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High-J states in ^{23}Na

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The ^{12}C(^{12}C,p) reaction, at a bombarding energy of 39.0 MeV, has been used to locate candidates for high-spin states. Angular distributions and angle-integrated cross sections are presented for 43 levels (or groups of levels) of which at least 10 probably have $J \geq \frac{9}{2}$.

The nucleus ^{23}Na has been the subject of many investigations, with a variety of reactions.[1-8] And yet, very few levels above 6.5 MeV excitation have unique J^{π} assignments. In particular, several high-spin states that are expected have not yet been located. We have used the ^{12}C(^{12}C,p)^{23}Na reaction to search for candidates for such high-J states.

The experiment was performed with a 39.0-MeV beam of ^{12}C from the University of Pennsylvania tandem Van de Graaff accelerator. Outgoing protons were momentum analyzed in a multiangle spectrograph and detected in nuclear-emulsion plates. Mylar foils in the focal plane stopped all particles heavier than protons. The target was a 6-μg/cm^2 self-supporting foil of enriched (99.99%) ^{12}C. The use of such a thin target enabled good resolution, despite the large stopping power of ^{12}C ions.

Data were collected at 11 angles from 7.5° (lab) to 90° in steps of 7.5°. A typical spectrum is displayed in Fig. 1. Overall resolution (full width at half maximum) is about 40 keV. Excitation energies were obtained from observed peak positions and the known magnet calibration. These are listed in Tables I and II along with values from the literature. States up to just above 9.0 MeV excitation were analyzed at all angles. Their angular distributions are displayed in Figs. 2 and 3, and the angle-integrated (0°–90°) cross sections are listed in Tables I and II.

Table I contains results for states with unique J^{π} assignments. The grazing partial wave in the ^{12}C + ^{12}C

TABLE I. Results of ^{12}C(^{12}C,p)^{23}Na for states of known spin and parity.

Present	Previous[a]		σ_{tot}[b]	$\frac{\sigma_{\text{tot}}}{2J+1}$	
E_x (keV)	E_x (keV)	J^{π}	(μb)	(μb)	$\frac{\sigma(^{12}\text{C,p})^{c}}{\sigma(\text{d},\alpha)}$
0.0	0.0	$\frac{3}{2}^+$	82±6	20.5±1.5	0.66±0.05
433±4	439.8±0.15	$\frac{5}{2}^+$	83±7	13.8±1.2	0.43±0.04
2073±4	2076.4±0.3	$\frac{7}{2}^+$	126±7	15.8±0.9	0.55±0.05
2390±7	2390.9±0.3	$\frac{1}{2}^+$	46±4	23.0±2.0	1.27±0.18
2657±7	2639.8±0.3	$\frac{1}{2}^-$	54±5	27.0±2.5	1.24±0.11
2700±4	2703.7±0.4	$\frac{9}{2}^+$	124±6	12.4±0.6	0.51±0.03
2982±4	2982.4±0.2	$\frac{3}{2}^+$	85±6	21.3±1.5	0.75±0.06
3674±4	3678.3±0.4	$\frac{3}{2}^-$	62±5	15.5±1.3	0.82±0.09
3859±5	3848.2±0.8	$\frac{5}{2}^-$	101±6	16.8±1.0	0.58±0.04
3911±4	3914.7±0.5	$\frac{5}{2}^+$	95±6	15.8±1.0	0.77±0.07
4417±10	4432.0±0.8	$\frac{1}{2}^+$	40±5	20.0±2.5	0.79±0.11
4769±4	4775.6±0.5	$\frac{7}{2}^+$	129±7	16.1±0.9	0.76±0.04
5384±5	5377 ±2	$\frac{5}{2}^+$	70±5	11.7±0.8	0.47±0.04
5530±4	5533 ±3	$\frac{11}{2}^+$	380±12	31.7±1.0	1.44±0.08
6350±4	6305.5±0.6	$\frac{1}{2}^+$	294±10	24.5±0.8	0.72±0.03
	6348 ±3	$\frac{9}{2}^-$			

[a] Reference 1.

[b] $\sigma_{\text{tot}}=2\pi\int_{0^\circ}^{90^\circ}\sigma(\theta)\sin\theta\,d\theta$.

[c] (d,α) results from Ref. 2.

TABLE II. $^{12}C(^{12}C,p)^{23}Na$ results for additional levels.

Present	Previous		σ_{tot}	
E_x (keV)	E_x (KeV)	J^π	(μb)	$\frac{\sigma(^{12}C,p)}{\sigma(d,\alpha)}$
5754±6	5741 ±2	$(\frac{3}{2},\frac{5}{2})^+$	65±5	0.29 ±0.02
	5766 ±2	$(\frac{1}{2}^+-\frac{5}{2}^+)$		
	(5781 ±8)			
5943±7	5929 ±3	$(\frac{1}{2},\frac{3}{2})^-$	119±6	0.52 ±0.03
	5967 ±2			
6032±5	6042 ±2	$(\frac{3}{2}-\frac{7}{2}^-)$	102±6	0.61 ±0.04
6113±3	6117 ±3	$(\frac{5}{2}^+-\frac{11}{2}^+)$	1103±20	2.99 ±0.14
6229±4	6193 ±3	$(\frac{3}{2}-\frac{7}{2}^+)$	345±10	0.89 ±0.06
	6237 ±3	$(\frac{9}{2},\frac{13}{2})^+$		
6350±4	6305.5±0.6	$\frac{1}{2}^+$	294±10	0.72 ±0.03
	6348 ±3	$\frac{9}{2}^-$		
6582±7	6577 ±2	$(\frac{5}{2},\frac{9}{2}^+)$	82±6	0.44 ±0.05
6610±8	6617 ±2		84±5	0.55 ±0.04
6730±7	6733 ±2	$(\frac{3}{2},\frac{5}{2})^+$	51±4	0.54 ±0.04
6825±8	6819 ±2		55±4	0.43 ±0.04
6874±6	6866 ±2	$(\frac{3}{2},\frac{5}{2})^+$	83±5	0.46 ±0.05
6936±6	6918 ±2	$\frac{3}{2}^-$	110±6	0.75 ±0.05
	6946 ±2	$(\frac{1}{2}^+-\frac{5}{2}^+)$		
7075±4	7070 ±2	$(\frac{3}{2}-\frac{7}{2}^+)$	151±7	0.76 ±0.06
	7080 ±2	$\frac{3}{2}^-$		
7119±5	7122 ±3	$\frac{5}{2}^+$	185±8	0.48
	7132 ±2			
7176±8	7166 ±5		122±6	0.74
	7185 ±3			
7272±3	7267 ±3		835±17	2.17
	7273 ±2			
7398±4	7393 ±2		655±15	1.24 ±0.19
	7412 ±3			
	7448 ±2	$\frac{5}{2}^+$		
	7489 ±2	$(\frac{1}{2},\frac{3}{2}^-)$		
7566±3	7563 ±2		121±6	1.252±0.13
7697	7685 ±3		218±8	0.64 ±0.04
	7720 ±2	$(\frac{1}{2},\frac{5}{2}^+)$		
	7747 ±3			
7863±6	7833 ±3		344±10	0.65
	7872 ±2			
	7888 ±2	$\frac{5}{2}^+;\frac{3}{2}$		
7987±6	7965 ±2		274±10	
	7990 ±3			
8068±4	8061 ±3		112±6	
	8106 ±7			
	8128 ±6			
	8155 ±5			
	8178 ±6			

TABLE II. (*Continued*).

Present E_x (keV)	Previous E_x (KeV)	 J^π	σ_{tot} (μb)	$\frac{\sigma(^{12}\text{C,p})}{\sigma(\text{d},\alpha)}$
8326±4	8226 ±5		532±13	
	8260 ±3			
	8300 ±2			
	8329 ±3			
	8359 ±3	$(\frac{3}{2}^+ - \frac{7}{2}^+)$		
8483±4	8416 ±3		212±8	
	8469 ±3	$(\frac{3}{2},\frac{5}{2})^+$		
	8505 ±3			
8633±5	8560 ±3		249±9	
	8610 ±3			
	8630 ±3			
	8648 ±3			
8722±12	8663 ±2	$\frac{1}{2}^+;\frac{3}{2}$	95±6	
	8720 ±3			
	8799 ±3			
8839±15	8822 ±3	$\frac{1}{2}^+$	300±9	
	(8862)			
	(8894)			
8965±9	8945 ±3	$\frac{7}{2}^-$	344±10	
	8972 ±3			
9051±7	(9000)		1550±30	
	9041 ±2			
	9072 ±3			

channel at this energy is 10 or 12, whereas the outgoing proton can carry out only l's up to about 4. Thus, in a statistical compound-nucleus reaction, we might expect high-J final states to be greatly favored. We use this expectation to locate candidates for high-J states. In fact, we may loosely define such a candidate (to have $J \geq \frac{9}{2}$) as one having $\sigma_{\text{tot}} \gtrsim 150\ \mu$b.

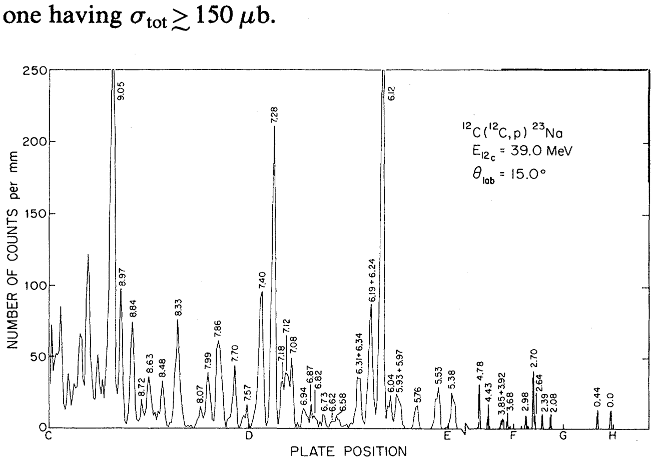

FIG. 1. Spectrum of the reaction ^{12}C(^{12}C,p)^{23}Na at a bombarding energy of 39.0 MeV and a laboratory angle of 15.0 deg.

States below 9.07 MeV and not given in Table I are listed in Table II, along with available information on J^π and results of the present experiment. Clearly, a few of the states, e.g., those at 6.12, 7.20, and 9.05 MeV, are greatly enhanced in the present ^{12}C(^{12}C,p)^{23}Na reaction study. Their cross sections are much too large to be a measure of J_f, unless J is very large. In fact, it was in this reaction that the resonant behavior[9] of these states was first noted. We thus slightly rearrange our earlier definition to read: If $\sigma_{\text{tot}} > 150\ \mu$b, then likely $J \gtrsim \frac{9}{2}$ or the state resonates at 39.0 MeV in ^{12}C(^{12}C,p).

Of course, most peaks in the present work above 6.5 MeV contain two or more levels, so the criteria should be relaxed somewhat. Our 6.23-MeV group, with $\sigma_{\text{tot}} = 345\ \mu$b, contains two known states, one at 6.19 MeV with $J^\pi = \frac{3}{2} - \frac{7}{2}^+$, the other at 6.24 MeV with $J^\pi = (\frac{9}{2},\frac{13}{2})^+$. For any value $J = \frac{3}{2} - \frac{7}{2}$ for the lower member, our cross section would suggest $J = \frac{9}{2}$, not $\frac{13}{2}$, for the upper member. We return to this point later. We can use a comparison between (d,α) (Ref. 2) and (^{12}C,p) results to look for states that are enhanced in the present reaction. The last column of both Tables I and II lists $\sigma_{\text{tot}}(^{12}\text{C,p})/\sigma_{\text{tot}}(\text{d},\alpha)$. We note enhanced ratios for some $J = \frac{1}{2}$ states and for the $J = \frac{11}{2}$ state at 5.53 MeV, as well as for the 6.12- and 7.27-MeV levels mentioned earlier.

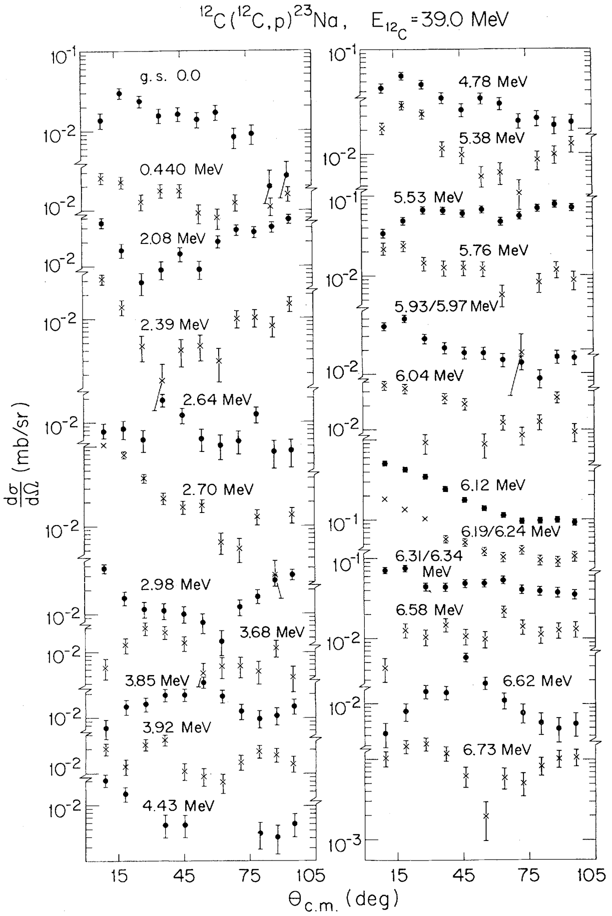

FIG. 2. Angular distributions for ^{12}C(^{12}C,p)^{23}Na, at $E(^{12}C)=39.0$ MeV, for levels of ^{23}Na with $E_x < 6.8$ MeV.

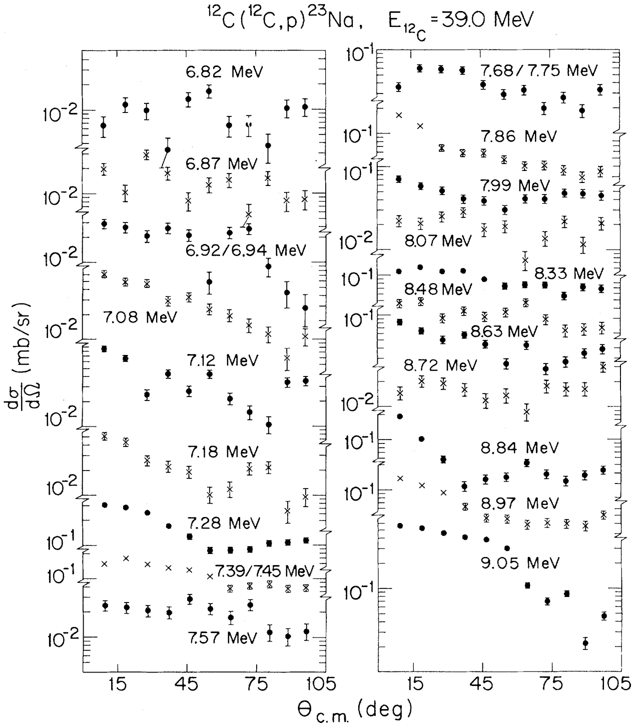

FIG. 3. Same as Fig. 2, but with $E_x = 6.8-9.1$ MeV.

As pointed out above, the present results favor $\frac{9}{2}$, rather than $\frac{13}{2}$, for the 6.24-MeV state. In (d,α), this level was weaker than expected for a $\frac{13}{2}^+$ state, but the data are consistent for $J=\frac{9}{2}$. If this state is not $\frac{13}{2}^+$, the only other nearby candidate is at 6.12 MeV. This state is very strong in (d,α) and in (^{12}C,p), and may indeed be a doublet of high-J states.

Below 8.0 MeV, the shell model predicts 11 levels with $J \geq \frac{9}{2}$, five with $J^\pi = \frac{9}{2}^+$, four with $J^\pi = \frac{11}{2}^+$, and two with $J^\pi = \frac{13}{2}^+$. Combined results of (d,α) and (^{12}C,p) locate only eight candidates if the 6.12-MeV level is a high-J doublet, and seven otherwise. Kekelis *et al.*[5] have suggested $J^\pi = \frac{13}{2}^+$ for a state at 7.267 MeV, which is probably to be identified with our 7.27-MeV state, and with a theoretical $\frac{13}{2}^+$ level at 7.313 MeV. The ^{12}C(^{15}N,α) reaction results[6,7] suggested $J^\pi = \frac{13}{2}^+$ for a level at 8.32 MeV, probably to be identified with a $\frac{13}{2}^+$ shell-model state at 8.429 MeV. Our results are not in disagreement with such an assignment. Locations of the other high-J states below 8 MeV remain a mystery.

Our results strongly suggest $J \geq \frac{15}{2}$ for one number of the 9.05-MeV doublet. We note that the first $\frac{15}{2}^+$ shell-model state is at 9.001 MeV, with a second one very close by, at 9.548 MeV.

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