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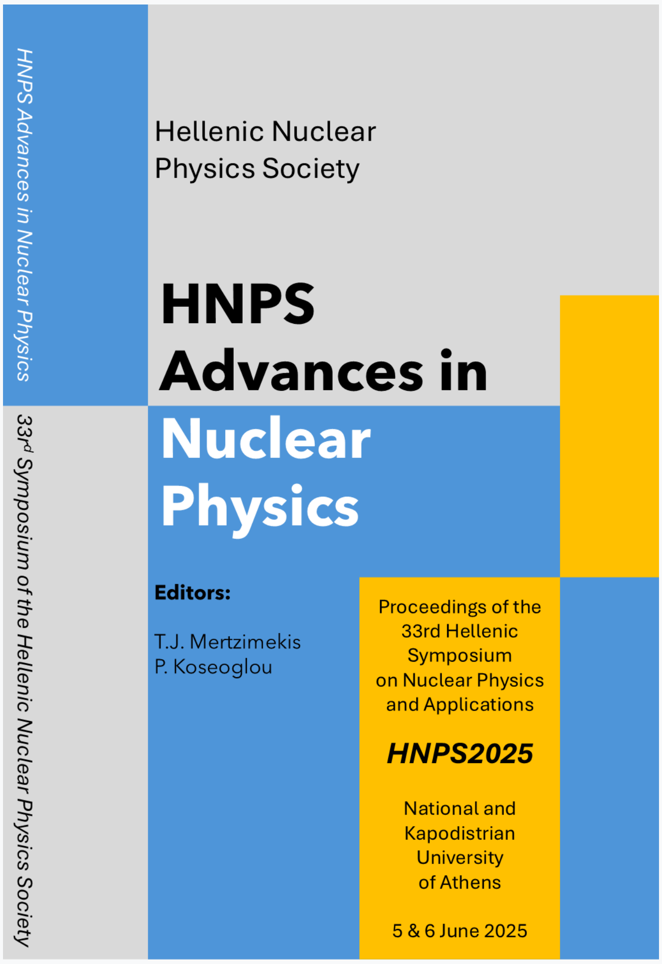


# Abnormal large reaction cross sections for weakly bound nuclei at deep sub-barrier energies

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ARTICLE

# Abnormal large reaction cross sections for weakly bound nuclei at deep sub-barrier energies.

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**Abstract**
We review previous total reaction cross sections of weakly-bound projectiles at deep sub-barrier energies versus the reaction cross section of the mostly tightly-bound nucleus $^{4}$He on lead. Abnormal large reaction cross sections are traced at deep sub-barrier energies for the exotic nucleus $^{8}$B and the weakly-bound radioactive or stable $^{7}$Be and $^{6}$Li nuclei with ratios a million times higher than relevant results at barrier energies. The results are discussed.

**Keywords:** total reaction cross sections, weakly-bound nuclei, exotic nuclei

## 1. Introduction

The total reaction cross section is a crucial observable in nuclear physics both for understanding the nuclear structure and providing information about the interaction between nuclei and the properties of the nuclear force. It is often used to put constraints in the determination of the optical potential, especially at sub- and near-barrier energies [1, 2]. Further on, it may play a crucial role at deep sub-barrier energies, where it may account for a fusion hindrance effect [3]. Indeed, from a measurement at the deep sub-barrier energy of $E_{lab}$=30 MeV for $^{8}$B+$^{208}$Pb, it was found that breakup exhausts all the total reaction cross section indicating, despite the large uncertainties, a possible fusion hindrance [4]. A possible fusion hindrance was also sought for $^{7}$Be on heavy and light targets in Ref. [2], concluding for such a possibility only for the heavier targets. Finally, we note that the dominance of direct reaction paths for weakly-bound nuclei leads well below the barrier (C.b.) to a stabilization of the total reaction cross section at rather high values, in contrast to well-bound projectiles where the reaction cross section approaches values closer to zero, at near-barrier energies.

We will present in this paper a systematic comparison of total reaction cross sections in a reduced form [5], of weakly-bound, exotic and well-bound nuclei on lead and other targets, with the intention to attract the interest of the community to open subjects and unusual behaviors of weakly-bound

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nuclei at deep sub-barrier energies. As a reference we will adopt the reduced cross section of the tightly bound nucleus $^{4}$He on a $^{208}$Pb target. Tabulated values of it can be found in Ref. [6] according to Peter Mohr calculations. These are based on ($\alpha$,n) reactions [6, 7] and in particular by using $^{208}$Pb($\alpha$,n) $^{211}$Po data under the assumption that the total reaction cross section is well approximated by the ($\alpha$,n) cross section for heavy target nuclei at energies above the ($\alpha$,n) threshold and below the ($\alpha$,2n) threshold. We also note that with deep sub-barrier energies we refer to collisions with a head on distance of closest approach at least two times the standard sum radius R of the two colliding nuclei corresponding to $R = 1.2 * (A_1^{1/3} + A_2^{1/3})$.

## 2. COMPARISONS OF TOTAL REACTION CROSS SECTIONS AT NEAR-, SUB-, AND DEEP SUB-BARRIER ENERGIES

Reduced cross sections were obtained according to Ref. [5] for the following systems: $^{8}$B on ($^{208}$Pb, $^{120}$Sn, $^{90}$Zr), from Refs. [4, 8, 9], of $^{8}$Li on $^{208}$Pb, from Ref. [10], $^{7}$Li on ($^{208}$Pb, $^{120}$Sn, $^{58}$Ni, $^{28}$Si) from Refs. [11–15], $^{7}$Be on ($^{208}$Pb, $^{90}$Zr) from Refs [16, 17], $^{9}$Be on ($^{208}$Pb, $^{27}$Al) from Refs. [18, 19], $^{6}$Li on ($^{208}$Pb, $^{120}$Sn, $^{28}$Si) from Refs. [11, 12, 20], $^{6}$He on ($^{208}$Pb, $^{64}$Zn) from Refs. [21, 22] and the well-bound nucleus $^{16}$O on ($^{208}$Pb, $^{90}$Zr,$^{58}$Ni) from Refs. [23–25]. The elastic scattering of all these systems, apart from the ones with $^{6}$He projectiles, were analyzed into the same theoretical phenomenological concept, by taking into account a BDM3Y1 interaction and considering the same potential for both the real and imaginary part but using different normalization factors [20]. We should note that at deep sub-barrier energies it is not possible to obtain total reaction cross sections via elastic scattering angular distributions, since the nuclear potential is very weak with the predominance of Rutherford scattering and fits of calculated differential angular distributions with the appropriate potential, to experimental data are uncertain. In this case other methods should be invoked.

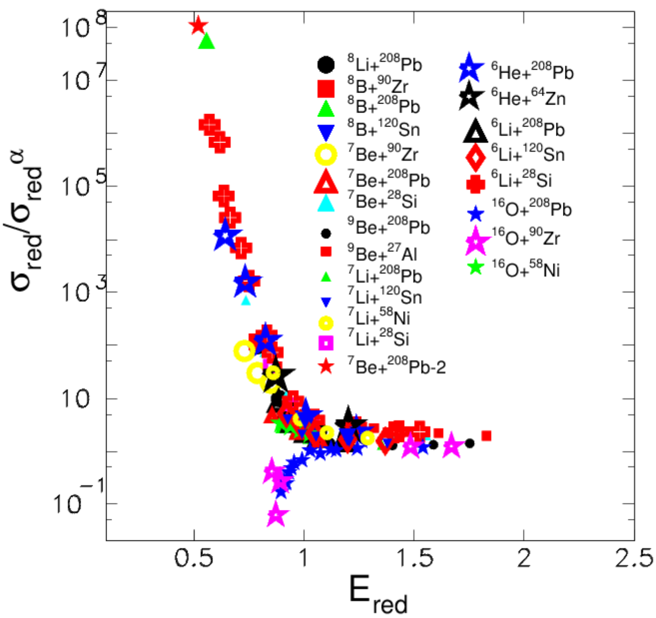


**Figure 1.** Ratios of reduced total reaction cross sections, as described in the inset, versus the one for $^{4}$He on $^{208}$Pb. The total reaction cross sections were obtained from previous elastic scattering measurements under the same theoretical context. For $^{4}$He+$^{208}$Pb we have adopted calculations based on ($\alpha$,n) reactions, reported in Refs. [6, 7]. For $^{6}$Li+$^{28}$Si total reaction cross sections were obtained with a $\gamma$-spectroscopy technique [26].

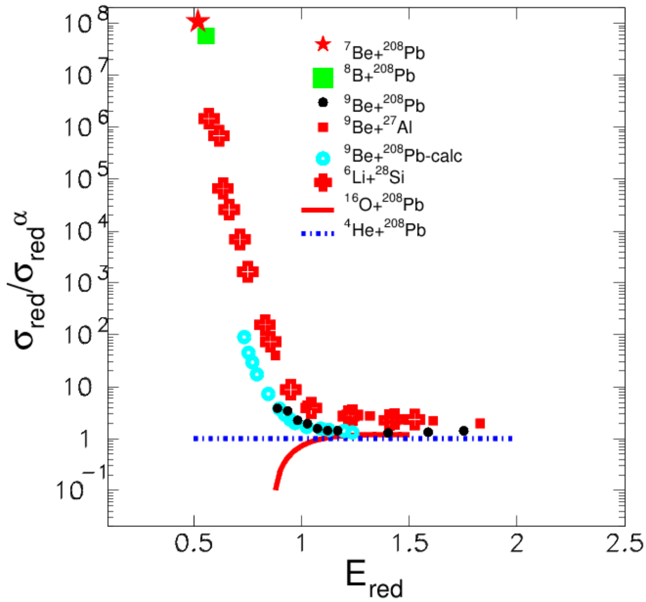


**Figure 2.** Same as in Figure 1, but limited to few systems to clearly indicate the variation due to target. Note that the ciel open circles originate from an extrapolation, to the data described by the solid black circles.

The only existing total reaction cross section data from sub- to deep sub-barrier energies down to $E/V_{C.b.}$=0.7 corresponding to $E_{red}$=0.57 and $D_0/R \sim 2$, are for $^{6}$Li+$^{28}$Si. These were obtained via gamma-ray spectroscopy [26]. Further on, the reaction cross section of $^{8}$B+$^{208}$Pb was inferred from a breakup measurement in comparison with a calculated reaction cross section [4] at $E/V_{C.b.}$ = 0.58 corresponding to $E_{red}$ =0.56 and to $D_0/R \sim 2.2$ and the datum for $^{7}$Be+$^{208}$Pb at $E/V_{C.b.}$=0.54 corresponding to $E_{red}$ =0.52 and $D_0/R \sim 2.3$ was extracted from systematic with extrapolations of the data included in Ref. [27].

For $^{4}$He+$^{208}$Pb, tabulated results were used reported in Ref. [6], and based on ($\alpha$,n) reactions [7]. Ratios of total reaction cross sections of all these systems versus the cross section of $^{4}$He on lead, reduced according to Ref. [5], are presented in Fig. 1. To clearly observe the variation due to target, we plot limited results only on a light and a heavy target in Fig. 2. An inspection of Figures 1 and 2 discloses the following conclusions, outlined in summary in the following paragraph

## 3. SUMMARY-CONCLUSIONS

We have reviewed total reaction cross sections of various weakly-bound stable and radioactive nuclei at near-, sub- and deep sub-barrier energies, reduced according to the prescription reported in Ref. [5] and compared with the total reaction cross section of $^{4}$He+$^{208}$Pb, reduced similarly. We conclude the following:

- A smooth steep exponential increase of the ratio of total reaction cross sections for weakly-bound projectiles either exotic or simply radioactive or/and stable on various targets, versus the total reaction cross section of $^{4}$He on $^{208}$Pb was observed, validating the findings reported in Ref. [6] and extending these at deep sub-barrier energies via our previous total reaction cross section results of $^{8}$B+$^{208}$Pb, $^{7}$Be+$^{208}$Pb and $^{6}$Li+$^{28}$Si.

- The above is in contrast to the behavior of the well-bound nuclei on a heavy and a medium target ($^{208}$Pb, $^{90}$Zr) where an exponential drop occurs around barrier. For $^{58}$Ni the situation is reversed following the trend of weakly-bound nuclei. We can speculate that when the mass number of the projectile and therefore its area is comparable with this of the target, the effective area seen by the projectile and therefore the cross section in a geometrical approach is larger than when the projectile's mass is much smaller than that of the target. However, for light halo nuclei like $^{6}$He and $^{8}$B the extended nuclear matter defines a large area for these nuclei and therefore according to the above, they see a large effective area of the target and therefore present large cross sections. Why this is apparent at the lower energies below and at deep sub-barrier energies this is an open question. Why this is followed by all weakly-bound nuclei is also an open question.
- We also report here a target variation of the ratios of weakly-bound nuclei with higher values for light targets and lower for heavy ones. All these are observed close and above barrier. At deep sub-barrier energies, a convergence in the trend of the ratios, is expected, following the steep increase for all targets.
- The reactivity of halo nuclei as $^{8}$B at deep sub-barrier energies is in general large and enormous when compared with that of a well bound nucleus as $^{4}$He. The same applies to other weakly-bound nuclei like $^{7}$Be and $^{6}$Li with ratios of reduced cross sections versus the reduced cross section of $^{4}$He to $^{208}$Pb, reaching the values at $E_{red}$ =0.52 of ∼100 million, at $E_{red}$.=0.55 of ∼54 million and at $E_{red}$ =0.57 of ∼1.5 million to be compared at above barrier energies with values of ∼1 to 2.5. "Abnormally" large cross sections were traced before and reported in Ref. [27].
- The big question is what could be the type of interaction which causes this enormous effect! Certainly not the nuclear interaction as we know it.
- Another question is: Does a "structural" change occurs below barrier? Could this be a compression of the cluster $\alpha$-part or an inert $\alpha$-part of the nucleus core under investigation and the elongation of the rest of the nuclear matter?

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