Low-Energy Behavior of the Astrophysical S Factor in Radiative Captures to Loosely Bound Final States

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The knowledge of the energy behavior of the direct capture astrophysical factors as $E \to 0$ is of crucial importance for nuclear astrophysics. It turns out that, depending on the system, S-factors can feature completely opposite behaviors as one approaches zero energy. Despite the long history of S-factor calculations and the numerous papers published on this subject, no satisfactory physical explanation for the different behaviors has been presented. The purpose of our work is a search for the understanding of the general physical features governing the low-energy behavior of the direct capture S-factors. The findings of this work have implications for a great number of today's interesting astrophysical cases. We demonstrate that the behavior of the S-factors is governed by six essential ingredients. Two act in an attractive sense, creating a negative slope for $S(0^+)$: the remnant of the initial Coulomb barrier (left after extracting the Gamow penetration factor) and the singularity at $E = \varepsilon$ (where ε is the binding energy of the final state). Three act as *real* penetration barriers, producing a positive slope for $S(0^+)$: both initial and final centrifugal barriers and the final-state Coulomb barrier. The effect of the final centrifugal and Coulomb barriers are minor compared with the initial centrifugal and Coulomb. Finally, there is still a photon factor k_γ^{2L+1}, (where L is the multipolarity of transition), which tends to increase the derivative of S(E). The resulting energy behavior of the S-factors is defined by the competition of these six factors. We have derived analytical expressions for the S-factor. We have tried to demystify the idea that the energy behavior of the S-factor around threshold is dominated by the pole $E = -\varepsilon$ [1]. Finally, we have not only illustrated our findings with a few sets of study cases, but also applied it to specific examples relevant in astrophysics. In Fig. 1 we present the energy behavior of the pole $S_{(0)}(E)$, for $a(p,\gamma)b$, for atomic numbers $A_a = 7$ and $A_b = 8$, initial and final angular momenta $l_i = 0$, $l_f = 1$, and $L = 1$. It mimics $^7Be(p,\gamma)\,^8B$, but a different set of proton binding energies are used. All $S_{(0)}(E)$ are normalized to unity at zero energy. It is obvious that, even for the smallest binding energy in which the pole is closest to threshold, $S_{(0)}(E)$ decreases as $E \to 0$. In Fig. 2 we demonstrate the difference in the energy behavior of the direct capture S-factors for notorious astrophysical processes with either $l_i = 1$ or $l_f = 1$. For all cases, the centrifugal barriers are not strong enough to win over the effect of the singularity at $E = -\varepsilon$ and the initial remnant Coulomb barrier. In Fig. 3 we present the astrophysical factors with either $l_i = 2$ or $l_f = 2$. For the first two cases, the slope is positive because the centrifugal barrier wins over the initial remnant Coulomb barrier and the singularity. However, for the capture on ^{22}Mg, the very large initial remnant Coulomb barrier is able to make the slope negative.

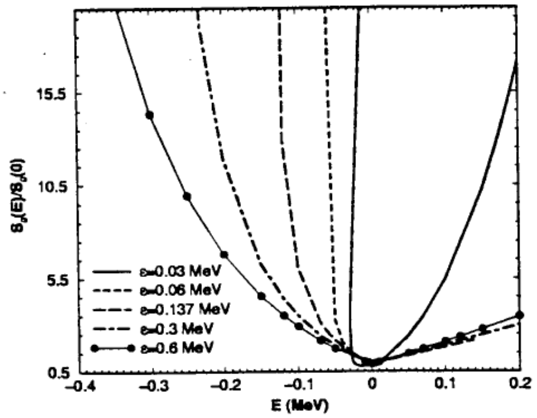

Figure 1: $S_{(0)}(E)$ for $l_i = 0 \rightarrow l_f = 1$ proton capture, for a set of binding energies of the final state. Masses and charges are the same as for $^7Be(p,\gamma)\,^8B$.

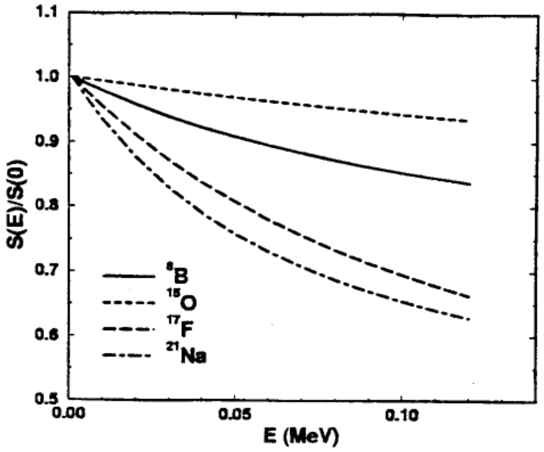

Figure 2, Figure 4: S-factors for: $^7Be(p,\gamma)\,^8B$ (solid), $^{14}N(p,\gamma)\,^{15}O(3/2^+)$ (dotted), $^{16}O(p,\gamma)\,^{17}F(1/2^+)$ (dashed), $^{20}Ne(p,\gamma)\,^{21}Na(1/2^+)$ (dot-dashed).

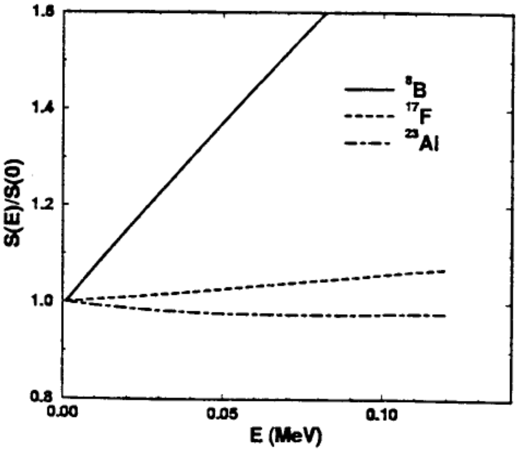

Figure 3: S-factors for $^7Be(p,\gamma)\,^8B$ (solid), $^{16}O(p,\gamma)\,^{17}F(5/2^+)$ (dashed), $^{22}Mg(p,\gamma)\,^{23}Al(5/2^+)$ (dotted).

References

[1] B. K. Jennings, *et al.*, Phys. Rev. C **58**, 3711 (1998); Phys. Rev. C **58**, 579 (1998).