gave a good estimate of the a_0 coefficients for all four transitions, and using these measured intensities, plus the previously mea-

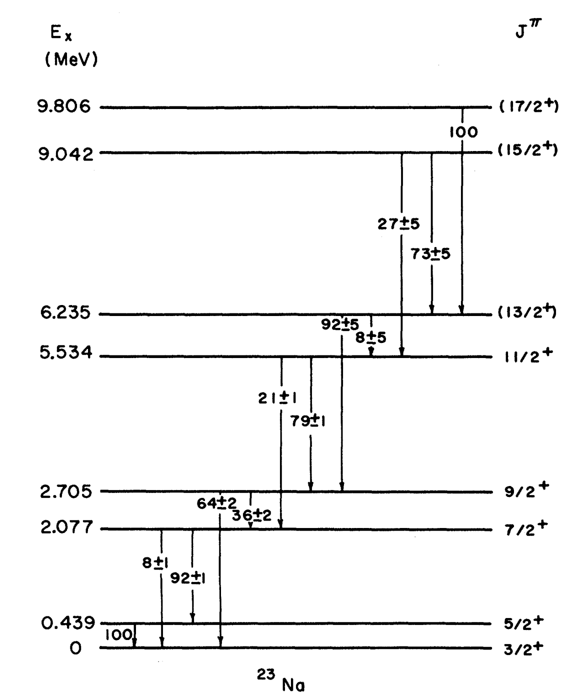

FIG. 4. The ground state rotational band of ^{23}Na. The results for the 9.042 and 9.806 MeV levels are from the present work and all other data were taken from Refs. 2, 3, and 4.

TABLE I. γ-ray angular distribution coefficients. All values of J_i^π consistent with the measured angular distributions are included in the table. The errors on the mixing ratios are calculated using the "χ^2+1" rule, as suggested by Rogers (Ref. 5).

E_i (MeV)	E_f (MeV)	a_2	a_4	J_i^π	δ
9.042	6.235	-0.22 ± 0.04	0.06 ± 0.04	$\frac{15}{2}^+$	-0.03 ± 0.03
				$\frac{11}{2}^+$	-0.03 ± 0.04
9.042	5.534	0.44 ± 0.06	-0.28 ± 0.07	$\frac{15}{2}^+$	$E2$
				$\frac{11}{2}^+$	$-1.88<\delta<-0.58$
					$-0.03<\delta<0.75$
9.806	6.235	0.40 ± 0.10	-0.04 ± 0.12	$\frac{9}{2}^+$	$E2$
				$\frac{11}{2}^+$	$0.28<\delta<3.73$
				$\frac{13}{2}^+$	$-0.60<\delta<0.31$
				$\frac{15}{2}^+$	$-19.0<\delta<-2.47$
					$-0.64<\delta<-0.29$
				$\frac{17}{2}^+$	$E2$

sured[2] branching ratios for the 6.235 and 5.534 MeV levels to calculate the branching ratio for the 9.042 MeV state. These two calculations gave consistent results of $(27\pm 5)\%$ for the $9.042\to 5.534$ MeV branch.

A summary of the decay scheme and branching ratios for the postulated ground state rotational band including the 9.042 and 9.806 MeV levels is contained in Fig. 4.

IV. ANGULAR CORRELATION MEASUREMENTS

Since the γ rays deexciting the 9.042 and 9.806 MeV levels in ^{23}Na could not be resolved from other transitions at all angles, it was not possible to measure the angular correlations of the individual transitions. Instead, the intensities of the unresolved doublets were fitted to the expected angular correlation for different values of the spin of

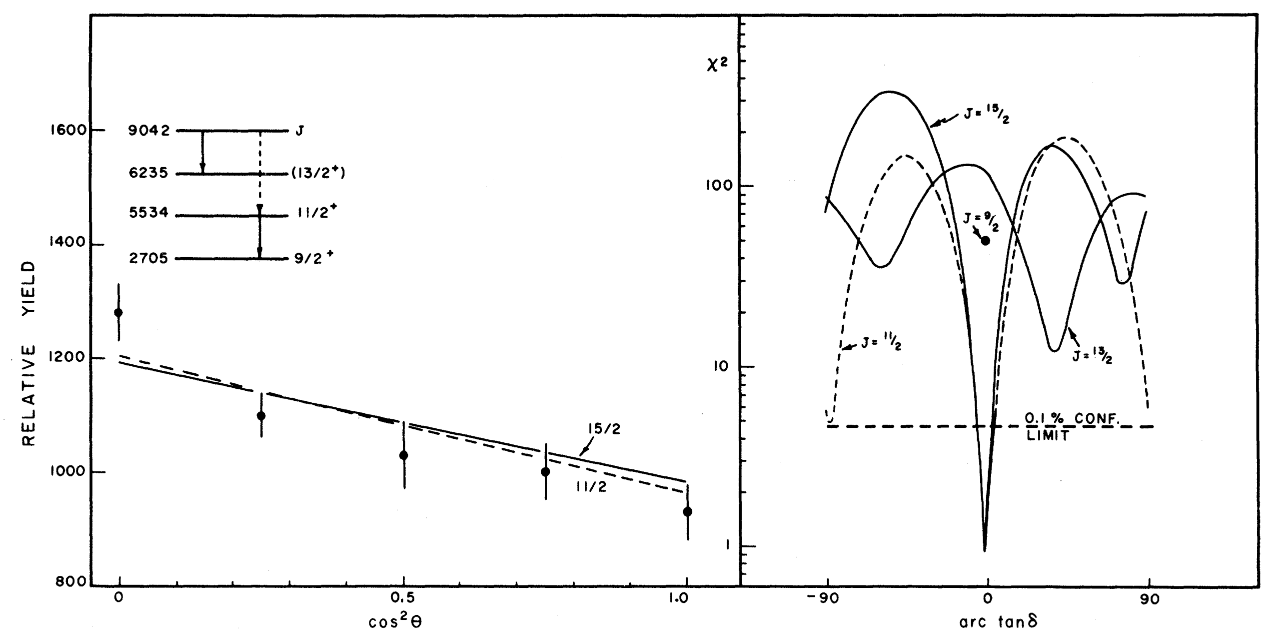

FIG. 5. Angular distribution measurements for the unresolved $9.042\to 6.235$ and $5.534\to 2.705$ doublet. δ is the mixing ratio of the $9.042\to 6.235$ transition.

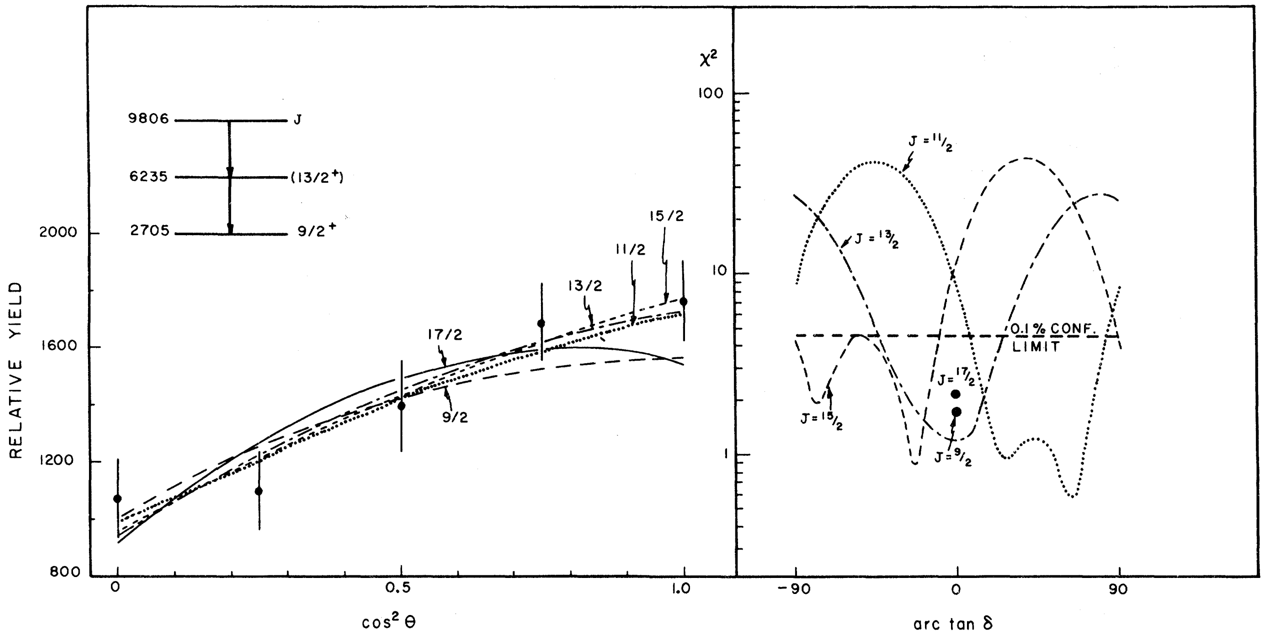

FIG. 6. Angular distribution measurements for the unresolved 9.806→ 6.235 and 6.235→ 2.705 doublet. δ is the mixing ratio of the 9.806→ 6.235 transition.

the initial state and mixing ratio of the primary transition. The parameters for the transitions from the 6.235 and 5.534 MeV levels were taken from Refs. 2 and 3. It was assumed in all cases that the initial state in the decay was completely aligned. For the large spins considered here, small admixtures of $P(\frac{3}{2})$ and $P(\frac{5}{2})$ do not change the angular distributions appreciably.

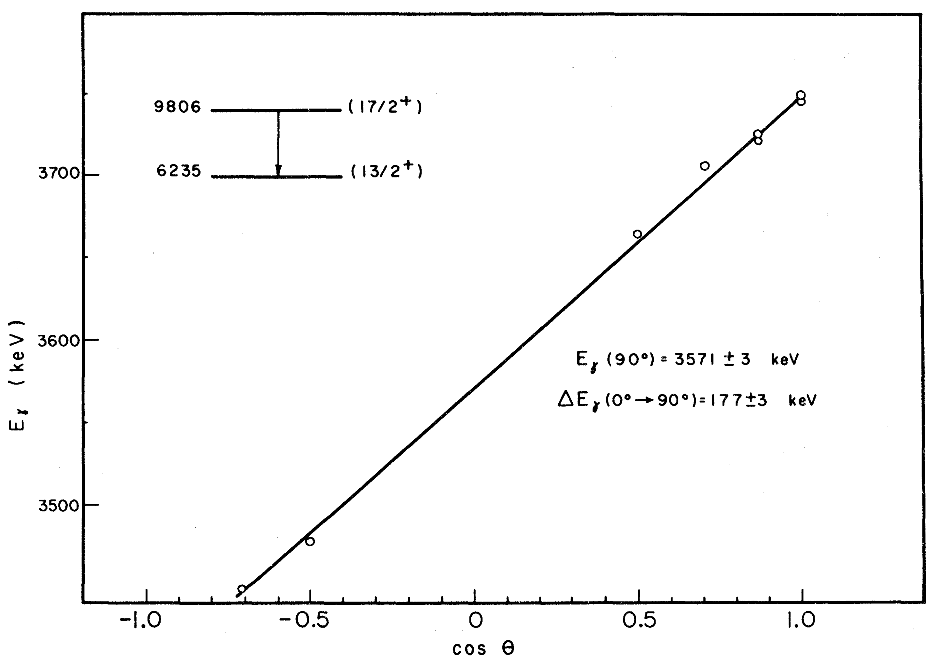

FIG. 7. A plot of the observed energy of the 9.806→ 6.235 transition as a function of the cosine of the detector angle. The errors on the measured points are about the size of the plotted points. The best fit straight line corresponds to $F(\tau) = 1.02 \pm 0.03$.

The results of the angular correlation measurements are summarized in Table I.

A. 9.042 MeV level

The 9.042 MeV level was observed to decay $(73 \pm 5)\%$ to the 6.235 MeV level (probably $J=\frac{13}{2}$) and $(27 \pm 5)\%$ to the 5.534 MeV state ($J=\frac{11}{2}$). The angular distribution of the unresolved $9.042 \rightarrow 6.235$ and $5.534 \rightarrow 2.705$ doublet is shown in Fig. 5. The effect of changing the mixing ratio of the (unobserved) $9.042 \rightarrow 5.534$ transition was found to be very small, and this parameter was fixed at 0. All other spins and mixing ratios were taken from Refs. 2 and 3. From this measurement, the spin of the 9.042 MeV level can be limited to $\frac{11}{2}$ or $\frac{15}{2}$. The angular correlation of the unresolved 9.042 $\rightarrow 5.534$ and $6.235 \rightarrow 2.705$ doublet was consistent with both of these spin assignments, and no further information could be obtained from this measurement.

B. 9.806 MeV level

The 9.806 MeV level was observed to decay only to the ($J=\frac{13}{2}$) level at 6.235 MeV. The angular distribution of the $9.806 \rightarrow 6.235 \rightarrow 2.705$ doublet is shown in Fig. 6. An acceptable fit is obtained for an assumed spin sequence of $\frac{17}{2} \rightarrow \frac{13}{2} \rightarrow \frac{9}{2}$ and pure quadrupole radiation, although other spins, as indicated in Table I, cannot be ruled out.

V. LIFETIME MEASUREMENTS

Two techniques were used in an attempt to measure lifetimes for the 9.042 and 9.806 MeV levels. Simultaneously with the angular correlation measurements, data were obtained for the Doppler shift as a function of angle. As mentioned before it was not possible to resolve the peaks of interest for angles near 90° but it was nevertheless possible to obtain data for both forward angles and for angles near 135°. Figure 7 shows a plot of E_γ versus $\cos\theta$ for the $9.806 \rightarrow 6.235$ transition, together with the best fit straight line for $F(\tau)=1.02 \pm 0.03$. The slowing down of the recoiling ^{23}Na ions was calculated using the Lindhard[6] theory, and corrections have been included for solid angle effects and for the second order Doppler effect. In this case, as well as for the case of primaries from the 9.042 MeV level, the data are consistent with $F(\tau)=1$ within approximately 3%. In the cases of the two primaries from the 9.042 MeV level there are contributions from unresolved secondaries but these secondaries arise from levels for which it is known that $F(\tau) \approx 1$.

In order to obtain a better limit on these lifetimes a second experiment was carried out using the backed-unbacked target technique in which a γ-ray detector at 0° was used to record the spectra alternately from a 40 $\mu g/cm^2$ carbon self-support-

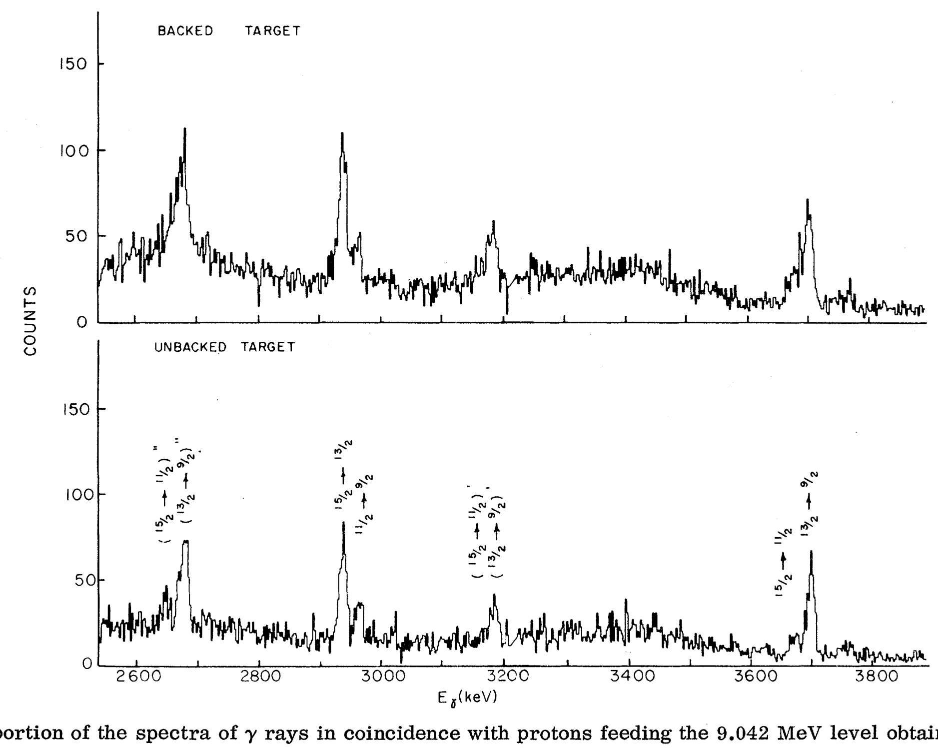

FIG. 8. A portion of the spectra of γ rays in coincidence with protons feeding the 9.042 MeV level obtained with backed and unbacked targets.

TABLE II. Measured lifetime limits for the 9.042 and 9.806 MeV levels in ^{23}Na.

E_i (MeV)	E_f (MeV)	$F(\tau)$	τ (fs)
9.042	5.534	0.995 ± 0.010	<10
	6.235	0.993 ± 0.008	
9.806	6.235	0.986 ± 0.015	<20

ing target and a 40 $\mu g/cm^2$ carbon target on a 0.125 mm gold backing. For the measurements with the unbacked target the beam was stopped on a 0.125 mm gold foil placed about 2 mm behind the target.

Spectra were measured alternately for about one hour on each target, and the gated data for each run were then summed to produce the spectra shown in Fig. 8 for the 9.042 MeV level. The total running time was approximately 24 h with an average target current of 200 nA. Similar data were obtained for the 9.806 MeV level. The existence of a measurable lifetime for the decaying state would result in the peak centroids being shifted to the left in the spectrum obtained with the backed target and, within the statistical accuracy of our data, no such shift was observed. The analysis of these data leads to the lifetime limits in Table II.

VI. DISCUSSION

The levels observed at $E_x = 9.042$ and 9.806 MeV in ^{23}Na have been tentatively identified by previous authors[1,2,7] as the $J^\pi = \frac{15}{2}^+$ and $\frac{17}{2}^+$ members of the $K = \frac{3}{2}$ ground state rotational band of ^{23}Na, and the results obtained in this work lend further support to this hypothesis. The spin of the 9.042 MeV level has been limited to either $J = \frac{11}{2}$ or $J = \frac{15}{2}$ in the present work. The lifetime measurement of $\tau < 10$ fs yields a reduced transition probability of $|M(E2)|^2 > 10$ W.u. (Weisskopf units) for the 9.042 → 5.534 transition, which is comparable to the values observed for the decays of the lower members of the band.[2,4] For the 9.042 → 6.235 transition, ($\delta = -0.03 \pm 0.07$) the reduced rate is $|M(M1)|^2 > 0.1$ W.u. This value for the mixing ratio compares extremely well with the value $|\delta| = 0.02$ expected for an in-band transition.[8]

The 9.806 MeV level was observed to decay only to the 6.235 MeV state, and the measured angular distribution is consistent with an assignment of $J = \frac{17}{2}$. The lifetime limit ($\tau < 20$ fs) gives a reduced rate of $|M(E2)|^2 > 18$ W.u. Assuming an $M1$ strength of about 0.2 W.u. for the 9.806 → 9.042 branch, the expected branching ratio for this decay is approximately 4%, which is consistent with our observation of less than a 5% branch.

†Work supported in part by a grant from the National Research Council of Canada.

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