

Microscopic calculations for solar nuclear reactions*

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We have studied the ${}^4\text{He}({}^3\text{He}, \gamma){}^7\text{Be}$, ${}^3\text{He}({}^3\text{He}, 2p){}^4\text{He}$, and ${}^7\text{Be}(p, \gamma){}^8\text{B}$ reactions of the solar p-p chain, using microscopic cluster models. Among other results, we showed that the ${}^6\text{Li} + p$ channel has a nontrivial effect on the ${}^7\text{Be}$ -producing reaction, that the existence of a resonance in ${}^6\text{Be}$ close to the ${}^3\text{He} + {}^3\text{He}$ threshold is rather unlikely, and that the correlations between some properties of ${}^7\text{Be}/{}^8\text{B}$ and the low-energy cross section of ${}^7\text{Be}(p, \gamma){}^8\text{B}$ might help one to constrain the value of the $S_{17}(0)$ astrophysical S-factor.

1. INTRODUCTION

The very-low-energy cross sections of the solar nuclear reactions are used as input parameters in solar models [1]. In order to get reliable results from these models for the energy generation, neutrino fluxes, etc., of our sun, all input parameters, including those coming from nuclear physics, should be known as precisely as possible. Despite the tremendous improvements in our understanding of these processes in the past decades, some uncertainties still exist, which could considerably influence the predictions of solar models [2].

In order to try to reduce some of these uncertainties, we have performed a systematic study of some of the key reactions of the solar p-p chain by using a microscopic cluster model. The wave function of our model looks like

$$\Psi = \sum_{L,S} \mathcal{A} \left\{ \left[\left[\Phi^A \Phi^B \right]_S \chi_L(\boldsymbol{\rho}) \right]_{JM} \right\}, \quad (1)$$

where \mathcal{A} is the intercluster antisymmetrizer, Φ are the cluster internal states, $\boldsymbol{\rho}$ is the intercluster relative coordinate, while L , S , and J are the orbital angular momentum, intrinsic spin, and total spin, respectively. The internal states of the $A \leq 4$ clusters are simple $0s$ harmonic oscillator shell-model functions, while the heavier subsystems are described by two-cluster wave functions, similar to Eq. (1) (for example, ${}^7\text{Be}$ inside ${}^8\text{B}$ is described as a ${}^4\text{He} + {}^3\text{He}$ two-cluster system). The intercluster relative motions χ , which are the most important degrees of freedom, are treated with high precision, using variational methods [3].

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2. SOLAR NUCLEAR REACTIONS

We briefly summarize the physics motivation and the main results of Refs. [4–7], where the model, discussed above, was applied to selected reactions of the solar p-p chain. Further details can be found in the original papers.

${}^4\text{He}({}^3\text{He}, \gamma){}^7\text{Be}$: We studied the effects of the ${}^6\text{Li} + p$ channel on the reaction cross section and on the properties of ${}^7\text{Be}$ [4]. It is known that the zero-energy astrophysical S-factor ($S(E) = \sigma(E) \exp[2\pi\eta(E)]$, where $\sigma(E)$ is the cross section and η is the Coulomb parameter) is correlated with the quadrupole moment of ${}^7\text{Li}/{}^7\text{Be}$. This relation was used to estimate the value of $S_{34}(0)$ [8]. As the ${}^6\text{Li} + p$ configuration brings in large charge polarization in ${}^7\text{Be}$, it might have some interesting effects on these relations and on the determination of $S_{34}(0)$. We have shown that the inclusion of the ${}^6\text{Li} + p/n$ channel in the description of the ${}^4\text{He}({}^3\text{He}, \gamma){}^7\text{Be}$ and ${}^4\text{He}({}^3\text{H}, \gamma){}^7\text{Li}$ reactions really has an appreciable effect [4]. However, detailed analyses indicate that in order to have a clear picture, one should use a more sophisticated ${}^6\text{Li}$ state than the one used by us ($\alpha + d$ with pure $L = 0$ relative motion between the α and the d). The careful study of the correlations between the quadrupole moments of ${}^7\text{Be}/{}^7\text{Li}$ and the reaction cross sections revealed that the currently accepted $S_{34}(0)$ value seems to be in conflict with the recommended quadrupole moment of ${}^7\text{Li}$.

${}^3\text{He}({}^3\text{He}, 2p){}^4\text{He}$: We searched for narrow resonances in ${}^6\text{Be}$, close to the ${}^3\text{He} + {}^3\text{He}$ threshold [5]. Such a state, if it exists, could strongly enhance the reaction cross section and, as a consequence, suppress the fluxes of the ${}^7\text{Be}$ - and ${}^8\text{B}$ -type solar neutrinos. We used methods which allowed us to rigorously treat 2-body (${}^3\text{He} + {}^3\text{He}$) or 3-body (${}^4\text{He} + p + p$) resonances, if they exist. We found no indication for narrow resonances. It seems to us that the only remaining possibility for the existence of such a state is that it might come from the interplay between the s - and d -states (not present in our model) of the two ${}^3\text{He}$ clusters.

${}^7\text{Be}(p, \gamma){}^8\text{B}$: This reaction is responsible for the production of the highest-energy solar neutrinos (except for the *hep*-neutrinos [1]). Recently it has been the target of many experimental and theoretical analyses. We would like to point out that a possible way of finding the most probable values of the zero-energy astrophysical S-factor, $S_{17}(0)$, of the reaction is to find correlations between it and some measurable quantities of ${}^7\text{Be}$ and ${}^8\text{B}$ [6]. Fig. 1 shows the results of our model for $S(0)$ in correlation with some measurable properties of ${}^7\text{Be}/{}^8\text{B}$. We note that in Ref. [6] an incorrect value was used for the phenomenological Coulomb-displacement energy. We correct this error in Fig. 1. As one can see, our model cannot produce a low value for $S_{17}(0)$. It remains a question whether one could get a small $S_{17}(0)$ by going beyond the ${}^4\text{He} + {}^3\text{He} + p$ model-space.

3. CONCLUSION

We have studied some of the important nuclear reactions of the solar p-p chain, using microscopic models. We believe that in order to make significant further advances in the description of these processes, one should probably use a full A -body dynamical model. However, the fully consistent description of the bound and scattering states in such an approach will be a difficult task.

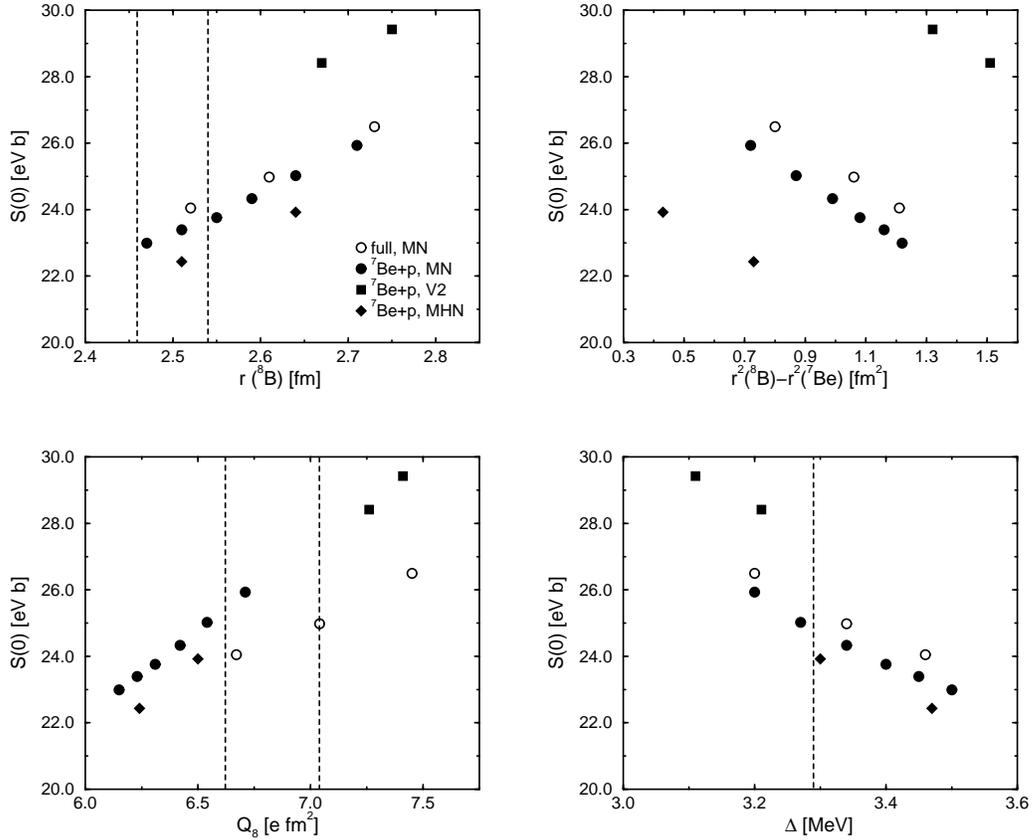


Figure 1. Correlations between the zero-energy astrophysical S factor of the ${}^7\text{Be}(p, \gamma){}^8\text{B}$ reaction and the ${}^8\text{B}$ point-nucleon radius $r({}^8\text{B})$ (in fm), the $r^2({}^8\text{B}) - r^2({}^7\text{Be})$ value (in fm^2), the ${}^8\text{B}$ quadrupole moment Q_8 (in $e\text{fm}^2$), and the $\Delta = E({}^8\text{Li}) - E({}^8\text{B})$ Coulomb displacement energy (in MeV). The symbols show the results coming from different N-N forces and model-spaces, while the vertical lines/bands indicate the phenomenologically suggested values/ranges. For the details, see Ref. [6].

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