Astrophysical S-factor for the reaction $^7Be+p\rightarrow{}^8B+\gamma$

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The astrophysical S-factor $S_{17}(0) =$ is calculated for the reaction $^7Be + p\rightarrow{}^8B + \gamma$. Information on the vertex constant is taken into account. The value $S_{17}(0) = 0.0155$ keV·b is found.

The astrophysical S-factor for the reaction $^7Be + p\rightarrow{}^8B + \gamma S_{17}(E_p)$ at an incident-proton energy $E_p \gtrsim 20$ keV is a quantity of fundamental importance to calculations of the flux of solar neutrinos which are detectable in Davis's experiment. The currently accepted value[1] of the astrophysical S-factor at zero energy, $S_{17}(0) = 0.024 \pm 0.002$ keV·b, is an average of $S_{17}(0)$ values found through the extrapolation of various experimental data to the point $E_p = 0$. Various values of $S_{17}(0)$ are predicted theoretically. We would like to call attention to the value $S_{17}(0) = 0.030$ keV·b which has been found by the generator-coordinate method,[2] the value $S_{17}(20\text{ keV}) = 0.0254$ keV·b found by the resonating-group method,[3] and the values of $S_{17}(0)$ in the interval 0.012–0.020 keV·b which were calculated from the direct-capture potential model with parameter values found by fitting the calculated cross sections for the radiative capture of thermal neutrons, $^7Li(n,\gamma)^8Li$, to the experimental cross sections.[4,5] In view of the differences among the estimates of $S_{17}(0)$ found by the different methods and the importance of this astrophysical S-factor, we would like to propose a new method for calculating $S_{17}(0)$.

The basic idea of the method is to make use of the fact that the very small energy for the detachment of a p from $^8B(\epsilon = 136\text{ keV})$ means that the capture of a proton by a ^7Be nucleus occurs at a fairly large distance from this nucleus. The capture cross section σ_{ls} in the channel with a given spin s contains a radial overlap integral of the ^8B and ^7Be wave functions, $I_{ls}(r)$, for which we have the asymptotic expressions[6]

$$I_{ls}^{(r)} \approx C_{ls}\exp(-\kappa r-\eta\ln 2\kappa r)/r, \tag{1}$$

where l is the orbital angular momentum of the relative motion of the p and the ^7Be in ^8B, $\kappa = \sqrt{2\mu\epsilon}, \eta = Ze^2\mu/\kappa$ is the Coulomb parameter of the bound state $p + {}^7Be$, μ is the reduced mass of the p and the ^7Be, Ze is the charge of the ^7Be nucleus, and C_{ls} is a normalization factor for the asymptotic expression of the radial overlap integral, which is related to the vertex constant G_{ls} for the virtual decay $^8B\rightarrow{}^7Be + p$ by[6]

$$G_{ls} = -\exp(i\pi(l+\eta)/2)\sqrt{\pi}\,C_{ls}/\mu. \tag{2}$$

The factor which arises from effects of the antisymmetrization between the p and the ^7Be nucleons is incorporated in C_{ls}. Throughout this paper we are using a system of units with $\hbar = c = 1$. Since the reaction $^7Be + p\rightarrow{}^8B + \gamma$ is of a surface nature, we find, using (1) and (2),

(3)

The reduced cross section $\tilde{\sigma}_{ls}$ is determined by a matrix element which can be expressed in terms of the asymptotic expression for the radial overlap integral, $r^{-1}\exp(-\kappa r-\eta \ln 2\kappa r)$. It does not depend on the nuclear structure, all information about which is contained in $|G_{ls}|^2$. In the standard approach, on the other hand, the cross section for the surface reaction, σ_{ls} is parametrized through the product[1)] $C^2_{ls}=S_{ls}b^2$, where S_{ls} is the spectroscopic factor, and b is a normalization coefficient for the asymptotic expression for the one-particle wave function of a proton in the ^{8}B nucleus. Since there is some uncertainty in the choice of S_{ls} and b, we are obliged to appeal to various indirect methods, e.g., an analysis of the mirror reaction[4,5] ^{7}Li$(n,\gamma)^8$Li.

The vertex constants for the nuclei of the $1p$ shell, including the vertex constant G_{ls} for the virtual decay $^8\mathrm{B}\rightarrow{}^7\mathrm{Be}+p$, were calculated by a microscopic approach in Ref. 7: $|G_{11}|^2=0.012$ fm and[2)] $|G_{12}|^2=0.065$ fm. The vertex constants calculated in Ref. 7 agree very well with the solidly established empirical values of the vertex constant for the detachment of a neutron from the nuclei ^{13}C and ^{14}N. In the present study, we have calculated the value of the astrophysical S-factor $S_{17}(E)=E\exp(2\pi\eta)\sigma_{17}(E)$ at a zero energy by introducing information about the vertex constant with the help of (3). The reduced cross sections σ_{17} were taken from Refs. 8 and 4. The corresponding S-factors turned out to be $S_{17}(0)=0.0157$ keV·b and $S_{17}(0)=0.0153$ keV·b.

It has already been mentioned that an interval of values of $S_{17}(0)$ was found in Ref. 4. The uncertainty regarding the value of $S_{17}(0)$ stems from the uncertainty in the choice of the spectroscopic factor S_{ls} and the geometric parameters r_0 and α of the Woods-Saxon potential of the bound state of the p in the nucleus ^{8}B. The value of b depends on these quantities. In Ref. 4, the values of S_{ls}, r_0, and α were varied in order to reproduce the experimental cross section for the reaction ^{7}Li$(n,\gamma)^8$Li at low energies. Various choices of the parameters S_{ls}, r_0, and α at the vertex $^8\mathrm{Li}\rightarrow{}^7\mathrm{Li}+n$ led to values of $|G_{11}|^2+|G_{12}|^2$ lying in the interval from 0.063 to 0.073 fm, which agree with the value of 0.068 fm which we have calculated.[7]

The average value of the astrophysical S factors which we have found is thus $S_{17}(0)=0.0155$ keV·b. Since the value $S_{17}(0)=0.024$ keV·b is customarily used in standard calculations of the flux of boron neutrinos,[1] and since boron neutrinos make up to 75% of the total flux of high-energy solar neutrinos, the theoretical flux of these neutrinos is reduced by a factor of 1.4 if our value of $S_{17}(0)$ is used.

In conclusion we feel it necessary to point out an important point. It is presently believed that the most reliable theoretical values of the astrophysical S factor can be found by the resonating-group method or (its variant) the generator-coordinate method. The value of $S_{17}(0)$ has already been calculated on the basis of the three-cluster resonating-group method.[2] In the case of the surface radiative-capture reaction $^7\mathrm{Be}+p\rightarrow{}^8\mathrm{B}+\gamma$, the complex apparatus of the resonating-group method is used only to find C_{ls} (or G_{ls}). A correct determination of the normalization coefficient for the asymptotic behavior of the overlap integral, however, will require a correct calculation of the wave function of the ^8B nucleus in not only the outer region but also the inner region. In the inner region, however, where the clusters lose their individuality because of the pronounced overlap, the resonating-group method may itself be incompetent. Furthermore, the value of the normalization coefficient for the asymptotic behavior of C_{ls} depends on the choice of the *NN* potential, which figures in the resonating-group method. Different potentials may reproduce the scattering phase shifts equally well in the resonating-group method (in this sense, the different potentials are phase-equivalent) but lead to different values of C_{ls}. A comparison of the values of C_{ls} found in the resonating-group method,with the values which we have calculated by a microscopic approach makes it possible to test the reliability of the resonating-group method in determining the normalization coefficient for the asymptotic behavior (or the vertex constant) and to select (if possible) those *NN* potentials which led to values of C_{ls} that are close to the values of C_{ls} found by the microscopic approach or to phenomenological values of C_{ls} which have been reliably established.

[1)] That this partitioning is contrived follows from the fact that S_{ls} is, by definition, the square of the norm of the overlap integral, which is dominated by the region of small r, while C_{ls} determines the normalization of the asymptotic expression for the overlap integral.

[2)] Values of the vertex constant G_{lj} for the virtual decay $A \to B + p$ were given in Ref. 7. This quantity is related to G_{ls} by $G_{lj} = \Sigma_S (-1)^{J_B + 1/2 - S} \hat{S}\hat{j} W(J_B \frac{1}{2} J_A l, Sj) G_{ls}$, where j is the total angular momentum of the transferred proton, J_i is the spin of nucleus i, and W is the Racah coefficient. Here $\Sigma_S |G_{ls}| = \Sigma_j |G_{lj}|^2$.

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