Use of energy-averaged cross sections for nuclear spectroscopy: ^{26}Mg states in the continuum

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Energy averaged cross sections for the $^{12}C(^{18}O,\alpha)^{26}Mg$ reaction were studied. Over 80 states between $E_x(^{26}Mg)=5$ and 20 MeV were observed for many bombarding energies in the range $E(^{18}O)=46$–50 MeV. Broad, noncorrelated structures observed in the excitation functions prevent the application of Hauser-Feshbach analysis for spin spectroscopy to this particular data set. By implication, our results cast doubt on the previously suggested backbend in the ^{26}Mg yrast sequence.

The investigation of highly excited states in the continuum of medium weight nuclei has been of special interest in recent years due to the suitability of heavy ion compound reactions for the selective population of high spin states.[1-4] Several techniques have been systematically exploited for nuclear yrast spectroscopy. Particle-particle correlations[5] have been studied in a few cases and permit unique spin assignments typically through $J \simeq 8\hbar$. In many more cases the analysis of angular distributions within the Hauser-Feshbach formalism has led to a number of tentative spin assignments in some cases reaching $J = 12\hbar$. The application of this latter method must be carried out with proper attention to the statistical characteristics of the reaction mechanism. In practical cases, this generally limits the method to reactions with high channel spin or to the observation of very high spin states near $\theta_{c.m.}=90°$. Either of these conditions guarantees that a large number of fluctuating amplitudes contribute to the observed cross section with a consequent damping of the Ericson fluctuations of the cross section. Even in the most favorable cases, a careful statistical fluctuations analysis reveals that spins inferred with this method are correct at the 75% probability level. The prudent approach, therefore, has been to regard spins assigned in this manner as reliable within $\pm 1\hbar$.

An alternative approach has been applied in cases where the channel spin is low. Excitation functions measured at relatively forward angles are used to produce energy averaged cross sections which when compared with Hauser-Feshbach predictions can be used to infer unknown spins. Aside from the obvious fact that this method must be carefully calibrated against a large set of states of known spin it is essential that the experimental energy averaging interval be large compared to the characteristic width of the Ericson fluctuations (Γ). A typical experimental procedure, therefore, has been to choose a beam energy stop size comparable to the fluctuation width such that each measured point is statistically independent. In cases where the fluctuation width is not directly measured, extensive systematics (Ref. 6) can be used to estimate Γ.

The structure of ^{26}Mg at high spin is a subject of particular interest due to the reported occurrence of a backbend in the yrast sequence at the rather low spin $J = 6\hbar$ while no corresponding backbend is observed in ^{24}Mg through $J = 10\hbar$ and possibly $J = 12\hbar$. The ^{26}Mg backbend was proposed in Ref. 7 based on spin assignments made using energy averaged cross sections for the $^{12}C(^{18}O,\alpha)^{26}Mg$ reaction in the range $43.2 < E(^{18}O) < 45.9$ MeV. Motivated by the striking reported difference between ^{26}Mg and ^{24}Mg we have reinvestigated the $^{12}C(^{18}O,\alpha)^{26}Mg$ reaction using a wider energy averaging interval so as to improve the energy averaged cross sections. We have also expanded the range of excitation energies studied to $E_x(^{26}Mg) \lesssim 20$ MeV.

In the present work we report the observation of ~ 80 excited states in ^{26}Mg (see Fig. 1). A self-supporting, natural C target of ~ 10 μg/cm^2 thickness was bombarded with an ^{18}O beam from the University of Rochester tandem accelerator. α particles were observed in the focal plane of a split-pole magnetic spectrograph by means of a $[\Delta E - E]$ position sensitive proportional counter. The energy calibration was performed using the low lying ^{24}Mg states from the

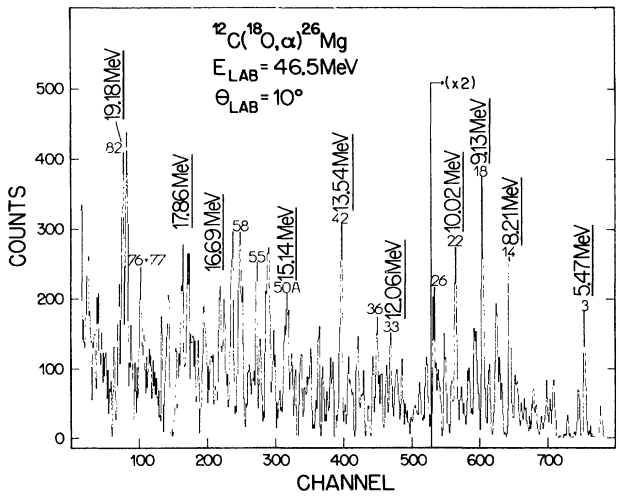

FIG. 1. Typical background subtracted spectrum of the $^{12}C(^{18}O,\alpha)^{26}Mg$ reaction. The α continuum has been fitted by means of a fifth order polynomial.

$^{12}C(^{16}O,\alpha)$ reaction as well as previously known low lying ^{26}Mg states by means of the $^{12}C(^{18}O,\alpha)$ reaction. The overall resolution was of the order of 60 keV (see Fig. 1).

Excitation functions were measured for most of the observed transitions in the 46 MeV $< E(^{18}O) < 50$ MeV bombarding energy interval, in $\Delta E(^{18}O) = 300$ keV steps (see Table I and Fig. 2). It is important to notice that this step value is comparable to the Ericson width [see Figs. 2(a)–2(c)].

Absolute cross sections were obtained by remeasuring, at the University of São Paulo Pelletron accelerator, the $^{12}C(^{18}O,\alpha)$ spectra as well as the $^{12}C+^{18}O$ elastic scattering at bombarding energies near the Coulomb barrier using $\Delta E - E$ silicon detector telescopes. The α continuum of the spectra was used to normalize the spectrograph with respect to the telescope spectra.

Averaged absolute cross sections were obtained for most of the transitions and are listed in Table I. These cross sections were compared to the values published in Ref. 7 and show serious discrepancies for most of the reported levels. These discrepancies are *not,* however, the result of an overall cross section normalization error in either experiment. Indeed, the total cross section for all states $E_x \lesssim 12$ MeV are in acceptable agreement. Inspection of the excitation functions in Figs. 2(a)–2(c) immediately reveals the origin of the average cross section discrepancy between Ref. 7 and the present work. Most of the observed transitions exhibit broad structures in their energy dependence with $\Gamma >> \Gamma_{\text{Ericson}}$. Noting in particular that the cross section scale in Figs. 2(a)–2(c) is logarithmic, it is clear that the measured average cross sections will depend sensitively on the energy interval chosen. In several cases the widths of the broad structures approach a significant fraction of the entire energy interval studied.

The origin of these broad structures, which for the most part are uncorrelated from channel to channel, is unknown. For the present purpose, it is sufficient to note that their presence indicates nonstatistical contributions to the $(^{18}O,\alpha)$ reaction. Similar broad structures have already been reported in the reactions $^{10}B(^{16}O,\alpha)$,[9] $^{12}C(^{15}N,\alpha)$,[10,11] and $^{12}C(^{16}O,\alpha)$.[12]

The influence of the broad structures on the analysis of

TABLE I. Cross sections for the reaction $^{12}C(^{18}O,\alpha)^{26}Mg$.

Level number	E^* (MeV)[a]	E^* (MeV)[b]	$\left\langle \frac{d\sigma}{d\Omega} \right\rangle_{\text{exp}} \times 10^{-2}$ (mb/sr)	Level number	E^* (MeV)[a]	E^* (MeV)[b]	$\left\langle \frac{d\sigma}{d\Omega} \right\rangle_{\text{exp}} \times 10^{-2}$ (mb/sr)
3	5.47 ± 0.01	5.473	1.49	A	14.57 ± 0.02	14.56[c]	6.75
4	5.71 ± 0.02	5.716	0.77	48	14.70 ± 0.02	14.70[c]	7.04
5	6.14 ± 0.03	6.126		49	14.87 ± 0.03	14.86[c]	
6	6.62 ± 0.02	6.616	1.31	50A	15.14 ± 0.03	15.14[c]	10.68
10	7.37 ± 0.03	7.41	1.86	51	15.31 ± 0.03	15.35[c]	5.49
13	7.98 ± 0.03	7.944	3.81	52	15.46 ± 0.02	15.46[c]	7.14
14	8.21 ± 0.02	8.188	4.43	53	15.59 ± 0.03	15.56[c]	
16	8.66 ± 0.03	8.694	5.28	54	15.84 ± 0.03	15.84[c]	4.88
17	8.93 ± 0.02	8.918	1.99	55	15.96 ± 0.04	15.98[c]	12.70
18	9.13 ± 0.02	9.156	3.39	57	16.32 ± 0.04	16.35[c]	11.25
19	9.37 ± 0.06	9.30[c]	5.00	58	16.42 ± 0.03		
20	9.60 ± 0.02	9.564	3.95	59	16.60 ± 0.03		
21	9.84 ± 0.02	9.841	2.74	60	16.75 ± 0.03		7.52
22	10.02 ± 0.02	10.028	5.81	61	16.90 ± 0.04		13.15
23	10.14 ± 0.02	10.118		62	17.12 ± 0.02		2.80
24	10.37 ± 0.02	10.358	4.35	63	17.35 ± 0.04		5.59
26	10.71 ± 0.03	10.74[c]		64	17.50 ± 0.04		9.70
27	10.96 ± 0.02	10.96[c]	5.09	65	17.64 ± 0.04		
28	11.16 ± 0.03	11.16[c]	5.44	66	17.74 ± 0.05		
31	11.72 ± 0.01	11.77[c]	2.17	67	17.86 ± 0.04		10.40
32	11.92 ± 0.02	11.94[c]	5.71	68	18.01 ± 0.04		8.72
33	12.06 ± 0.02	12.03[c]	6.61	69	18.11 ± 0.05		
34	12.20 ± 0.01	12.20[c]	2.91	70	18.18 ± 0.05		9.20
36	12.51 ± 0.02	12.53[c]		71	18.22 ± 0.07		4.83
37	12.59 ± 0.02	12.63[c]		72	18.31 ± 0.06		11.23
38	12.75 ± 0.02		2.83	73	18.54 ± 0.03		9.27
39	12.88 ± 0.03	12.88[c]		74	18.65 ± 0.06		2.99
40	13.04 ± 0.02	13.06[c]	6.66	75	18.72 ± 0.04		8.91
B	13.21 ± 0.03	13.19[c]	4.64	78	18.93 ± 0.05		
41	13.31 ± 0.02	13.35[c]	5.01	79	19.03 ± 0.09		
42	13.54 ± 0.02	13.52[c]	11.41	82	19.18 ± 0.04		12.83
43	13.83 ± 0.02	13.85[c]		83	19.27 ± 0.04		10.51
44	14.07 ± 0.02	14.08[c]	8.58				
45	14.17 ± 0.03	14.14[c]	11.68				
46	14.44 ± 0.01	14.50[c]					

[a]Present work.
[b]Values from Ref. 8.
[c]Values from Ref. 7.

the present data for spin assignments in ^{26}Mg is shown in Fig. 3. Here, we plot the observed energy averaged cross sections versus excitation energy in ^{26}Mg. The solid error bars on each point reflect the experimental uncertainties in the measured cross sections while the narrow vertical bar reflects the observed variance of the experimental excitation functions. In the present case, where structures with widths comparable to the entire energy interval are observed, it is more appropriate to regard the observed variance $\delta = \Delta[\sigma(E_B^*,J)]/\sigma(E^*,J)$ as the uncertainty in the energy averaged cross section.

An uncertainty in the energy-averaged cross section is related within the Hauser-Feshbach formalism to an uncertainty in the spin which can be assigned to a particular state. The relevant theoretical factor is the reaction selectivity

$$S = \frac{d}{dJ}\left[\frac{d\sigma}{d\Omega}(E^*,J)\right] \text{ mb/sr}\hbar \ ,$$

or

$$s = \frac{S}{(d\sigma/d\Omega)(E^*,J)}\hbar^{-1} \ ,$$

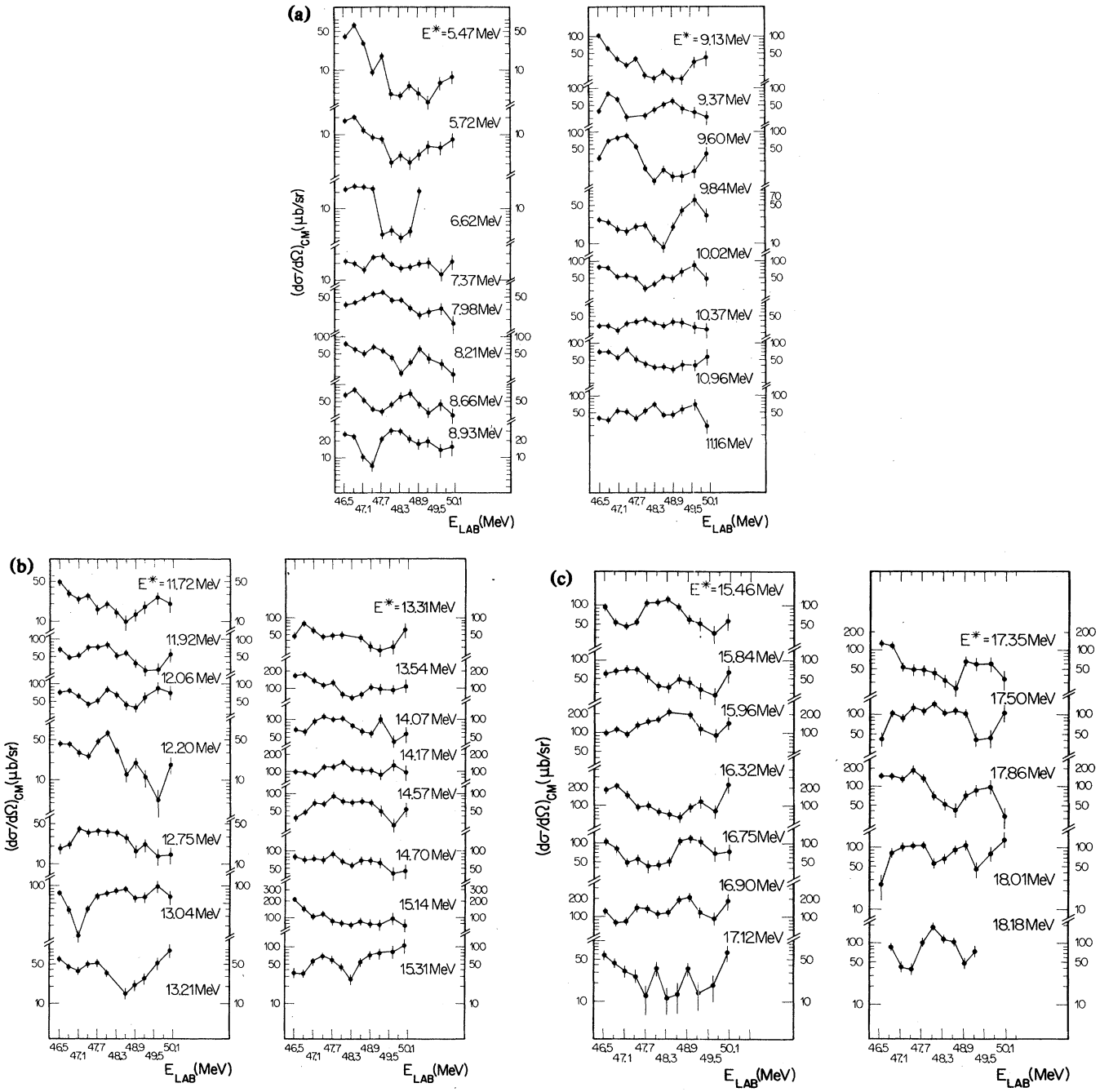

FIG. 2. (a)–(c) Experimental excitation functions for some of the observed transitions.

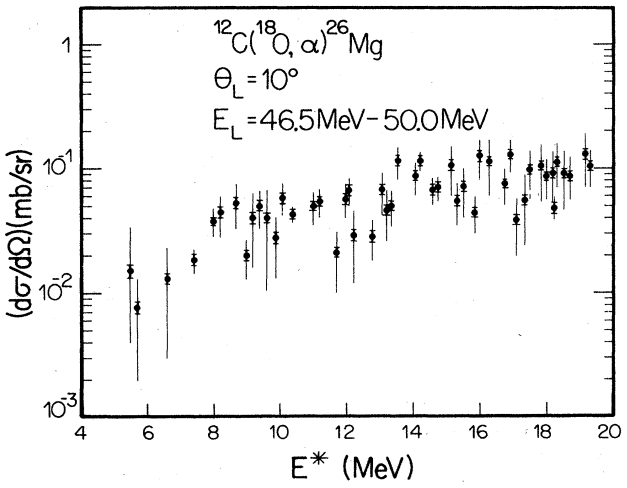

FIG. 3. Energy averaged cross sections for the observed transitions to ^{26}Mg states. The solid error bars reflect the experimental uncertainties and the narrow vertical bars reflect the observed variance of the experimental excitation functions.

which measures the sensitivity of the cross section to variation of the spin J.

For the present reaction, the selectivity is only moderate with the result that the uncertainties shown in Fig. 3 correspond to a rather broad acceptable spin range for most states. Hauser-Feshbach calculations performed with CODE STATIS[13] and model parameters from Ref. 14 indicate that for this reaction, the selectivity $S(E^* = 5.47$ MeV, $J = 4^+) \simeq 1.8$ mb/sr$\cdot\hbar$ and $s = 100\%/\hbar$ since $\sigma(5.47$ MeV, $4^+) \sim 1.8$ mb/sr. The uncertainties δ attributed to the averaged cross sections are of the order 100%–300% (and consequently $\delta > s$); the comparison of the experimental data with the Hauser-Feshbach predictions is of no help for spectroscopic purposes. Furthermore, the spin assignments made in Ref. 7 using the same reaction reported here cannot be supported by the present data.

We conclude that the presence of a backbend in ^{26}Mg is in doubt and deserves further investigation. More reliable spin attributions are permitted if energy-averaged angular distributions as well as double (or triple) particle-particle correlations measurements are carried out. It has been shown[4] that the anisotropy of high spin states angular distributions can be sensitive to the final state angular momentum in cases where the effective number of channels is significant.

We emphasize that the present results are not universal. The breakdown of the utility of energy-averaged compound nucleus cross sections for high spin spectroscopy occurs in the present case as a result of the rather low selectivity of this reaction. Some reactions, e.g., $^{12}C(^{16}O,\alpha)$ exhibit a selectivity nearly 10 times that encountered here. In such cases the broad oscillations reported here are much less significant.

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