Shell model study of astrophysically important resonant states of ^{15}O

Sathi Sharma[1] and M. Saha Sarkar[1*]
[1] *Saha Institute of Nuclear Physics, HBNI, Kolkata - 700 064, INDIA*

Introduction

The reactions of interest in nuclear astrophysics mostly have very small cross - sections over the Gamow energy range. The ^{14}N(p,γ)^{15}O reaction, being the slowest one in the CNO cycle appears as a bottleneck in the synthesis of heavier nuclei. Its reaction rate is dominated by resonant captures to sub-threshold as well as above the particle-emission threshold excited states. Thus the rates depend critically on the nuclear properties of these levels involved. Since last several years, various experimental groups have studied this reaction experimentally [1]. Still, a sub-threshold resonance state at $E_{c.m.}$= -504 keV, corresponding to the E_x = 6.792 MeV state in ^{15}O, has the most uncertainty associated with its width.

The strengths of these resonances and their widths are directly related to the spectroscopic factors of the states. Shell Model calculations have been performed long back to study the structural properties of some of these resonant states in light mass nuclei. Reduced γ- ray transition strengths, level lifetimes, branchings, spectroscopic factors are deduced from this model. However, a very few microscopic large basis theoretical calculations [2] have been done recently.

So, in this work, we report on Large Basis Shell Model calculations of low lying energy levels, level lifetimes, proton spectroscopic factors of ^{15}O nucleus up to the resonance state at 7.556 MeV and results of the calculation are compared with the existing experimental data. These theoretical calculations can also predict weaker resonances at important energy windows to provide guidelines to plan new experiments.

*Electronic address: maitrayee.sahasarkar@saha.ac.in

TABLE I: Comparison of lifetimes of excited levels of ^{15}O with shell model predictions.

Energy (MeV)			Level lifetimes	
Initial	Final	E_γ	Theo.	Expt.[7]
5.181	0.0	5.181	1.69 fs	5.7(7) fs
5.240	0.0	5.240	1.07 ps	2.25 (21) ps
6.172	0.0	6.172	1.49 fs	<1.74 fs
6.792	0.0	6.792	0.05 fs	<20 fs
6.859	5.240	1.619	30.51 ps	11.1(17) ps
7.276	5.240	2.036	2.56 ps	0.49(11) ps

TABLE II: Comparison of experimental spectroscopic factors of ^{15}O with shell model predictions. The ground state of ^{14}N (1^+) couples with the proton in the single particle orbital j to generate the final state J^π in ^{15}O.

Energy			C^2S		
			Theory	Expt.	
(MeV)	J^π	j	Present	Ref. [5]	Ref. [6]
0.0	$1/2^-$	$1p_{1/2}$	1.23	1.29 (18)	0.87 - 1.08
5.181	$1/2^+_1$	$2s_{1/2}$	0.01	0.004 (1)	0.0 - 0.02
5.240	$5/2^+_1$	$1d_{5/2}$	0.10	0.06 (1)	0.0 - 0.11
6.172	$3/2^-_1$	$1p_{1/2}$	0.001	0.038 (16)	0.04 - 0.16
6.792	$3/2^+_1$	$2s_{1/2}$	0.96	0.49 (1)	0.27 - 0.47
		$1d_{5/2}$	0.004	-	-
6.860	$5/2^-_2$	$1d_{5/2}$	0.74	0.37 (1)	0.36 - 0.64
7.276	$7/2^+_1$	$1d_{5/2}$	0.99	0.35 (1)	0.29 - 0.60
7.556	$1/2^+_2$	$2s_{1/2}$	0.56	$\approx$ 0.49	0.35 - 0.58

Shell Model Calculation

Large Basis Shell Model calculations (LBSM) have been carried out using NuShellX [3] code. We have considered ZBM model space with ^{12}C as inert core and $1p_{1/2}$, $1d_{5/2}$ and $2s_{1/2}$ as valence orbitals. Amongst the available interactions in this model space, the REWIL isospin interaction [4] has been chosen for the calculations. At first, the energy spectra till 20 MeV have been calculated using the full valence space. The reduced transition probabilities are also calculated theoretically for E2 and E1 transitions with effective charges e_p=1.35e and e_n=0.35e. Standard values of intrinsic magnetic moments have been used to obtain the reduced transition probabilities for M1 and M2 transitions. The gamma ray branching ratio from the 7.556 MeV resonance state to the low lying states of ^{15}O is also calculated. The level lifetimes of the ^{15}O nucleus are calculated by using theoretical reduced transition probabilities and experimental γ- energy values and branching ratios wherever needed. As the astrophysical reaction rate of ^{14}N(p,γ)^{15}O reaction depends on the proton spectroscopic factors of the ground state as well as the low lying states in ^{15}O, we have calculated the ground state (g.s.) wavefunction for initial nucleus (^{14}N) and also for final nucleus (^{15}O) with the same interaction. So, after calculating the wavefunctions for both the nuclei, the overlap integral for ^{14}N g.s. with all the states of ^{15}O have been calculated.

Results and Discussions

Using full valence space, all the positive and negative parity states are reproduced reasonably well except the $3/2^-_1$ state i.e. 6.172 MeV state (see Table I), which is overpredicted. The branching ratio of 7.556 MeV state determined from the theoretical transition probabilities, do not match with the experimental values as the E1 strength for the 7.556 $\rightarrow$ 0 transition is also overpredicted. However, the calculated lifetimes of other states matched well with experimental data (given in Table I). The proton spectroscopic factors of ^{15}O have been calculated theoretically (Table II) and compared with experimental values from the literature [5, 6]. There are some disagreements for a few states. As the energy of $3/2^-_1$ state is not reproduced well from shell model calculation, the spectroscopic factor is also underpredicted compared to experimental value, indicating the need for inclusion of $1p_{3/2}$ in the model space. The $1/2^+_2$ resonance state at 7.556 MeV is reproduced theoretically at 7.646 MeV. The spectroscopic factor for this unbound state is 0.56, which matches the literature value within error limit (see Table II).

Summary

The spectroscopic factors and level lifetimes are reproduced well using shell model calculations. However, there are also some disagreements which indicates need of expansion of the model space. The possibilities of improvement of the results will be discussed in detail.

References

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