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High spin states in ^{23}Na and the $E_{\text{c.m.}} = 19.3$ MeV ^{12}C + ^{12}C resonance

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Lifetime and angular correlation measurements of the γ decays of the 9.04- and 9.81-MeV levels in ^{23}Na have been performed. These results are consistent with the identification of these two states as the $\frac{15}{2}^+$ and $\frac{17}{2}^+$ members of the ^{23}Na ground state rotational band. These spins, together with other considerations, suggest $J^\pi = 12^+$ for the $E_{\text{c.m.}} = 19.3$ MeV ^{12}C + ^{12}C resonance.

[NUCLEAR REACTIONS ^{12}C(^{12}C, $p\gamma$), $E_{^{12}\text{C}} = 38.6$ MeV; measured $F(\tau)$, p-γ angular correlations, ^{23}Na deduced levels, τ, J, π.]

The recent discovery[1] of a narrow resonance ($\Gamma_{\text{c.m.}} \sim 400$ keV) in the ^{12}C + ^{12}C system at $E_{\text{c.m.}} = 19.3$ MeV has led to renewed interest in the nature of such structures in the continuum. The resonance was first observed in the ^{12}C(^{12}C, p)^{23}Na reaction[1] and was most apparent in the yields to two states at excitation energies of 9.04- and 9.81-MeV, respectively. Since then, observation of the resonance has also been reported in the ^{12}C(^{12}C, n)-^{23}Mg and ^{12}C(^{12}C, α)^{20}Ne reactions.[2,3]

Obviously crucial to any discussion of the nature of this resonance is a determination of its spin, and it is therefore important that the nature of the states populated in the decay of the resonance be determined as precisely as possible. Accordingly, we have studied the γ decays of the 9.04- and 9.81-MeV states in ^{23}Na populated in the ^{12}C(^{12}C, p)^{23}Na reaction at $E_{\text{c.m.}} = 19.3$ MeV. The lifetimes of these two states, which are quasibound, have been determined using the Doppler-shift attenuation method (DSAM). These results, together with angular correlation measurements of the decay γ rays, suggest $J^\pi = \frac{15}{2}^+$ and $\frac{17}{2}^+$ for the 9.04- and 9.81-MeV levels, respectively.

A target consisting of 51-μg/cm^2 natural carbon mounted on a thick gold backing was bombarded with a 38.6-MeV ^{12}C^{4+} beam from the Niels Bohr Institute tandem accelerator. Reaction protons were detected in a 1 mm annular silicon surface barrier detector centered at 180° with respect to the beam axis. The angular range subtended by the detector was from 168° to 177°. A nickel foil placed in front of the detector prevented α particles from the ^{12}C(^{12}C, α)^{20}Ne reaction and beam particles scattered from the target backing from striking the detector. γ rays were detected in time coincidence with protons in two large ($\sim$80 cm^3) Ge(Li) detectors mounted at 90° with respect to each other and movable with respect to beam axis. Proton singles spectra and coincident γ-ray spectra were collected event by event with an on-line computer. Digital windows were set on the two protons peaks of interest to obtain spectra of the γ rays originating from these levels. Spectra were recorded at angles of 0°, 45°, and 90° with both Ge(Li) counters.

Figure 1 shows a singles proton spectrum from one of the runs. The resolution was ~250 keV and was largely due to kinematic broadening. The 9.04- and 9.81-MeV levels, which dominate the spectrum at this bombarding energy, are clearly separated. Previous high resolution data indicate that no other levels in this excitation region are excited with appreciable intensity. The positions of the windows set on the two groups are also indicated.

Figure 2 shows γ-ray spectra obtained at 0° and 90° in coincidence with the proton groups corresponding to the 9.04- and 9.81-MeV levels. Lines identified as primary transitions from these levels and their branching ratios are shown in Fig. 3(a) and are listed in Table I. All other γ lines observed in coincidence with the two proton groups

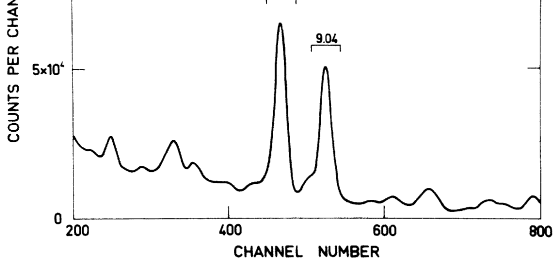

FIG. 1. Singles proton spectrum. The 9.04- and 9.81-MeV levels are indicated together with the windows set on these peaks.

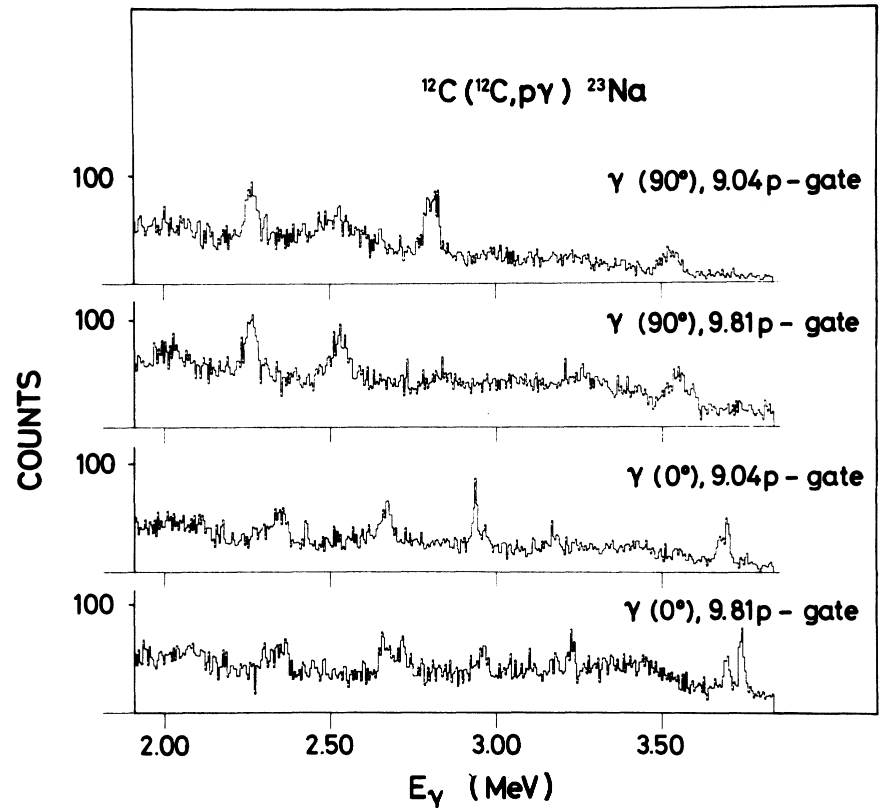

FIG. 2. γ-ray spectra in coincidence with the 9.04- and 9.81-MeV levels.

could be identified as arising from transitions within the ground-state band. Values for $F(\tau)$ for the 9.04- and 9.81-MeV levels were obtained from the 9.04 → 6.24-MeV and 9.81 → 6.24-MeV transitions, respectively, both of which were clearly resolved at 0° and 45°. The centroids obtained from the 90° spectra were also consistent with the above values. Further, the 90° energies were checked in a separate experiment in which the Ge(Li) detector was placed further from the target. All the above values (appropriately weighted) were incorporated in the final values for $F(\tau)$ given in Table I. The branching ratios were obtained from the measured angular distributions, except in the case of the 9.04 → 5.53-MeV transition which was only resolved from the neighboring 6.24 → 2.70-MeV transition at 0°. The angular distribution was therefore assumed to be pure quadrupole in shape.

The measured $F(\tau)$ were converted to mean lifetimes using $F(\tau)$ *versus* τ curves calculated for ^{23}Na ions slowing down in layers of carbon and gold, averaged over the thickness of the carbon and taking into account the effects of large angle scattering.[5] Electronic stopping powers were taken from the compilation of Northcliffe and Schilling[6] and atomic stopping, although unimportant at these high recoil velocities, was calculated according to the theory of Lindhard, Scharff, and Schiøtt.[7] The tabulated lifetimes include an uncertainty in the density of the carbon of ±0.25 g/cm^3 as well as the uncertainties in the measured $F(\tau)$. The deduced lifetimes are listed in Table I.

Figures 3(b) and 3(c) show the angular correlations measured for the 9.81 → 6.24-MeV and 9.04 → 6.24-MeV transitions together with calculations assuming pure quadrupole and dipole transitions, respectively.

The correlation for the transition from the 9.81-MeV level to the 6.24-MeV level [thought to be the $\frac{13}{2}^+$ member of the ground state band[8] although rigorously $J^\pi = (\frac{9}{2}, \frac{13}{2})^+$] shows the presence of a quadrupole γ ray. The $M2$ possibility can be discounted as the short lifetime implies an unreasonably high transition strength [>1000 Weisskopf unit (W.u.)], and thus fixes the parity as positive and, if $J(6.24) = \frac{13}{2}$, the possible spin values from $\frac{9}{2}$ to $\frac{17}{2}$.

The 9.04-MeV level decays to the 6.24-MeV ($J^\pi = \frac{13}{2}^+$) and 5.53-MeV ($J^\pi = \frac{11}{2}^+$)[9] levels. The correlation for the transition to the 6.24-MeV level shows a dipole contribution, thereby limiting the spin possibilities to $J = \frac{15}{2} \rightarrow \frac{11}{2}$. The lifetime measurement further limits the spin-parity possibilities to $J^\pi = \frac{15}{2}^+, \frac{13}{2}^\pm, \frac{11}{2}^\pm$.

The above limits on the spin of the 9.04- and

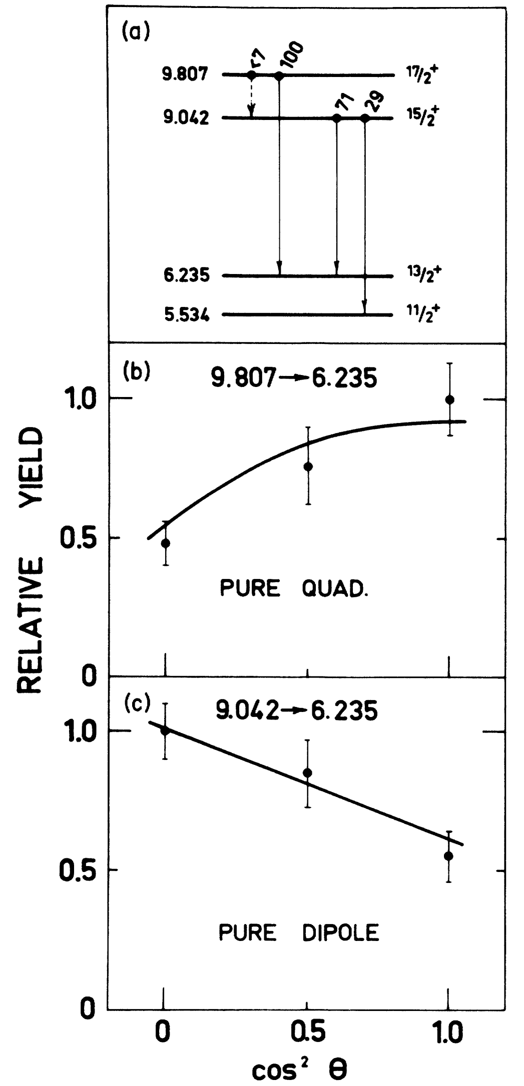

FIG. 3. (a) Branching ratios of γ decays from the 9.04- and 9.81-MeV levels. (b) Angular correlation for the 9.81 → 6.24-MeV transition. (c) Angular correlation for the 9.04 → 6.24-MeV transition.

9.81-MeV levels, together with their excitation energies and decay schemes, suggest that they should be identified as the $\frac{15}{2}^+$ and $\frac{17}{2}^+$ members of the ^{23}Na ground-state band. The reduced transition probabilities for the $E2$ transitions show quite nice agreement with the simple rotational model predictions [calculated from the measured $B(E2)$ for the $\frac{7}{2}^+ \rightarrow \frac{3}{2}^+$ transition] which are given in Table I. Additionally, if the 9.04 → 6.24-MeV transition is pure $M1$, we obtain $B(M1) = 0.09^{+0.53}_{-0.04}$ W.u., in fair agreement with the calculated value of 0.22 given in Ref. 8.

As mentioned earlier, the primary interest in the 9.04- and 9.81-MeV levels arises as a result of their preferential population in the decay of the $E_{\mathrm{c.m.}} = 19.3$ MeV ^{12}C + ^{12}C resonance, and the hope that a knowledge of their spin-parities will shed some light on the spin of the resonant state in ^{24}Mg. The resonance must have $J^\pi = \text{even}^+$, a constraint imposed by the identical bosons in the entrance channel, and the barrier penetrabilities in this channel limit the possible spin values to $J \leq 14$. In the proton decay of the resonance, the $J^\pi = (\frac{15}{2})^+$ and $(\frac{17}{2})^+$ members of the ^{23}Na ground state band are strongly populated, whereas the $J^\pi = \frac{11}{2}^+$, $(\frac{13}{2})^+$ and lower members of this band do not show the resonance. The l value of the decays to the $(\frac{15}{2})^+$ and $(\frac{17}{2})^+$ states must be ≤ 4. (The total cross sections for these decays lead to a minimum value for the proton width of the resonance which is an order of magnitude larger than the single-particle value for a $l = 6$ proton). The absence of the resonance in the yields to the $\frac{11}{2}^+$ and $(\frac{13}{2})^+$ states suggests that the spin of the resonance is such that a $l_p = 4$ decay to these states is forbidden by conservation of angular momentum. These states, being members of the ground-state band, have a similar intrinsic structure to the 9.04- and 9.81-MeV levels and would therefore be expected to show the resonance if a $l_p = 4$ decay was allowed. The above considerations therefore suggest a J^π

TABLE I. Branching ratios and lifetimes obtained for the decays of the 9.04- and 9.81-MeV levels.

E_i (keV)	E_f (keV)	Branch (%)	$F(\tau)$	τ_m [a] (fs)	$B(E2)$ (W.u.) Exp.	Calc [b]
9807 ± 3	6235	100	0.962 ± 0.012	12 ± 8	30^{+60}_{-12}	30
	9042	<7				
9042 ± 2	6235	71 ± 7	0.966 ± 0.014	11^{+8}_{-9}		
	5534	29 ± 7 [c]			10^{+50}_{-5}	29

[a] The errors given for τ_m correspond to two standard deviations in $F(\tau)$ plus the uncertainty in $\rho(^{12}\mathrm{C})$.

[b] Calculated assuming that these are the $\frac{17}{2}^+$ and $\frac{15}{2}^+$ members of the ground state rotational band and using $B(\frac{7}{2}^+ \rightarrow \frac{3}{2}^+) = 14$ W.u.

[c] Assumed angular distribution.

$=12^+$ assignment for the resonant state in ^{24}Mg.

In conclusion, we have measured the lifetimes and γ decays of the 9.04- and 9.81-MeV states in ^{23}Na, and propose them to be the $J^\pi=\frac{15}{2}^+$ and $\frac{17}{2}^+$ members of the ground-state band, respectively. This, together with other considerations lead to a suggested $J^\pi=12^+$ for the $E_{\text{c.m.}}=19.3$ MeV ^{12}C $+^{12}$C resonance. Finally, we note that this resonance lies ~2 MeV below the combined Coulomb and centrifugal barriers for $L=12$ in the ^{12}C$+^{12}$C system, suggesting that it may be related in some way to the low-spin subbarrier resonances of Almqvist, Bromley, and Kuehner.[10]

Note added: Since the completion of the present work, the results of a similar study have appeared[11] in which additional branches for both the 9.04- and 9.81-MeV levels are reported. The present data are not sufficient to confirm or deny these results. However, the lifetimes and spin-parity limits from the present work are not affected except that the $\frac{17}{2}^+$ possibility would be ruled out for the 9.81-MeV level.

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