Unexpected properties of the \(^{33}\text{S}(\alpha,p)^{36}\text{Cl}\) reaction cross section at low energies

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New experimental data for the \(^{33}\text{S}(\alpha,p)^{36}\text{Cl}\) reaction show a very unusual energy dependence. Contrary to common findings for many other \(\alpha\)-induced reactions, statistical model calculations underestimate the measured cross sections at very low energies. The relatively huge cross sections at these low energies require a significant amount of single-particle strength in the measured energy range which exceeds by far 100\% as soon as the additional strength from the competing \(^{33}\text{S}(\alpha,n)^{36}\text{Ar}\) reaction is taken into account. In addition, the new data deviate from a general trend for the energy dependence of \(\alpha\)-induced reaction cross sections.

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Recently Bowers et al. \[1\] have measured the cross section of the \(^{33}\text{S}(\alpha,p)^{36}\text{Cl}\) reaction at energies around the Coulomb barrier from about 2.5 to 9 MeV. The experiment has been done at the University of Notre Dame using the activation technique. A \(^{33}\text{S}\) beam in combination with a \(^{4}\text{He}\) gas cell was used for the production of the \(^{36}\text{Cl}\) nuclei in inverse kinematics, and the number of produced \(^{36}\text{Cl}\) nuclei was determined from accelerator mass spectrometry. The focus of \[1\] was the production of short-lived radionuclides like \(^{36}\text{Cl}\) in the early solar system by solar energetic particles. The main result of \[1\] was that the production of \(^{36}\text{Cl}\) depends both on the astrophysical event parameters and on the reaction cross sections of several nuclear reactions, especially \(^{34}\text{S}(^{4}\text{He},p)^{36}\text{Cl}\), \(^{34}\text{S}(\alpha,n)^{36}\text{Cl}\), and \(^{33}\text{S}(\alpha,p)^{36}\text{Cl}\). Additionally it was noticed that calculations in the statistical model underpredict the experimental data significantly, and it was not possible to find a parameter set which is able to reproduce the new experimental data.

It is the focus of the present study to highlight and critically discuss the very unexpected properties of the new experimental data for the \(^{33}\text{S}(\alpha,p)^{36}\text{Cl}\) reaction in \[1\]. For this purpose I estimate an upper limit for the reaction cross section which is derived from the single-particle strength, and I compare the data to a systematics for so-called reduced cross sections and reduced energies.

For many \(\alpha\)-induced reaction cross sections at energies around the Coulomb barrier it is found that typical statistical model calculations are able to reproduce the experimental data above the Coulomb barrier whereas below the barrier experimental cross sections are significantly overestimated, see e.g. \[2,3\]. Similar to this general finding, the present \(^{33}\text{S}(\alpha,p)^{36}\text{Cl}\) data \[1\] are roughly reproduced at the highest energy. However, in strict contrast to the typical behavior, at lower energies the experimental data are not overestimated, but dramatically underestimated. In Fig. \[1\] the experimental data \[1\] are compared to the results of two widely used statistical model codes TALYS \[14\] and NON-SMOKER \[15\] (results taken from \[16\]). It has been stated that the typical overestimation of cross sections at very low energies is related to the missing energy dependence of the widely used \(\alpha\)-nucleus potential of McFadden and Satchler \[17\], and various attempts have been made to provide \(\alpha\)-nucleus potentials with an energy-dependent imaginary part \[2,11,12,13,20\] which essentially defines the reaction cross section. A reduction of reaction cross sections at low energies is related to an imaginary potential which decreases towards lower energies; such a behavior can be naturally understood from the smaller number of open reaction channels at low energies. However, the reproduction of the new \(^{33}\text{S}(\alpha,p)^{36}\text{Cl}\) data requires an increasing imaginary part at low energies which is at least an unexpected result.

Contrary to the original presentation in Fig. 8 of \[1\] where the cross section \(\sigma(E)\) is plotted versus the energy per nucleon of the \(^{33}\text{S}\) projectile, here I present the astrophysical S-factor \(S(E)\) versus the center-of-mass energy \(E\). (Note that \(E\) refers to the center-of-mass energy in this paper except explicitly stated.) The S-factor vs. \(E\) presentation should show only a mild energy dependence because the dominating Coulomb effect on the energy dependence is separated from the data.

The \(^{33}\text{S}(\alpha,p)^{36}\text{Cl}\) reaction has a slightly negative \(Q\)-value of \(Q = -1.93\) MeV. Almost the same \(Q\)-value is found for the \(^{33}\text{S}(\alpha,n)^{36}\text{Ar}\) reaction with \(Q = -2.00\) MeV. Thus, it can be expected that close above the almost common threshold the \((\alpha,n)\) cross section dominates because the proton emission from the \(^{37}\text{Ar}\) compound nucleus is suppressed by the Coulomb barrier. At higher energies the \((\alpha,p)\) and \((\alpha,n)\) reactions have similar cross sections, even slightly favoring the \((\alpha,p)\) reaction because of the larger number of open channels for the decay of \(^{37}\text{Ar}\) into the residual odd-odd \(^{36}\text{Cl}\) nucleus. The calculated ratio \(r = \sigma(\alpha,n)/\sigma(\alpha,p)\) is shown in Fig. \[2\].

Calculations of the \(^{33}\text{S}(\alpha,p)^{36}\text{Cl}\) reaction cross section in \[1\] and in this work are based on the statistical model (StM). This requires a brief discussion on the applicability of the StM and on the relevance of the various ingredients of the StM. A basic prerequisite of the
FIG. 1. (Color online) Astrophysical S-factor of the $^{33}\text{S}(\alpha,p)^{36}\text{Cl}$ reaction: comparison of the new experimental data $^1$ to statistical model calculations using the NON-SMOKER default parameters and TALYS default and TALYS with the McFadden/Satchler $\alpha$-nucleus potential $^1$.

$^a$ Similar to Fig. 8 of $^1$, the upper limit $\sigma < 0.1 \text{ mb}$ is presented as $0.1 \pm 0.1 \text{ mb}$ or $S(E) = (1.44 \pm 1.44) \times 10^{18} \text{ eV b}$.

StM is a sufficiently high level density in the compound nucleus (here $^{37}\text{Ar}$). The level density increases with excitation energy and with the mass number $A$ of the compound nucleus. The new data of $^1$ correspond to $E^* \approx 9 \text{–} 16 \text{ MeV}$ in the even-odd nucleus $^{37}\text{Ar}$. The smooth energy dependence of the experimental S-factors (see Fig. 1) within the relatively broad energy widths of the data points ($\approx 380 \text{–} 480 \text{ keV}$) is a clear experimental indication that the measured cross sections are composed of many overlapping resonances and not of very few isolated resonances; thus, for the measured average cross sections within the experimental energy windows the StM should be applicable. This finding is further strengthened by the successful application of the StM to various reactions in this mass region (e.g., $\alpha$-induced reactions for target nuclei between $^{27}\text{Al}$ and $^{51}\text{V}$, see $^21$ $^23$).

The calculations in the StM obviously depend on the chosen input parameters which are the level densities, optical potentials, and $\gamma$-ray strength functions. Fortunately, in the present case the relevance of the various ingredients can be nicely disentangled. The cross section of a $(\alpha,X)$ reaction in the StM is proportional to $(T_{\alpha,0}T_X)/T_{\text{total}}$ with the transmissions $T_i$ as e.g. defined in $^24$ and the total transmission $T_{\text{total}} = \sum T_i$. Except very close above the respective thresholds around $E \approx 2 \text{ MeV}$, the transmissions $T_n$ and $T_p$ into the $^{36}\text{Ar}-n$ and $^{36}\text{Cl}-p$ channels are much larger than $T_{\alpha}$ and $T_{\alpha}$. Hence, $T_{\text{total}} \approx T_n + T_p$ which leads to the following approximate proportionality: $\sigma(\alpha,n) \sim (T_{\alpha,0}T_n)/(T_n + T_p)$, $\sigma(\alpha,p) \sim (T_{\alpha,0}T_p)/(T_n + T_p)$, $\sigma(\alpha,n)/\sigma(\alpha,p) \sim T_n/T_p$, and $\sigma_{\text{total}} \sim T_{\alpha,0}$.

Consequently, the total reaction cross section is practically only sensitive to the chosen $\alpha$-nucleus potential, and the ratio $r = \sigma(\alpha,n)/\sigma(\alpha,p)$ depends only on the chosen nucleon-nucleus potential. The parametrization of the level densities has almost no effect on the calculated cross sections because the StM codes $^14$ $^15$ use the well-known experimental level schemes at low energies for the involved nuclei close to stability. These low-lying states are the most important final states at low energies, see e.g. Eq. (64) in $^24$.

As expected, the calculated ratio $r$ is practically insensitive to the choice of the $\alpha$-nucleus potential (see Fig. 2), thus, such ratios are an excellent test for the remaining parameters of the StM except the $\alpha$-nucleus potential. The ratio $r$ is nicely constrained because of the good agreement of the different calculations using a variety of global nucleus-nucleus potentials; in particular, the potentials of Refs. $^25$ $^27$ have been used for the calculations in Fig. 2. It should be noted that in any case the same nucleon-nucleus potential has been used for the proton and the neutron channel; this leads to a relatively well-constrained ratio $r$. No attempt was made using inconsistent combinations like the potential from $^25$ for the neutron channel and from $^27$ for the proton channel.

Summarizing the above arguments, the StM should be well applicable to the $^{33}\text{S}(\alpha,p)^{36}\text{Cl}$ reaction under study. The huge discrepancy between the StM calculations and the recent experimental data $^1$ at low energies cannot be explained in a simple way. Thus, further investigations of the unexpected energy dependence of the $^{33}\text{S}(\alpha,p)^{36}\text{Cl}$ reaction cross sections have been performed.

At the energies under study in $^1$, the $^{33}\text{S}(\alpha,p)^{36}\text{Cl}$ and $^{33}\text{S}(\alpha,n)^{36}\text{Ar}$ reactions are governed by many resonances corresponding to levels in the $^{37}\text{Ar}$ compound nucleus at excitation energies from about 9 to 16 MeV. Following e.g. the definitions in $^28$, the decay width $\Gamma_{X,L}$ for a particular channel $X$ with relative angular momentum $L$
can be estimated from the single-particle (s.p.) limit
\[
\Gamma_{s,L}^{s,p}(E) = \frac{2kR}{F_L^2(E, R) + G_L^2(E, R)} \times \frac{\hbar^2}{\mu R^2} \tag{1}
\]
with the wave number \( k \), the nuclear radius \( R = R_0 \times (A_{1/3}^{1/3} + A_{1/3}^{1/3}) \) and \( R_0 = 1.25 \text{ fm} \), the regular and irregular Coulomb functions \( F_L \) and \( G_L \), and the reduced mass \( \mu \). The decay widths with small angular momenta \( L \) are dominated because of the smaller centrifugal barrier and because all \( J^\pi \) of the relevant levels in \( ^{33}\text{S}, ^{36}\text{Cl}, ^{36}\text{Ar} \), and \( ^{37}\text{Ar} \) are small. Furthermore it is found that the larger Coulomb barrier in the \( \alpha \) channel leads to \( \Gamma_\alpha \ll \Gamma_p \) and \( \Gamma_\alpha \ll \Gamma_n \) for practically the full energy range under study. Consequently, the total width \( \Gamma \) is essentially defined by the sum of the dominating partial widths \( \Gamma_p \) and \( \Gamma_n \) (the radiation width \( \Gamma_\gamma \) is also small). The cross sections \( \sigma(E) \) measured in [1] are the average cross sections (averaged over all contributing resonances within the broad experimental energy window \( \Delta E \) which is defined by the energy loss of the \( ^{33}\text{S} \) beam in the helium gas target). From a detailed study of partial widths [29] it has been concluded that on average experimental \( \Gamma_\alpha \) are about 2\% of the single-particle limit in Eq. (1).

From the single-particle limits of the decay widths \( \Gamma_{s,L}^{s,p} \) it is possible to calculate a limit for the cross section \( \sigma_{L}^{s,p} \) for the \( L \)-th partial wave in an energy interval \( \Delta E \). As the condition \( \Gamma < \Delta E \approx 500 \text{ keV} \) is fulfilled for most states, this can be done easily using the narrow-resonance formalism (using the resonance strength \( \omega_\gamma \approx \omega_\Gamma \)). For an isolated resonance with \( \Gamma_{s,L}^{s,p} \) this leads to
\[
\sigma_{L}^{s,p} = \frac{1}{\Delta E} \int \sigma(E)dE \approx \frac{\pi^2 \hbar^2}{\mu E \Delta E} \times (2L + 1) \Gamma_{s,L}^{s,p} \tag{2}
\]
with the experimental energy range \( \Delta E \). The results are listed in Table I in more detail. If a \( s \)-wave resonance \( (L = 0; J^\pi = 3/2^+) \) with full single-particle strength \( (\theta^2 = 1.0) \) is located within the energy window \( \Delta E = 0.476 \text{ MeV} \) around \( E = 3.503 \text{ MeV} \) (i.e., between 3.265 and 3.741 MeV), it will contribute with \( \sigma_{L=0}^{s,p} = 2.47 \text{ mb} \) to the measured average cross section at this energy. The same result is obtained if several \( s \)-wave resonances with a summed \( \theta^2 = 1.0 \) are located within this energy window (neglecting the energy dependence of the width \( \Gamma_{s,L}^{s,p} \) within the energy window \( \Delta E \); see also below). For \( p \)-waves \( (L = 1, J^\pi = 1/2^-, 3/2^-, 5/2^-) \) the single-particle cross section within \( \Delta E \) is \( \sigma_{L=1}^{s,p} = 5.03 \text{ mb} \). The sum over single-particle cross sections from all partial waves is 13.8 mb. If the experimental result were also 13.8 mb, then all single-particle strength for all partial waves must be located in this energy window, thus no \( \alpha \) strength remaining for energies outside \( \Delta E \). The experimental result of \( 2.4 \pm 0.3 \text{ mb} \) corresponds to 17\% of the single-particle strength of all partial waves which is still a very high value for a \( \Delta E \approx 0.5 \text{ MeV} \) energy window. Summing up the \( \alpha \)-strength over the five measured intervals \( \Delta E \) reaches already 45\% of the single-particle strength for all partial waves, and assuming a smooth energy dependence for the \( \alpha \)-strength between the data points leads to about 100\% of the available single-particle strength. The \( \alpha \)-strength is shown in Fig. 3; here the \( \alpha \)-strength has been normalized to a 1 MeV interval because the energy intervals of the experimental data points are not exactly identical. Furthermore, it can be read from Fig. 3 that the single-particle strength increases strongly towards lower energies.

As already stated above, the cross section for the \( ^{33}\text{S}(\alpha,n)^{36}\text{Ar} \) reaction exceeds the \( ^{33}\text{S}(\alpha,p)^{36}\text{Cl} \) cross section at low energies (see also Fig. 2), and therefore the measured \( \alpha \)-strength in the \( \alpha(p,n) \) reaction is only a small part of the total \( \alpha \)-strength. From the calculated ratio \( r = \sigma(\alpha,n)/\sigma(\alpha,p) \) in Fig. 2 the cross section of the \( ^{33}\text{S}(\alpha,n)^{36}\text{Ar} \) reaction can be derived, and the corresponding \( \alpha \)-strength in the \( (\alpha,n) \) reaction can be estimated (see Fig. 3). The total \( \alpha \)-strength exceeds by far the single-particle limit; this is again a very unexpected finding.

![FIG. 3.](image_url) (Color online) Single-particle strength per MeV for the \( ^{33}\text{S}(\alpha,p)^{36}\text{Cl} \) (red) and \( ^{33}\text{S}(\alpha,n)^{36}\text{Ar} \) (blue) reactions vs. excitation energy \( E_x \) in \( ^{37}\text{Ar} \) \( E_x = E + S_\alpha \) with the \( \alpha \) separation energy \( S_\alpha = 6.787 \text{ MeV} \).
TABLE I. Cross section $\sigma^{s,p}_{L}$ (in mb) within the experimental energy range $\Delta E$ from the single-particle limits $\Gamma^{s,p}_{\alpha,L}$ in Eq. (1). The contribution of partial waves with $L > 6$ to the sum $\sum \sigma^{s,p}_{L}$ remains negligible ($\lesssim 1\%$).

| $E$ (MeV) | $\Delta E$ (MeV) | $L = 0$ | $L = 1$ | $L = 2$ | $L = 3$ | $L = 4$ | $L = 5$ | $\sum \sigma^{s,p}_{L}$ | $\sigma_{\exp}$ | $\sigma_{\exp}/\sum \sigma^{s,p}_{L}$ |
|-----------|------------------|--------|--------|--------|--------|--------|--------|-----------------|-------------|------------------|
| 2.730     | 0.09             | 0.17   | 0.12   | 0.05   | 0.01   | 0.00   | 0.00   | 0.44            | < 0.1       | < 0.23           |
| 3.503     | 0.476            | 2.47   | 5.03   | 3.90   | 1.78   | 0.53   | 0.11   | 0.02            | 13.83       | 2.4(3)           |
| 4.568     | 0.465            | 38.5   | 84.8   | 75.7   | 41.2   | 15.1   | 3.9    | 0.7             | 259.9       | 37(5)            |
| 5.632     | 0.454            | 167.6  | 403.6  | 423.2  | 282.7  | 128.9  | 41.7   | 9.9             | 1458        | 105(8)           |
| 6.751     | 0.378            | 426.3  | 1109.7 | 1356.1 | 1121.4 | 651.9  | 268.2  | 79.9            | 5014        | 199(16)          |
| 8.400     | 0.454            | 565.0  | 1568.2 | 2200.2 | 2275.6 | 1791.7 | 1041.5 | 435.9           | 9878        | 330(40)          |

(calculated from the new ATOMKI-V1 potential \textsuperscript{13} for \textsuperscript{140}Ce \textsuperscript{51}). The cross section of the \textsuperscript{33}S(\textalpha,p)\textsuperscript{36}Cl reaction at the highest energy is found below the general trend, but as soon as the additional contribution of the \textsuperscript{33}S(\textalpha,n)\textsuperscript{36}Ar reaction is taken into account, the total reaction cross section of \textsuperscript{33}S fits nicely into the general trend of the data. However, the energy dependence of the \textsuperscript{33}S(\textalpha,p)\textsuperscript{36}Cl reaction is much flatter than the usual trend, and even the cross sections of the \textsuperscript{33}S(\textalpha,p)\textsuperscript{36}Cl reaction at lower energies by far exceed the general trend of total reaction cross sections. Adding the additional contribution of the \textsuperscript{33}S(\textalpha,n)\textsuperscript{36}Ar reaction obviously sharpens this discrepancy.

FIG. 4. (Color online) Total reduced cross section $\sigma_{\text{red}}$ versus reduced energy $E_{\text{red}}$ for many $\textalpha$-induced reactions \textsuperscript{13}, compared to the recent \textsuperscript{33}S(\textalpha,p)\textsuperscript{36}Cl \textsuperscript{1} and \textsuperscript{33}S(\textalpha,n)\textsuperscript{36}Ar cross sections; the latter is calculated from the ratio $r$ in Fig. 2.

The total reaction cross sections which are presented as $\sigma_{\text{red}}$ in Fig. 4 have been derived from the analysis of elastic scattering angular distributions. Such experiments are difficult for small $E_{\text{red}}$ in the mass range of the present study because the angular distributions may be dramatically affected by compound resonances. Nevertheless, total reaction cross sections can be estimated from the contributions of the different open channels. If one considers the sum of measured (\textalpha,p), (\textalpha,n), and (\textalpha,\gamma) cross sections as total reaction cross section, then the data in \textsuperscript{32} for \textsuperscript{64}Zn can be used to extend the $\sigma_{\text{red}}$ values from elastic scattering down to lower energies, and e.g. at $E_{\text{red}} = 0.7$ MeV a reduced cross section of $\sigma_{\text{red}} \approx 0.18$ mb is found. This value for \textsuperscript{64}Zn is slightly higher than the general trend for heavier nuclei but still an order of magnitude below the results for \textsuperscript{33}S.

Recently, a new systematics has been suggested for the comparison of cross sections from various fusion reactions. This new systematics uses a different way for the calculation of the reduced energy and takes into account the $Q$-value of the fusion reaction \textsuperscript{33}. A similar deviation of the new data for \textsuperscript{33}S from the general trend for heavier nuclei is also found in this case.

In the present study the energy dependence of the widths $\Gamma^{s,p}_{\alpha,L}$ within the energy window $\Delta E$ is neglected. Because a similar energy dependence of the cross section $\sigma(E)$ within $\Delta E$ has also been neglected in \textsuperscript{1}, the derived strengths from the ratio $\sigma_{\text{exp}}/\sum L \sigma^{s,p}_{L}$ should be consistent. Taking into account this energy dependence in the analysis of the experimental data will lead to slightly reduced cross sections; however, the changes should be of the order of $10\%$ and thus do not affect the main conclusion of the present study.

In summary, the new experimental data for the \textsuperscript{33}S(\textalpha,p)\textsuperscript{36}Cl reaction \textsuperscript{1} show a very unexpected behavior in all respects. First of all, the experimental S-factor data increase dramatically towards lower energies and exceed any theoretical prediction within the statistical model whereas usually the calculated cross sections exceed the experimental results. The huge S-factor of the \textsuperscript{33}S(\textalpha,p)\textsuperscript{36}Cl reaction at low energies requires a significant amount of $\alpha$-strength already within the measured energy intervals. It reaches already $100\%$ of the single-particle strength if one assumes a smooth energy dependence of the $\alpha$-strength between the measured energy intervals. The excess of $\alpha$-strength far over $100\%$ of the single-particle strength becomes visible as soon as the additional strength in the \textsuperscript{33}S(\textalpha,n)\textsuperscript{36}Ar reaction is taken into account. Finally, the new experimental data deviate
significantly from the general behavior of the energy dependence of α-induced reaction cross sections in the σ_{red} vs. E_{red} presentation. Hence, the new experimental data for the ^33S(α,p)^36Cl reaction – if confirmed – point to an extraordinary behavior of the ^33S-α system and will be an extreme challenge for theoretical models.

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Note added in proof:
Very recently, new data for the ^23Na(α,p)^26Mg reaction have been measured [31]. The analysis of these data shows that statistical model calculations underestimate the experimental data by about a factor of 40, i.e. even more dramatic than for the ^33S(α,p)^36Cl reaction studied in this work. Further investigations of (α,p) reactions in the mass range 20 ≲ A ≲ 50 are urgently needed to resolve these unexpected huge discrepancies.