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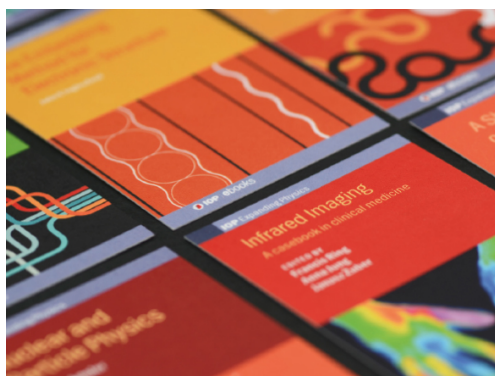
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# Activation measurement of $\alpha$ -induced cross sections for $^{197}\text{Au}$ : analysis in the statistical model and beyond

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**Abstract.** Cross sections of  $(\alpha, \gamma)$ ,  $(\alpha, n)$ , and  $(\alpha, 2n)$  reactions for  $^{197}\text{Au}$  were measured below the Coulomb barrier using the activation technique. The new data are analyzed in the statistical model and in a simple barrier transmission model. Sensitivities of the resulting cross sections on the underlying parameters are discussed. It is found that the cross sections in the statistical model depend sensitively on the tail of the imaginary  $\alpha$ -nucleus potential at large radii outside the colliding nuclei. Contrary, the cross sections in the barrier transmission model depend only on the real part of the  $\alpha$ -nucleus potential. The calculated cross sections in the barrier transmission model agree nicely with the new experimental data. Furthermore, the available experimental data for heavy targets above  $A \approx 150$  are also well reproduced within the barrier transmission model.

## 1. Introduction

The nucleosynthesis of heavy neutron-deficient nuclei, the so-called  $p$ -nuclei, proceeds via a series of  $(\gamma, n)$ ,  $(\gamma, p)$ , and  $(\gamma, \alpha)$  photodisintegration reactions at temperatures of several Giga-Kelvin ( $T_9 \approx 2 - 3$ ) [1]. A typical reaction network for this  $\gamma$ -process contains more than 1,000 nuclei and 10,000 reactions [2], and thus it is obvious that experiments cannot provide all required data. Most of the reaction rates have to be taken from calculations in the statistical model (StM) [3].

Two important findings resulted from the pioneering work by Somorjai *et al.* on the  $^{144}\text{Sm}(\alpha, \gamma)^{148}\text{Gd}$  reaction [4]: First, the StM cross sections of  $(\alpha, \gamma)$  and  $(\gamma, \alpha)$  reactions depend mainly on the  $\alpha$ -nucleus optical potential (AOMP) whereas the other ingredients of the StM like the nucleon optical model potential, the  $\gamma$ -ray strength function, and the level density, have only minor relevance. Second, the early AOMP by Watanabe [5] (default setting in the StM code TALYS until version 1.6) and the widely used AOMP by

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McFadden and Satchler [6] dramatically overestimate the experimental cross sections, in particular towards low energies which is the astrophysically relevant energy range. The latter finding was confirmed in a series of subsequent experiments on heavy target nuclei.

Here we present an extended analysis of our new data of  $\alpha$ -induced cross sections for <sup>197</sup>Au which complement previously available data [7, 8] towards significantly lower energies. Details of the experiment and the standard analysis in the StM are provided in our recent publication [9].

## 2. Statistical model: sensitivities

In a schematic notation, the cross section of an  $\alpha$ -induced ( $\alpha, X$ ) reaction is given by

$$\sigma(\alpha, X) \sim \frac{T_{\alpha,0} T_X}{\sum_i T_i} = T_{\alpha,0} \times b_X \quad (1)$$

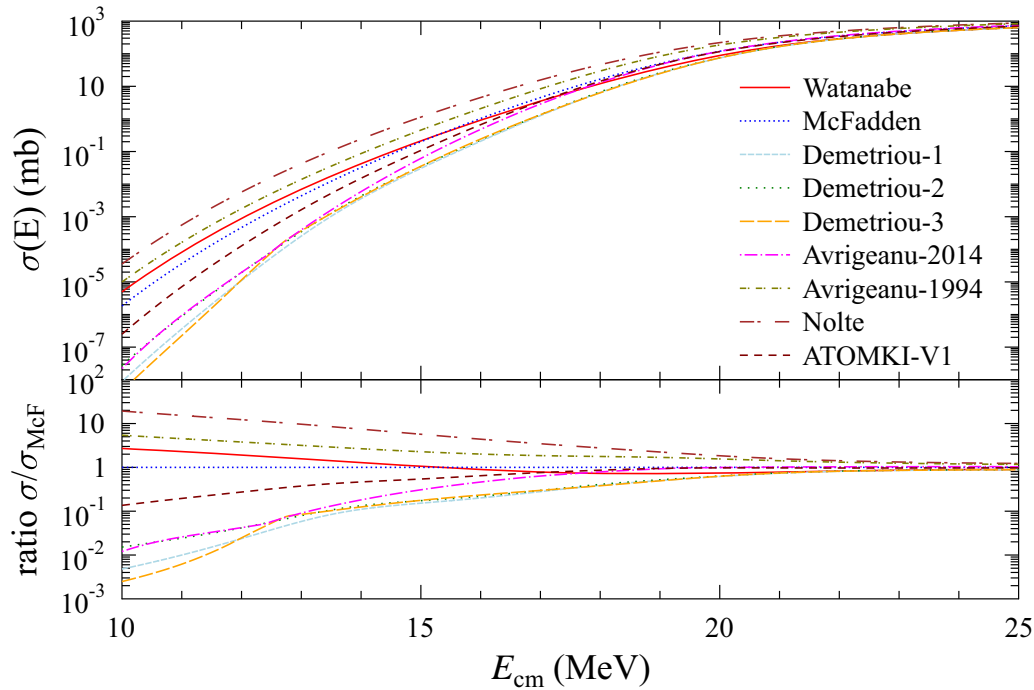
with the transmission coefficients  $T_i$  into the  $i$ -th open channel and the branching ratio  $b_X = T_X / \sum_i T_i$  for the decay into the channel  $X$ . The total transmission is given by the sum over all contributing channels:  $T_{\text{tot}} = \sum_i T_i$ . The  $T_i$  are calculated from global optical potentials for the particle channels and from the  $\gamma$ -ray strength function (GSF) for the photon channel. For further details of the definition of  $T_i$ , see [10].

Because of the high Coulomb barrier for heavy target nuclei,  $T_{\alpha,0}$  is much smaller than the dominating  $T_\gamma$  (below the neutron threshold) or  $T_n$  (above the neutron threshold). As a consequence, the branching  $b_X$  in Eq. (1) approaches unity, and  $\sigma(\alpha, X)$  scales with  $T_{\alpha,0}$ ; i.e., the ( $\alpha, X$ ) cross section is essentially sensitive to the underlying AOMP. The dramatic sensitivity of the  $T_{\alpha,0}$  and the resulting total reaction cross section  $\sigma_{\text{reac}}$  on the underlying AOMP is shown in Fig. 1. The chosen AOMPs are the eight options inside the TALYS code (version 1.9) [11] and the ATOMKI-V1 potential [12]. In detail, the TALYS AOMPs are taken from Watanabe [5], McFadden and Satchler [6], Demetriou *et al.* [13] (versions 1 – 3), Avrigeanu *et al.* [14], Nolte *et al.* [15], and Avrigeanu *et al.* [16]. The latter two AOMPs were mainly adjusted at higher energies, and it is not surprising that these AOMPs deviate from experimental data at low energies.

The range of predictions for the total reaction cross section  $\sigma_{\text{reac}}$  is within less than a factor of two at the highest energy of 25 MeV in Fig. 1, but exceeds four orders of magnitude at 10 MeV which is close to the Gamow window for typical temperatures of the  $\gamma$ -process. Even if the two potentials by Nolte *et al.* [15] and Avrigeanu *et al.* [16] are excluded which have been adjusted at higher energies, there still remains a range of three orders of magnitude at 10 MeV. The origin of this huge range (and thus huge uncertainty in the prediction of  $\alpha$ -induced reaction rates) needs further investigation.

The total reaction cross section  $\sigma_{\text{reac}}$  results from the solution of the Schrödinger equation using the complex AOMPs as defined in the previous paragraph.  $\sigma_{\text{reac}}$  is given

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**Figure 1.** Total reaction cross section  $\sigma_{\text{reac}}$  for  $^{197}\text{Au} + \alpha$  from different AOMPs. The upper part shows the absolute cross sections; in the lower part the cross sections are normalized to the widely used McFadden/Satchler potential to better visualize the range of predictions which exceed four orders of magnitude at the lowest shown energy of 10 MeV (which is close to the astrophysically relevant Gamow window).

by

$$\sigma_{\text{reac}} = \sum_L \sigma_L = \frac{\pi}{k^2} \sum_L (2L+1) [1 - \eta_L^2(E)] \quad . \quad (2)$$

where the  $\eta_L$  are the real reflexion coefficients. It is important to note that any purely real nuclear potential leads to  $\eta_L = 1$  for all partial waves  $L$ , and thus the total reaction cross section vanishes:  $\sigma_{\text{reac}} = 0$ . Hence, an important role of the imaginary part of the nuclear potential is obvious.

The huge range of the predicted total cross sections  $\sigma_{\text{reac}}$  is related to the properties of the AOMPs under study. In the following we analyze qualitatively which radial range of the real and imaginary potentials has the largest impact. The given numbers refer to the simple and energy-independent AOMP by McFadden and Satchler [6] where the effective barrier of the potential is located around 10.8 fm and has a height of 19.9 MeV (for  $s$ -waves with angular momentum  $L = 0$ ; for  $L > 0$  an additional centrifugal barrier has to be taken into account).

- At energies significantly above the barrier the incoming  $\alpha$  can reach small radii  $r$ , and absorption occurs at the nuclear surface which corresponds to the appearance of the imaginary part of the AOMP. The  $\eta_L$  in Eq. (2) approach  $\eta_L \rightarrow 0$  for small  $L$ , corresponding to no reflexion or full absorption of the incoming  $\alpha$ . The resulting

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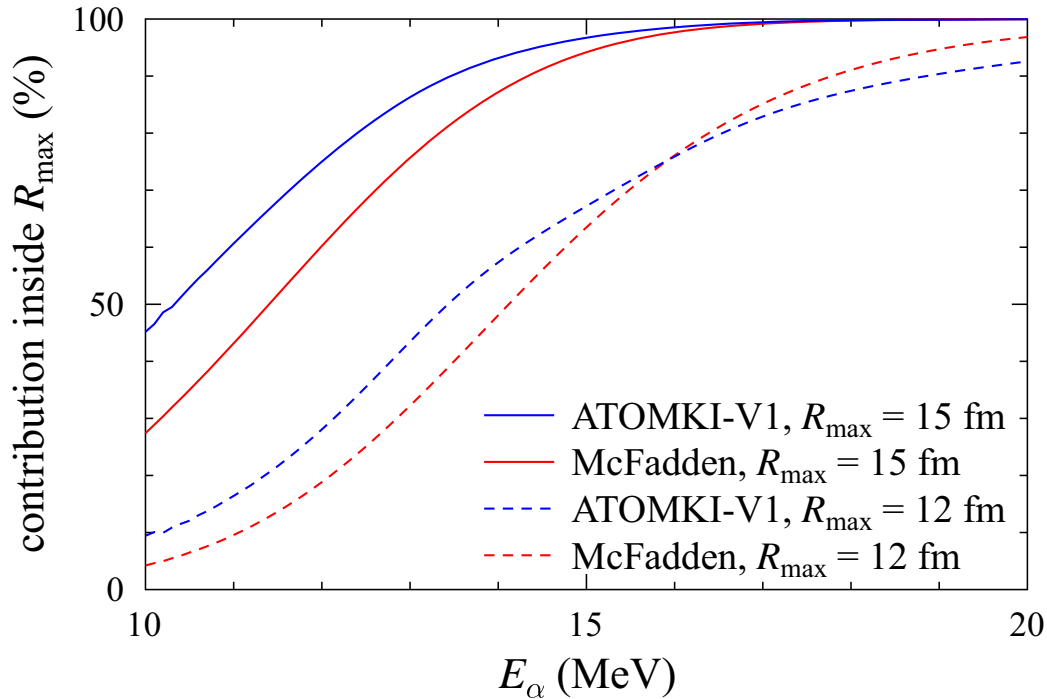
cross sections  $\sigma_{\text{reac}}$  exceed 1 b and are essentially sensitive only to the range of the imaginary part of the AOMP. All AOMPs with a realistic range of the imaginary potential predict similar cross sections  $\sigma_{\text{reac}}$  which is confirmed in Fig. 1 (see also [17, 18]).

- Already at energies slightly below the barrier, say around 18 MeV, fusion is classically forbidden for the incoming  $\alpha$ , i.e., most of the incoming  $\alpha$  particles are reflected, and only few of the incoming  $\alpha$  particles are absorbed. We find  $\eta_L \approx 0.97 - 1$  and  $1 - \eta_L^2 \leq 0.05$ , leading to  $\sigma_{\text{reac}} \approx 17$  mb. The sensitivity to the range of the imaginary potential persists, and an additional sensitivity to the real potential in a narrow range around the barrier ( $r \approx 10 - 12$  fm) appears. The predicted  $\sigma_{\text{reac}}$  from different AOMPs start to diverge.
- At energies around 14 MeV reflexion becomes more dominant, leading to  $\eta_L \geq 0.99995$ ,  $1 - \eta_L^2 \leq 10^{-4}$ , and  $\sigma_{\text{reac}} \approx 32$   $\mu\text{b}$ . Again, the sensitivity to the range of the imaginary potential persists, but now  $\sigma_{\text{reac}}$  depends on a somewhat larger radial range of the real potential around the barrier ( $r \approx 9 - 15$  fm). The predictions from the different AOMPs under study become more discrepant by at least one order of magnitude.
- At energies far below the barrier at 10 MeV, i.e., around the Gamow window for  $\gamma$ -process temperatures, it is practically impossible for the incoming  $\alpha$  particle to tunnel through the huge barrier. Now we find  $\eta_L \geq 0.999999999$ ,  $1 - \eta_L^2 \leq 10^{-9}$ , and  $\sigma_{\text{reac}} \approx 1.8$  nb. Interestingly, now – at least in the calculation – the damping of the wave function by the imaginary potential occurs already in and even outside the barrier, i.e., at much larger radii  $r \gg 10$  fm. At these large radii the real part of the potential is governed by the Coulomb part, and the real nuclear potential has practically vanished. Consequently, the calculated  $\sigma_{\text{reac}}$  depends mainly on the tail of the imaginary potential. The range of predictions for  $\sigma_{\text{reac}}$  from different AOMPs becomes huge and exceeds several orders of magnitude.

The above finding is visualized in Fig. 2. For two different AOMPs (McFadden/Satchler and ATOMKI-V1) it is shown which contribution to  $\sigma_{\text{reac}}$  results from absorption inside a maximum radius of  $R_{\text{max}} = 12$  or 15 fm. These radii  $R_{\text{max}}$  are far outside the radii of the colliding nuclei with  $R \approx 5.4$  fm for <sup>197</sup>Au and  $R \approx 1.7$  fm for the  $\alpha$  particle [19]. As expected, at 20 MeV more than 90% of  $\sigma_{\text{reac}}$  results from absorption inside  $R_{\text{max}} = 12$  fm. However, at 10 MeV this changes completely: more than 90% of  $\sigma_{\text{reac}}$  results from absorption outside  $R_{\text{max}} = 12$  fm, and more than 50% results from outside  $R_{\text{max}} = 15$  fm. This finding raises the question whether compound nucleus formation (as assumed in the StM) indeed occurs at radii far outside the colliding nuclei. Furthermore, it should be noted that the depth of the imaginary potentials is tiny at large radii (e.g., for the McFadden/Satchler potential one finds a depth of about 15 keV at 12 fm and 50 eV at 15 fm). Typically, the shape of the imaginary potential is determined from the analysis of elastic scattering angular distributions. Practically, the imaginary potential at such large radii is strongly affected by the chosen parametrization

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(e.g., volume Woods-Saxon or squared volume Woods-Saxon or surface Woods-Saxon or sum of Fourier-Bessel). Whereas the imaginary potential is well-constrained by elastic scattering around the nuclear surface, the tiny tail of the imaginary potential at such large radii is essentially unconstrained. Thus, the huge range of predictions of  $\sigma_{\text{reac}}$  from different AOMPs at low energies is not very surprising (see Fig. 1).



**Figure 2.** Contribution to the total reaction cross section  $\sigma_{\text{reac}}$  for  $^{197}\text{Au} + \alpha$  inside  $R_{\text{max}} = 12$  or  $15$  fm for two different AOMPs (McFadden/Satchler and ATOMKI-V1). As expected, at  $20$  MeV the dominating contribution comes from smaller radii. However, at  $10$  MeV less than  $10\%$  of  $\sigma_{\text{reac}}$  results from contributions inside  $R_{\text{max}} = 12$  fm. As a consequence, this leads to a strong sensitivity to the tail of the imaginary at large radii. Further discussion see text.

### 3. An alternative approach: pure barrier transmission model

An alternative approach for the calculation of the total reaction cross sections  $\sigma_{\text{reac}}$  is suggested in this study. The model is widely used for heavy-ion fusion reactions, and its properties are discussed in further detail in [20] as so-called pure barrier transmission model (pBTM). The calculations are made with the code CCFULL [21].

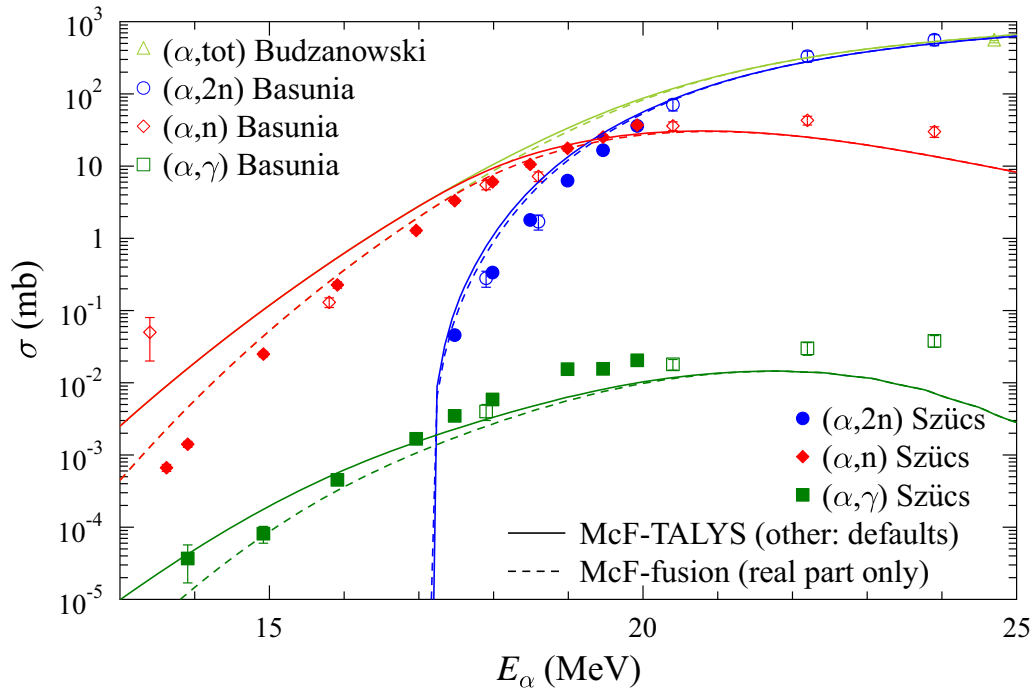
In the pBTM the total cross section  $\sigma_{\text{reac}}$  results from the transmission through the effective barrier in a real potential. By definition, the model assumes fusion, corresponding to absorption of the incoming particle, as soon as the incoming particle has succeeded to tunnel through the barrier. This assumption is reasonable for the calculation of the total cross section  $\sigma_{\text{reac}}$  because the tunneling of the absorbed  $\alpha$

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particle back to large radii is very unlikely, compared to the de-excitation of the compound nucleus by  $\gamma$ -ray or neutron emission.

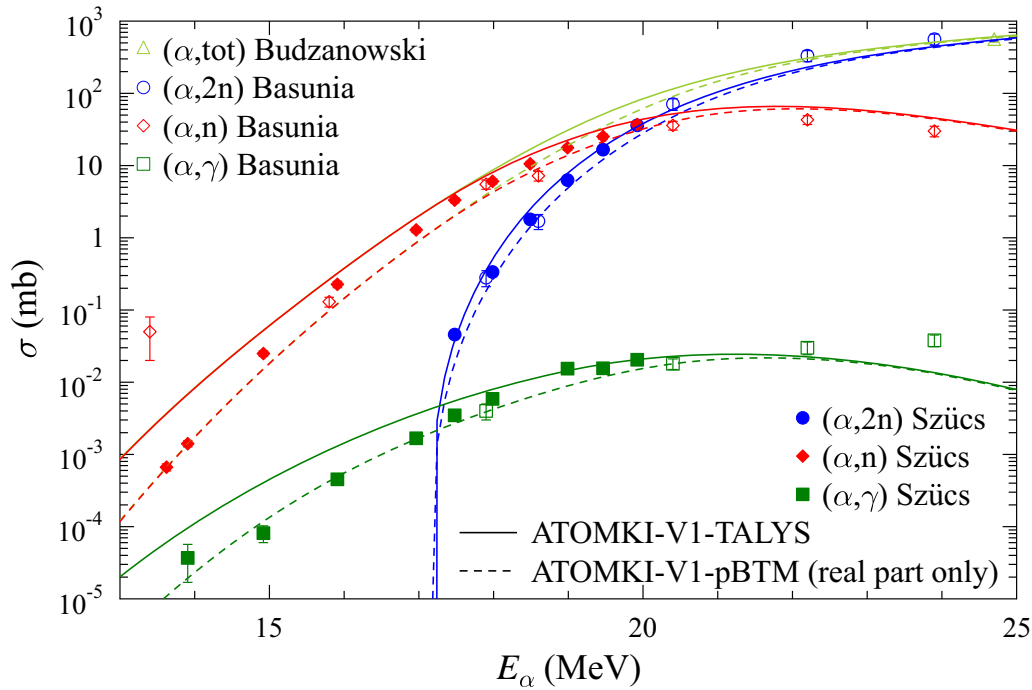
In the usual StM calculations, the total cross section  $\sigma_{\text{reac}}$  is calculated in the optical model (OM) using a complex nuclear potential. Compared to these OM calculations, the above suggested pBTM has several advantages. The pBTM is a simple model with very few adjustable parameters. As soon as the real part of the potential is well-defined, the total cross section  $\sigma_{\text{reac}}$  can be calculated without any further adjustment of parameters. In addition, by definition of the pBTM, there is no contribution to  $\sigma_{\text{reac}}$  from the far nuclear exterior. Finally, the numerical treatment is more stable in the pBTM than in the OM.

Typically, folding potentials are considered as reliable, and the parameters of the folding potentials are fine-tuned from the analysis of elastic scattering. Thus, all parameters are fixed, and the pBTM can be used for predictions of  $\sigma_{\text{reac}}$ . The results of the pBTM and the StM are compared to the experimental data in Fig. 3 for the McFadden/Satchler AOMP and in Fig. 4 for the ATOMKI-V1 potential. The partial cross sections in the pBTM were calculated using  $\sigma_{\text{reac}}$  from the pBTM and the branching ratios  $b_X$  in Eq. (1) of the StM.



**Figure 3.** Cross sections of the  $^{197}\text{Au}(\alpha, \gamma)^{201}\text{Tl}$ ,  $^{197}\text{Au}(\alpha, n)^{200}\text{Tl}$ , and  $^{197}\text{Au}(\alpha, 2n)^{199}\text{Tl}$  reactions and the total cross section  $\sigma_{\text{reac}}$ . The full lines represent the StM using TALYS in combination with the McFadden/Satchler AOMP; the dashed lines correspond to the pBTM model using the real part of the McFadden/Satchler potential. Further discussion see text. The experimental data were taken from [7, 8, 9].

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**Figure 4.** Same as Fig. 3, but for the ATOMKI-V1 AOMP.

Fig. 3 shows that the McFadden/Satchler AOMP significantly overestimates the cross sections at low energies in the StM (full lines). The disagreement with the experimental data is reduced in the pBTM (dashed lines), but still there remains an overestimation by about a factor of 2 – 3 at the lowest energies in the dominating  $(\alpha, n)$  channel.

Fig. 4 repeats Fig. 3, but replaces the McFadden/Satchler AOMP by the ATOMKI-V1 AOMP. Again, it is found that the StM calculation overestimates the experimental data at low energies. However, when changing from the StM to the pBTM, the agreement between the calculation (dashed lines) and the experimental data becomes excellent. This indicates that the pBTM in combination with a reasonably chosen folding potential is able to predict the total reaction cross section  $\sigma_{\text{reac}}$  of  $\alpha$ -induced reactions at low energies with quite limited uncertainties.

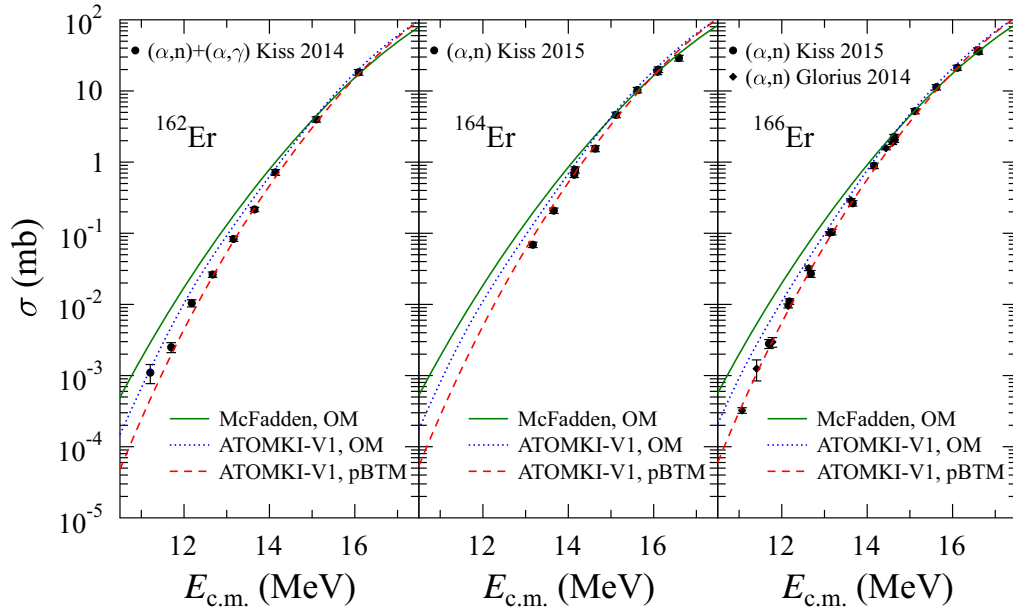
Preliminary calculations have been made to test the predictions of the pBTM for a series of heavy target nuclei, including  $^{144}\text{Sm}$ ,  $^{162,164,166}\text{Er}$ ,  $^{165}\text{Ho}$ ,  $^{169}\text{Tm}$ ,  $^{187}\text{Re}$ , and  $^{191,193}\text{Ir}$ . In all cases the experimental data are reproduced within less than a factor of two. As an example, the results for  $^{162,164,166}\text{Er}$  are shown in Fig. 5.

#### 4. Conclusions

New experimental data have been measured for the  $^{197}\text{Au}(\alpha, \gamma)^{201}\text{Tl}$ ,  $^{197}\text{Au}(\alpha, n)^{200}\text{Tl}$ , and  $^{197}\text{Au}(\alpha, 2n)^{199}\text{Tl}$  reactions [9]. The data have been analyzed in the usual way



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**Figure 5.** Total cross sections  $\sigma_{\text{reac}}$  in the pBTM using the ATOMKI-V1 potential (red dashed) in comparison to experimental data [22, 23, 24] for the dominating  $(\alpha, n)$  channel for  $^{164,166}\text{Er}$  and to the sum of the  $(\alpha, n)$  and  $(\alpha, \gamma)$  data for  $^{162}\text{Er}$ . Calculations in the OM overestimate the experimental data at low energies.

within the statistical model, and it was confirmed that the calculated cross sections essentially depend on the chosen  $\alpha$ -nucleus optical model potential. In addition, it was noted that the calculated cross sections in the statistical model at low energies are very sensitive to the tail of the imaginary part of the potential at large radii far outside the colliding nuclei. This explains the huge range of predictions for  $\alpha$ -induced cross sections at energies far below the Coulomb barrier.

To avoid these complications in the statistical model, as an alternative a simple barrier transmission model was used for the calculation of the total reaction cross sections  $\sigma_{\text{reac}}$ . Surprisingly, it was found that this simple model in combination with reasonably chosen folding potentials is able to predict the total reaction cross section of  $\alpha$ -induced reactions for  $^{197}\text{Au}$  and also for other heavy nuclei over a wide energy range, including the astrophysically most relevant low-energy region around the Gamow window.

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of the Hungarian Academy of Sciences.

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