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α-Scattering Experiment on ^{64}Zn and the low energy α-nucleus optical potential

A. Ornelas[∗a,b], **D. Galaviz**[b], **Gy. Gyürky**[a], **G. Kiss**[a], **Zs. Fülöp**[a], **E. Somorjai**[a], **T. Szücs**[a,1], **M.P. Takács**[a,1], **P. Mohr**[a,c], **R.T. Güray**[d], **Z. Korkulu**[a,d], **N. Özkan**[d], **C. Yalçın**[d]
[a]*ATOMKI, H-4001 Debrecen, POB. 51, Hungary*
[b]*Centro de Física Nuclear, University of Lisbon, 1649-003 Lisbon, Portugal*
[c]*Diakonie-Klinikum, D-74523 Schwäbisch Hall, Germany*
[d]*Kocaeli University, Department of Physics, TR-41380 Umuttepe, Kocaeli, Turkey*
[1]*current adress: Helmholtz-Zentrum Dresden-Rossendorf (HZDR), D-01328 Dresden, Germany*

E-mail: ornelas@atomki.mta.hu

In this work we present the experimental details and the results of the α scattering measurement on ^{64}Zn performed at the Atomki cyclotron, at energies close to the Coulomb barrier (12.08 MeV and 16.15 MeV). A comparison of the cross sections to different global α-nucleus potential predictions is also presented. Inelastic scattering cross sections leading to the first few excited states of ^{64}Zn were also determined. Total cross sections important for the statistical model are also derived and compared with the available experimental data.

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∗Speaker.

1. Introduction

The *p*-nuclei, a group of 35 stable nuclei beyond the iron peak, located on the proton-rich side of the valley of the β-stability, are thought to be produced mainly by a series of photodisintegration reactions from neutron rich isotopes, previously produced by neutron-capture processes. The so-called γ-process is believed to occur in the O/Ne layers of Type II Supernovae at temperatures of a few GK [1, 2] or during the thermonuclear explosion of a white dwarf (Type Ia Supernovae) [3].

For the calculation of *p*-nuclei abundances, the rates of reactions involved in a γ-process network have to be known. Among other ingredients, the α-nucleus optical potential [4] is needed for the calculation of (α,γ) and (γ,α) reaction rates. The optical potential can be studied experimentally e.g. via precise elastic scattering measurements. The resulting cross sections can then be compared to different global α-nucleus potential predictions [5 – 9]. Inelastic scattering cross sections leading to the first few excited states of the target nucleus can also be obtained, and total cross sections important for the statistical model can be derived and compared with the available experimental data. In the present work the α-scattering on the ^{64}Zn isotope was studied extending our earlier work [10].

2. Experiment

The α scattering experiment on ^{64}Zn was performed at the Atomki cyclotron laboratory using α beams of 12.08 MeV and 16.15 MeV (close to the Coulomb barrier) and following the experimental proceedings of several previous experiments [11 – 14]. The α particles were scattered on ^{64}Zn targets inside a vacuum scattering chamber. The resulting angular distributions (see Fig. 2) were measured by an array of detectors - mounted on 2 turntables - in the angular range of 20° to 175°. A typical spectrum is shown in Fig. 1. Note the most prominent peaks labeled with the corresponding excitation energies. The overall uncertainty of the measurements was below 5%, which is mainly caused by the uncertainty in determining the scattering angle for the forward region and statistical uncertainties for the backward region.

3. Analysis

The elastic scattering cross section was determined in the angular range of 20° to 175°. The resulting elastic scattering cross section is shown together with the predictions of several global optical potential models [5 – 9] in the upper panel of Fig. 2 for the experiment at 12.08 MeV beam energy and in the lower panel at 16.15 MeV. The general form of the complex optical model potential (OMP) is given by:

$$U(r) = V_C(r) + V(r) + iW(r) \tag{3.1}$$

To find a local potential that can better describe the experimental data, we used in the fitting procedure a double folding parametrization for the real part $V(r)$:

$$V(r) = \lambda V_F(r/w) \tag{3.2}$$

This parameterization is based on the widely used DDM3Y interaction [15 – 17]. The parameterization in equation 3.2 can be modified by varying the width parameter w and a strength

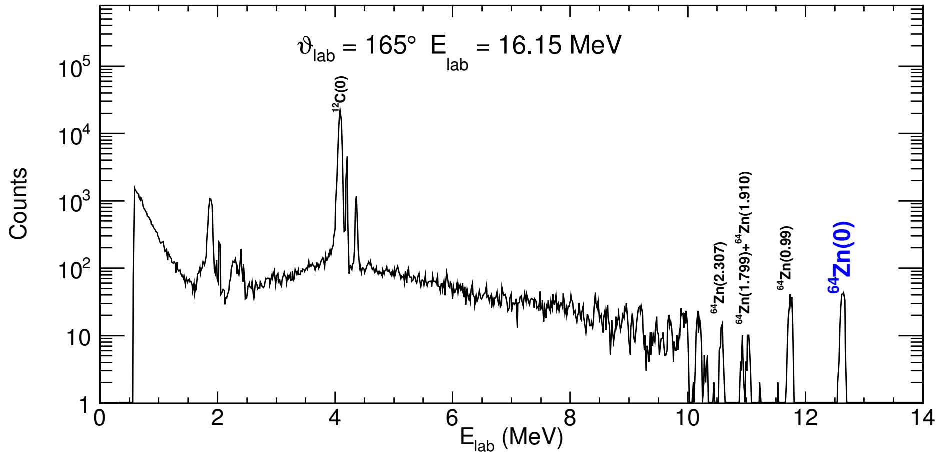

Figure 1: Spectrum of ^{64}Zn$(\alpha,\alpha)^{64}$Zn at $E_{lab} = 16.15$ MeV and $\vartheta_{lab} = 165°$. The most prominent peaks are labeled with its the corresponding excitation energies.

parameter λ. The imaginary potential $W(r)$ is based on a Woods-Saxon parameterization, generally described as:

$$W(r) = W_V\ f_{V,I}(r) + (-4)\ a_{S,I}\ W_S \frac{df_{S,I}(r)}{dr} \tag{3.3}$$

$$with\ f_{i,I} = \left(1 + exp\left(\frac{r - R_{i,I}}{a_{i,I}}\right)\right)^{-1} \quad i = V, S$$

With W_V and W_S respectively representing the imaginary volume and imaginary surface potential depth, $R_{i,j}$ is the imaginary potential radius, and $a_{i,j}$ is the imaginary diffuseness.

In this particular fitting, the imaginary surface potential was enough to adequately describe the experimental data, while the imaginary volume part was found to be negligible. The resulting local potential (henceforth called Local potential) depends thus only on the width parameter w and a strength parameter λ for the real part, and on the surface potential depth W_S, surface radius R_S and surface diffuseness a_S for the imaginary part. Based on the scattering data and on the Local potential fit, the total reaction cross sections were calculated and compared with cross sections from particle induced reaction data [10].

Further studies were performed to identify the inelastic peaks and obtain the inelastic scattering angular distributions for the first few excited states in ^{64}Zn. These were measured as it is shown in Fig. 3. The excitation energies with (J^{π}) of the first four excited states are as follows: 991.6 keV (2^+), 1799.4 keV (2^+), 1910.3 keV (0^+) and 2306.8 keV (4^+). The second and third excited states were impossible to separate in our experimental data due to the relative low resolution of the spectra, caused mainly by the target thickness and the energy straggling of the α beam.

The first inelastic peak measurements cover an angular region from $\approx 30°$ to $175°$, while the second + third and fourth excited states measurements only cover an angular region from $\approx 60°$ to $175°$. Full angular coverage is not possible for two main reasons: first, the elastic scattering peaks from ^{12}C and ^{16}O present in the target and backing obscure and overlap the inelastic peaks of the ^{64}Zn at the missing forward angular regions; second, the statistics of the inelastic peaks (especially the second + third inelastic and the fourth inelastic) are so low, that is impossible to distinguish them from the background counts.

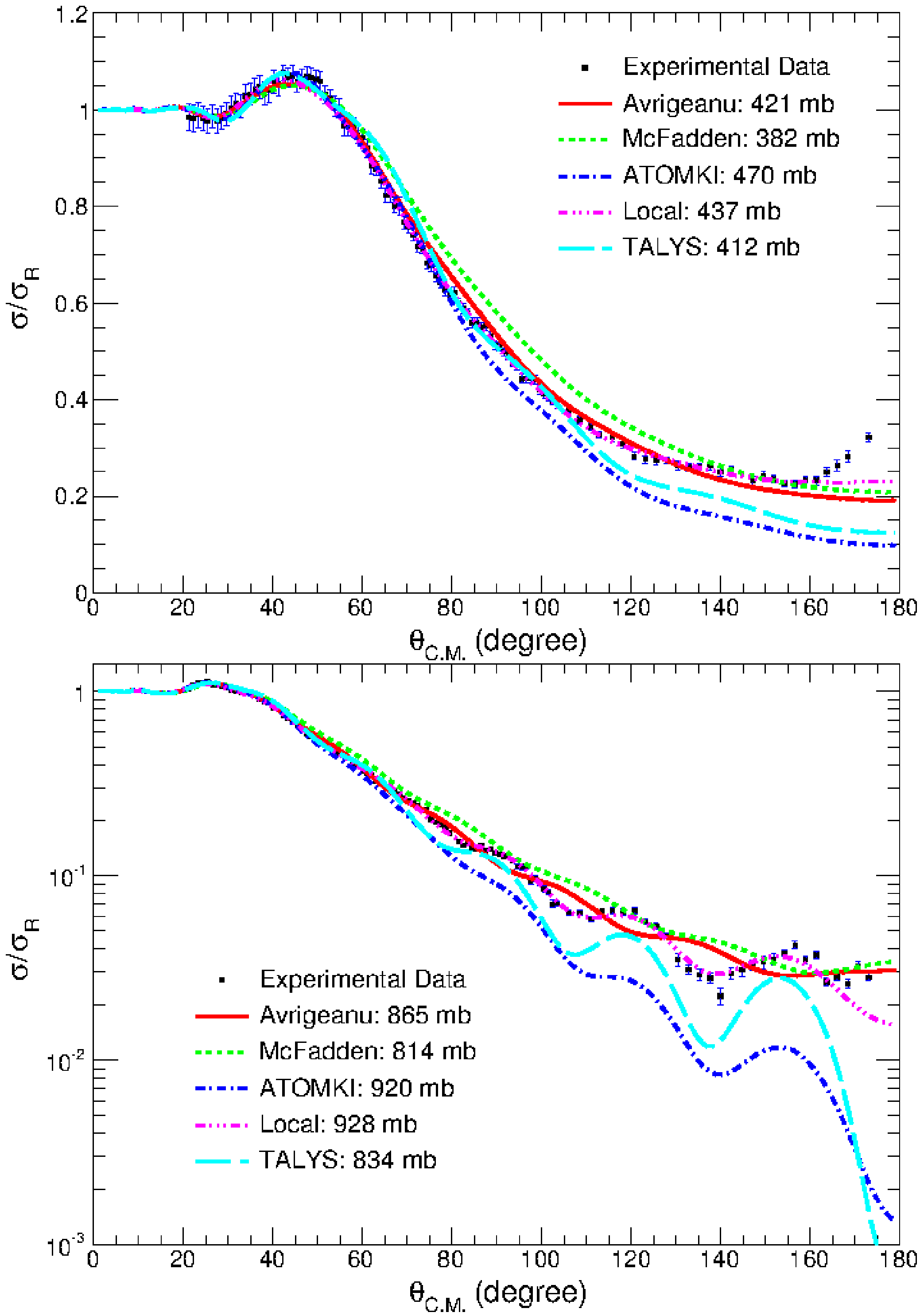

Figure 2: Angular distribution for the reaction ^{64}Zn(α,α)^{64}Zn measured at E_{lab} = 12.08 MeV (upper panel) and at E_{lab} = 16.15 MeV (lower panel) with the predictions from global α nucleus optical potentials and the Local potential. The total reaction cross section are quoted for each potential.

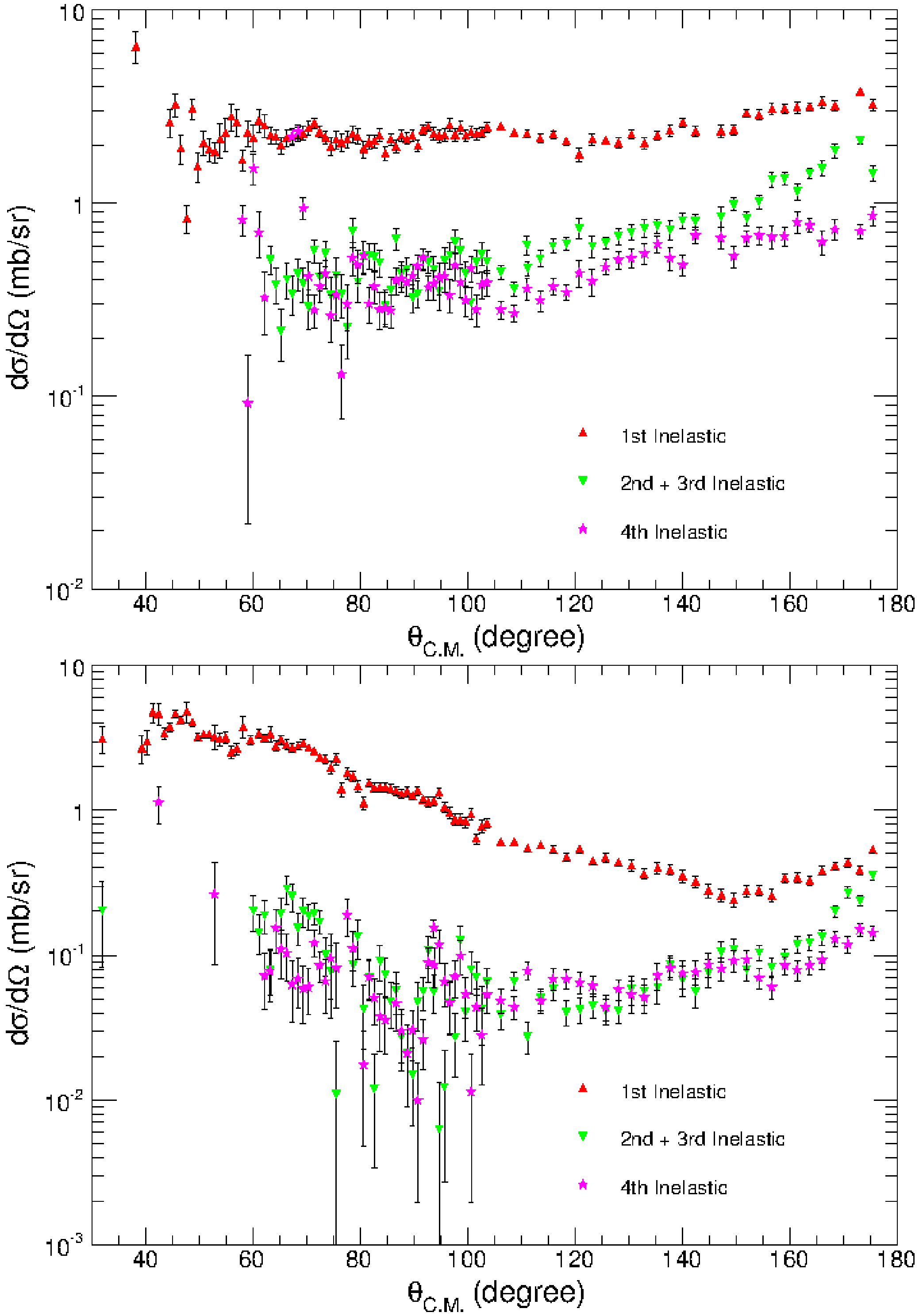

Figure 3: Angular distribution for the inelastic scattering ^{64}Zn$(\alpha,\alpha)^{64}$Zn measured at $E_{lab} = 12.08$ MeV (upper panel) and at $E_{lab} = 16.15$ MeV (lower panel).

4. Results

Following the theoretical analysis and considering the 12.08 MeV data, we obtained that the total cross section predictions vary between 382 mb of the McFadden OMP [6] and the 470 mb of the ATOMKI OMP [5]. The actual, experimental cross section is estimated at σ_{total} = 428±7 mb (from scattering), with $\sigma_{(\alpha,p),(\alpha,n),(\alpha,\gamma)}$ = 366±40 mb, the estimate for Coulex (first 2^+) = 22 mb and the nuclear inelastic cross section to first 2^+ Coulex = 22 mb.

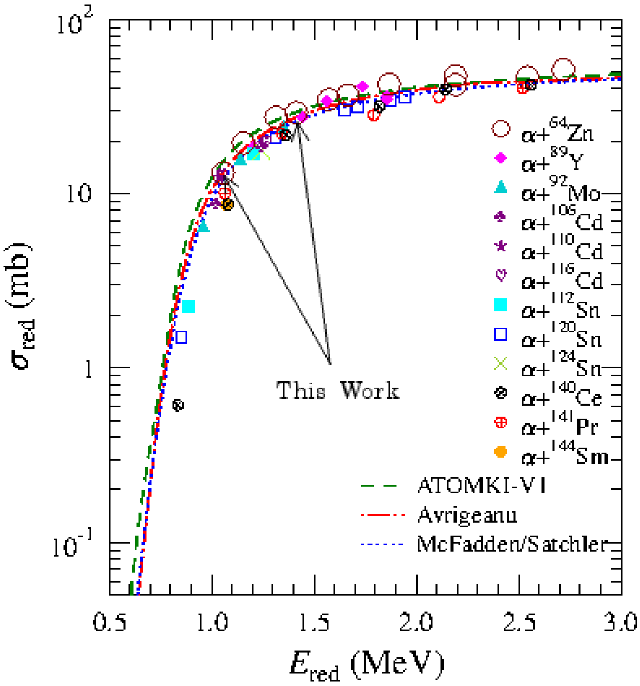

Figure 4: Systematics of the σ_{red} [5] with the values obtained in the present work.

For the 16.15 MeV data, the total cross section predictions vary between 814 mb of the McFadden potential [6] and 928 mb of the local potential. This is in agreement with the experimental results which estimates a σ_{total} = 905±18 mb (from scattering). However, the sum of $\sigma_{(\alpha,p),(\alpha,n),(\alpha,\gamma)}$ = 668±72 mb with the estimate for Coulex (first 2^+) = 37 mb and the nuclear inelastic cross section to first 2^+ Coulex = 37 mb are slightly lower than the experimental value of σ_{total} from scattering.

The predicted total reaction cross sections are thus within about 10% of the experimental value, although the agreement with the angular distribution at backward angles is poor in some cases. However, it is still possible to compare the total reaction cross sections for various projectile-target systems at different energies. That can be achieved by using equations 4.1 and 4.2 to calculate the reduced energy E_{red} and reduced cross section σ_{red}.

With these equations we rescale the $E_{c.m.}$ and σ_{reac} [5].

$$E_{red} = \frac{\left(A_P^{1/3} + A_T^{1/3}\right) E_{c.m.}}{Z_P Z_T} \tag{4.1}$$

$$\sigma_{red} = \frac{\sigma_{reac}}{\left(A_P^{1/3} + A_T^{1/3}\right)^2} \tag{4.2}$$

Using E_{red} we take into consideration the different Coulomb barrier heights of each of the projectile-target systems and by using σ_{red} the cross section is scaled according to the geometrical size of the projectile-target system. For E_{lab} = 12.08 MeV and σ_{reac} = 428 mb this results in E_{red} = 1.06 MeV and σ_{red} = 13.72 mb; at E_{lab} = 16.15 MeV and σ_{reac} = 905 mb we obtained E_{red} = 1.42 MeV and σ_{red} = 29.00 mb. The resulting data fit well into the trend obtained with heavier isotopes when expressed in this form σ_{red} versus E_{red} (see Fig. 4) [5].

5. Conclusions

The performed experiments allowed for the extraction of the elastic scattering differential cross sections of the ^{64}Zn at 12.08 MeV and 16.15 MeV with high precision (overall uncertainty below 5%), this in turn allowed for a detailed analysis at both energies using several well known global OMPs [5 – 9]. Following the analysis, we concluded that the global cross sections are not able to describe well the elastic scattering data, especially at backward angles, however the total cross sections are in good agreement with the data from particle induced cross sections, as the predicted total cross sections are within 10% of the experimental data. Further analysis, especially for the inelastic data is still in progress.

Acknowledgments

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