Comparison of $^{120}\text{Sn}(^{6}\text{He},^{6}\text{He})^{120}\text{Sn}$ and $^{120}\text{Sn}(\alpha,\alpha)^{120}\text{Sn}$ elastic scattering and signatures of the $^{6}\text{He}$ neutron halo in the optical potential

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Cross sections of $^{120}\text{Sn}(\alpha,\alpha)^{120}\text{Sn}$ elastic scattering have been extracted from the $\alpha$ particle beam contamination of a recent $^{120}\text{Sn}(^{6}\text{He},^{6}\text{He})^{120}\text{Sn}$ experiment. Both reactions are analyzed using systematic double folding potentials in the real part and smoothly varying Woods-Saxon potentials in the imaginary part. The potential extracted from the $^{120}\text{Sn}(^{6}\text{He},^{6}\text{He})^{120}\text{Sn}$ data may be used as the basis for the construction of a simple global $^{6}\text{He}$ optical potential. The comparison of the $^{6}\text{He}$ and $\alpha$ data shows that the halo nature of the $^{6}\text{He}$ nucleus leads to a clear signature in the reflexion coefficients $\eta_L$: the relevant angular momenta $L$ with $\eta_L \gg 0$ and $\eta_L \ll 1$ are shifted to larger $L$ with a broader distribution. This signature is not present in the $\alpha$ scattering data and can thus be used as a new criterion for the definition of a halo nucleus.

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I. INTRODUCTION

In the last decade a series of experiments has been performed on elastic scattering of unstable nuclei at energies around the Coulomb barrier. It has been found that the scattering cross sections show a significantly different behavior for weakly bound projectiles compared to tightly bound projectiles like e.g. the $\alpha$ particle. The small binding energy of valence nucleons in orbitals with small angular momentum leads to wave functions which extend to very large radii, exceeding by far the usual $A^{1/3}$ radius dependence. Due to the corresponding long range absorption the Fresnel diffraction peak in the elastic scattering angular distribution is damped, and the elastic scattering cross section at backward angles is relatively small. As a consequence, the derived total reaction cross section $\sigma_{\text{tot}}$ for these exotic nuclei (e.g. $^{6}\text{He}$) is much larger than for tightly bound projectile (e.g. $\alpha$ particle) induced reactions. Fusion, breakup, and transfer reactions have been studied as the relevant reaction mechanisms.

As one focus on elastic scattering experiments with $^{6}\text{He}$, results have been reported for heavy target nuclei like $^{197}\text{Au}$, $^{208}\text{Pb}$, and $^{209}\text{Bi}$,$^{1,7}$ and intermediate mass nuclei like $^{64}\text{Zn}$ and $^{65}\text{Cu}$.$^{8,10}$ Some data are also available for lighter target nuclei like $^{12}\text{C}$ (e.g.,$^{11,12}$). In addition, elastic scattering of $^{11}\text{Be}$ has been studied recently$^{13,14}$. For a complete list of references, see the recent reviews.$^{15,16,17}$

Moreover, a series of theoretical investigations$^{15,30}$ on $^{6}\text{He}$ elastic scattering has been performed in the last years; they are also summarized in the review articles by Keeley and coworkers$^{16,17}$. The present study reanalyzes recently published data of the $^{120}\text{Sn}(^{6}\text{He},^{6}\text{He})^{120}\text{Sn}$ elastic scattering cross section$^{31}$ which filled the gap between targets with $A \ll 100$ and $A \approx 200$. We compare these results to $^{120}\text{Sn}(\alpha,\alpha)^{120}\text{Sn}$ elastic scattering data which have been obtained in the same experiment. The similarities and the differences of the weakly bound projectile $^{6}\text{He}$ and the tightly bound projectile $\alpha$ are nicely visible in this comparison.

The present study uses double folding potentials for the real part of the potential; this type of potentials is widely used in literature. The imaginary part is parametrized by Woods-Saxon potentials. The parameters of the potentials are restricted by the systematics of volume integrals which was found for many $\alpha$-nucleus systems$^{32}$; this systematics was successfully extended to $^{6}\text{He}$ in$^{14,15}$. Further information on the $^{120}\text{Sn}$-$\alpha$ potential is obtained from the analysis of angular distributions at higher energies$^{33,36}$ and excitation functions at lower energies$^{37,38}$.

The most important quantity for the description of elastic scattering data below and around the Coulomb barrier are the reflexion coefficients $\eta_L$ which define the total reaction cross section. There is a characteristic increase of the $\eta_L$ from $\eta_L \approx 0$ (i.e. almost complete absorption) for small angular momenta $L$ to $\eta_L \approx 1$ (i.e. no absorption) for large $L$ corresponding to large impact parameters in a classical picture. It will be shown that the dependence of $\eta_L$ on the angular momentum $L$ differs significantly for $^{120}\text{Sn}(^{6}\text{He},^{6}\text{He})^{120}\text{Sn}$ and $^{120}\text{Sn}(\alpha,\alpha)^{120}\text{Sn}$ elastic scattering. This difference can be considered as a new criterion for unusual strong absorption because of the halo nature of $^{6}\text{He}$.

This article is organized as follows: In Sect. I we repeat very briefly a discussion of the experimental set-up which is identical to$^{31}$. Sect. II contains an optical model (OM) analysis of the $^{120}\text{Sn}(^{6}\text{He},^{6}\text{He})^{120}\text{Sn}$ (Sect. II A) and $^{120}\text{Sn}(\alpha,\alpha)^{120}\text{Sn}$ (Sect. II B) scattering data and a discussion of the results (Sect. II C). Finally, conclusions are drawn in Sect. IV. Energies are given in...
the center-of-mass (c.m.) system except explicitly noted as laboratory energy $E_{\text{lab}}$.

II. EXPERIMENTAL TECHNIQUE

The scattering experiment has been performed at the SUD São Paulo Pelletron Laboratory at the RIBRAS (Radioactive Ion Beams in Brazil) facility \[39\]. A primary $^7\text{Li}^{3+}$ beam with energies around 25 MeV and a beam current of 300 nA hits the primary $^9\text{Be}$ target. The reaction products are collimated and enter a solenoid which focuses the primary $^7\text{Li}$ particles onto a “lollipop” where the $^7\text{Li}$ particles are stopped. Because of the different magnetic rigidity, the secondary $^6\text{He}$ and $\alpha$ particles do not hit the “lollipop”, but reach the secondary $^{120}\text{Sn}$ target. Typical beam intensities are about $10^4 - 10^5$ particles per second at the secondary target position. A 3.5 mg/cm$^2$ isotopically enriched (98.29\%) $^{120}\text{Sn}$ target and a 3.0 mg/cm$^2$ $^{197}\text{Au}$ target have been used as secondary targets. As the scattering $^4\text{He}+^{197}\text{Au}$ is pure Rutherford at forward angles in the energies of the present experiment, runs with gold target have been performed just before and after every $^{120}\text{Sn}$ run in order to normalize the $^4\text{He}+^{120}\text{Sn}$ cross sections \[31\].

The scattered particles are detected and identified in a system of $\Delta E$ and $E$ silicon detectors. A schematic view of the set-up is given in Fig. 1 of \[31\].

The $^4\text{He}$ beam is produced by one-proton removal from $^7\text{Li}$ in the $^9\text{Be}(^7\text{Li},^6\text{He})^{10}\text{B}$ reaction. But also the reaction $^9\text{Be}(^7\text{Li},\alpha)^{12}\text{B}$ may occur in the primary target, leading to an $\alpha$ contamination of the secondary beam. Because of the much larger $Q$-value of the $\alpha$-producing reaction ($Q_\alpha = +10.5$ MeV compared to $Q_{^4\text{He}} = -3.4$ MeV) the $\alpha$ particles have slightly higher energies around 30 MeV. The $\alpha$ beam contamination is clearly visible in the $\Delta E - E$ spectra in Fig. 2 of \[31\]. This contamination can be used to measure the $^{120}\text{Sn}(\alpha,\alpha)^{120}\text{Sn}$ elastic scattering cross section simultaneously with the $^{120}\text{Sn}^{6}(^{6}\text{He},^{6}\text{He})^{120}\text{Sn}$ experiment.

The result of the previous $^{120}\text{Sn}^{6}(^{6}\text{He},^{6}\text{He})^{120}\text{Sn}$ experiment \[31\] is shown in Fig. 1B together with the original analysis of \[31\] and the new analysis which is discussed in the following Sect. II.1. The new $^{120}\text{Sn}(\alpha,\alpha)^{120}\text{Sn}$ elastic scattering data are shown in Fig. 2A together with the theoretical results of this work. For the 20 MeV data which was obtained in a previous $^{8}\text{Li}+^{120}\text{Sn}$ experiment \[40\], the laboratory energies of the $\alpha$-beams are related to the $^4\text{He}$ energies by $E_{\alpha,\text{lab}} = \frac{2}{3}E_{\text{He,lab}}$ due to the band-pass of the solenoid ($B\rho = \sqrt{2}mE_{\text{lab}}/q$).

III. OPTICAL MODEL ANALYSIS

The complex optical model potential (OMP) is given by:

$$U(r) = V_C(r) + V(r) + iW(r),$$  \(1\)

where $V_C(r)$ is the Coulomb potential, $V(r)$, and $W(r)$ are the real and the imaginary parts of the nuclear potential, respectively. The real part of the potential is calculated from the folding procedure \[11\] using a density-dependent nucleon-nucleon interaction. The calculated folding potential is adjusted to the experimental scattering data by two parameters

$$V(r) = \lambda V_F(r/w)$$  \(2\)

where $\lambda \approx 1.1 - 1.4$ is the potential strength parameter \[32\] and $w \approx 1.0 \pm 0.05$ is the width parameter that slightly modifies the potential width. (Larger deviations

![FIG. 1: (Color online) Rutherford normalized elastic scattering cross sections of $^{120}\text{Sn}^{6}(^{6}\text{He},^{6}\text{He})^{120}\text{Sn}$ reaction at $E_{\text{lab}} = 17.4$, 18.05, 19.8, and 20.5 MeV versus the scattering angle $\vartheta_{\text{c.m.}}$ in the center-of-mass system (from \[31\]). The black dashed lines are the results from the original analysis in \[31\]. The blue full lines are obtained from the fit to the 20 MeV data, and the green dotted lines are obtained from the fit to the 17 MeV data. The dash-dotted red lines are the interpolations for the 18 and 19 MeV data. The parameters of the fits are listed in Table II. Further discussion see text (Sect. III.A)].
from the \(^6\)Li density determined in \cite{47}; both nuclei \(^6\)He and \(^6\)Li have 2 nucleons in the \(p\)-shell with similar separation energies. This density has been applied successfully in the calculation of \(^{208}\)Bi(\(^6\)He, \(^6\)He)\(^{208}\)Bi elastic scattering \cite{4,18}. Limitations of this choice may become visible in the width parameter \(w\) of the real part of the potential. However, a very similar folding potential is obtained from recently published theoretical densities of \(^9\)He \cite{48}; the consequences of the different choices for the \(^6\)He density will be studied in a subsequent paper. For further details of the folding potential, see also \cite{19,50}.

The imaginary part \(W(r)\) is taken in the usual Woods-Saxon parametrization. For the fits to the experimental data we use volume and surface potentials:

\[
W(r) = W_V \times f(x_V) + 4 W_S \times \frac{df(x_S)}{dx_S}
\]  

(3)  

with the potential depths \(W_V\) and \(W_S\) of the volume and surface parts and

\[
f(x_i) = \frac{1}{1 + \exp(x_i)}
\]  

(4)  

and \(x_i = [r - R_i (A_{1/3}^{1/3} + A_{1/3}^{1/3})]/a_i\) with the radius parameters \(R_i\) in the heavy-ion convention, the diffuseness parameters \(a_i\), and \(i = S, V\). It is well established that at very low energies the surface contribution of the imaginary part is dominating; e.g., in \cite{61} it is suggested that the surface contribution is about 80 \% for \(\alpha\) scattering of the neighboring nuclei \(^{112}\)Sn and \(^{124}\)Sn at energies below 20 MeV. At higher energies, i.e. significantly above the Coulomb barrier, the volume contribution is dominating.

The Coulomb potential \(V_C(r)\) is taken in the usual form of a homogeneously charged sphere. The Coulomb radius \(R_C\) is taken from the root-mean-square (rms) radius of the real folding potential with \(w = 1.0\); the sensitivity of the calculations on minor changes of \(R_C\) is negligible.

For a fit to few data points of elastic scattering around the Coulomb barrier, the number of adjustable parameters should be as small as possible because there are significant ambiguities for the derived potentials; the underlying problem is that the elastic scattering cross section is sensitive to the phase shifts and reflection coefficients which are properties of the wave function far outside the nuclear radii: (i) the so-called “family problem” is a discrete ambiguity where real potentials with different depths lead to a similar description of the scattering data because the wave functions are very similar in the exterior, whereas in the interior the number of nodes may change. (ii) Continuous ambiguities are found: e.g., a larger potential depth may be compensated by a smaller radius parameter, leading to more or less the same total potential strength and thus to the same wave function in the exterior region. In some cases this leads to a so-called “one-point potential” (e.g. \cite{29, 38, 50, 52}).

For a reduction of the adjustable parameters we use the systematic behavior of the volume integrals of the potentials which has been found in \cite{18,52}. For intermediate

![FIG. 2: (Color online) Rutherford normalized elastic scattering cross sections of the \(^{120}\)Sn(\(\alpha\),\(\alpha\))\(^{120}\)Sn reaction at \(E_{lab} = 20.0\), 26.1, 27.1, 29.7, and 30.8 MeV versus the scattering angle \(\vartheta_{c.m.}\) in center-of-mass system. The lines are the results from the optical model calculations in Sect. III B using different width parameters \(w\) of the real part and different imaginary radii \(R_S\) and diffusenesses \(a_S\) as indicated in the figure. In addition, the influence of an increased imaginary radius \(R_S\) is shown for the 20 MeV data. The calculation of Tabor et al. \cite{67} was adjusted to reproduce low-energy excitation functions (see Sect. III B.3). Further details see text (Sect. III B).](image)
mass and heavy nuclei the volume integrals \( J_R \) of the real part of the potential are practically independent of the chosen nuclei and depend only weakly on energy with a maximum around 30 MeV. A Gaussian parameterization has been suggested in [53] for energies below and slightly above the maximum of \( J_R \) at \( E_{\text{R},0} = 30 \text{ MeV} \):

\[
J_R(E) = J_{R,0} \times \exp \left[ -\frac{(E - E_{R,0})^2}{\Delta_R^2} \right]
\]  
(5)

with the maximum value \( J_{R,0} = 350 \text{ MeV fm}^3 \) and the width \( \Delta_R = 75 \text{ MeV} \). Potentials with \( J_R \) from Eq. (4) have been used for \( \alpha \) scattering [52], \( \alpha \) decay [53], and \( \text{He}^6 \) scattering [4, 15]. The energy dependence of \( J_R \) is weak; e.g., \( J_R \) changes by only a few per cent in the considered energy range of this work. (Note that the negative signs of the volume integrals are, as usual, neglected in the discussion.)

Contrary to the real volume integrals \( J_R \), the imaginary volume integrals \( J_I \) depend on the chosen nuclei and on energy. The energy dependence of \( J_I \) has been parametrized according to Brown and Rho [54]

\[
J_I(E) = J_{I,0} \times \frac{(E - E_{I,0})^2}{(E - E_{I,0})^2 + \Delta_I^2}
\]  
(6)

with a saturation value \( J_{I,0} \), the threshold value \( E_{I,0} = 1.171 \text{ MeV} \) (corresponding to the first excited \( 2^+ \) state in \( ^{120}\text{Sn} \)), and the slope parameter \( \Delta_I \). Saturation values around \( J_{I,0} \approx 100 \text{ MeV fm}^3 \) have been found in \( \alpha \) scattering with a trend to smaller \( J_{I,0} \) for doubly-magic targets and increasing \( J_{I,0} \) for semi-magic or non-magic targets. For the combination of a semi-magic \( \text{He}^6 \) projectile and a semi-magic \( ^{209}\text{Bi} \) target \( J_{I,0} = 127 \text{ MeV fm}^3 \) and \( \Delta_I = 12.7 \text{ MeV} \) were found [15]; these values are adopted for the analysis of \( ^{120}\text{Sn} \) elastic scattering which is also a combination of a semi-magic projectile and a semi-magic target. For \( ^{120}\text{Sn} \) elastic scattering a smaller saturation value of \( J_{I,0} = 80 \text{ MeV fm}^3 \) is used which is derived from scattering data at higher energies (see Sect. III B).

From the above considerations the volume integrals \( J_R \) and \( J_I \) for the analysis of \( ^{120}\text{Sn} \) elastic scattering are fixed. Hence the two adjustable parameters in the real part (strength parameter \( \lambda \) and width parameter \( w \)) are related by the volume integral \( J_R \) in Eq. (5), and the three adjustable Woods-Saxon parameters (depth \( W_V \) or \( W_S \), radius \( R_V \) or \( R_S \), and diffuseness \( a_V \) or \( a_S \)) are related by the volume integral \( J_I \) in Eq. (6).

**A. \( ^{120}\text{Sn} \) elastic scattering**

In addition to the above restrictions for the volume integrals \( J_R \) and \( J_I \), we fix the imaginary surface diffuseness to a standard value \( a_S = 0.7 \text{ fm} \). The small volume part of the imaginary potential at low energies [51] is neglected: \( W_V = 0 \).

In a next step we adjust the remaining parameters to the \( ^{120}\text{Sn} \) elastic scattering data at \( E_{\text{lab}} = 20.5 \text{ MeV} \) (referred to as “20 MeV data” in the following; the same convention of referring to the integer part of the laboratory energy \( E_{\text{lab}} \) will be used for all data). An excellent description of the 20 MeV data is found (see Fig. 1, full blue line) using a relatively small width parameter of \( w = 0.95 \) (see also Sect. III C). The same potential is now applied to the measured angular distributions at lower energies. Increasing discrepancies are observed for lower energies (Fig. 1, full blue lines): the calculated cross section at backward angles is larger than the measured values.

Because of the minor energy dependence of the real potential, the width parameter \( w \) was fixed now, and we tried to fit the lowest 17 MeV data by a readjustment of the imaginary part of the potential with a fixed \( J_I \) from Eq. (5). A clear increase of the radius parameter \( R_S \) by about 15 % was found; then an excellent description of the 17 MeV data can be obtained. This 17 MeV potential is not able to describe the angular distributions at the other energies, where the calculated cross sections underestimate the experimental results at backward angles (Fig. 1, dotted green lines).

Finally, we interpolate the imaginary radius parameter \( R_S \) between the 17 MeV and the 20 MeV results and use it for the remaining 18 MeV and 19 MeV angular distributions. An excellent agreement is obtained for all measured angular distributions (Fig. 1, dash-dotted red lines). The resulting parameters of the potentials are listed in Table I.

The total reaction cross sections \( \sigma_{\text{reac}} \) can be calculated from the refexion coefficients \( \eta_L \). We find that \( \sigma_{\text{reac}} \) decreases only slightly with energy from \( \sigma_{\text{reac}} = 1546 \text{ mb} \) at the highest energy \( E_{\text{lab}} = 20.5 \text{ MeV} \) to \( \sigma_{\text{reac}} = 1479 \text{ mb} \) at the lowest energy of \( E_{\text{lab}} = 17.4 \text{ MeV} \) (see Table I). These results agree with the original optical model analysis of [31] within less than 5 %.

For comparison, Fig. 1 shows also the original analysis of [31] using Woods-Saxon potentials without any restriction (black dashed lines). It is obvious that the systematic potentials from this work are able to reproduce the measured angular distributions with the same quality as the unrestricted Woods-Saxon potentials which do not show any systematic behavior; their volume integrals \( J_R \) and \( J_I \) vary strongly with energy.

**B. \( ^{120}\text{Sn} \) elastic scattering**

The analysis of the \( ^{120}\text{Sn} \) elastic scattering benefits from the fact that three angular distributions have been measured at higher energies [33–36]. These angular distributions can be used to fix the real part of the optical potential with small uncertainties. Thus, the number of adjustable parameters in the analysis of the new angular distributions at lower energies (see Fig. 2) is reduced, and the imaginary part can be deduced.
from the experimental data for a subsequent comparison with the $^6$He case. Further information on the potential can be obtained from the analysis of excitation functions which have been measured at lower energies [37, 38].

Data at higher energies can be best reproduced using an imaginary potential of Woods-Saxon volume type. Somewhat arbitrary, we take the three data sets from literature at $E_{labb} = 34.4$ MeV [33], 40.0 MeV [34, 35], and 50.5 MeV [36] as the “high-energy” data which are analyzed with a volume Woods-Saxon imaginary part, whereas our new data below 30 MeV are analyzed as “low-energy” data using a surface Woods-Saxon imaginary part. Obviously, there must be an intermediate energy range with the transition from surface Woods-Saxon to volume Woods-Saxon potentials. This transitional region is around the 34 MeV data of [33]; however, these data are not adequate for a precise determination of the optical potential (see below).

1. Angular distributions above approx. 30 MeV

Three angular distributions of $^{120}$Sn($^{6}$He,$^{6}$He)$^{120}$Sn elastic scattering have been published. The data by Kuterbekov et al. [37] have been measured at $E_{labb} = 50.5$ MeV. The data cover an angular range from about 10° to 60°. The numerical data are available in the EXFOR data base, but no further information on the experiment is available. The data of Baron et al. [34] are described in detail in an earlier report [33], including the numerical data with statistical errors. Because of very tiny statistical error bars in the forward direction of far below 1%, a systematic error of 5% has been added quadratically to all data points. In addition, the given energy of $E_{c}$ = 40.00 ± 0.25 MeV [33] has been reduced to an effective energy $E_{labb}$ = 39.95 MeV because of the energy loss in the target. This angular distribution covers almost the full angular range from about 20° to 150°. Finally, the data of Kumabe et al. [35] cover only a very limited angular range from about 20° to 60°. The data have been extracted from Fig. 2 of [35], which shows the absolute cross sections without error bars. Because of the limited angular range, the uncertainties of the digitization procedure, and the missing error bars, any fit of these data has significant uncertainties.

The three angular distributions have been fitted using two adjustable parameters in the real part (strength parameter $\lambda$ and width parameter $w$) and three parameters in the imaginary part (depth $W_V$, radius $R_V$, and diffuseness $a_V$). Additionally, the absolute values of the measured cross sections were allowed to vary. It is well-known that the cross sections at forward directions do practically not depend on the underlying potentials; in particular, at very forward directions the cross section approaches the Rutherford cross section for all optical potentials. Thus, it is common practice to normalize the measured data to calculated values at forward directions because an absolute measurement requires the absolute determination of the target thickness and uniformity, detector solid angle, and beam current and a proper dead-time correction. The scaling factor $s$ for the correction of the experimental data is defined by $\sigma_{exp}^{corr} = s \times \sigma_{exp}^{raw}$ where $\sigma_{exp}^{raw}$ are the published cross section data. It has been stated e.g. in [33] that this theoretical normalization $s$ deviates by 10–25% from unity for the tin targets used in that experiment. It is interesting to note that the obtained potential parameters are not very sensitive to the scaling factor $s$ as long as $s$ remains far below a factor of two because the diffraction pattern in the experimental data at higher energies nicely defines the underlying potential.

The results of the analysis are shown in Fig. 3 and the obtained parameters are listed in Table II. An excellent agreement between the scaled experimental data and the theoretical analysis is found for all energies under study.

| $E_{labb}$ (MeV) | $\lambda$ (MeV) | $w$ (fm³) | $J_{R}$ (MeV fm³) | $r_{R,rms}$ (fm) | $J_{I}$ (MeV fm³) | $r_{I,rms}$ (fm) | $W_{S}$ (MeV) | $R_{S}$ (fm) | $a_{S}$ (fm) | $\sigma_{reac}$ (mb) |
|------------------|----------------|-----------|----------------|----------------|----------------|----------------|----------------|-------------|-----------|-----------------|
| 17.40            | 1.207          | 0.95      | 339.0          | 5.477          | 75.6           | 9.320          | 19.2           | 1.315       | 0.7       | 1479            |
| 18.05            | 1.191          | 0.95      | 339.9          | 5.477          | 78.0           | 9.074          | 21.0           | 1.277       | 0.7       | 1503            |
| 19.80            | 1.219          | 0.95      | 342.4          | 5.477          | 83.8           | 8.415          | 26.6           | 1.174       | 0.7       | 1538            |
| 20.50            | 1.222          | 0.95      | 343.2          | 5.477          | 85.9           | 8.153          | 29.3           | 1.133       | 0.7       | 1546            |

*fixed value, adjusted to the 20 MeV data

from Gaussian parameterization, Eq. (4)

from Brown-Rho parameterization, Eq. (5)

Table I: Parameters of the potentials of $^{120}$Sn($^{6}$He,$^{6}$He)$^{120}$Sn elastic scattering in Fig. 3.
TABLE II: Parameters of the potentials of $^{120}$Sn($\alpha$,$\alpha$)$^{120}$Sn elastic scattering at higher energies above 30 MeV in Fig. 3

| $E_{\text{lab}}$ (MeV) | $s$ | $\lambda$ | $w$ | $J_R$ (MeV fm$^3$) | $r_{R,\text{rms}}$ (fm) | $J_I$ (MeV fm$^3$) | $r_{I,\text{rms}}$ (fm) | $W_V$ (MeV) | $R_V$ (fm) | $\alpha_V$ | $\sigma_{\text{reac}}$ (mb) |
|--------------------|-----|----------|-----|----------------|-------------------|----------------|-------------------|--------------|-----------|------------|-------------------|
| 34.4               | 0.97| 1.222    | 1.029 | 340.5         | 5.461             | 55.6           | 6.496            | 129          | 1.213     | 0.983     | 1472              |
| 40.0               | 1.48| 1.190    | 1.048 | 347.4         | 5.561             | 77.2           | 6.495            | 16.7         | 1.173     | 0.543     | 1927              |
| 50.5               | 1.18| 1.227    | 1.018 | 324.1         | 5.407             | 78.6           | 6.315            | 18.2         | 1.197     | 0.490     | 1939              |

FIG. 3: (Color online) Rutherford normalized elastic scattering cross sections of $^{120}$Sn($\alpha$,$\alpha$)$^{120}$Sn reaction at higher energies $E_{\text{lab}}$ = 34.4, 40.0, and 50.5 MeV $^{33}$ $^{36}$ versus the scattering angle $\vartheta_{\text{c.m.}}$ in center-of-mass frame. The calculated angular distributions use a double-folding potential in the real part and a volume Woods-Saxon potential in the imaginary part. Further details see text.

The data of Baron et al. $^{33}$ $^{36}$ cover almost the full angular range and are thus an ideal data set for the determination of the optical potential. The reproduction of the angular distribution is excellent over the full angular range. However, a significant scaling of the data ($s = 1.48$) was necessary; this seems to be justified because otherwise the most forward data point at $18^\circ$ deviates by almost a factor of two from the Rutherford cross section.

As pointed out above, the data at 34 MeV $^{33}$ have less explanatory power. Here a small scaling factor of $s = 0.97$ is found. The reason for this $s \approx 1$ is simply that $^{33}$ have already applied the same normalization procedure to their data. The found deviation of 3% thus simply provides an estimate for the uncertainty of the digitization procedure which had to be used to extract the data from their Fig. 2.

From the obtained parameters (see Table II) the following conclusions can be drawn. The real part of the potential behaves very regularly with the expected decrease of the real volume integral $J_R$ at higher energies $^{32}$. The resulting $J_R$ remain close to the suggested Gaussian parameterization in Eq. 5 although this parameterization is not expected to remain valid far above the maximum around 30 MeV $^{53}$. The width parameter $w$ is always slightly above 1.0; thus, for the following calculations at lower energies we adopt the average value of $\bar{w} = 1.032$. Together with the parameterization of $J_R$ at low energies in Eq. 5, the real part of the optical potential is completely fixed now. The imaginary part increases with energy and saturates at $J_{I,0} \approx 80$ MeV fm$^3$. As expected, this value is somewhat smaller than the result for $^4$He ($J_{I,0} = 127$ MeV fm$^3$). The available data are not sufficient to derive the slope parameter $\Delta_I$ of the Brown-Rho parameterization in Eq. 6. Instead, we use the same value $\Delta_I = 12.7$ MeV for $\alpha$ and $^6$He in this paper.

The relatively large value of $w = 1.032$ from the $^{120}$Sn($\alpha$,$\alpha$)$^{120}$Sn data at higher energies together with the small value of $w \approx 0.95$ derived from the $^{120}$Sn($^6$He,$^6$He)$^{120}$Sn data indicates that there is no major problem with the underlying $^{120}$Sn density which should show up as modification for $w$ in the same direction in both experiments. This is not surprising because the $^{120}$Sn charge density has been measured in two independent experiments $^{44}$ $^{45}$, and there is no evidence for a peculiar behavior of the neutron density (e.g. neutron skin) in $^{120}$Sn $^{57}$ $^{58}$. Instead, it may be concluded that the chosen $^6$He density is not very precise. Surprisingly, this problem was not found in the analysis of $^{209}$Bi($^6$He,$^6$He)$^{209}$Bi scattering data $^{4}$ $^{18}$; however, it may have been masked there by the larger Coulomb barrier of $^{209}$Bi.

The largest width parameter $w = 1.048$ was obtained...
from the analysis of the 40 MeV angular distribution of \[34, 35\]. A smaller width parameter of \( w \approx 1.02 \), closer to unity and in better agreement with the other data, can be obtained if the energy is changed to 42 MeV instead of 40 MeV. It is interesting to note that the authors of \[34, 35\] later refer to their data as “42-MeV scattering data” \[57\], whereas in \[35\] it is explicitly stated that “the incident beam energy is 40.00 \( \pm \) 0.25 MeV”.

2. Angular distributions below approx. 30 MeV

After fixing the complete real potential and the imaginary volume integral \( J_I \) as described in the previous section, now we fixed the geometry of the imaginary part for the low-energy data below \( \approx 30 \) MeV. Because of the dominating volume term at higher energies and the dominating surface term at lower energies (e.g. \[51\]), it is impossible to use at low energies the same geometry of the imaginary potential obtained at higher energies. Instead, we follow a procedure similar to the low-energy \( ^6 \)He data. We fix the imaginary surface diffuseness at \( a_S = 0.7 \) fm, and we take the radius parameter \( R_S \) from the highest energy of the \( ^{120} \)Sn\( ^6 \)He,\( ^6 \)He\( ^{120} \)Sn data: \( R_S = 1.133 \) fm. The depth of the potential \( W_S \) is adjusted to reproduce the volume integral \( J_I \) from Eq. \([6]\) with the parameters \( J_{I,0} = 80 \) MeV fm\(^3\) and \( \Delta_I = 12.7 \) MeV (as discussed in the previous subsection). As a consequence, all parameters of the potential are fixed, either to systematics or to the experimental data at higher energies. The reproduction of the \( ^{120} \)Sn\( \alpha \)\( ^{120} \)Sn elastic scattering cross section is good for all energies, see Fig. 2. The parameters are listed in Table II. The total reaction cross section \( \sigma_{\text{reac}} \) shows the usual energy dependence, i.e. it increases strongly with increasing energy.

In addition, we have studied the sensitivity of the data to minor variations of the potential. First, a width parameter \( w = 1.0 \) of the real potential was used instead of \( w = 1.03 \) together with a reduced imaginary radius parameter \( R_S = 1.021 \) fm (red dotted line in Fig. 2) adjusted to reproduce the excitation functions of \[37\] (green dashed), see Sec. III B 3). Second, the diffuseness \( a_S \) of the imaginary part was decreased to \( a_S = 0.43 \) fm instead of 0.7 fm (green dashed line, again adjusted to reproduce the excitations of \[37\]). In both cases the influence on the scattering cross sections remains relatively small although the 20 MeV data around 50° are clearly overestimated using \( w = 1.0 \) and \( R_S = 1.021 \) fm or \( a_S = 0.43 \) fm from the analysis of the excitation functions.

A significant reduction of the calculated scattering cross section is found if the increased radius parameter \( R_S \) from the 17 MeV \( ^6 \)He data is taken at the lowest energy of the \( \alpha \) data (magenta dash-dotted line). Here it becomes obvious that the new experimental \( ^{120} \)Sn\( \alpha \)\( ^{120} \)Sn data are not compatible with the strong increase of the radius parameter \( R_S \) at low energies which was essential for the reproduction of the \( ^{120} \)Sn\( ^6 \)He,\( ^6 \)He\( ^{120} \)Sn data.

3. Excitation functions at low energies

Excitation functions have been measured by Tabor et al. \[37\] and Badawy et al. \[37, 38\]. Unfortunately, the latter paper only mentions the measurement and derives a so-called one-point potential, but does not show the data for \( ^{120} \)Sn\( \alpha \)\( ^{120} \)Sn; thus, these data \[38\] are not accessible and cannot be used in the analysis. Tabor et al. \[37\] show two excitation functions at \( \vartheta_{\text{lab}} = 120^\circ \) and 165° in the energy range from 10 to 17 MeV in their Fig. 1. These data are shown together with the original analysis using a Woods-Saxon potential and the new reanalysis in Fig. 4.

In general, it is not possible to extract an optical potential from low-energy excitation functions because of ambiguities in the derived potentials. This has been clearly shown by Badawy et al. \[38\] in their analysis:
"The only statement that can be made on the three parameters characterizing a Woods-Saxon real potential is that they are linked by the relation: "..." the results are very insensitive to the value of W ...".

Further details on the one-point potential and its relation to the so-called "family problem" of α-nucleus potentials are discussed in [50] using the precisely determined angular distribution of 114Sn(α,α)114Sn at E ≈ 20 MeV (see Figs. 5 and 6 of [50]).

Although it is not possible to extract the optical potential, it is nevertheless possible to test the systematic potentials of this work using the measured excitation functions of [57]. It is found that the standard potential with \( w = 1.03 \), \( R_S = 1.133 \)fm, and \( a_S = 0.7 \)fm does not describe the excitation functions at low energies (full blue line in Fig. 4) and underestimates the measured cross sections. Instead of \( a_S = 0.7 \)fm, the diffuseness parameter of the surface imaginary part has to be decreased to \( a_S = 0.43 \)fm to find reasonable agreement with the measured excitation functions (green dashed line in Fig. 4). Alternatively, an excellent description of the data is also obtained using a reduced imaginary radius parameter \( R_S = 1.021 \)fm, \( a_S = 0.7 \)fm, and a width parameter \( w = 1.0 \)of the real part; however, such a width parameter \( w \) has been excluded by the high-energy angular distributions. This latter result is almost identical to the original analysis of Tabor et al. [57]: similar to that result, the angular distribution at 20 MeV is clearly overestimated around 50° (see Fig. 2).

Similar to the angular distributions shown in Fig. 2, a huge deviation from the measured excitation functions is found if the increased radius parameter \( R_S = 1.315 \)fm is used which has been obtained from the lowest energy in 120Sn(9He,8He)120Sn scattering (dash-dotted magenta lines in Figs. 2 and 4).

The calculated excitation functions may also change when the energy dependence of the volume integrals \( J_R \) and \( J_I \) in Eqs. (5) and (6) is varied. However, a variation of the Brown-Rho parameters of the order of 10% has only minor influence on the calculated excitation functions as long as the geometry of the imaginary potential is not changed.

The parameters of the potentials are also listed in Table III at the average energy \( E_{lab} \approx 13.5 \)MeV of the measured excitation functions [37]. At this energy both calculations with the slightly modified standard potential agree nicely with the measured data (see Fig. 4). However, the preferred calculation with \( w = 1.03 \) leads to slightly smaller elastic scattering cross sections which have significant impact on the total reaction cross section \( \sigma_{reac} \): \( w = 1.03 \) and \( a_S = 0.43 \)fm corresponds to \( \sigma_{reac} = 86 \)mb, \( w = 1.0 \) and \( R_S = 1.021 \)fm corresponds to \( \sigma_{reac} = 61 \)mb. The standard potential underestimates the elastic scattering cross sections of [37] and thus leads to a very high \( \sigma_{reac} = 150 \)mb. This discrepancy for \( \sigma_{reac} \) will affect the prediction of \( \alpha \)-induced cross sections in the statistical model.

### C. Discussion

For a better understanding of the different behavior of the 120Sn(α,α)120Sn and 120Sn(9He,8He)120Sn scattering data we show in Figs. 5 and 6 the reflexion coefficients \( \eta_L \) which are related to the scattering matrix \( S_L \) by \( S_L = \eta_L \times \exp(2i\delta_L) \); the reflexion coefficients \( \eta_L \) and the phase shifts \( \delta_L \) are real. The shown \( \eta_L \) correspond to the S-matrices from the calculations of Figs. 4 and 2. Both data sets show the usual behavior from \( \eta_L \) close to zero for small angular momenta \( L \) (corresponding to almost total absorption), increasing \( \eta_L \) for intermediate \( L \).
ever, there are also significant differences in the shown data points for each (partial absorption), and the width $\Delta L$ is larger for $\alpha$ systems. The obtained values for the position $L_0$ of the maximum slope of $\eta_L$ and the width $\Delta L$ are shown in dependence of the reduced energy $E_{\text{red}}$ in Fig. 7.

It is obvious from Fig. 7 that the maximum slope of $d\eta_L/dL$ is found for larger $L_0$ in the $^6\text{He}$ case at the same reduced energy $E_{\text{red}}$, thus reflecting the larger mass and momentum and the larger absorption radius of the halo nucleus $^6\text{He}$. And, more important, the width $\Delta L$ is larger for $^6\text{He}$ at the same $E_{\text{red}}$ and increases significantly with decreasing energy. A similar effect is not seen for $^{120}\text{Sn}(\alpha,\alpha)^{120}\text{Sn}$, and such a significant increase of the width $\Delta L$ is also not found in a series of high precision $\alpha$ scattering data in this mass region on $^{89}\text{Y}$, $^{92}\text{Mo}$, $^{106,110,116}\text{Cd}$, and $^{112,124}\text{Sn}$. These interesting findings for $^6\text{He}$ are directly related to the energy dependence of the imaginary radius parameter $R_S$ in the $^6\text{He}$ case.

For a demonstration of the strong influence of $R_S$ in the $^6\text{He}$ case we show in Fig. 5 the reflexion coefficients using the narrow imaginary potential from 20 MeV for which takes into account the Coulomb barrier (which is the same for $^6\text{He}$ and $\alpha$) and the different sizes of the $^{120}\text{Sn}$ and $^{120}\text{Sn}$-$\alpha$ systems. The obtained values for the position $L_0$ of the maximum slope of $\eta_L$ and the width $\Delta L$ are shown in dependence of the reduced energy $E_{\text{red}}$ in Fig. 6.

For a better comparison of the $^6\text{He}$ data and the $\alpha$ data which have been measured at slightly different energies, we use the so-called reduced energy

$$E_{\text{red}} = E \times \frac{A_p^{1/3} + A_T^{1/3}}{Z_p Z_T}$$

for a shape close to Gaussian

$$\frac{d\eta_L}{dL} \approx a \times \exp \left[ -\frac{(L - L_0)^2}{(\Delta L)^2} \right]$$

in the upper parts of Figs. 5 and 6. One finds curves with the maximum slope at the angular momentum $L_0$ and the width $\Delta L$. In general, the width $\Delta L$ is larger for the $^6\text{He}$ data than for the $\alpha$ data. And in addition, a significant increase of the width $\Delta L$ towards lower energies is found for the $^6\text{He}$ data which is not present in the $\alpha$ data. Significant absorption is found for all partial waves with $L \leq L_0 + \Delta L$.

For $^{120}\text{Sn}(\alpha,\alpha)^{120}\text{Sn}$ elastic scattering at $E_{\text{lab}} = 17.4$, 18.05, 19.8, and 20.5 MeV (lower part) and the derivatives $d\eta_L/dL$ (upper part). The full symbols correspond to the calculations in Fig. 1 and Tab. II: the open symbols are obtained using the 17 MeV potential at 20 MeV and vice versa. A clear broadening of the derivative $d\eta_L/dL$ at low energies can be seen. The data points for each $L$ are connected by dotted lines to guide the eye. Further discussion see text.
The 17 MeV data and vice versa (open symbols); these calculations are in clear disagreement with the measured data, see Fig. 4. The narrow 20 MeV potential used at 17 MeV leads to a maximum of $d\eta_L/dl$ at lower $L_0$ and a smaller width $\Delta L$. In parallel, $\sigma_{\text{reac}}$ is reduced from 1479 mb to 1114 mb. The wide 17 MeV potential used at 20 MeV leads to an increased $L_0$, a larger width $\Delta L$, and an increased $\sigma_{\text{reac}} = 1950$ mb instead of 1546 mb. In the $\alpha$ case, a similar result is found in the calculations where the increased radius parameter $R_S$ at the lowest energy leads to an increased $L_0$, larger width $\Delta L$, and an increased $\sigma_{\text{reac}} = 1459$ mb instead of 1121 mb. As can be seen from Fig. 2, the experimental data at 20 MeV are not reproduced using the larger radius parameter, and thus such an increase of $L_0$ and $\Delta L$ is excluded by the new $^{120}\text{Sn}(\alpha,\alpha)^{120}\text{Sn}$ scattering data. The description of the excitation functions at lower energies requires either a reduced diffuseness $a_S = 0.43$ fm or a reduced radius $R_S = 1.021$ fm in combination with $w = 1.0$, but does clearly not require any increased imaginary radius as derived from the low-energy $^6\text{He}$ data. Again, this clearly excludes any increase in $L_0$ or $\Delta L$ in the $\alpha$ case (see Fig. 7).

In summary, we find the following properties of the $^{120}\text{Sn-}\alpha$ potential. The high-energy data define the width parameter $w = 1.03$ for the folding potential in the real part. The volume integrals $J_R$ and $J_I$ of the real and imaginary potentials are consistent with several systematic studies. The geometry of the imaginary part is of Woods-Saxon volume type at higher energies; here the parameter can be fitted to the measured angular distributions. At lower energies the surface contribution is dominating. The imaginary diffuseness is fixed here at a standard value $a_S = 0.7$ fm. The reduced radius parameter $R_S$ is constant above 20 MeV and identical to the analysis of $^{120}\text{Sn}(^6\text{He},^6\text{He})^{120}\text{Sn}$ scattering at the highest measured energy. Only at very low energies either $a_S$ has to be reduced, or $w = 1.0$ and a reduced imaginary radius $R_S = 1.02$ fm have to be used. In any case, there is no significant broadening of the $d\eta_L/dl$ vs. $L$ curve; a significant broadening of $d\eta_L/dl$ is only seen for the $^6\text{He}$ case.

We have repeated the above analysis of the slope $d\eta_L/dl$ with the original Woods-Saxon potentials which were fitted to the experimental $^{120}\text{Sn}(^6\text{He},^6\text{He})^{120}\text{Sn}$ data [31]. The same general behavior of $L_0$ and $\Delta L$ is found from this analysis (see open symbols in Fig. 7). Thus, it can be concluded that the experimental $^{120}\text{Sn}(^6\text{He},^6\text{He})^{120}\text{Sn}$ data clearly require a larger value $L_0$ and an increasing width $\Delta L$ at lower energies. This finding is independent whether systematic folding potentials or fitted Woods-Saxon potentials are applied in the analysis. Consequently, this increase of the width $\Delta L$ in the $d\eta_L/dl$ vs. $L$ curve may be taken as a signature for the halo properties of the $^6\text{He}$ projectile. Whereas $\Delta L$ changes by about +0.2 for $E_{\text{red}}$ between 0.85 MeV and 1.85 MeV in the $\alpha$ case, one order of magnitude stronger variation of about −0.6 within a much smaller range of 1.1 MeV $\leq E_{\text{red}} \leq 1.3$ MeV is found for the $^6\text{He}$ case:

$$\frac{\Delta(\Delta L)}{\Delta E_{\text{red}}} \approx +0.2/\text{MeV} \quad \text{for } \alpha$$  \hspace{1cm} (10)

$$\frac{\Delta(\Delta L)}{\Delta E_{\text{red}}} \approx -3.0/\text{MeV} \quad \text{for } ^6\text{He}$$  \hspace{1cm} (11)

Halo properties may be assigned as soon as the variation of $\Delta L$ with $E_{\text{red}}$ is clearly below a value of $\Delta(\Delta L)/\Delta E_{\text{red}} \approx -1/\text{MeV}$ around $E_{\text{red}} \approx 1$ MeV.

The increase of the imaginary radius parameter $R_S$ has been explained in [13] with the fact that the area where reactions may occur moves to larger distances at lower energies. This has been clearly shown e.g. for low-energy capture data in the $^{16}\text{O}(p,\gamma)^{17}\text{F}$ reaction [61–63]. Further work is required to follow this idea in more detail.

The systematic behavior of the potentials in the real and imaginary parts may be used as the basis for the construction of a simple global $^6\text{He}$ potential. Because of the smooth variation of all parameters the predictive power of such a global $^6\text{He}$ potential should be very good. In particular, it has to be pointed out that the so-called “threshold anomaly” is avoided in the present study. Such “threshold anomalies”, i.e. potentials with a strong or unusual energy dependence at energies around
the Coulomb barrier, or with unusual geometry parameters like e.g. a huge imaginary diffuseness $a_S$ of several fm, had to be used in many studies to reproduce the huge total reaction cross sections of halo nuclei around the barrier (e.g. [3, 31]). For a deeper discussion of threshold anomalies and dynamic polarization potentials, see e.g. [64–67]).

For completeness, it has also to be pointed out that an unusually large reaction cross section is not already a clear signature of a halo wave function. Such an unusual $\sigma_{\text{react}}$ only indicates the strong coupling to other channels which may not at all be related to halo properties. E.g., such a behavior has been found in the elastic scattering of $^{18}$O by $^{184}$W where the coupling to the low-lying $2^+$ state of $^{184}$W leads to an unusual elastic scattering angular distribution and a huge $\sigma_{\text{react}}$ [68, 70].

IV. SUMMARY AND CONCLUSIONS

We have presented new experimental data for $^{120}$Sn($\alpha$,\,$\alpha$)$^{120}$Sn elastic scattering at energies around and slightly above the Coulomb barrier which were measured simultaneously with a recent $^{120}$Sn($^6$He,$^6$He)$^{120}$Sn experiment. The data are successfully analyzed using systematic folding potentials in the real part and smoothly varying Woods-Saxon potentials in the imaginary part. These potentials are also able to reproduce $^{120}$Sn($\alpha$,\,$\alpha$)$^{120}$Sn angular distributions at higher energies and excitation functions at lower energies which are available in literature. A comparison with the $^{120}$Sn($^6$He,$^6$He)$^{120}$Sn scattering data shows that similar potentials with a smooth mass and energy dependence are also able to reproduce these data. Thus, this smoothly varying potential may be used as the basis for the construction of simple global $^6$He potential with expected good predictive power.

The halo properties of $^6$He lead to an enhanced total reaction cross section at low energies which is related to a relatively small elastic scattering cross section at intermediate and backward angles. This behavior requires – as the only special feature for the $^6$He case – an energy-dependent radius parameter $R_S$ which increases towards lower energies. Such an increase of the radius parameter $R_S$ is not seen in the new $^{120}$Sn($\alpha$,\,$\alpha$)$^{120}$Sn data and was also not found in a series of high precision $\alpha$ scattering of neighboring target nuclei around 20 MeV. At very low energies even an opposite trend is seen in the analysis of the excitation functions of [67].

The increase of the radius parameter $R_S$ of the $^6$He potential towards lower energies is related to a relatively smooth rise of the reflexion coefficients $\eta_L$ as a function of angular momentum $L$. In particular, it is found that the width $\Delta L$ of the almost Gaussian shaped slope $d\eta_L/dL$ is significantly larger for $^6$He compared to $\alpha$. The width $\Delta L$ shows an increase towards lower energies for $^6$He which is not present in the $\alpha$ scattering data. This characteristic behavior of the $^6$He data can be used as a signature for the halo properties of $^6$He, and it should be tested as a general signature of halo properties in elastic scattering in other cases like e.g. $^{11}$Be. We suggest a value below $\Delta(\Delta L)/\Delta E_{\text{red}} \approx \sim 1$/MeV at $E_{\text{red}} \approx 1$ MeV as signature for halo properties. Although the quality of the presented new $^{120}$Sn($\alpha$,\,$\alpha$)$^{120}$Sn scattering data is clearly inferior compared to recent high precision data in this mass region, only the combined analysis of the new data for $^{120}$Sn($\alpha$,\,$\alpha$)$^{120}$Sn scattering together with angular distributions at higher energies and excitation functions at lower energies enables the comparison between $^{120}$Sn($\alpha$,\,$\alpha$)$^{120}$Sn and $^{120}$Sn($^6$He,$^6$He)$^{120}$Sn elastic scattering and the derivation of the above new results.

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