

## Astrophysical relevance of $\gamma$ transition energies

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The relevant  $\gamma$  energy range is explicitly identified where additional  $\gamma$  strength must be located to have an impact on astrophysically relevant reactions. It is shown that folding the energy dependences of the transmission coefficients and the level density leads to maximal contributions for  $\gamma$  energies of  $2 \leq E_\gamma \leq 4$  unless quantum selection rules allow isolated states to contribute. Under this condition, electric dipole transitions dominate. These findings allow us to more accurately judge the relevance of modifications of the  $\gamma$  strength for astrophysics.

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*Introduction.* Predictions made by nuclear theory are essential for all nucleosynthesis studies but especially for those dealing with explosive processes proceeding far from the line of nuclear stability. Reactions with highly unstable nuclei appearing in stellar explosions cannot be directly studied in the laboratory and most properties required to model the reactions cannot be measured yet. Current radioactive ion beam facilities are still limited to a region around stability and often reactions cannot be measured unless either the target or the residual nucleus is long-lived or stable. Because of the low interaction energies in astrophysically relevant reactions, the statistical Hauser-Feshbach model [1] can be used to predict reaction rates provided the level density in the compound nucleus is sufficiently high [2]. The model requires input based on nuclear structure physics, such as nuclear masses and deformations, optical model potentials, and nuclear level densities. These are exploited to calculate transmission coefficients (average widths) which, in turn, determine the reaction cross section. The reliability of the predictions hinges on two questions: (i) Is the model applicable for a given reaction and energy, and (ii) are the relevant inputs known or reliably predicted?

In the past and the present, much effort has been and still is devoted to measuring and understanding photon strength functions. Often discussed is the electric dipole ( $E1$ ) strength that exhibits a pronounced peak at the Giant Dipole Resonance (GDR) energy. The GDR can be well described by a Lorentzian although it has been proven to be necessary to introduce an additional energy dependence in the low-energy tail (see, e.g., Refs. [3,4]). Recently, a number of experimental investigations have indicated additional strength confined to a small energy range in the low-energy tail (see, e.g., Refs. [5–9]). Theory provides different possibilities to explain the additional strength, such as collective vibration of a neutron skin against an inert core composed of protons and neutrons (pygmy resonance) or other collective modes (see, e.g., Refs. [10–16]). Accordingly, the predictions regarding location and width of this additional  $E1$  resonance vary. The possible impact on astrophysical capture reactions is frequently quoted as motivation for investigating these phenomena. It is the aim of this article to substantiate these claims and to outline some general considerations for the importance of altered  $\gamma$  strengths in astrophysics.

*Energetics.* The average transmission coefficient  $T = 2\pi \frac{\langle \Gamma \rangle}{D}$  is the central quantity in Hauser-Feshbach type cal-

culations, relating an average width to the level spacing  $D$ . The capture cross section  $\sigma$  is proportional to the transmission  $T_i$  in the initial channel, to the  $\gamma$  transmission  $T_\gamma$ , and to the total transmission  $T_{\text{tot}}$  that comprises all energetically possible channels:

$$\sigma(E_{\text{proj}}) \propto \sum_{J,\pi} \frac{T_i^{U,J,\pi} T_\gamma^{U,J,\pi}}{T_{\text{tot}}^{U,J,\pi}}. \quad (1)$$

For laboratory reactions,  $T_i$  describes the formation of a compound nucleus from the target ground state and particle emission back into the initial channel. In astrophysical plasmas, it additionally accounts for compound formation from thermally excited target states. The formed compoundstate is characterized by its excitation energy  $U$ , spin  $J$ , and parity  $\pi$ . The excitation energy  $U = S_{\text{proj}} + E_{\text{proj}}$  is computed from the separation energy of the projectile in the compound nucleus  $S_{\text{proj}}$  and the projectile energy  $E_{\text{proj}}$ . Deexcitation of the compound state by  $\gamma$  emission is described by

$$T_\gamma^{U,J,\pi} = \left( \sum_{\mu=0}^{\mu_{\text{max}}} T_\gamma^{(U,J,\pi) \rightarrow \mu} \right) + \int_{E_{\mu_{\text{max}}}}^U \sum_{J',\pi'} \rho(E', J', \pi') \times T_\gamma^{(U,J,\pi) \rightarrow (E',J',\pi')} dE', \quad (2)$$

where the first sum includes discrete states  $\mu$  and an integration over a level density  $\rho = 1/D$  is performed for the energy region with many, unresolved states with energy  $E'$ , spin  $J'$ , and parity  $\pi'$ . The transmission coefficients on the right-hand side include  $\gamma$  emission with all multipole orders allowed by the standard spin and parity selection rules. Only the lowest multipole orders are important and therefore most Hauser-Feshbach calculations only include  $E1$  and  $M1$  transitions, a few also  $E2$ . Here the descriptions of Refs. [3] and [17] were used for  $E1$  and  $M1$ . However, the following discussion focuses on  $E1$  transitions because the results can be understood in terms of the electric dipole alone. For the discussed cases where the level density enters,  $E1$  is dominating. Neglecting  $M1$  totally changes the results only by a few percent. This is in agreement with experiment [18].

From the above it follows that the energies of the emitted photons are in the range  $0 \leq E_\gamma \leq S_{\text{proj}} + E_{\text{proj}}$ . A sketch of the situation is given in Fig. 1. In astrophysical nucleosynthesis processes, the relevant neutron energies are below 100 keV, which is almost negligible compared to neutron separation

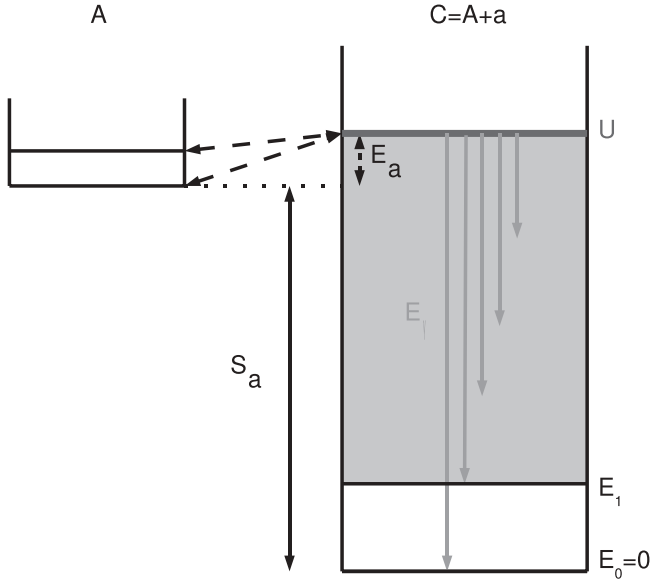


FIG. 1. Sketch of the relevant energies in a compound capture reaction: target  $A$  captures a projectile  $a$  by formation of a compound nucleus  $C$ . The excitation energy  $U$  of the compound nucleus depends on the projectile energy  $E_a$  and the separation energy  $S_a$  of the projectile in the compound nucleus. The nucleus  $C$  is deexcited via  $\gamma$  emission to discrete states or “average states” given by a level density (gray area). Thus, the possible photon energies  $E_\gamma$  can only be in the range  $0 \leq E_\gamma \leq S_a + E_a$ . For astrophysical neutron capture,  $E_a \ll S_a$ .

energies of several MeV, even for very neutron-rich, unstable nuclei. The situation is different for charged projectiles because the relevant projectile energies are shifted to 5–10 MeV, depending on the charges of the target and the projectile [19].

The transmission coefficient  $T_\gamma^L$  for  $\gamma$  emission with multipolarity  $L$  is related to the (downward) strength function  $f$  by  $T_\gamma^L = 2\pi E_\gamma^{2L+1} f(E_\gamma)$ . It is to be noted that only for the strength function  $f$  defined in this way is there a direct connection to the Hauser-Feshbach transmission coefficients. There are many approaches to derive  $f$ , each leading to a basic energy dependence of the  $E1$  transmission given by a Lorentzian,

$$T_{E1}(E_\gamma) \propto \frac{\Gamma_{\text{GDR}} E_\gamma^4}{(E_\gamma^2 - E_{\text{GDR}}^2)^2 + \Gamma_{\text{GDR}}^2 E_\gamma^2}, \quad (3)$$

around the Giant Dipole Resonance (GDR) at energy  $E_{\text{GDR}}$  with a width  $\Gamma_{\text{GDR}}$ , but they differ in the details describing the strength at very low energy [4].

Although transitions with the largest  $\gamma$  energies (close to  $U$ ) are the strongest due to the  $E_\gamma^4$  dependence [Eq. (3)], they receive less weight in the integrand appearing in Eq. (2) because the nuclear level density  $\rho$  decreases with increasing  $E_\gamma$  with  $\rho(E_\gamma) \propto \exp(2\sqrt{a(U - E_\gamma)})$  (with  $a$  being the usual level density parameter). Thus, there will be a competition of a few strong transitions with many weak ones and only a closer inspection of the integrand will reveal the relative importance. As an example, the relative contribution to the integrand of different  $E_\gamma$  is shown in Fig. 2 for two nuclei. The computation was performed by adopting the descriptions

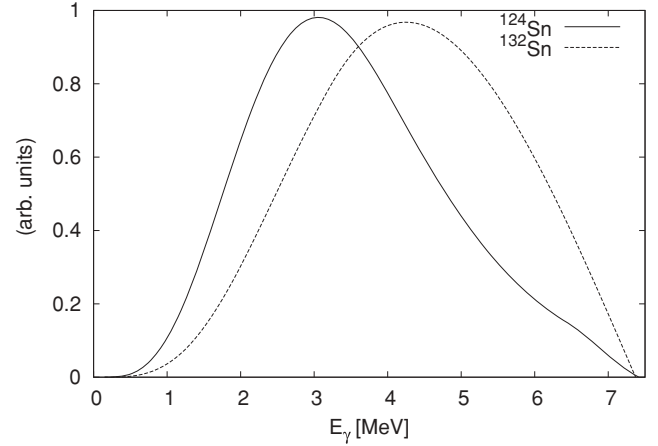


FIG. 2. The integrand of Eq. (2) in the two compound nuclei  $^{124,132}\text{Sn}$  when capturing 60 keV neutrons (renormalized to the same maximal value to show the similar shapes).

of Refs. [3] and [17] for  $T_{E1}$  (and  $T_{M1}$ ) and  $\rho$ , assuming that  $E_{\text{proj}} = 60$  keV and  $\mu_{\text{max}} = 0$ . It can clearly be seen that the largest contribution stems from the energy range about midway between the ground state and the formed compound state. This conclusion holds even when employing different descriptions of low-energy GDR strength as given in Ref. [4]. The resulting changes in the location of the maxima are on a level of 10% or smaller.

When the level density is low, the smooth averaged integral is fractionated into contributions of single, isolated states that are accounted for in the first sum of Eq. (2), including the contribution of the transition to the ground state. For light or closed-shell nuclei, the sum can extend high in excitation energy. Depending on their spin and parity, these isolated states can carry a considerable fraction of the total strength when they can be reached by a single  $E1$  transition. Even in the absence of such a fractionation, the contribution of the transitions to the ground state may not be neglected; i.e., the first sum in Eq. (2) has at least one term. However, even when such a state is a main contributor to  $T_{E1}$  for a given compound state  $(U, J, \pi)$ , it may still not be dominating the reaction cross section. That compound state may not be populated significantly in the reaction due to the spins and parities in the initial channel formed by the projectile and target. In other words, while  $T_\gamma^{U,J,\pi}$  may be dominated by a certain state for a few values of  $J$  and  $\pi$ ,  $T_i^{U,J,\pi}$  may be significantly larger for  $(J, \pi)$  values where that state is not contributing. Thus, it depends sensitively on the quantum numbers of projectile, target state, and final state  $\mu$  whether  $E_\gamma = U - E_\mu$  is a relevant  $\gamma$  energy. An example of this is shown in Fig. 3, where the ground state contribution would be large but is completely suppressed. In general, the transitions to the ground state with  $E_\gamma = S_{\text{proj}} + E_{\text{proj}}$  are only important in nuclei with an inherent low level-density where the application of the statistical model is doubtful anyway.

*Implications for astrophysics.* It has been shown that a change in the low-energy tail of the GDR strength, such as the one caused by a pygmy resonance, can lead to a significant change in the neutron capture cross sections for neutron-rich

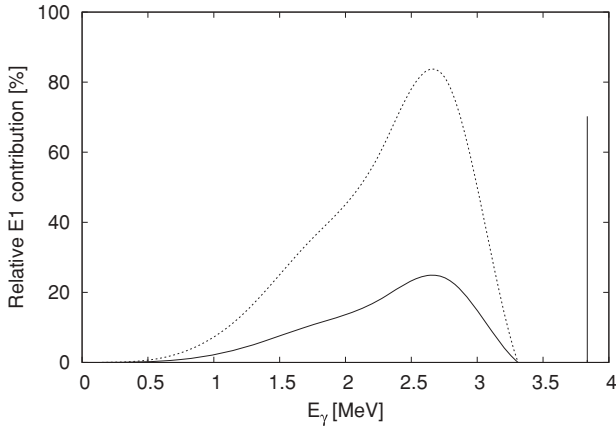


FIG. 3. Relative contribution to  $T_{E1}$  of Eq. (2) and for  $^{135}\text{Sn}(n, \gamma)$  at 60 keV. The full line shows the contributions of the ground state transition and the averaged excited states as given by Eq. (2) and summed over all  $J, \pi$  in the compound nucleus. The dotted line shows the relative contribution to the cross section when including the weighting by  $T_i$  as shown in Eq. (1). In the latter case, the contribution of the ground state transition is completely suppressed because the target nucleus has  $J^\pi = 7/2^-$  [23] and the ground state of the compound nucleus has  $J^\pi = 0^+$ .

nuclei [20–22]. Although experiments have indicated additional  $E1$  strength at low excitation energy [5–9], the origin of this strength and a prediction of its properties for more neutron-rich nuclei remains controversial. Nevertheless, using the above arguments the energy can be derived at which the additional strength must be located to have an impact on astrophysically relevant reactions. As above, the descriptions of Refs. [3] and [17] were adopted for  $T_{E1}$  and  $\rho$  and information for ground and excited states was taken from Refs. [23] and [24].

Neutron capture on very neutron-rich nuclei can be relevant in  $r$  process nucleosynthesis [20,25], on proton-rich nuclei in the  $p$  process [26,27]. Figures 4–7 show the maximally

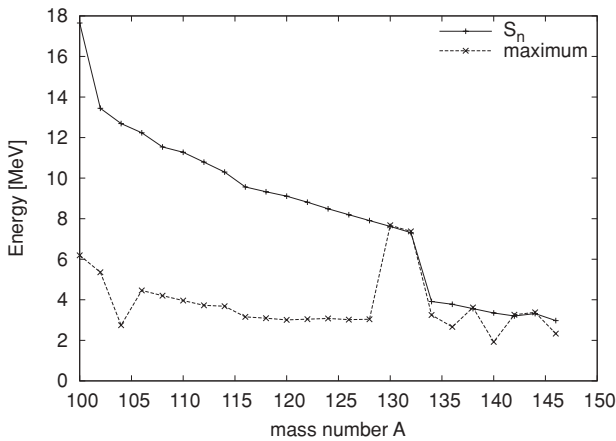


FIG. 4. The maximally contributing  $\gamma$  energies when capturing 60 keV neutrons on Sn isotopes with odd mass numbers  $A$  are compared to the neutron separation energies  $S_n$  in the compound nuclei. The horizontal axis gives the mass number  $A$  of the final (compound) nucleus.

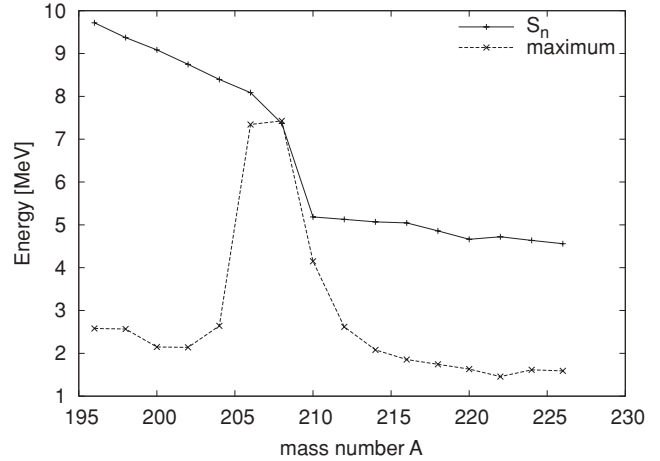


FIG. 5. Same as Fig. 4 but for Pb isotopes.

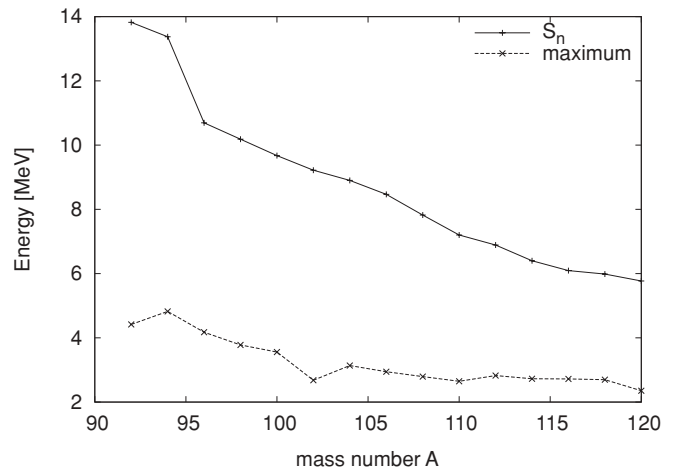


FIG. 6. Same as Fig. 4 but for Ru isotopes.

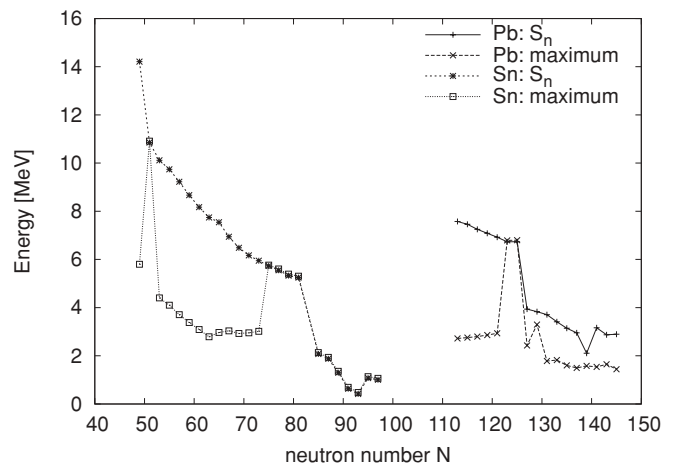


FIG. 7. Same as Fig. 4 but for neutron capture on isotopes of Sn and Pb with even mass number  $A$ . The horizontal axis gives the neutron number  $N$  of the final nucleus.

contributing  $\gamma$  energies for sequences of Sn, Pb, and Ru isotopes. The weighting by  $T_i$  is considered according to Eq. (1). The neutron separation energy is decreasing in an isotopic chain with increasing neutron number but at the same time the maximal level density is also decreasing due to the lower excitation energies  $U$  encountered. In almost all shown cases the energy of the maximal  $E1$  contribution is in the range  $2 \leq E_\gamma \leq 4$  MeV. Jumps can be found for nuclei where the selection rules allow the compound-nucleus ground state to be reached by a combination of  $s$ -wave neutrons and  $E1$   $\gamma$ s. In this case the relevant  $E_\gamma$ , sensitive to modifications of the strength  $f$ , is a sharply defined energy and equal to  $S_n + E_{\text{proj}} \approx S_n$ .

Experimentally, additional  $E1$  strength was found in  $^{132}\text{Sn}$  and attributed to a pygmy resonance [7]. However, it is located several MeV above  $S_n$ , in accordance with theoretical predictions. Thus, it does not affect the neutron capture cross section. In comparison with an available prediction of the pygmy resonance energy within an isotopic chain, it can be seen that it is predicted to always lie well above  $S_n$  [14–16]. If this is confirmed, it would mean that the pygmy resonance does not play a role in astrophysical neutron capture unless it is sufficiently wide to bring some additional strength below  $S_n$ . To have a wide and strong pygmy resonance may prove difficult, however, without violating the  $E1$  sum rule (Thomas-Reiche-Kuhn sum rule). On a side note it should be remembered that the Hauser-Feshbach model cannot be applied when the level density is too low at the compound formation energy [17]. This will occur in nuclei with  $S_n$  of only a few MeV. In the absence of resonances direct capture will dominate neutron capture on nuclei close to the neutron dripline, which does not excite collective modes in the  $\gamma$  emission to the continuum and is not sensitive to pygmy effects. Furthermore, most  $r$  process models predict the  $r$  process path to be characterized by an  $(n, \gamma)$ – $(\gamma, n)$  equilibrium in which individual cross sections do not play a role [28]. In these models, neutron captures only have a moderate effect during the relatively fast freeze-out at the end of the  $r$  process. Those captures will also occur closer to stability as compared to the  $r$  process path.

Energetically, the situation is different for capture of charged particles. Due to the Coulomb barrier, the astrophysically relevant interaction energies are shifted to higher energies. Reactions with charged particles occur at the line of stability and on the proton-rich side of the nuclear chart in  $p$  [26,29],  $rp$  [30], and  $\nu p$  process [31] nucleosynthesis. In the most extreme case, nonequilibrium proton captures involve protons of 5–7 MeV maximum energy. For  $\alpha$  particles, the maximum energies are around 10–12 MeV. These energies depend on the charge of the target nucleus [19]. Because they are comparable to or exceed the proton or  $\alpha$  separation energies, respectively, the sensitive  $E_\gamma$  will be at or above the projectile separation energy in the compound nucleus. Otherwise, similar rules apply as for neutron capture. However, a widely accepted explanation of the pygmy resonance is that it is caused by a collective motion of a neutron skin against a proton-neutron core. This is not likely to occur in neutron-deficient nuclei but other ways to generate additional strength beyond the GDR may still be found. Figures 8–11

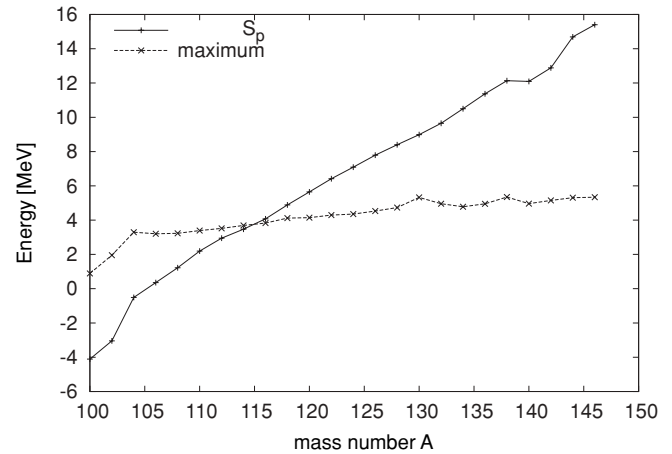


FIG. 8. The maximally contributing  $\gamma$  energies when capturing 5 MeV protons on Sn isotopes are compared to the proton separation energies  $S_p$  in the compound nuclei. The horizontal axis gives the mass number  $A$  of the final nucleus.

show the relevant  $\gamma$  energies in comparison to the separation energies for proton and  $\alpha$  capture on Sn and Sm isotopes. It is interesting to note that the energies again remain in the range of about  $2 \leq E_\gamma \leq 4$ , even for  $\alpha$  captures with negative  $Q$  values.

*Summary.* The relevant  $\gamma$  energy range was explicitly identified where additional  $\gamma$  strength must be located for having an impact on astrophysically relevant reactions. It was shown that folding the energy dependences of the transmission coefficients and the level density leads to maximal contributions for  $\gamma$  energies in the range of about  $2 \leq E_\gamma \leq 4$  MeV. The distributions show a full width at half maximum of about 2 MeV. Quantum selection rules allow isolated states to contribute only in special cases, mainly for neutron capture around closed shells or at low neutron separation energy when also the application of the statistical model becomes problematic. This can be seen in Figs. 4, 5, and 7 for neutron

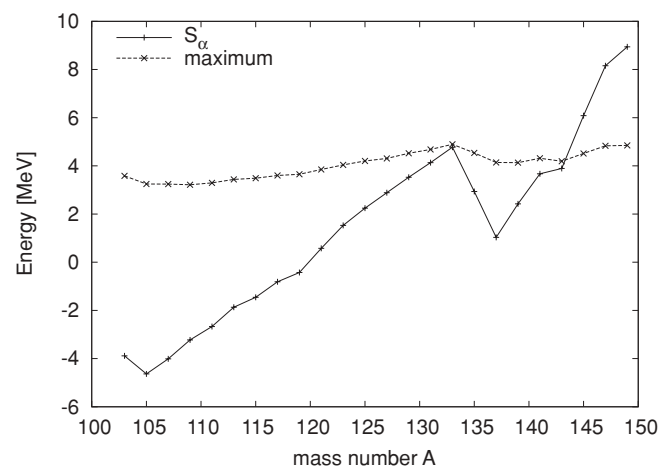


FIG. 9. The maximally contributing  $\gamma$  energies when capturing 10 MeV  $\alpha$  particles on Sn isotopes are compared to the  $\alpha$  separation energies  $S_\alpha$  in the compound nuclei. The horizontal axis gives the mass number  $A$  of the final nucleus.

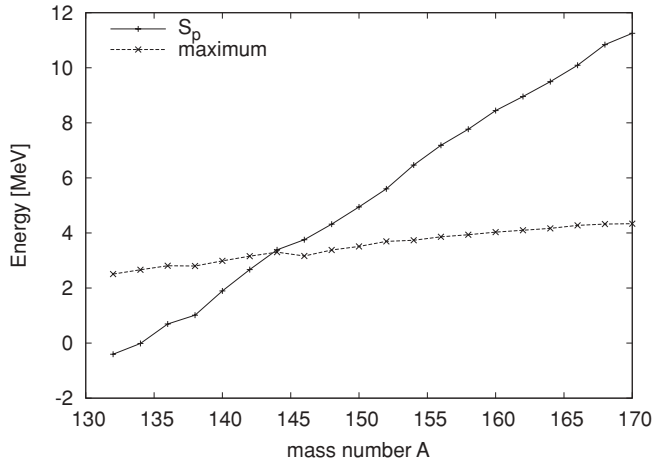


FIG. 10. The maximally contributing  $\gamma$  energies when capturing 5 MeV protons on Sm isotopes are compared to the proton separation energies  $S_p$  in the compound nuclei. The horizontal axis gives the mass number  $A$  of the final nucleus.

capture on  $^{208-211}\text{Pb}$ , as well as on  $^{100,124,126,128-130}\text{Sn}$  and most isotopes beyond  $^{130}\text{Sn}$  where the neutron separation energy remains low. These findings allow us to more accurately judge the astrophysical relevance of modifications of the  $\gamma$  strength, either found experimentally or derived theoretically.

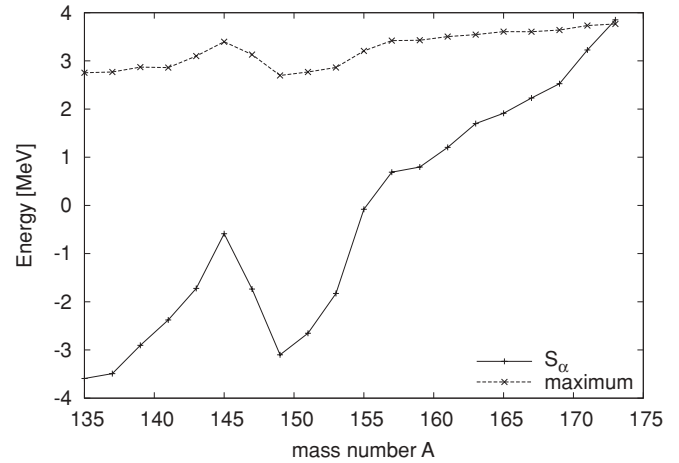


FIG. 11. The maximally contributing  $\gamma$  energies when capturing 10 MeV  $\alpha$  particles on Sm isotopes are compared to the  $\alpha$  separation energies  $S_\alpha$  in the compound nuclei. The horizontal axis gives the mass number  $A$  of the final nucleus.

The importance of experimentally obtaining spectroscopic information for nuclei with low inherent level densities far off stability is also evident.

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