Scattering of 30 MeV ^{3}He from ^{185}Re

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(Received 29 November 2008; published 23 January 2009)

The scattering of 30 MeV ^{3}He from a ^{185}Re target has been investigated. The measured elastic scattering is in disagreement with calculations using common optical model parameter sets found in the literature. A new optical model parameter set has been determined that reproduces the data for both the elastic and the inelastic scattering channels.

DOI: 10.1103/PhysRevC.79.017601 PACS number(s): 25.55.Ci, 24.10.Eq, 24.10.Ht

There are many situations where calculations of reaction processes must be relied upon. In many cases, calculations use an optical model, for which optical model parameters (OMPs) must be given. These parameters can be determined from microscopic theories (see, e.g., Refs. [1] and [2]) in some cases, but often are found by empirical fits to reaction data. One of the most basic pieces of data used in such fits is elastic scattering cross sections, and, where known, total reaction cross sections. The spin-orbit part of the potential is best probed by fitting the analyzing powers (see, e.g., Ref. [3]). Determination of OMPs that reproduce the scattering data is critical if, for example, reliable reaction cross sections are needed. This includes applications such as the extraction of spectroscopic strengths from nucleon transfer reactions.

In the course of performing (^{3}He,d) single-proton-transfer experiments on targets of ^{185,187}Re to investigate the nuclear structures of ^{186,188}Os, measurements of the elastic scattering were performed to determine the target thicknesses needed for absolute cross sections. In addition, an angular distribution measurement of the elastic scattering from the ^{185}Re target was measured to check the suitability of the OMPs. It was found that the common sets of OMPs used for analysis of (^{3}He,d) reactions did not accurately reproduce the present elastic scattering data, and thus a new parameter set was determined. This lack of a suitable OMP set to describe the elastic scattering from ^{185}Re may be related to the paucity of data for targets with $A > 150$. In fact, the only cases known to the authors, for $A > 150$ and $E(^{3}\text{He}) < 100$ MeV, reported in the literature are in Refs. [4–7] for targets of ^{152}Sm, ^{166}Er, ^{176}Yb, ^{184}W, and ^{206}Pb. This Brief Report presents both the measurements and a new set of OMPs that have been determined for ^{3}He that accurately fits the elastic scattering data for ^{185}Re.

The experiment was performed at the Maier-Leibnitz tandem Van de Graaff accelerator laboratory of the Ludwig-Maximilians-Universität and Technische Universität München. Beams of 30 MeV ^{3}He particles, with currents up to 1.2 μA, bombarded a target of ^{185}Re that was enriched to 96.7% as indicated by the supplier, the Isotope Sales Division of Oak Ridge National Laboratory. The ^{185}Re target was prepared by vacuum evaporation of the Re metal onto an 8 μg/cm^{2} $^{\text{nat}}$C backing. The number of beam particles was measured by integrating the current in a Faraday cup located at 0° with respect to the beam direction in the target chamber. The products of the reaction were momentum analyzed with a Q3D magnetic spectrograph, with a solid angle of acceptance up to 11.6 msr. The particles from the reaction were observed at the focal plane with a detector [8] that consisted of a position-sensitive proportional counter with a cathode-foil readout and a thick plastic scintillator that yielded, in addition to the position information, particle identification using the ΔE and E signals, where E is the detected particle energy. The elastic (and inelastic) scattering spectrum was measured at 10 angles from 20° to 110° in 10° steps. Figure 1 displays the ^{3}He spectrum observed at a scattering angle of 70° where the members up to $I^{\pi} = \frac{11}{2}^{+}$ of the $\frac{5}{2}[402]$ ground state rotational band are labeled. The resolution obtained was typically 15 keV full width at half maximum (FWHM).

The peak areas were converted into cross sections using the known solid angles of the spectrograph (determined by slits controlled with micrometers), the number of beam particles from the current integrator, the dead time of the detector (never

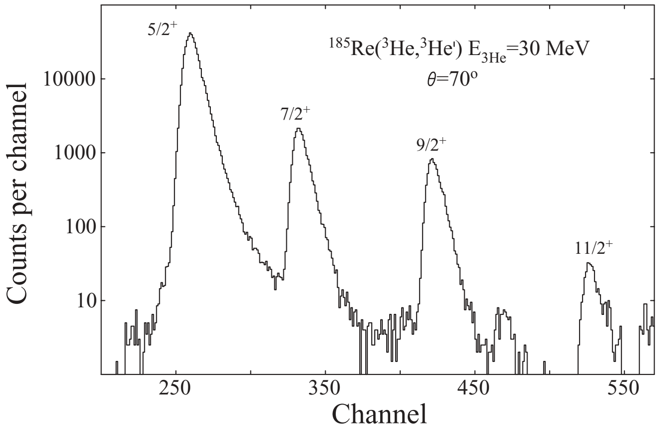

FIG. 1. Portion of the spectrum observed at $\theta_{\text{lab}} = 70^\circ$ in the inelastic scattering of 30 MeV ^{3}He from a target of ^{185}Re.

exceeding 0.5%) and the data acquisition system (varying from 1% at backward angles to 22% at forward angles), and the target thickness. The target thickness was determined by a comparison of the elastic scattering data at angles of 20° and 30° with the predictions of distorted wave Born approximation (DWBA) calculations performed with the DWUCK4 code [9]. Fortunately, at such angles and ^{3}He beam energies, the cross section is essentially that of pure Rutherford scattering and thus is largely insensitive to the details of the choice of OMPs. The ^{185}Re target thickness was determined to be 74.3 μg/cm^2 with an assigned ±2.5% systematic uncertainty arising from the determination of the number of beam particles, the solid angle, dead-time corrections, and a small contribution from the OMPs. The 2.5% systematic uncertainty assigned to the target thickness was added in quadrature with the statistical uncertainty on the elastic cross sections. Table I lists the measured elastic and inelastic cross sections as a function of angle where the quantities measured in the laboratory frame have been transformed into the center of mass frame.

TABLE I. Center of mass elastic and inelastic cross sections measured using a 30 MeV ^{3}He beam on a ^{185}Re target. Values in parentheses are the uncertainties on the last digits and include the 2.5% estimate of the systematic uncertainty added in quadrature with the statistical uncertainty.

c.m. angle (deg.)	$I^\pi = \frac{5}{2}^+ \frac{d\sigma}{d\Omega}$ (mb/sr)	$I^\pi = \frac{7}{2}^+ \frac{d\sigma}{d\Omega}$ (mb/sr)	$I^\pi = \frac{9}{2}^+ \frac{d\sigma}{d\Omega}$ (mb/sr)	$I^\pi = \frac{11}{2}^+ \frac{d\sigma}{d\Omega}$ (mb/sr)
20.32	33750(850)		5.6(12)	
30.47	7487(190)	13.3(22)	6.5(11)	
40.60	2271(58)	8.38(37)	2.94(20)	
50.72	728(19)	8.71(25)	3.02(10)	0.0178(16)
60.81	227.7(58)	6.32(18)	2.243(67)	0.0576(86)
70.88	80.4(20)	4.20(11)	1.574(44)	0.0596(49)
80.92	29.09(73)	2.496(78)	0.933(27)	0.0600(43)
90.93	11.70(30)	1.520(45)	0.608(18)	0.0517(38)
100.92	4.84(13)	0.871(26)	0.355(11)	0.0395(31)
110.88	2.017(53)	0.472(15)	0.212(8)	0.0248(28)

The ECIS03 [10] calculations of the scattering cross sections used the OMP sets of Lu and Alford [6] and Wirth *et al.* [11]. Both of these sets have been used in the analysis of (^{3}He,d) transfer reaction data, with the former used extensively over 30 years, and involve only real and imaginary volume terms of Wood-Saxon form. Inelastic scatterings to the $\frac{7}{2}^+$, $\frac{9}{2}^+$, and $\frac{11}{2}^+$ members of the ground state band were taken into account within the coupled-channel formalism using the rotational model option for the matrix elements within the ECIS03 code. The deformation parameters β_2 and β_4 were adjusted to achieve a satisfactory description of the inelastic cross sections ($\beta_2 = 0.17$ for OMPs of Lu and Alford [6], $\beta_2 = 0.19$ for OMPs of Wirth *et al.* [11], with $\beta_4 = -0.05$). The OMP set of Wirth *et al.* [11] is very similar to that of Becchetti and Greenlees [12], and was used to describe the (^{3}He,d) reaction on ^{195}Pt. Both the Lu and Alford [6] and Wirth *et al.* [11] OMP sets produce very similar predictions for the elastic scattering cross sections, as shown in Fig. 2. However, as can be seen, at angles of 40° and greater, the previous parameter sets seriously underpredict the data. By tuning the OMPs, especially those associated with the imaginary volume term, a satisfactory reproduction of the data can be obtained. Table II lists the OMP set determined in the present work, together with those of Lu and Alford [6] and Wirth *et al.* [11] for comparison. Other OMP sets, like those of Trost, Lezoch, and Strohbusch [13], use a surface imaginary term rather than a volume form. Calculations with the OMPs of Trost, Lezoch, and Strohbusch [13] were tested, but were found unsatisfactory and also required modification to fit the present elastic data. While good fits to the elastic data could be obtained, the fits to the inelastic data (see below) were considerably poorer than those achieved with an imaginary volume term.

The inelastic scatterings to the $\frac{7}{2}^+$, $\frac{9}{2}^+$, and $\frac{11}{2}^+$ members of the ground state band were also calculated using the ECIS03 code [10] where the matrix elements were derived from the axially symmetric rotational model as outlined by Tamura [14].

TABLE II. Optical model parameters of Lu and Alford [6] and Wirth *et al.* [11] and those determined in the present study. The potential was taken to involve only real and imaginary volume terms. The ECIS03 code [10] was used, with deformation parameters β_2 and β_4 necessary to describe the inelastic scattering.

Parameter	Lu and Alford [6]	Wirth *et al.* [11]	Present
V_r (MeV)	175.0	155.3	155.3
r_r (fm)	1.14	1.20	1.17
a_r (fm)	0.723	0.72	0.68
W_V (MeV)	17.5	38.3	32.3
r_W (fm)	1.60	1.40	1.31
a_W (fm)	0.81	0.88	0.88
r_C (fm)	1.40	1.30	1.30
β_2	0.17	0.19	0.19
β_4	−0.05	−0.05	−0.05

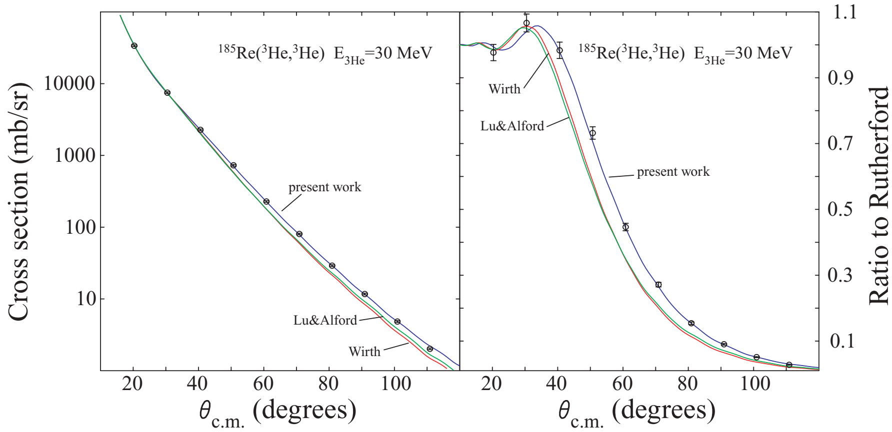

FIG. 2. (Color online) Elastic scattering cross section (left), and ratio to the Rutherford cross section (right), observed with 30 MeV ^{3}He from a target of ^{185}Re. The solid lines are the results of ECIS03 [10] calculations, described in the text, using the optical model parameters of Lu and Alford [6], Wirth *et al.* [11], and the present work.

Deformation parameters of β_2 and β_4 were used to describe the deformed shape, and the values 0.19 and -0.05, consistent with systematics of the shape parameters in the mass 180 region [15,16], provided excellent fits. The results of the calculations using the newly determined OMP set are shown in Fig. 3, and both the magnitude and the shape of the cross sections are well reproduced. Therefore, the new OMP set is able to reproduce both the elastic and the inelastic channels in the ^{185}Re(^{3}He,^{3}He$'$) reaction at 30 MeV.

In summary, the elastic scattering of 30 MeV ^{3}He from a ^{185}Re target revealed deficiencies in current optical model parameter sets often used in the analysis of (^{3}He,d) transfer reactions. A new parameter set has been determined that provides an excellent fit for both the elastic scattering from the $\frac{5}{2}^+$ ground state and the inelastic excitation of the $\frac{7}{2}^+$, $\frac{9}{2}^+$, and $\frac{11}{2}^+$ rotational band members. The present data should prove valuable to the establishment of accurate OMP sets for ^{3}He scattering on nuclei in the rare-earth region.

This work was supported in part by the Natural Sciences and Engineering Research Council, Canada.

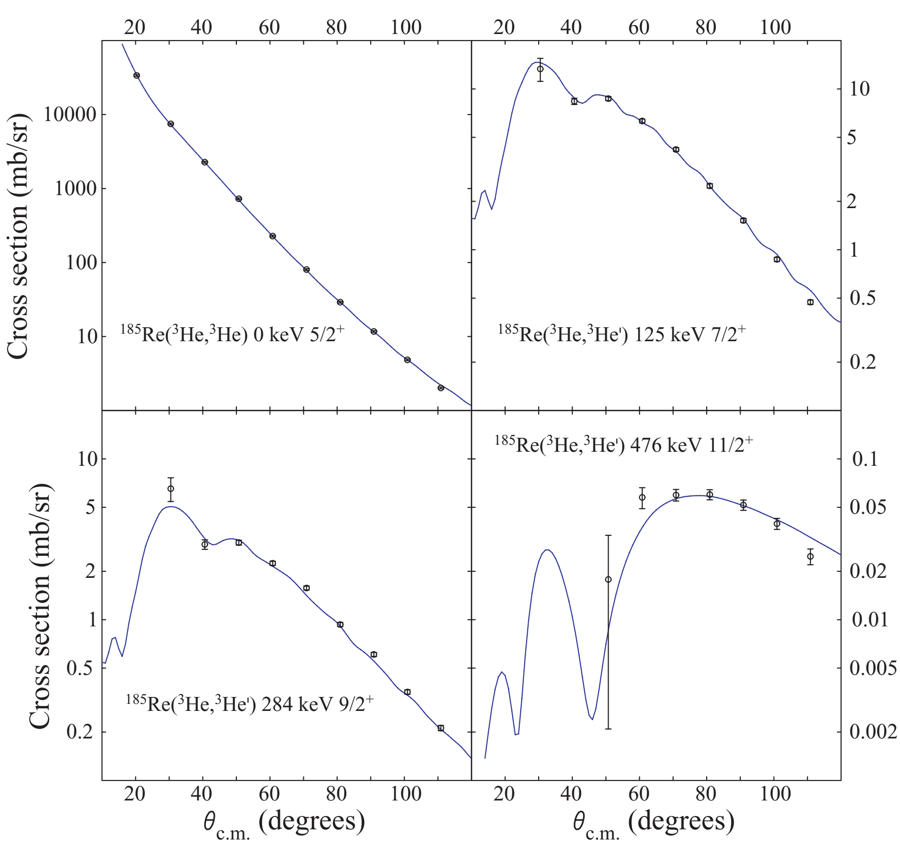

FIG. 3. (Color online) Cross sections observed for the $\frac{5}{2}^+$, $\frac{7}{2}^+$, $\frac{9}{2}^+$, and $\frac{11}{2}^+$ spin members of the ground state rotational band in the inelastic scattering of 30 MeV ^{3}He from a target of ^{185}Re. The solid lines are the results of ECIS03 calculations [10], described in the text, using the optical model parameters determined in the present work.

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