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Relation between total cross sections from elastic scattering and α-induced reactions: The example of ^{64}Zn

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The total reaction cross section is related to the elastic scattering angular distribution by a basic quantum-mechanical relation. We present new experimental data for α-induced reaction cross sections on ^{64}Zn which allow for the first time the experimental verification of this simple relation at low energies by comparison of the new experimental reaction data to the result obtained from ^{64}Zn(α,α)^{64}Zn elastic scattering.

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A main application of quantum mechanics is nuclear physics. Here basic theoretical relations can be tested experimentally with high precision. An interesting example is the simple relation between the total (nonelastic) reaction cross section $\sigma_{\rm reac}$ and the elastic scattering cross section:

$$\sigma_{\rm reac} = \frac{\pi}{k^2} \sum_L (2L+1)\left(1-\eta_L^2\right). \qquad (1)$$

Here $k = \sqrt{2\mu E_{\rm c.m.}}/\hbar$ is the wave number, $E_{\rm c.m.}$ is the energy in the center-of-mass (c.m.) system, and η_L and δ_L are the real reflection coefficients and scattering phase shifts which define the angular distribution $(\frac{d\sigma}{d\Omega})(\vartheta)$ of elastic scattering. Equation (1) is derived from a partial wave analysis using the standard two-body Schrödinger equation. Equation (1) is widely used, in particular in the calculation of reaction cross sections using the statistical model (StM; to avoid confusion with the widely used abbreviation "SM" for "shell model"). In the following discussion we will focus on α-induced reactions at low energies.

In the StM the reaction cross section of an α-induced (α,X) reaction is calculated in two steps. In the first step the total reaction cross section $\sigma_{\rm reac}$ is calculated using Eq. (1); the reflection coefficients η_L are determined by solving the Schrödinger equation using a global α-nucleus potential, e.g., the widely used potential by McFadden and Satchler [1]. Compound formation is the dominating absorption mechanism at energies from a few MeV up to about several tens of MeV; thus, it is assumed that the compound formation cross section is approximately given by the total reaction cross section: $\sigma_{\rm comp} \approx \sigma_{\rm reac}$. In the second step $\sigma_{\rm comp}$ is distributed among all open channels. The decay branching is obtained from the transmission factors into the various open channels which are again calculated using global potentials for each (outgoing particle + residual nucleus) channel or from the photon strength function in the case of the (α,γ) channel. Further details of the StM can be found in the recent review [2].

To our knowledge, the underlying basic relation in Eq. (1) has never been verified experimentally for α-induced reactions at low energies around or below the Coulomb barrier. Although there is no special reason to suspect the application of Eq. (1) to the particular case of α-induced reactions, an experimental verification ensures its application to the calculation of reaction cross sections, which has turned out to be difficult especially at low energies (see discussion below). Alternatively, if the validity of Eq. (1) is assumed *a priori*, it can be used as a stringent test for consistency between different methods for the determination of $\sigma_{\rm reac}$.

$\sigma_{\rm reac}$ has been measured at higher energies up to 200 MeV using transmission experiments [3–6]. The experimental results have significant uncertainties, and earlier results [5] have been questioned later by the same group [6]. For the early experiments [5] it was found that $\sigma_{\rm reac}$ from the transmission data is significantly smaller than $\sigma_{\rm reac}$ derived from (α,α) elastic scattering using Eq. (1) [5,7,8] whereas agreement was found using the latest transmission data [6] where $\sigma_{\rm reac}$ is about 10–30% higher compared to earlier results [5].

At lower energies, α-induced reactions have been studied intensively in the last few decades to determine a global α-nucleus potential which is then used for the prediction of α-induced reaction cross sections and their inverse, mainly (γ,α), reaction cross sections. Often the motivation came from astrophysics where (γ,α) reaction rates under stellar conditions play an important role in the nucleosynthesis of heavy neutron-deficient nuclei (the so-called p nuclei) [9–12]. It turned out over the years that it is very difficult or even impossible to obtain a consistent description of elastic (α,α) scattering and (α,X) cross sections. Especially the reproduction of (α,γ) capture cross sections for heavy targets (above $A \approx 100$) at the lowest experimentally accessible energies (i.e., the most relevant energy range for the calculation of stellar reaction rates) was poor [13–19]; with significant effort, better results have been obtained very recently, mainly for (α,n) reactions at slightly higher energies [20–23].

It is the aim of the present work to provide an experimental confirmation of Eq. (1) at relatively low energies around the Coulomb barrier because it is implicitly used in all the above-mentioned studies of (α,γ) and (α,n) reactions [13–23]. The target nucleus ^{64}Zn is an almost perfect candidate for such a study because (i) a series of experiments has measured angular distributions of elastic (α,α) scattering in the energy range from 12 to 50 MeV [24,25] which enables us to study the ^{64}Zn-α potential in a wide energy range, and (ii) almost all

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relevant reaction channels at low energies lead to unstable residual nuclei which can be measured using the activation technique. Thus, this experiment can use a completely different experimental approach for the determination of $\sigma_{\rm reac}$ where the systematic uncertainties of transmission experiments can be avoided (see discussion in Ref. [6]). In addition we point out that the activation technique is the most appropriate tool for the determination of total (α, X) reaction cross sections whereas, e.g., in-beam (α,γ) experiments might miss weak γ-ray branches.

Although several data sets for (α, X) cross sections on ^{64}Zn are already available (e.g., in Refs. [26–30]), the data quality is relatively poor. So we have remeasured the cross sections of the ^{64}Zn$(\alpha,\gamma)^{68}$Ge, ^{64}Zn$(\alpha,n)^{67}$Ge, and ^{64}Zn$(\alpha,p)^{67}$Ga reactions at low energies. Relatively low energies were chosen not only because of the underlying astrophysical request for a low-energy α-nucleus potential, but also because of the relatively small numbers of open channels. In the energy range under study, the total reaction cross section is given by the following sum:

$$\sigma_{\rm reac} = \sigma(\alpha,\gamma)+\sigma(\alpha,n)+\sigma(\alpha,p)+\sigma(\alpha,\alpha') + \sigma(\alpha,2\alpha)+\sigma(\alpha,\alpha p)+\sigma(\alpha,2p)+\sigma(\alpha,\alpha n). \quad (2)$$

In the following we present first our new experimental data for the ^{64}Zn$(\alpha,\gamma)^{68}$Ge, ^{64}Zn$(\alpha,n)^{67}$Ge, and ^{64}Zn$(\alpha,p)^{67}$Ga reactions. Then we estimate the cross sections of the remaining open channels in Eq. (2) which are much smaller than the dominant (α,p) and (α,n) cross sections. Next we compare the sum of the α-induced cross sections to the total reaction cross section $\sigma_{\rm reac}$ from the analysis of an angular distribution of ^{64}Zn$(\alpha,\alpha)^{64}$Zn elastic scattering and find agreement within the uncertainties; i.e., we confirm the basic quantum-mechanical relation in Eq. (1). Finally, we suggest potential improvements to reduce the uncertainties.

The cross sections of the three studied α-induced reactions have been measured with the activation method. The experimental technique was similar to the one described in one of our recent works [31]. Some important aspects are briefly described here. For further details see also [32].

The targets were prepared by evaporating natural isotopic composition metallic Zn onto 2 μm thick Al foils. The target thicknesses (typically between 100 and 500 μg/cm^2) were measured by weighing and Rutherford backscattering spectrometry. The α irradiations were carried out at the cyclotron accelerator of ATOMKI, which provided an α beam with up to 1 μA intensity. The durations of the irradiations varied between half an hour and one day. Changes in the beam intensity were taken into account by recording the current integrator counts in multichannel scaling mode with 1 min time constant. The stability of the targets was continuously monitored by detecting the elastically scattered α particles from the target with an ion implanted Si detector built into the chamber at 150°. With a beam intensity not higher than 1 μA no target deterioration was observed.

The cross sections of the ^{64}Zn$(\alpha,\gamma)^{68}$Ge, ^{64}Zn$(\alpha,p)^{67}$Ga, and ^{64}Zn$(\alpha,n)^{67}$Ge reactions were determined from the measurement of the γ radiation following the β decay of the reaction products having half-lives of 270.93 d, 3.26 d, and 18.9 min, respectively. The decay parameters of the reaction products are summarized in Table I. Owing to the largely different half-lives of the reaction products, the γ-counting of one target has been done two or three times.

TABLE I. Decay parameters of the reaction products. Only the strongest γ transitions used for the analysis are listed. Data are taken from Refs. [33,34]. Since the decay of ^{68}Ge is not followed by γ radiation, the decay of its short-lived daughter, ^{68}Ga, has been measured.

Reaction	Product isotope	Half-life	E_γ (keV)	Relative intensity (%)
^{64}Zn(α,γ)	^{68}Ge	270.93 d	–	–
^{68}Ge decay	^{68}Ga	67.71 min	1077.3	3.22 ± 0.03
^{64}Zn(α,p)	^{67}Ga	3.26 d	184.6	21.41 ± 0.01
			209.0	2.46 ± 0.01
			300.2	16.64 ± 0.12
			393.5	4.56 ± 0.24
^{64}Zn(α,n)	^{67}Ge	18.9 min	167.0	84.28 ± 4.52
			828.3	2.99 ± 0.27
			1472.8	4.9 ± 0.2

The γ measurements were carried out with a 100% relative efficiency high-purity germanium (HPGe) detector equipped with a 4π low background shielding. The absolute efficiency of the detector at a large source-to-detector distance of 27 cm was measured with several calibrated sources [31]. In this geometry the true coincidence summing effect is completely negligible. The strong activity of the short-lived ^{67}Ge reaction product was measured in this far geometry.

At higher α energies the (α,p) cross section was large enough so that the target activity could be measured in the far geometry. At low energies, on the other hand, a close source-to-detector distance of 1 cm was used where the true coincidence summing effect was strong. To take this into account, spectra of strong ^{67}Ga sources were measured both in far and close geometries, and for all studied transitions a conversion factor between the two geometries was calculated. This factor accounts for the ratio of the efficiencies as well as the effect of summing.

The weak source activities from the ^{64}Zn$(\alpha,\gamma)^{68}$Ge reaction could only be measured in the close counting geometry. Owing to the simple decay scheme of ^{68}Ga, however, the summing effect is negligible here. Therefore, for the ^{68}Ga activity measurement, the absolute efficiency of the detector was measured directly in close geometry using summing-free, single line calibration sources (^{7}Be, ^{54}Mn, ^{65}Cu, and ^{137}Cs).

A typical γ spectrum of the ^{64}Zn$(\alpha,p)^{67}$Ga reaction channel was shown in Ref. [32]. Here in Fig. 1, two spectra are shown which were used to determine the ^{64}Zn$(\alpha,n)^{67}$Ge (upper panel) and ^{64}Zn$(\alpha,\gamma)^{68}$Ge (lower panel) cross sections at $E_{\rm c.m.} = 12.37$ MeV. The waiting time between the end of the irradiation and the start of counting as well as the durations of the countings are indicated. The peaks used for the analysis are marked by arrows.

Table II lists the measured cross sections for the three reactions. The cross section of the ^{64}Zn$(\alpha,p)^{67}$Ga reaction was measured in a wide energy range between $E_{\rm c.m.} = 5.8$

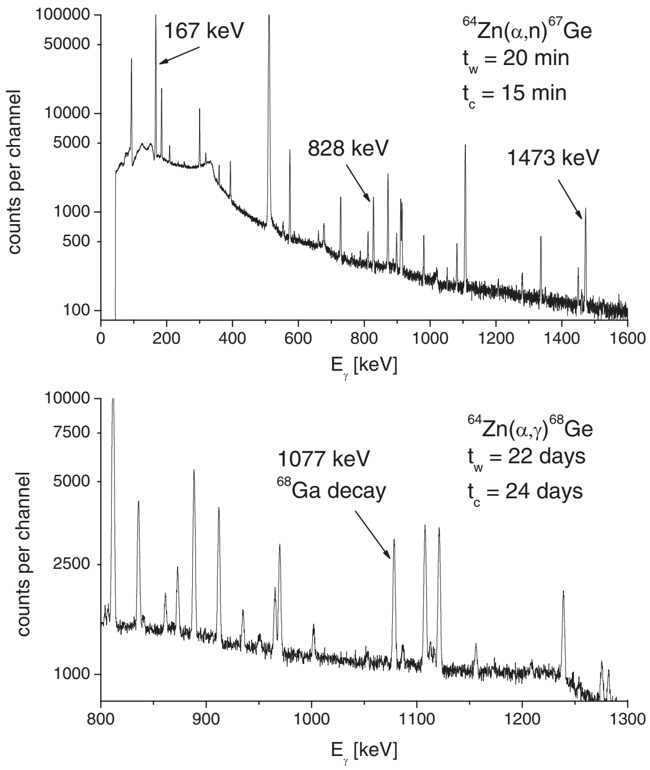

FIG. 1. γ spectra measured on a target irradiated with a 13.2 MeV α beam. Upper panel: spectrum measured directly after the irradiation where the decay of the ^{64}Zn$(\alpha, n)^{67}$Ge reaction product is dominant. Lower panel: spectrum taken after 22 days of cooling time of the target in order to detect the low activity of the (α, γ) reaction product. The peaks used for the analysis are indicated.

and 12.4 MeV. The ^{64}Zn$(\alpha, n)^{67}$Ge reaction was studied from the threshold up to 12.4 MeV at nine energies. Owing to the long half-life of the (α, γ) reaction product and the weak γ branching of the decay, the activation method is not optimal for the measurements of the very low (α, γ) cross sections. Therefore, the (α, γ) cross section was measured only at a few energies. Further (α, γ) measurements are planned using, e.g., the AMS method [35]. Data for the three channels (α, p), (α, n), and (α, γ) are available at 12.37 MeV (shown in bold face in Table II); these data are used for the determination of the total reaction cross section σ_{reac}.

The effective energies were calculated by taking into account the energy loss of the beam in the target. The uncertainty of the energy is the quadratic sum of the uncertainty of the beam energy (0.5%) and half of the energy loss in the target. The uncertainty of the cross section values is the quadratic sum of the uncertainties from the following components: target thickness (8%), detector efficiency (5%), current integration (3%), decay parameters (<4%), and counting statistics (typically about 0.3–5%, in the worst case <23%).

Figure 2 shows the results of the three reactions in the form of the astrophysical S factor. Along with the experimental data the predictions of two different StM codes, the NON-SMOKER [36] and TALYS [37] codes, are plotted using their standard parameters. Both codes give a good qualitative description of the measured data. At $E_{\text{c.m.}} = 12.37$ MeV, where the total cross section is determined, both codes reproduce well the (α, p) and (α, n) cross sections. The (α, γ) value is well predicted by TALYS and somewhat underestimated by NON-SMOKER, which code is not optimized for high energies. The discussion of the low energy cross sections and the astrophysical consequences will be the subject of a forthcoming publication.

Now we focus on the measurement at the energy $E_{\text{c.m.}} = 12.37$ MeV and determine the sum on the right-hand side (r.h.s.) of Eq. (2). The first three terms can be taken directly from our experimental results in Table II. The summed cross section of these three channels is 525 ± 57 mb, where for the calculation of the uncertainty the common uncertainties of the three measurements have been taken into account. The remaining five terms have to be estimated using theoretical considerations. Because these terms are relatively small compared to the dominating (α, p) and (α, n) cross sections, the sum in Eq. (2) is mostly defined by our experimental data.

(α, α'): Inelastic scattering is dominated by Coulomb excitation at energies below the Coulomb barrier. We have performed coupled-channel calculations with the code ECIS [38] in the vibrational model using the potential of Ref. [1] and the deformation parameter $\beta_2 = 0.242$, which was taken from compilation of Raman *et al.* [39]. For the first excited 2^+ state at $E_x = 992$ keV we find a Coulomb contribution of 34 mb (close to the semiclassical result for Coulomb excitation [40] using the adopted transition strength of $B(E2) = 20$ W.u. [41]) and a smaller nuclear contribution of 12 mb leading to a total excitation cross section of 46 mb with an estimated 20% uncertainty of 10 mb. The Coulomb-nuclear interference is practically negligible at the low energies under study. The cross sections of higher-lying excited states are much smaller, which is confirmed by the spectrum of inelastically scattered α particles at somewhat higher energies (see, e.g., Fig. 2 of Ref. [30]). So we estimate 23 ± 23 mb for the higher-lying states, i.e., a lower limit of zero and an upper limit identical to the dominating cross section of the first excited 2^+ state. By summing the dominating contribution of the first excited 2^+ state (46 ± 10 mb) and the estimated contribution of higher-lying states (23 ± 23 mb), we find in total $\sigma(\alpha, \alpha') = 69 \pm 25$ mb.

$(\alpha, 2\alpha)$, $(\alpha, \alpha p)$, $(\alpha, 2p)$, $(\alpha, \alpha n)$: The Q values for all two-particle emission reactions are strongly negative. Thus, the probability to emit one or even two charged particles from the compound nucleus ^{68}Ge with very low energies is extremely small. Calculations using the code TALYS [37] with different α-nucleus optical potentials always lead to negligible cross sections below 1 mb for each of the two-particle emission channels. Thus, we adopt 0.5 ± 0.5 mb for each of the two-particle channels.

Summing up all the above cross sections, we find a total reaction cross section of $\sigma_{\text{reac}} = 596 \pm 62$ mb for the r.h.s. of Eq. (2). Next, this number has to be compared to the total reaction cross section σ_{reac} derived from the elastic scattering angular distribution using Eq. (1).

Di Pietro *et al.* [24] have measured ^{64}Zn$(\alpha, \alpha)^{64}$Zn elastic scattering at the energy $E_{\text{c.m.}} = 12.4$ MeV. From their analysis using Woods-Saxon potentials of volume type, they determined a total reaction cross section of $\sigma_{\text{reac}} = 650 \pm 80$ mb. A reanalysis of these scattering data using a folding potential in

TABLE II. Measured cross sections of the three studied reactions. See text for details.

$E_{c.m.}^{eff}$ (MeV)	Cross section (mb)	$E_{c.m.}^{eff}$ (MeV)	Cross section (mb)
^{64}Zn(α, p)^{67}Ga reaction		^{64}Zn(α, p)^{67}Ga reaction (cont.)	
5.79 ± 0.08	(2.65 ± 0.38)×10^{-3}	10.38 ± 0.08	177 ± 20
5.86 ± 0.07	(3.03 ± 0.40)×10^{-3}	11.09 ± 0.09	254 ± 28
6.16 ± 0.08	(3.73 ± 0.42)×10^{-2}	11.24 ± 0.09	255 ± 28
6.26 ± 0.05	(3.69 ± 0.42)×10^{-2}	11.60 ± 0.06	265 ± 29
6.39 ± 0.08	(2.94 ± 0.33)×10^{-1}	12.22 ± 0.06	317 ± 36
6.52 ± 0.08	(2.76 ± 0.31)×10^{-1}	**12.37 ± 0.07**	**344 ± 40**
6.80 ± 0.08	(4.38 ± 0.49)×10^{-1}	^{64}Zn(α, n)^{67}Ge reaction	
7.01 ± 0.06	(7.08 ± 0.80)×10^{-1}	9.04 ± 0.08	10.6 ± 1.2
7.04 ± 0.05	(5.88 ± 0.66)×10^{-1}	9.68 ± 0.08	41.7 ± 4.6
7.15 ± 0.08	2.52 ± 0.28	10.30 ± 0.07	70.4 ± 7.7
7.51 ± 0.04	5.63 ± 0.63	10.38 ± 0.08	73.6 ± 8.1
7.51 ± 0.04	5.95 ± 0.67	11.09 ± 0.09	106 ± 12
7.70 ± 0.04	7.78 ± 0.88	11.24 ± 0.09	109 ± 12
7.96 ± 0.06	7.96 ± 0.89	11.60 ± 0.06	120 ± 13
8.07 ± 0.05	12.4 ± 1.4	12.22 ± 0.06	165 ± 18
8.47 ± 0.10	36.6 ± 4.1	**12.37 ± 0.07**	**179 ± 19**
8.79 ± 0.10	49.8 ± 5.6	^{64}Zn(α, γ)^{68}Ge reaction	
9.04 ± 0.08	72.3 ± 7.3	7.96 ± 0.06	0.92 ± 0.23
9.68 ± 0.08	123 ± 13	11.24 ± 0.09	2.42 ± 0.21
10.30 ± 0.07	172 ± 19	**12.37 ± 0.07**	**1.81 ± 0.19**

the real part and an imaginary surface Woods-Saxon potential (consistent with a global study of α-nucleus potentials at low energies [42]) leads to a slightly lower value of 610 mb with a significantly reduced χ^2/F. So we adopt $\sigma_{reac} = 610 \pm 80$ mb in the following discussion. This result also fits nicely into the systematics of so-called reduced cross sections σ_{red} versus reduced energy E_{red} [43,44] for ^{64}Zn(α,α)^{64}Zn scattering data at higher energies [24,25]; however, the obtained σ_{red} for ^{64}Zn are slightly higher than σ_{red} for other α-nucleus systems [22,44].

The energy difference between the elastic scattering data at 12.4 MeV and the activation data at 12.37 MeV is very small. The calculated σ_{reac} at 12.37 MeV differs by less than 0.5%

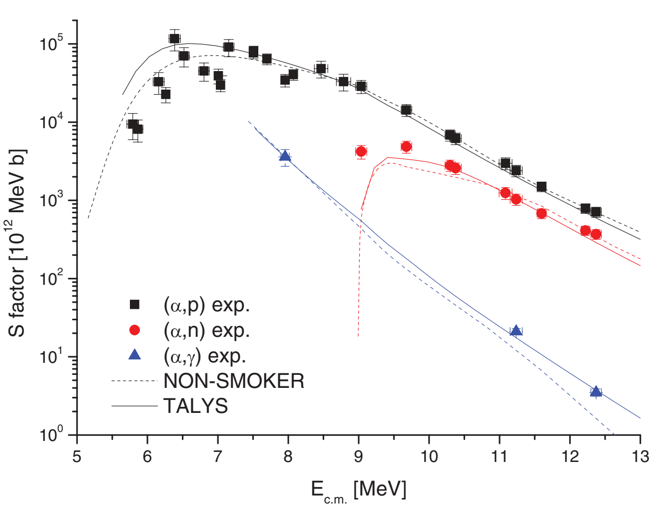

FIG. 2. (Color online) Astrophysical S factor of the measured reactions and the predictions of statistical model calculations.

from the result at 12.4 MeV. This tiny difference is neglected, and we take $\sigma_{reac} = 610 \pm 80$ mb for σ_{reac} in Eq. (1) at 12.37 MeV.

The ratio r = l.h.s./r.h.s between the left-hand side and right-hand side in Eq. (2) should be unity if the l.h.s. can be taken from Eq. (1). The experimental result of this work, $r = 1.02 \pm 0.17$, confirms the validity of Eqs. (1) and (2) within about 17% uncertainty, which is the first experimental confirmation of Eqs. (1) and (2) for α-induced reactions at low energies around the Coulomb barrier. A more precise confirmation requires a reduction of the uncertainties. Such a reduction is possible for the total reaction cross section from elastic scattering where uncertainties of the order of a few percent can be achieved if the angular distribution is measured over the full angular range with small uncertainties [44]. Such an experiment is in preparation at ATOMKI. It is also planned to measure inelastic scattering cross sections in this experiment; this will lead to a further reduction of the uncertainty of r because of a more precise determination of the (α,α') cross section in Eq. (2).

In the previous work [5,7,8], ratios of about $1.1 \leqslant r \leqslant 1.5$ were found for various nuclei at energies above the Coulomb barrier, whereas $r \approx 1$ was found using the latest transmission data [6]. However, there is no explicit determination of the ratio r in recent literature [5–7] because in most cases the energies of the transmission data did not exactly match the energies of the available elastic scattering angular distributions, and thus also no uncertainty for r is given. The experimental uncertainties for the transmission data are about 1–3% in Ref. [5] and 4–10% in Ref. [6]. As can be seen from Fig. 1 of Ref. [7], different parametrizations of the α-nucleus potential differ by about 10–20% in the calculation of σ_{reac}; the differences may result from the limited angular range of the angular distributions at higher energies. Together with an additional uncertainty from the mismatch of the energies between the transmission data and the scattering data we estimate a total uncertainty of at least 20% for the ratio r at higher energies. We recommend performing a new transmission experiment for a properly chosen target nucleus and a simultaneous study of the elastic and inelastic scattering angular distributions (with small uncertainties over a broad angular range) at exactly the same energy. With these data it should be possible to also confirm Eqs. (1) and (2) at energies significantly above the Coulomb barrier with small uncertainties.

We have also determined the total reaction cross section at the other energies, where we measured three reaction channels. The summed cross sections are 366 ± 39 mb (8.9 ± 1.0 mb) at 11.24 MeV (7.96 MeV). The given numbers do not include inelastic cross sections of 62 ± 22 mb (16 ± 5 mb). From these data it is possible to determine $\sigma_{\text{reac}} = 428 \pm 44$ mb at 11.24 MeV. We do not provide σ_{reac} at 7.96 MeV because σ_{reac} is dominated by inelastic scattering and not by our experimental data. A test of Eq. (1) is not possible at these lower energies because experimental angular distributions are not available. Such scattering experiments will be very difficult, in particular at the lower energy because the elastic scattering cross section will deviate from the Rutherford cross section by less than 10% here.

In conclusion, this work has confirmed for the first time experimentally that the total reaction cross section σ_{reac} of α-induced reactions from the sum over all open reaction channels (measured by the activation technique) and σ_{reac} from the analysis of elastic scattering angular distributions are identical. This is an important experimental confirmation of the basic quantum-mechanical relations in Eqs. (1) and (2) which are widely used in the prediction of reaction cross sections, e.g., in the statistical model, in particular because some previous studies [5,7,8] failed to confirm this identity. A close relation between reaction cross sections and backward angle elastic scattering was also found by the analysis of barrier distributions (e.g., Ref. [45]). If the validity of Eqs. (1) and (2) is assumed *a priori*, our result may also be interpreted as a consistency check of different methods for the determination of the total reaction cross section σ_{reac}. This result also strengthens the motivation for the study of elastic α scattering at low energies to determine σ_{reac} and to obtain a low-energy α-nucleus potential for a better prediction of (α,γ) capture cross sections [42,46].

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