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Level Structure of ^{30}S of Astrophysical Importance in the rp Reaction ^{29}P(p, γ)^{30}S

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Abstract. Level structure of the proton-unbound ^{30}S states, just above the proton threshold 4394.9(7) keV, is important to understand the αp and rp processes, as it plays a crucial role in the calculation of the ^{26}Si(α, p) and ^{29}P(p, γ) reaction rates. The spin-parity assignments of ^{30}S strongly determine the thermonuclear ^{29}P(p, γ)^{30}S reaction rate at temperatures characteristic of explosive hydrogen burning in classical novae and type I X-ray bursts. Specifically, the rate had been previously predicted to be dominated by two low-lying, levels in the Ex = 4.7–4.8 MeV region, with spin and parity assignments of 3^+ and 2^+. Several experiments were performed to study the structure of ^{30}S. The ^{30}S J$^\pi$ values were inferred from also a comparison to the known decay schemes of the corresponding mirror states in ^{30}Si.

We present, in this paper, results for levels in ^{30}S that are used for the ^{29}P(p, γ) rp reaction rate calculation. The positive- and negative- parity states have been calculated using the (0+1)$\hbar\omega$ PSDPF interaction, which is charge-independent Hamiltonian. The γ-decay lifetimes of ^{30}S and reduced electromagnetic transition strengths were also calculated. Based on experimental information on the ^{30}S energy spectrum as well as a comparison to the $T = 1$ isobaric analogue states in ^{30}Si and ^{30}P, the levels of excited states that are used to determine the ^{29}P(p, γ)^{30}S reaction rate are proposed.

1 Introduction

Calculation of the thermonuclear reaction rates, which affect the silicon isotopic abundance in novae, is crucial to determine the parent stellar sites for the presolar grains of potential nova origin [1, 2]. The most extensively studied grains are SiC grains, because they are relatively abundant [3]. One of the most interesting reactions for the study of presolar dust grains is the ^{29}P(p, γ)^{30}S, which influences type I X-ray bursts.

The rate of the ^{29}P(p, γ)^{30}S reaction depends sensitively on the detailed knowledge of the energy levels of proton-unbound states in ^{30}S [4], especially the two previously estimated states 3^+ and 2^+ [5] in the 4.7–4.8 MeV range just above the proton threshold (4394.9(7) keV). Many experiments were implemented in order to search for these states and identify their energies and

J^{π} assignments using different reactions, such as, ^{32}S$(p,t)^{30}$S [2, 4, 6–8] and ^{28}Si$(^{3}He, n\gamma)^{30}$S [7–10]. Attempts to determine the reaction rate using some methods were also provided [1, 3, 5, 8].

In the latest measurements [8] these important excited states, 3^{+} and 2^{+}, in ^{30}S have been observed at 4688.1(4) keV and 4809.8(6) keV, respectively. In the same work, the uncertainty in the updated ^{29}P$(p,\gamma)^{30}$S reaction rate in the temperature range of $0.1 \leq T \leq 1.3$ GK has been reduced by 72% relative to that previously determined [11]. Improvements in spin-parity assignments in ^{30}S can ameliorate the reaction rate. This may be made by theoretical estimates and comparison to the $A = 30$ isobaric mass triplet ^{30}Si, ^{30}P and ^{30}S.

Nuclear shell model calculation is useful to obtain the J^{π} assignments for states above the proton-emission threshold if the experimental levels can be matched with their theoretical counterparts [12].

In this paper, we present results of state-of-the art shell-model calculations based on the PSDPF effective interaction [13] concerning excitation energies and J^{π} assignments of the ^{30}S levels as well their lifetimes and reduced electromagnetic transition strengths. In this study, both positive- and negative- parity states were considered. A comparison of the experimental ^{30}S levels to the $T = 1$ isobaric analogue states in ^{30}Si and ^{30}P as well to the shell model results leads to propose a complete spectrum of the ^{30}S nucleus.

2 Experimental Revue of $A = 30$ Spectra

Most of the experimental excitation energies of the $A = 30$ isobaric mass triplet ^{30}Si, ^{30}P and ^{30}S are taken from Nuclear Data Sheets (NDS) [14, 15] and are summarized in Table 1. Known J^{π} values of ^{30}S are given in column 2 and excitation energies of the T = 1 isobaric states for the triplet ^{30}Si, ^{30}P and ^{30}S in columns 3–5, respectively. Excitation energies are ordered according to the level sequences in the ^{30}Si well-known spectrum, whose J^{π} values are represented in column 1, “i” denotes the number of levels for a given J^{π} value. As it is known, to obtain the $T = 1$ levels in ^{30}P, the energy of the first $T = 1$ level corresponding to the ground state in the doublet ^{30}Si and ^{30}S, 0^{+}, should be subtracted from all other states energy.

The $J^{\pi} = 0^{+}, 1^{+}, 3^{+}$ and 2^{+} were definitively assigned for the ^{30}S levels observed at 3667, 3677, 4688 and 4810 keV, respectively, in Refs. [8, 10]. Levels above 5 MeV have uncertain J^{π} values. The 3^{+}_{2} and $4^{+}_{1,2}$ were assigned to the observed states at 5218.8(3), 5132.1(1) and 5848.0(4) keV, respectively, in the ^{28}Si$(^{3}He, n\gamma)^{30}$S reaction [10] that are close to their mirror ^{30}Si counterparts observed at 5231, 5279 and 5951 keV, respectively. The third 0^{+} state was observed in the two different experiments β-delayed decay of ^{31}Ar at 5227(3) keV [3] and ^{32}S$(p,t)^{30}$S at 5225(2) keV [8], compatible also with the mirror ^{30}Si 0^{+}_{3} state observed at 5372 keV, the 0^{+}_{4} is taken from Ref. [7]. Energies of the negative parity states indicated by an asterisk in ^{30}S (column 5) were estimated from the isobaric mass multiplet equation (IMME) systematics in Ref. [12]. The higher energy states will be discussed in the next section.

The $T = 1$ levels in ^{30}P are well indicated in the NDS compilation [14] and seem to be well-established up to 5 MeV. The state observed at 5934 keV (5257 keV in Table 1) has no defined isospin value in NDS [14] but a level at 5930(8) keV in Ref. [16] has an isospin $T = 1$ in agrement with $T = 1$ analogue states in ^{30}Si and ^{30}S. The J^{π} assignments of the state at 6050 keV (5373 keV in Table 1) is taken also from Ref. [16] to be 0_3^+ in agreement also with its counterparts in the other $A = 30$ doublet. States above 6100 keV will tentatively be assigned based on the theoretical study of Ref. [12].

Levels with excitation energies between 6 and 7 MeV, given in Table 1, are those expected from the well-known levels in ^{30}Si. Many states, in this energy range, in ^{30}P and ^{30}S whose J^{π} values are uncertain may be compared to the calculated levels and matched with the well-established ^{30}Si states in this case.

Table 1. Experimental *vs.* theoretical excitation energies (in keV) of the $T = 1$ isobaric analogue states in $A = 30$ nuclei, see text for details

J_i^{π}	J^{π}	^{30}Si (Exp)	^{30}P-677 (Exp)	^{30}S (Exp)	^{30}S (PSDPF)	^{30}S (USDB-cdpn)
0_1^+	0^+	0	0	0	0	0
2_1^+	2^+	2235	2260	2211	2235	2244
2_2^+	2^+	3498	3505	3404	3457	3485
1_1^+	1^+	3769	3825	3677	4044	3976
0_2^+	0^+	3788	3791	3667	4061	3871
2_3^+	2^+	4810	4899	4810	4831	4805
3_1^+	3^+	4831	4832(2,3)	4688	4787	4825
3_2^+	3^+	5231	5329(3^+)	5219	5115	5111
4_1^+	(4^+)	5279	5257(3^+)	5132	5274	5278
0_3^+	(0^+)	5372	5373	5225	5357	5487
3_1^-	(3^-)	5487	5414	5318	5773	
2_4^+	(2^+)	5614	5593(2^-)	5389	5896	5867
4_2^+	(4^+)	5951	5921	5848	5819	5860
4_1^-		6503	6372	(6225)*	6249	
2_5^+	(2,3)	6537	6606	6536	6630	6497
2_1^-		6641	6546	(6435)*	6599	
0_4^+	0^+	6642	6530	6326	6651	6725
1_1^-		6744	6501	(6242)*	6664	
3_3^+	(3,4)	6865	6959(3^+)	6919	7029	6940
2_6^+	2^+	6915(2^+)	6886(2^+)	6766	6970	7024
5_1^+	≥ 4	6999	6693	6838	7125	6996
5_1^-	≥ 3	7043	6970	7294	7359	

3 Comparison with Shell Model Calculations

We used the state-of-the-art shell-model interaction ((0+1)$\hbar\omega$ PSDPF) to calculate the energy spectra and lifetimes of the studied $A = 30$ isobaric mass triplet ^{30}Si, ^{30}P and ^{30}S. This shell-model calculation has a ^{4}He core and uses the full p-sd-pf model space; one nucleon is allowed to jump across a major shell, from p to sd shells or sd to pf shells. PSDPF incorporates the USDB Hamiltonian developed by Brown and Richter [17] with slight adjustment, which interpret the similarity of their results for the positive parity states.

This study completes the previous theoretical one of Richter and Brown [12], using their USDB-cdpn interaction, especially for the negative parity states.

3.1 Excitation energies

Theoretical results are presented in columns 6 (using PSDPF) and 7 (using USDB-cdpn) of Table 1. Up to $\sim$ 6 MeV, the proposed excitation energies and J^{π} assignments of the $T = 1$ isobaric analogue states in the $A = 30$ isobaric mass triplet ^{30}Si, ^{30}P and ^{30}S are in quite good agreement with each other. Both PSDPF and USDB-cdpn interactions describe perfectly all those observed levels in this energy range. The 3^{-}_{1} is likewise well reproduced using PSDPF interaction.

In the case of ^{30}P, the uncertain J^{π} assignments of the $T = 1$ states of energies 4832 and 5329 keV and the proposed assignments for 5257 and 5593 keV states [12] can be confirmed following the comparison to their analogues in ^{30}Si and ^{30}S and to calculation as well.

In the case of ^{30}S, The J^{π} assignments made by Lotay *et al.* [10] for the states 3^{+}_{2} and $4^{+}_{1,2}$ can be confirmed here. Based on this comparison, we conclude that there is a doublet of states around 5.22 MeV; the first one is at 5219 keV, identified by Lotay *et al.* [10] to have $J^{\pi} = 3^{+}$, and the second one is at 5225 keV whose $J^{\pi} = (0^{+})$ proposed in the Refs. [3, 8]. The last established state in ^{30}S is the 0^{+}_{4} [7], which is in compatibility with the associated 0^{+}_{4} in ^{30}Si and ^{30}P, and agree very well with their theoretical counterparts.

Let discuss now the well-established positive parity states above 6.5 MeV in ^{30}Si and try to match them with levels in the doublet ^{30}P and ^{30}S according to the comparison with the two shell model calculations. Starting with the 2^{+}_{5} and 2^{+}_{6} observed at 6537 and 6915 keV, respectively. If we examine carefully the experimental ^{30}P spectrum one can found a state at 7283(-677=6606) keV assigned 2^{+}, $T = 1$ in Ref. [14] compatible with the observed one in ^{30}Si and with calculation. Although the second discussed state has no confirmed J^{π} in ^{30}Si but it is consistent with the calculated energies. In the other hand, there is an unconfirmed (2^{+}), $T = 1$ level observed at 7563(-677=6886) keV in ^{30}P [14], which is a good candidate.

Concerning the ^{30}S case, a candidate can be assigned 2^{+} observed at 6532 keV [14], which we think is the same state observed in the ^{32}S$(p,t)^{30}$S reaction at 6536(3) keV with $J^{\pi} = (2, 3)$ [8, 19]. There is another adopted level at 6766 keV assigned 2^+ in Ref. [14] in harmony with the calculated 2^+_6 as well with their associated levels in ^{30}Si and ^{30}P; we think also that this state is the same one observed at 6768(3) keV with a tentative $J^\pi = 2^{(-)}$ assignment [8].

The $T = 1$ level in ^{30}P observed at 7636(-677=6959) keV assigned (3^+) [14] can be associated with the 3^+_3 (6865 keV) in ^{30}Si that is well reproduced by PSDPF and USDB-cdpn. There is also a state observed at 7370(-677=6693) keV assigned $5^+, T = 1$ [18], but it is lower than the ^{30}Si 5^+ observed at 6999 keV. A tentative assignment for these two levels can be proposed in ^{30}S, whose spectrum is unknown at this energy range. The 3^+_3 and 5^+_1 states can be matched with the observed levels at 6919 and 6838 keV with $J^\pi = (3, 4)$ and ≥ 4, respectively [19].

The $T = 1$ state observed in ^{30}P at 7647(-677=6970) with $J^\pi = (4, 5, 6)^-$ in Ref. [14] and $J^\pi = 5^-$ in Ref. [18] has a consistent energy and J^π with the calculated 5^-_1 level and the observed one at 7043 keV in ^{30}Si. In the other hand, an observed ^{30}S state at 7294 keV with ≥ 3 [19] can be a good candidate to have $J^\pi = 5^-$; see also Ref. [7].

The observed negative parity states 4^-_1,1^-_1 and 2^-_1 in the doublet ^{30}Si and ^{30}P are well reproduced using the PSDPF interaction. Values marked with asterisk presented in Table 1 are the estimates of Richter and Brown [12] based IMME systematics. Many levels observed in ^{30}S at this energy range with undefined J^π can be associated to these $T = 1$ intruder analogue states.

3.2 Lifetimes for ^{30}S and ^{30}Si mirror levels

We have calculated the lifetimes of the ^{30}S levels and compared them to available experimental data as well to the mirror counterparts in ^{30}Si [14], the results are given in Table 2. A good agreement is obtained between experiment and theory using the two Hamiltonians for the three first states in ^{30}S, $2^+_{1,2}$ and 0^+_2.

New measurements of lifetimes for the 2^+_1 and 2^+_2 were obtained at 246(26) and 166(24) fs, respectively [20, 21], which are higher than the previous measured lifetimes and than the calculated ones too.

The reduced electromagnetic transition strengths, in Weisskopf units (W.u.), were recently likewise measured for these states [20, 21]. The obtained values are: B(E2: $2^+_1 \rightarrow 0^+_{g.s}$) = 7.9(8), B(E2: $2^+_2 \rightarrow 2^+_1$) = 103(15); B(M1: $2^+_2 \rightarrow 2^+_1$) = 0.031(5) and B(E2: $2^+_2 \rightarrow 0^+_{g.s}$) = 0.27(5) comparing to the calculated values obtained using PSDPF: B(E2: $2^+_1 \rightarrow 0^+_{g.s}$) = 11.3, B(E2: $2^+_2 \rightarrow 2^+_1$) = 17; B(M1: $2^+_2 \rightarrow 2^+_1$) = 0.097 and B(E2: $2^+_2 \rightarrow 0^+_{g.s}$) = 0.11.

Table 2. Experimental *vs.* theoretical lifetimes (in fs) for ^{30}S and ^{30}Si levels

J_i^π	^{30}Si (Exp)	^{30}S (USDB-cdpn)	^{30}S (PSDPF)	^{30}S (Exp)
2_1^+	215(28)	171	167	156(9)
2_2^+	58(17)	94	118	109(12)
0_2^+	8300(500)	3300	6830	> 1000
1_1^+	36(9)	11	25	97(55)
2_3^+	104(15)	64	63	
3_1^+	83(24)	144	181	
3_2^+	43(21)	202	140	38(14)
4_1^+	83(22)	73	48	
0_3^+	59(21)	88	106	
3_1^-	43(12)		6.5	
2_4^+	$<$21	9	12	
4_2^+	15(8)	18	23	
4_1^-	139(35)		200	
2_1^-	21(9)		3	
0_4^+		8.4	6.7	
1_1^-	$<$14		0.085	

4 Conclusion

The comparison between experimental and theoretical excitation energies and lifetimes provides nuclear structure information which may become crucial in many cases. We are interested in this work, to study the ^{30}S, especially, the determination of the energy levels and J^π assignments above the proton-emission threshold of 4.400 MeV that are necessary to calculate the rp reaction rate for the ^{29}P$(p,\gamma)^{30}$S reaction.

A complete spectrum with J^π assignments were proposed for the ^{30}S based on the comparison with the isobaric triplet assignments for $A = 30$, ^{30}P, ^{30}Si and ^{30}S as well with calculations using the (0+1)$\hbar\omega$ PSDPF and 0$\hbar\omega$ USDB-cdpn interactions. Calculated lifetimes and reduced electromagnetic transition strengths were also compared to known experimental data.

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