New horizons for MCAS: heavier masses and α-particle scattering

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and collaborators

Outline

The MCAS formulation, brief reviews: K. Amos, *et al*, Nuclear Physics, **A728** (2003) 65; **A912** (2013) 7

Mirror nuclei method

Application of MCAS method to ^{16}O, using the vibrational model

Final results for Nucleon + ^{16}O

Nucleon + mass-18 preliminary results

α-particle scattering from even-mass nuclei

MCAS:
Multichannel Algebraic Scattering Formalism

1. Discretization of the coupled-channel equations by separable expansion of the channel interactions.
2. Pauli principle inclusion by use of orthogonalizing pseudo-potentials.
3. Fast, effective search procedure for resonances and bound states.
4. Can use rotational or vibrational models for the structure of the target nucleus.

Why mirror nuclei

- Two nuclei are called "mirror nuclei" if one changes into the other by interchanging all protons and neutrons
- Example: ^{14}C, the isotope of carbon used in carbon dating (half-life ≅ 5700 years) has as its mirror ^{14}O, a short-lived isotope of oxygen (half life = 70.6 sec)
- Nuclei with a proton excess tend to be less stable than those with a neutron excess
- Current MCAS role: analyze bound and resonant spectra to support and interpret experimental work

Nucleon – ^{16}O scattering

The mirror concept cannot be used to get information on ^{16}O, since it is its own mirror.

However, energy levels of ^{16}O, as well as those of ^{17}O, the compound system of n+^{16}O, are well known.

So, we carry out MCAS calculations on n+^{16}O scattering, to get accurate fits to the spectrum, including resonant states, of ^{17}O. From these we extract neutron scattering “data”.

Using the same parameters, but adding a Coulomb force, we obtain a spectrum for ^{17}F, as well as proton scattering cross sections. ^{17}F is the mirror system to ^{17}O.

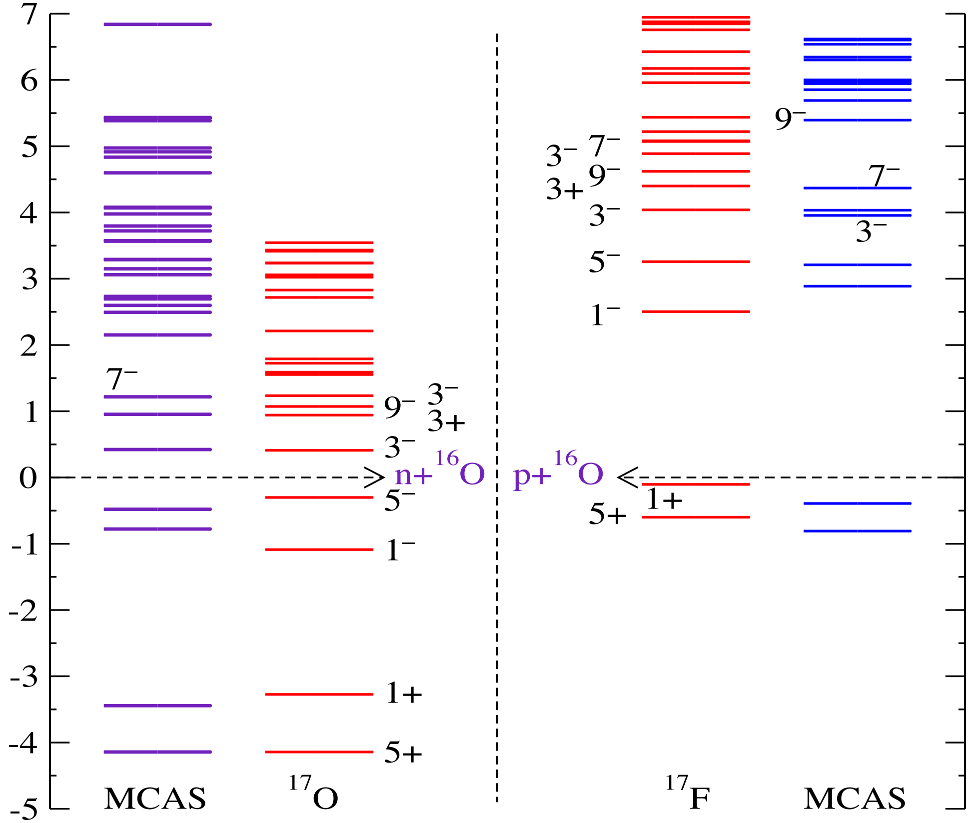
Difficulties with MCAS for ^{16}O

- ^{16}O is a doubly-magic nucleus: 8 protons in the $0s_{1/2}$, $0p_{3/2}$ and $0p_{1/2}$ states: filled s and p shells.
- That means ^{16}O is spherical in its ground state, which causes difficulties for us, since we need the assumption of a deformed target nucleus to which the incoming neutron or proton is coupled. The rotational model does not work well with a spherical ground state.
- So, instead, we use the vibrational model, for the first time with MCAS. Now the deformation is dynamic, and coupling to the projectile works better.
- Results shown here are obtained with the vibrational model. This is a more complicated model, and obtaining good results has required much work.

The parameters

MeV	parity -	parity +	geometry	value	Coulomb
V_0	– 47.15	– 50.6	R_0	3.15 fm	2.608 fm
V_{LL}	2.55	0.0	a	0.65 fm	0.513 fm
V_{Ls}	6.9	7.2	β_2	0.21	w= 0.051
V_{ss}	2.5	-2.0	β_3	0.42	
$I^{\pi}{}_{n}$	E_n (MeV)	$0s_{1/2}$	$0p_{3/2}$	$0p_{1/2}$	$0d_{5/2}$
$0^+{}_1$	0.0	10^6	10^6	10^6	0.0
$0^+{}_2$	6.049	10^6	10^6	0.0	0.0
$3^-{}_1$	6.13	10^6	10^6	5.0	0.0
$2^+{}_1$	6.92	10^6	10^6	0.0	0.0
$1^-{}_1$	7.12	10^6	10^6	5.0	1.0

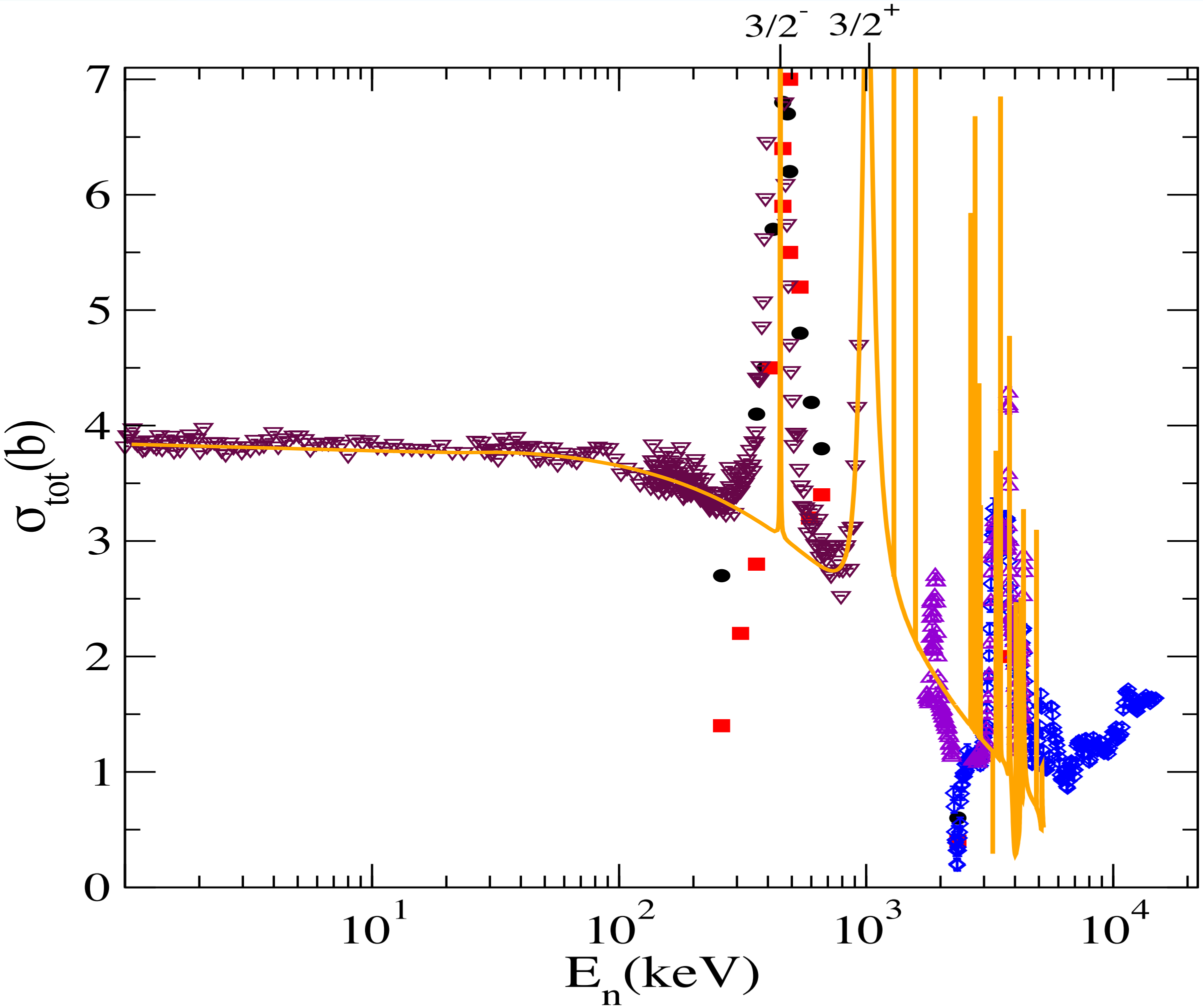
Spectra of ^{17}O and ^{17}F



The 10 lowest-E states

J^{π}	$^{17}O_{exp}$	Γ_{exp}	E_{mcas}	Γ_{mcas}	$^{17}F_{exp}$	Γ_{exp}	E_{mcas}	Γ_{mcas}
(5/2)+	–4.1436	—	–4.1432	—	–0.6005	—	–0.8079	—
(1/2)+	–3.2729	—	–3.4426	—	–0.1052	—	–0.3927	—
(1/2)–	–1.0882	—	–0.7781	—	2.5035	19	2.8874	$5.58(10)^{-5}$
(5/2)–	–0.3008	—	–0.4732	—	3.2565	1.5	2.5644	$9.80(10)^{-6}$
(3/2)–	0.4102	40	0.42264	1.277	4.0395	225	3.2104	0.00552
(3/2)+	0.9412	96	0.9534	129	4.3995	1.530	3.9557	0.906
(9/2)–	1.0722	< 0.1	2.1528	$1.08(10)^{-7}$	4.6195	–	5.3930	$1.26(10)^{-9}$
(3/2)–	1.2356	28	2.7332	0.2923	4.8875	68	5.826	$6.8(10)^{-5}$
(7/2)–	1.5537	3.4	1.2185	0.1615	5.0715	40	4.3679	$1.95(10)^{-3}$
(5/2)–	1.5892	<1	3.1504	0.1982	5.0815	< 0.6	6.3027	$6.8(10)^{-4}$

n+^{16}O total scattering cross section



Significance of the mass 17-19 systems

The structures of ^{17}O and ^{17}F are critical in the synthesis of elements, beyond carbon, within the stellar environment. The CNO cycle:

CN:

$$^{12}\mathrm{C} + p \rightarrow {}^{13}\mathrm{N} + \gamma$$
$$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + \nu$$
$$^{13}\mathrm{C} + p \rightarrow {}^{14}\mathrm{N} + \gamma$$
$$^{14}\mathrm{N} + p \rightarrow {}^{15}\mathrm{O} + \gamma$$
$$^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^{+} + \nu$$
$$^{15}\mathrm{N} + p \rightarrow {}^{12}\mathrm{C} + \alpha$$
$$^{15}\mathrm{N} + p \rightarrow {}^{16}\mathrm{O} + \gamma$$

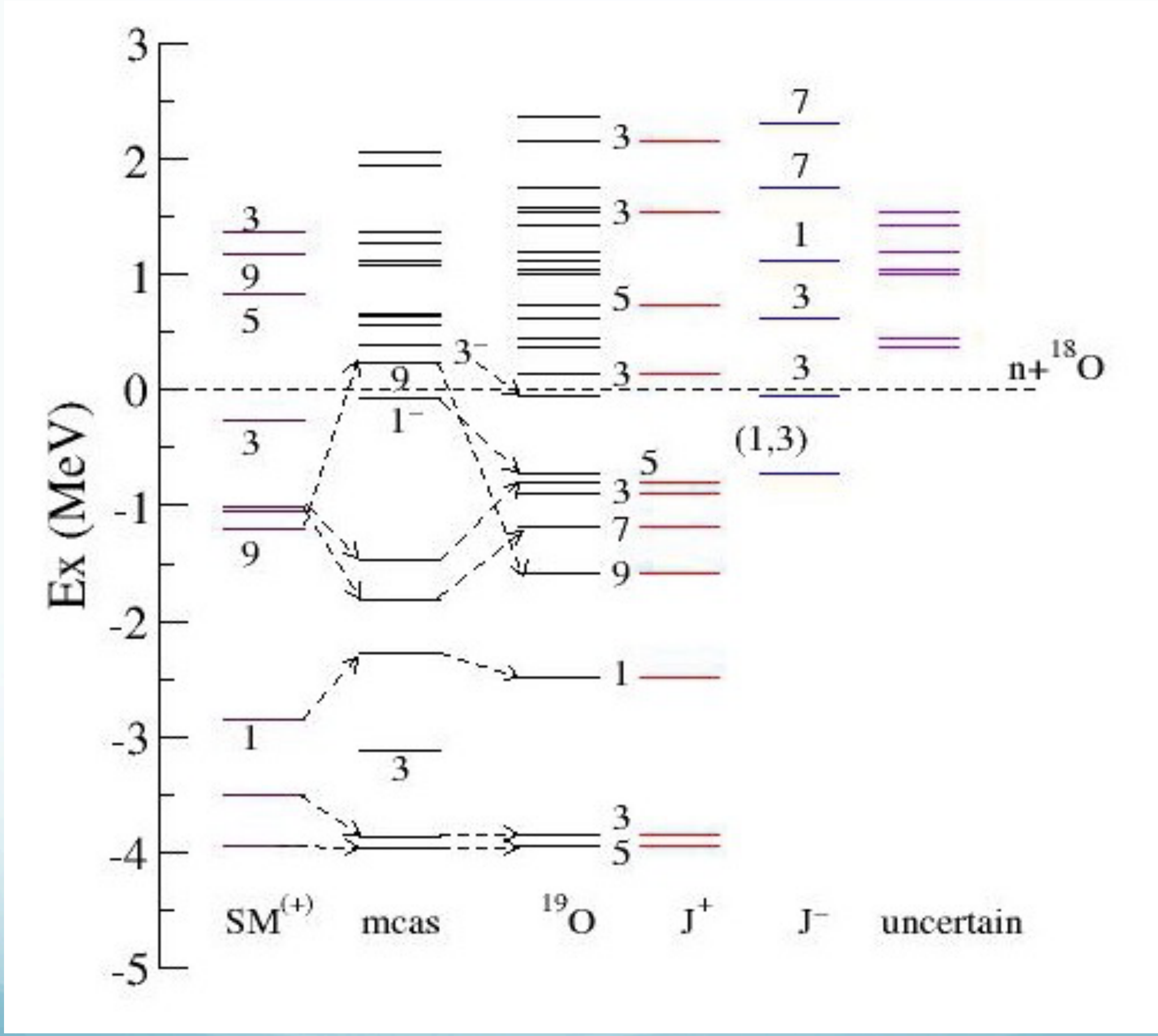
NO:

$$^{16}\mathrm{O} + p \rightarrow {}^{17}\mathrm{F} + \gamma$$
$$^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O} + e^{+} + \nu$$
$$^{17}\mathrm{O} + p \rightarrow {}^{14}\mathrm{N} + \alpha$$

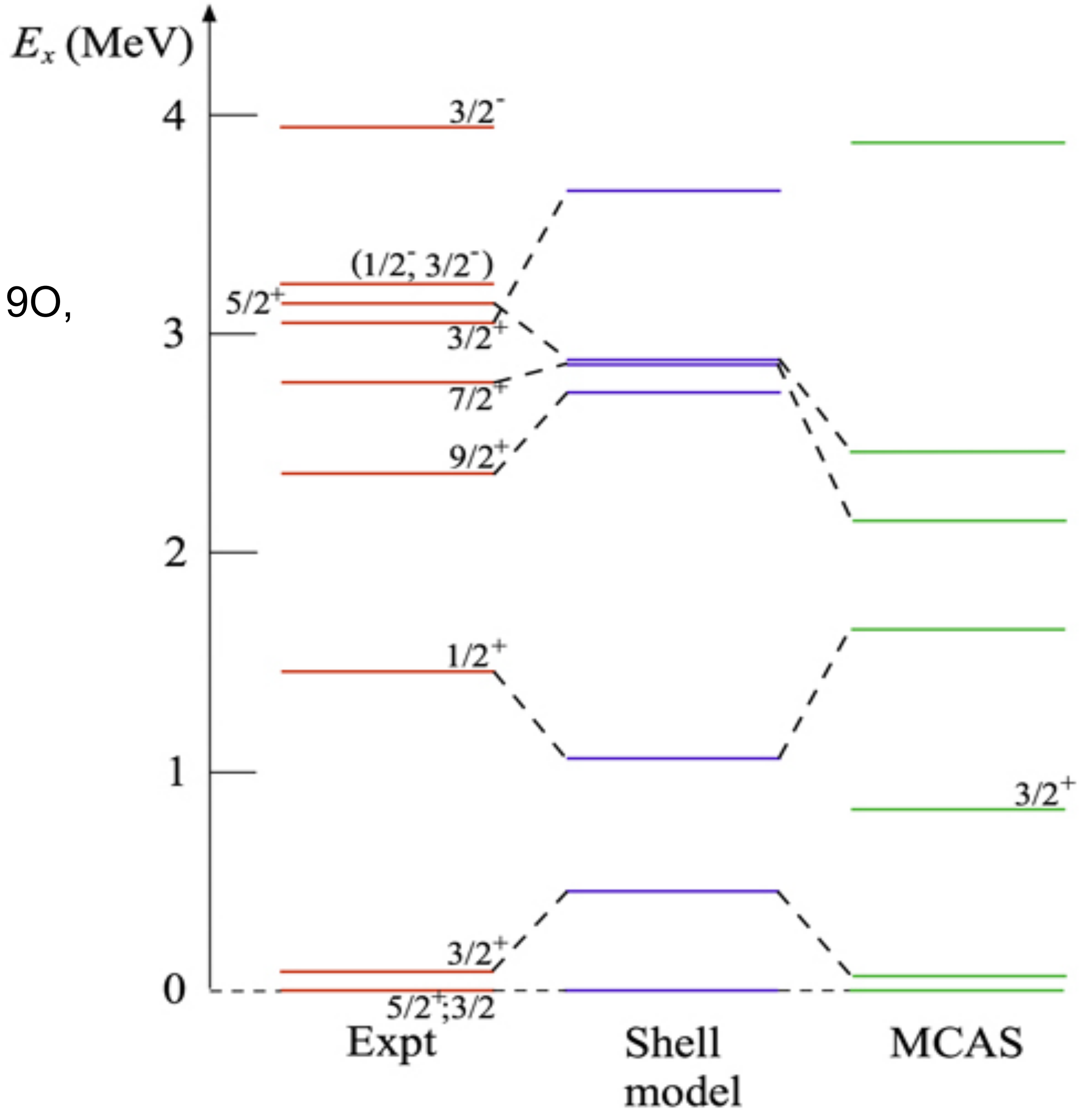
OF:

$$^{17}\mathrm{O} + p \rightarrow {}^{18}\mathrm{F} + \gamma$$
$$^{18}\mathrm{F} + e^{-} \rightarrow {}^{18}\mathrm{O} + \nu$$
$$^{18}\mathrm{O} + p \rightarrow {}^{19}\mathrm{F} + \gamma$$
$$^{19}\mathrm{F} + p \rightarrow {}^{16}\mathrm{O} + \alpha$$

Mass 18 and 19

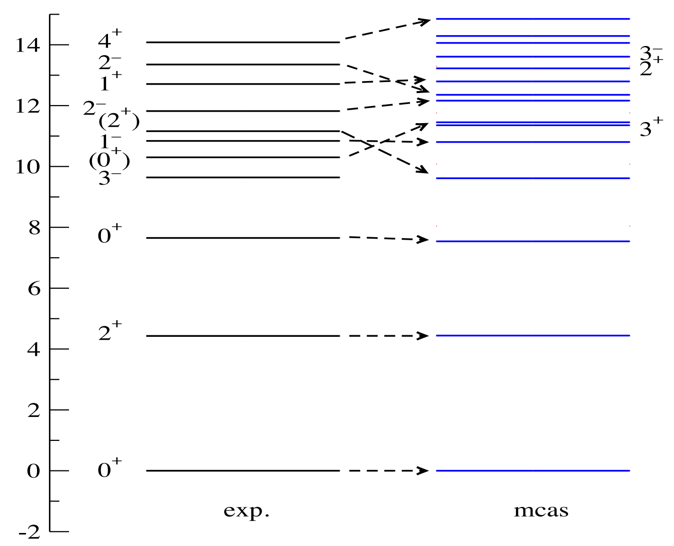


Spectrum of 19O, below n+18O threshold

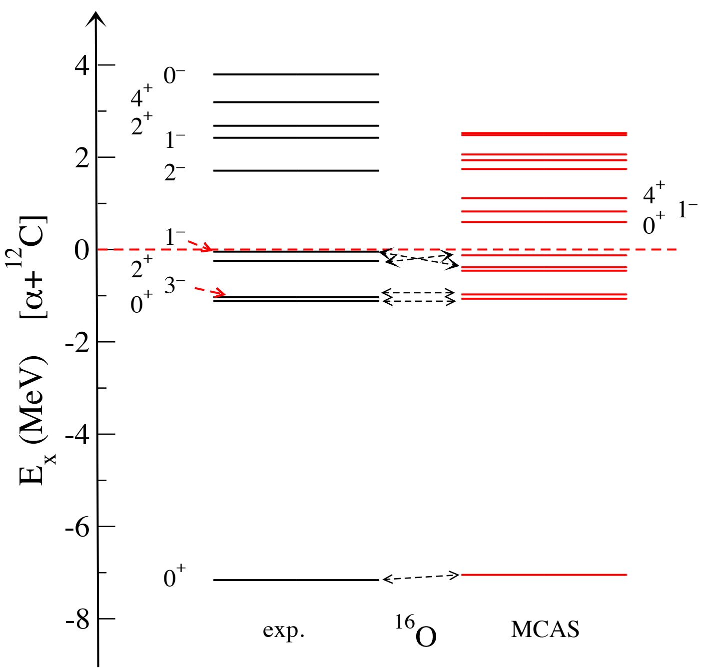


Results for α scattering from even-even nuclei.

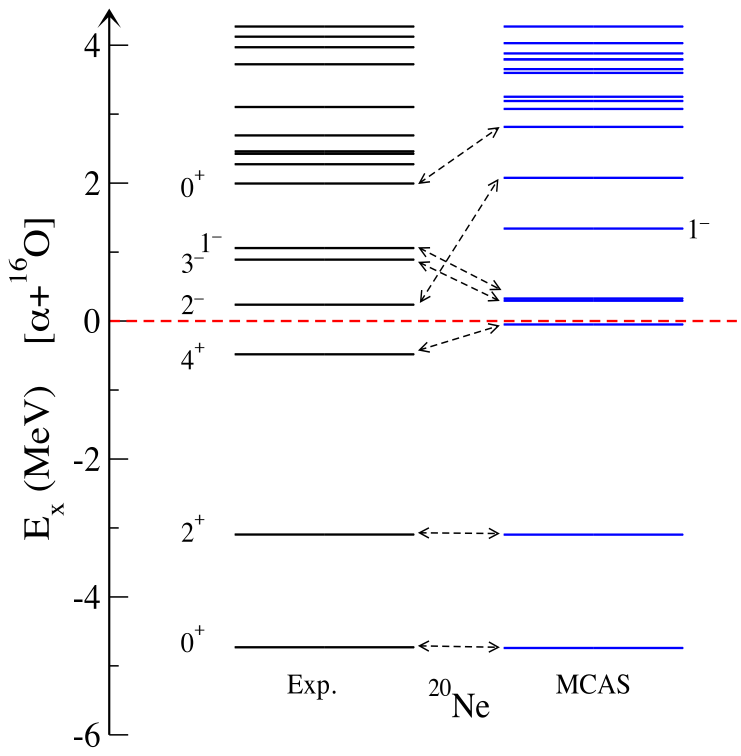
Here it is assumed an α particle scattering from the unstable ^{8}Be nucleus fuses to form ^{12}C.
The levels shown are the lowest levels in ^{12}C.



Alpha + $^{12}C \rightarrow {}^{16}O$



Alpha + $^{16}O \rightarrow$ ^{20}Ne



Mass-20 . . .

. . . and beyond: mass 22-23

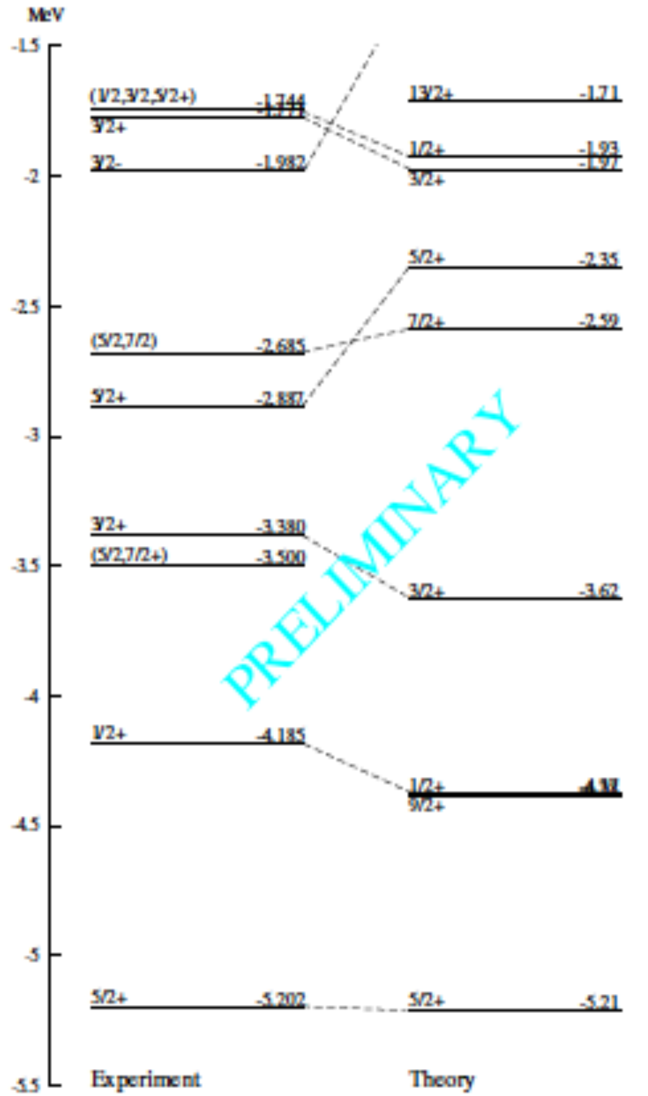


Figure 1. Experimental and MCAS ^{23}Ne spectrum.

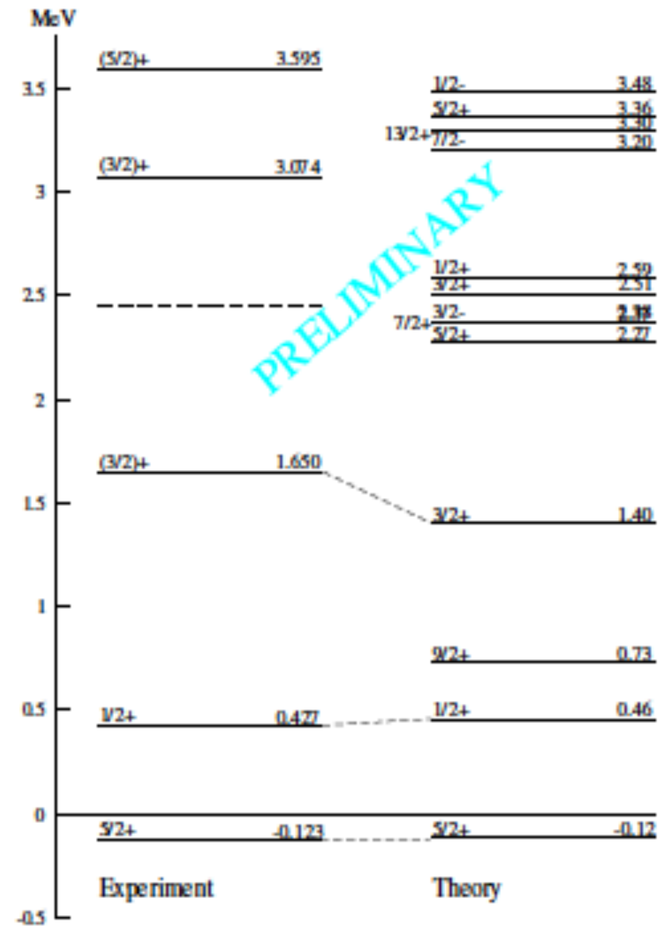
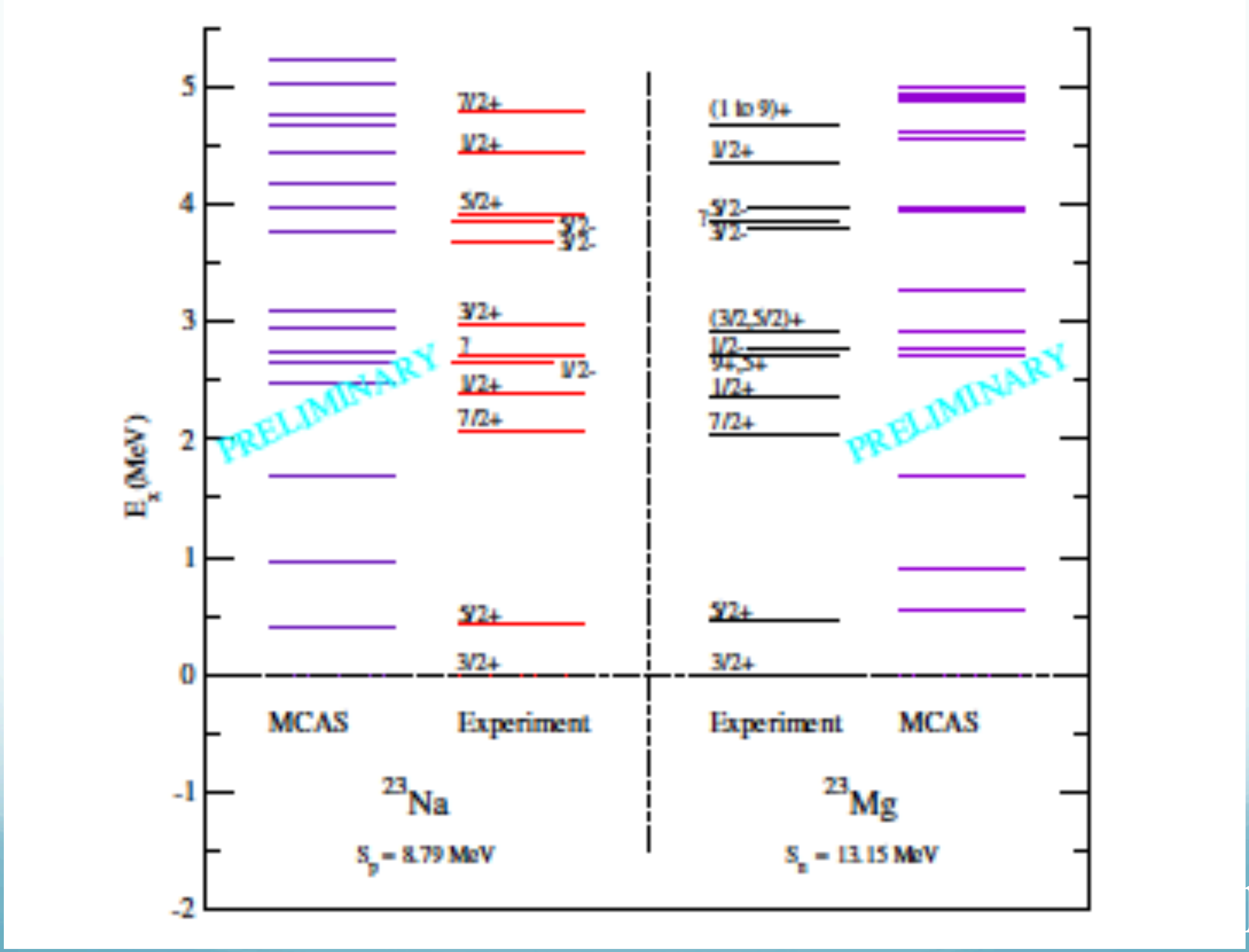


Figure 2. Experimental and MCAS ^{23}Al spectrum.

. . . to mass 23



E_x (MeV)
5
4
3
2
1
0
-1
-2
7/2+
1/2+
5/2+
3/2-
3/2-
3/2+
?
1/2-
1/2+
7/2+
5/2+
3/2+
(1 to 9)+
1/2+
5/2-
3/2-
(3/2,5/2)+
1/2-
9/+,5+
1/2+
7/2+
5/2+
3/2+
PRELIMINARY
PRELIMINARY
MCAS
Experiment
Experiment
MCAS
23Na
23Mg
S_p = 8.79 MeV
S_n = 13.15 MeV

Concluding remarks

Work on neutron-^{16}Oxygen scattering is near completion and results are in good agreement with experimental data.

Proton-^{16}Oxygen scattering calculations are also well advanced, and a spectrum of ^{17}F was shown.

Current work involves the mass 18-19 system, and alpha-nucleus scattering.

Work on mass-20 and beyond has commenced; preliminary results are promising.

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