Low-lying states in ^{17}C from a multi-channel algebraic scattering theory

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Abstract. The structure of ^{17}C is used to define a nuclear interaction that, when used in a multichannel algebraic scattering theory for the $n+$ ^{16}C system, gives a credible definition of the (compound) excitation spectra. When couplings to the low-lying collective excitations of the ^{16}C-core are taken into account, both sub-threshold and resonant states about the $n+$ ^{16}C threshold are found.

The spectra of radioactive nuclei, especially of masses at or just beyond a drip line, are most intriguing. To date, details of their spectra are at best poorly known. Few, if any, excited states have been identified. Likewise, the spin-parities of known states have not been, or are uncertainly, assigned. Nowadays, opportunities exist to investigate spectra of such exotic systems using isotope separator on-line facilities with which production of radioactive ion beams having energies typically $0.1A$ to $10A$ MeV is possible. Reactions using these beams with higher incident energy can be, and have been, used to study the structure of the radioactive ions as well. However, it is the low energy domain that interests us as we wish to consider structures of compound systems formed by amalgamation of the beam ion and a nucleon.

With light mass systems having charge number π and neutron number ν, there is often the possibility to link the structures of mirror systems. Usually there is a reasonably well known spectrum of a nucleus $({}^{A+1}_{\pi=Z}X_{\nu=N+1})$, which we treat as a compound of a neutron (n) with ${}^{A}_{\pi=Z}X_{\nu=N}$ to define a chosen nuclear model interaction. With that model, assuming charge invariance of the nuclear force and adjusting for Coulomb effects, the spectrum of the mirror, ${}^{A+1}_{\pi=N+1}Q_{\nu=Z}$, may be predicted. This has been done [1], for example, for the mass-7 isobars with multichannel algebraic scattering (MCAS) [2] evaluations of the spectra of the compound systems; ^{7}Li (as $n+{}^{6}$Li), ^{7}Be (as $p+{}^{6}$Li), ^{7}He (as $n+{}^{6}$He), and ^{7}B (as $p+{}^{6}$Be). Also, the approach predicted a spectrum for the (particle unstable) nucleus ^{15}F when treated as a compound of $p+{}^{14}$O, characteristics of which were later observed. In that study [3] the nuclear interaction was set by an analysis of the mirror system ^{15}C treated as $n+{}^{14}$C. It was found that key requirements for obtaining resonance states of ^{15}F were, a) the Coulomb barrier, which is essential in recreating the resonance aspect of the observed spin $\frac{1}{2}^{+}$ ground state, b) coupling of the extra core proton to distinct states of ^{14}O and c) consideration of the Pauli principle within a coupled-channel collective model prescription. The latter two features ensured a credible sequence of spin-parity values, a very good fit to the high-quality elastic scattering cross sections found at that time [4, 5], and prediction of a set of narrow resonances only a few MeV above the (two) known ones. Narrow resonances in the region of that excitation energy, subsequently have been observed [6]. (Note: There is an error in Ref. [6] relating to citation of the results of our earlier study [3]. In their table I, references 6 and 7 have been reversed in both the table caption and the header row.)

Recently, Timofeyuk and Descouvemont [7] used the same philosophy of fixing the nuclear aspect by a two center cluster model of ^{17}C, treated as $n+{}^{16}$C, to then find a spectrum of ^{17}Na as $p+{}^{16}$Ne. They expect there to be narrow resonances in the low excitation spectrum of the particle unstable isotope of Na with very broad ones above that. Those results were a spur to us to use the MCAS approach as a complementary study of that exotic nucleus. Thus, in this paper, we consider the nucleus ^{17}C ($n+{}^{16}$C) given that the low excitation spectrum of ^{17}C has been found experimentally [8, 9, 10] and microscopic models of that nucleus' structure have been proposed [8, 9, 11, 7]. An MCAS analysis of the low excitation spectrum of ^{17}C has been made before [11]. However, the results found were from an (overly) simple, two-channel, evaluation. In that study, we also considered a distorted wave approximation analysis of inelastic scattering data of 70A MeV ^{17}C ions from hydrogen targets. Those DWA evaluations were made using no-core shell model wave functions and the complete set of results allowed us to pose some constraints upon the structure of ^{17}C.

However, inadequacies remained due, in part, to simplifications in the previous MCAS evaluations. Experiments [9] now have suggested a number of spin-parity assignments, especially of the three closely spaced sub-threshold states of ^{17}C, which current microscopic (shell) models fail to match adequately. It has been suggested [7] that coupling of a neutron to states at about 4 MeV excitation in ^{16}C is needed to improve the results. That coupling was not included in our previous study [11] and so we present herein results of three state MCAS evaluations in which coupling to the 4^{+} state in the mass-16 nuclei is added.

We have made MCAS calculations of the $n+{}^{16}$C system using three states in ^{16}C; the 0^{+} (ground), 2^{+} (1.766 MeV), and 4^{+} (4.142 MeV) states. We presume that coupling to the other states (presumed $0^{+}_{2}, 2^{+}_{2}$, 3^{+}) in the spectrum between 3 and 5 MeV excitation do not strongly couple and that the rotational model, as defined previously [2], suffices in seeking the spectrum of ^{17}C. The parameter values required to get the results displayed in Fig. 1 are listed in Table 1. The potential parameter values and Pauli blocking/hindrance weights are quite similar to the

Table 1. The parameter values used to define the channel coupling properties of the $n+{}^{16}$C system. Energy units are MeV, length units are fm.

V_0	V_{ll}	V_{ls}	V_{Is}
-37.0	-2.0	9.0	1.6
R	a	β_2	β_4
2.9	0.8	0.33	0.1
state in		OPP λ_{lj}	
^{16}C	$(1s_{\frac{1}{2}}, 1p_{\frac{3}{2}}, 1p_{\frac{1}{2}})$	$1d_{\frac{5}{2}}$	$2s_{\frac{1}{2}}$
0^+ (0.000)	10^6	2.7	0.0
2^+ (1.766)	10^6	2.7	0.0
4^+ (4.142)	10^6	0.0	2.0

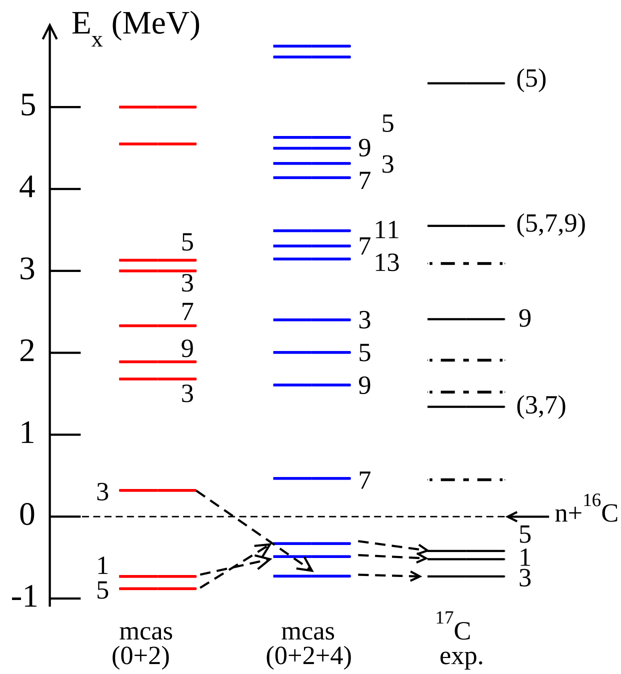

Figure 1. The spectrum of ^{17}C compared with the MCAS results.

set used previously [11], now with inclusion of a small hexadecapole deformation to link the 4^+ state to the ground in first order, and with some Pauli hindrance of the $2s_{\frac{1}{2}}$ orbit in the connections to the 4^+ target state.

The spectrum that results is shown in Fig. 1 and labelled 'mcas(0+2+4)'. It is compared with the spectrum found previously from the 2-state MCAS evaluation ('mcas(0+2)'), and with the experimentally-known one that is a combination of states listed in Table 4 of Ref. [9] and in Fig. 5 of Ref. [12]. The energies of that tabled spectrum have been adjusted by -0.729 MeV; the value of the $n+{}^{16}$C threshold in ^{17}C. Some states specified by Raimann *et al.* [12] are displayed by the dash-dot lines. Only positive parity states are known in the low excitation spectrum and (twice) their spins are given as the integers associated with the individual levels shown.

Clearly the three known subthreshold ($n+{}^{16}$C) states are now matched well in energy and spin-parity by the new MCAS results. The other known and uncertain spin-parity states also have matching MCAS partners in proximity of their excitation energies. Additionally, the uncertain states from Raimann *et al.* [12] seem to have possible matches with the first low-lying state above threshold expected to be a $\frac{7}{2}^+$ resonance. The MCAS spectrum has a number of aspects in common with that shown in Fig. 1 of Ref. [7]. Besides the three closely spaced and weakly bound sub-threshold states, there is a group of $\frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+$, and $\frac{9}{2}^+$ states in the region around 3 MeV excitation and a second group in the region of 5 MeV excitation. There is also a higher excited $\frac{1}{2}^+$ state found with both calculations above 6 MeV excitation, notable by being very broad (width $\Gamma = 5.6$ MeV with MCAS). The third $\frac{3}{2}^+$ state in the MCAS spectrum (centroid at 5.04 MeV excitation) is also very broad ($\Gamma = 4$ MeV). Such half-widths are typical of a single-particle potential resonance. Our MCAS result shows more states, including two very narrow ones of spin-parity $\frac{13}{2}^+$ and $\frac{11}{2}^+$ at 3.82 and 4.16 MeV excitation respectively.

Table 2. Spectra for ^{17}C. Units are MeV.

	Ref. [9]		Ref. [12]		MCAS	
J^π	E	Γ	E	J^π	E	Γ
$\frac{3}{2}^+$	0.00	—	0.000	$\frac{3}{2}^+$	0.00	—
$\frac{1}{2}^+$	0.21	—	0.292	$\frac{1}{2}^+$	0.16	—
$\frac{5}{2}^+$	0.31	—	0.295	$\frac{5}{2}^+$	0.22	—
			(1.18)	$\frac{7}{2}^+$	1.17	10^{-8}
$(\frac{3}{2}^+ - \frac{7}{2}^+)$	2.06	0.25	(2.25)	$\frac{9}{2}^+$	2.31	3x10^{-5}
			(2.64)	$\frac{5}{2}^+$	2.70	0.018
$\frac{9}{2}^+$	3.10	0.10		$\frac{3}{2}^+$	3.01	0.096
			(3.82)	$\frac{7}{2}^+$	4.03	3x10^{-5}
$(\frac{5}{2}^+, \frac{7}{2}^+, \frac{9}{2}^+)$	4.25	0.14		$\frac{11}{2}^+$	4.24	2x10^{-5}
				$\frac{7}{2}^+$	4.88	0.010
				$\frac{3}{2}^+$	4.94	1.78

Specifics of the states in the ^{17}C spectrum are listed in Table 2. Columns 1 to 3 display values of spin-parity J^π, excitation energy (or centroid) E, and half-widths $\frac{1}{2}\Gamma$, of resonances ascertained in a study [9] of three neutron transfer cross sections for ^{12}C scattering from ^{14}C. The excitation energies of states shown in Fig. 5 of Ref. [12] are listed in column 4, while the MCAS results are displayed in columns 5, 6, and 7. The three nucleon transfer reaction widths in general do not match those from the MCAS evaluation but the two sets are quite different; the latter being single nucleon removal values.

The resonant states found using MCAS in the region of 3 MeV excitation have widths that agree well with most of the matching ones from the MCM evaluation [7]. Widths quoted in Ref. [7] are $\left.\frac{7}{2}^+\right|_1$ (10^{-12} MeV), $\left.\frac{9}{2}^+\right|_1$ (10^{-6} MeV), and $\left.\frac{5}{2}^+\right|_2$ (0.015 MeV). The $\left.\frac{3}{2}^+\right|_2$ resonance half-width of 0.265 MeV is larger than the MCAS value of 0.102 MeV.

Now, it is said that ^{17}C has a 'peculiar' structure connected perhaps with the neutron separation energy from the ground state being only 0.728 MeV. That is typical of a halo nucleus. Indeed, the channel-coupling interaction we require to give the spectrum of ^{17}C reflects that with diffuseness being large. As well, features of this interaction are just as identified [7] as being required in a two-body potential model of this system, *viz.* *"The bound ^{17}C spectrum cannot be understood in the two-body potential model with deformation and the 2^+ excitation of the ^{16}C core either, if standard sets of potentials are used. An ℓ-dependent and nonstandard spin-orbit $n + {}^{16}C$ potential must be used for these purposes."* That is illustrated in Fig. 2 which shows

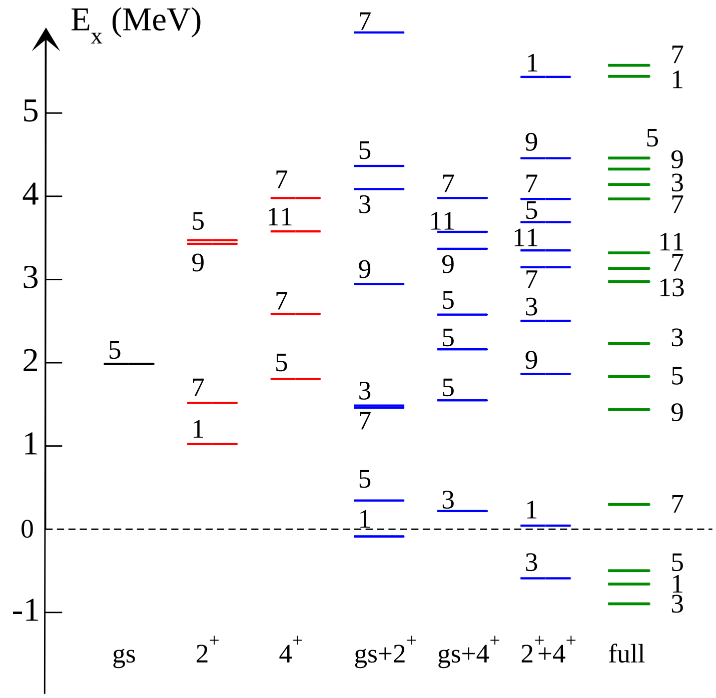

Figure 2. Spectra from MCAS evaluations restricting couplings to single- and two-channels of the three compared with the full three-channel spectrum. Again the energy scale is set with the $n + {}^{17}$C threshold as zero, to emphasise the sub-threshold from resonance states in each evaluation.

how spin states arise from underlying components of the coupled-channel approach. Calculations have been made for each subdivide of the full three target state coupled-channel problem. The numerals indicate two times the spin values. The first three columns from the left give the states found when each state alone is considered as a single channel problem. Obviously, within the searched energy range (to 6 MeV), the nucleon on the ground state gives only a single state from adding a $d_{\frac{5}{2}}$ neutron. The addition of a neutron (probably into a $d_{\frac{5}{2}}$ single-particle state) gives the set shown for the single channels of the 2^+ and 4^+. The order shown is due to the spin and angle dependent features used in the base interaction. The existence of the second $\frac{7}{2}^+$ state when a neutron is added to the isolated 4^+ state may be reflecting addition in a $d_{\frac{3}{2}}$ state.

The next three columns are the spectra found when two of the three ^{16}C states are allowed in the coupling. The results found coupling the ground and 2^+ states is very similar to what was published in an earlier paper [11]; differences reflecting changed interaction parameter values. The inclusion of the 4^+ state, whether in a 2- or the full 3-state coupling study, leads to a richer spectrum and shifts the order of states. Of note, only evaluations in which the 2^+ state is included give a low lying $\frac{1}{2}^+$ state. However, the three-state coupling markedly moves the energy value from that found otherwise.

The key feature is finding the three closely spaced sub-threshold states and in this spin order. Significant changes of the parameters, particularly with the deformations, radius and diffuseness to smaller values, cause such packing to be lost. The coupling of the 4^+ state in ^{16}C with the ground and 2^+ states causes notable changes to the predicted spectrum; changes that better align with (so far) experimentally defined states in ^{17}C, a few of which have been assigned spins. Clearly we predict many other (resonance) states, but whether they exist or can be found if they do, remains an open question. It is most unlikely that any direct $n + {}^{16}$C experiment will ever be done so one must rely on some surrogate approach, such as ^{16}C(d,p), or some study that identifies neutron emissions from ^{17}C.

We have described the low-energy spectrum of ^{17}C, as a neutron coupled to ^{16}C, using the MCAS framework, finding correspondence with the experimental spectrum. The results from the present calculation are a distinct improvement on the earlier results. Adding a Coulomb potential to the system would give the spectrum of the mirror nucleus ^{17}Na; work is currently under way to determine that spectrum to compare to the cluster model results.

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