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^{7}Be$(p,\gamma)^8$B and the high-energy solar neutrino flux

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Abstract. The importance of the ^{7}Be$(p,\gamma)^8$B reaction in predicting the high-energy solar neutrino flux is discussed. I present a microscopic eight-body model and a potential model for the calculation of the ^{7}Be$(p,\gamma)^8$B cross section.

1. Introduction

Today the neutron halo structure in some nuclei near the neutron drip line is well established. The proton drip line is, however, less well understood. The first (and so far still best) candidate for a proton halo structure was ^{8}B. In this paper I show how important it is to understand the structure of ^{8}B in order to be able to give precise predictions for the high-energy solar neutrino flux.

The high level of sophistication achieved in standard electroweak and stellar physics enables us to understand in detail the synthesis and evolution of the elements of the Universe in the Big Bang and in stars. The astronomical observations and theoretical predictions are in a very good general agreement with each other, with a few notable exceptions. Perhaps the most notorious of these exceptions is the solar neutrino problem. Despite thirty years of extensive experimental and theoretical work, the predicted solar neutrino fluxes are still in sharp disagreement with measurements. The solar neutrino measurements strongly suggest that the problem cannot be solved within the standard electroweak and astrophysical theories. Thus, the solar neutrino problem constitutes the strongest (and so far almost only) evidence for physics beyond the Standard Model [1].

Whatever the solution of the solar neutrino problem turns out to be, it is of paramount importance that the input parameters of the underlying electroweak and solar theories rest upon solid ground. The most uncertain nuclear input parameter in standard solar models is the low-energy ^{7}Be$(p,\gamma)^8$B radiative capture cross section. This reaction produces ^{8}B in the Sun, whose β^+ decay is the main source of the high-energy solar neutrinos. Many present and future solar neutrino detectors

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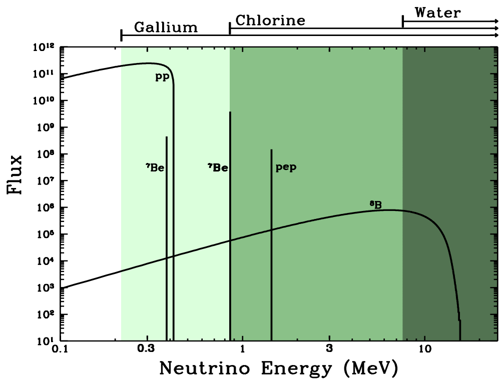

Fig. 1. Solar neutrino fluxes predicted by the solar model of Bahcall [1]. The thresholds of the various detectors are indicated.

are sensitive mainly or exclusively to the ^{8}B neutrinos (Fig. 1).

The predicted ^{8}B neutrino flux is proportional to S_{17}, the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ astrophysical S factor ($S(E) = \sigma(E)E\exp[2\pi\eta(E)]$), at solar energies ($E_{cm} = 20$ keV). Thus, the value of S_{17}(20 keV) is a crucial input parameter in solar models.

Currently there is a considerable confusion concerning the value of $S_{17}(0)$. The six direct capture measurements performed to date give $S_{17}(0)$ between 15 eVb and 40 eVb, with a weighted average of 22.2 ± 2.3 eVb, while a recent Coulomb dissociation measurement give $S_{17}(0) = 16.7 \pm 3.2$ eVb. The theoretical predictions for $S_{17}(0)$ also have a huge uncertainty, as the various models give values between 16 eVb and 30 eVb. For an experimental and theoretical summary, see [2].

In order to set tighter theoretical limits on the value of S_{17}, the nonresonant part of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction has been studied in a microscopic eight-body model [3] and in a ^{7}Be+p potential model [4], respectively.

2. $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ cross section constrained by A=7 and 8 observables

The relatively low temperature (on nuclear scale) of our Sun means that all charged-particle reactions in the energy-generating solar p-p chain take place well below the Coulomb barrier. In such cases the radiative capture cross section gets contributions almost exclusively from the external nuclear regions ($r > 6{-}8$ fm). At such distances the scattering (^{7}Be+p) and bound state (^{8}B) wave functions are fully determined, provided the scattering phase shifts and bound state asymptotic normalizations are known. At solar energies the phase shifts coincide with the (almost zero) hard sphere phase shifts, while the bound state wave function in the external region behaves like $\bar{c}W^+(kr)/r$, where W^+ is the Whittaker function and $\bar{c}$ is the asymptotic normalization. So the only unknown parameters that govern the solar radiative

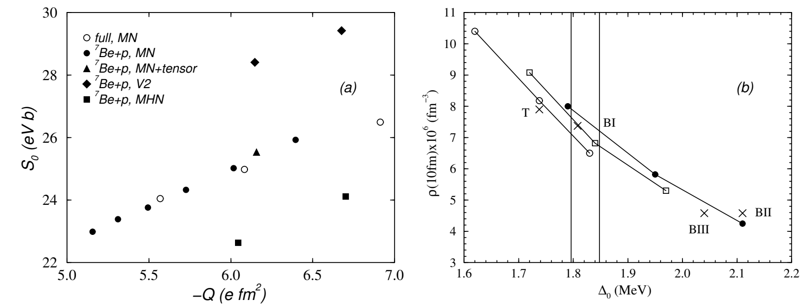

Fig. 2. Correlation between (a) the zero-energy astrophysical S factor of the ^{7}Be$(p,\gamma)^8$B cross section and the quadrupole moment of ^{7}Be in the microscopic eight-body model [3]; and (b) the valence-proton density at 10 fm and the Coulomb displacement energy in the potential model [4]. In Fig. (a) the results of several calculations, using various $N-N$ interactions and model spaces, are shown. In Fig. (b) the three lines join points obtained for different values of the diffuseness of the potential. The crosses show the results of potentials that are previously used in the literature. The region between the vertical lines are the range of values allowed by the displacement energy.

capture reactions, like ^{7}Be$(p,\gamma)^8$B, are the $\bar{c}$ values. The $\bar{c}$ normalization depends mainly on the effective ^{7}Be–p interaction radius. A larger radius results in a lower Coulomb barrier, which leads to a higher tunneling probability into the external region, and thus to a higher cross section. Our aim is to constrain the theoretical interaction radius by some properties of A=7 and 8 observables.

In the first model [3] an eight-body three-cluster wave function is used, which is variationally converged and virtually complete in the ^{4}He+^{3}He+p cluster model space. We find that the low-energy astrophysical S factor is linearly correlated with the quadrupole moment of ^{7}Be (Fig. 2a). A range of parameters is found where the most important ^{8}B, ^{7}Be and ^{7}Li properties are reproduced simultaneously; the corresponding S factor at zero energy is $25-26.5$ eVb.

Our second model [4] describes the ^{7}Be$(p,\gamma)^8$B process by assuming a local potential between a structureless ^{7}Be and p. The relationship between the Coulomb displacement energy for the A=8, J=2$^+$, T=1 state and the low-energy astrophysical S factor for the ^{7}Be$(p,\gamma)^8$B reaction is studied. The displacement energy is interpreted in a particle-hole model. The dependence of the particle displacement energy on the potential well geometry is investigated and is used to relate the particle displacement energy to the rms radius and the asymptotic normalization of the valence proton wave function in ^{8}B. We find that the theoretical Coulomb displacement energy strongly constrains the valence-proton density, and thus the asymptotic normalization, in the external region (Fig. 2a). The asymptotic normalization is used to calculate S_{17}. The model predicts S_{17} to be 24.5 ± 2.9 eVb at zero energy.

The energy dependence of the S factor is also studied [5] with the aim to understand the apparent disagreement between the predictions of the microscopic

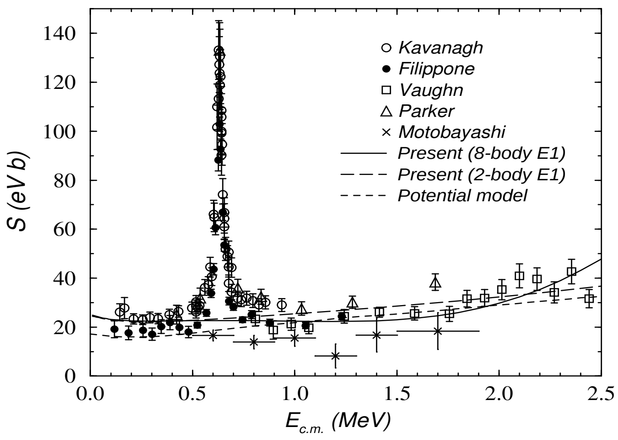

Fig. 3. Astrophysical S factor for the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction [5]. The symbols show the various experimental data. The solid and long-dashed lines are the $E1$ components of the S factors in the eight-body model of [3] with and without antisymmetrization in the electromagnetic transition matrix, respectively. The short-dashed line is the result of a typical potential model.

eight-body model [3] and potential models. It is found that off-shell effects, like antisymmetrization and core-excitation and deformation, significantly influence the energy dependence of the S factor. The proper treatment of these effects results in a virtually flat E1 component of the S factor at $E_{cm} = 0.3 - 1.5$ MeV in the present eight-body model (Fig. 3). Off-shell effects can cause 15–20% changes in the value of $S_{17}(0)$ extrapolated from high-energy ($E_{cm} > 0.7$ MeV) data.

3. Conclusion

The zero-energy S factors, predicted by our models, are slightly higher than but compatible with $S_{17}(0) = 22.4 \pm 2.1$ eVb, used in standard solar models [1].

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