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COMPARISON OF NUCLEAR MASS MODELS IN THE CROSS-SECTION CALCULATIONS FROM THE REACTION ^{37}Cl ON ^{100}Mo*

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This study investigates the effects of four nuclear mass models on the calculations for reaction cross-sections: Myers–Swiatecki–Lysekil; Myers liquid droplet; Groote–Hilf–Takahashi; and Seeger models. We calculate cross-sectional values for the decay of the compound nucleus, ^{137}Pr* from the reaction: ^{37}Cl on ^{100}Mo, using all possible sequences for neutron, proton, and α-particle emission obtained with the Hauser–Feshbach formula. We present mass-distributions for Pr, Ce, and La nuclei in the $A =$ 128–134 range at beam energies of 130–180 MeV and also include calculations for the case of dual-targets. The addition of the Wigner term to three of the models is expressed in terms of a linear, empirical function relating the atomic mass to the reaction cross sections.

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1. Introduction

Reaction Cross-Sections (RCS) are normally calculated in preparation for an in-beam, heavy-ion, fusion experiment in order to determine the optimal beam energy that would maximize the residual product of interest. Prior to the experiment, excitation functions are also generated to maximize the ratio of one isotope relative to another, using an energy window suggested by the RCS. This procedure insures a proper beam-energy determination. The actual experiment was performed at the Holifield Research Facility at Oak Ridge National Laboratory using a ^{37}Cl^{+7} beam provided by the Tandem accelerator and an experimental target comprised of two, thin foils of isotopically enriched ^{100}Mo [1]. We calculated RCS for the decay of the compound nucleus, ^{137}Pr* using all possible sequences for neutron,

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proton, and α-particle emission obtained with the Hauser–Feshbach formula in the CASCADE code by Pühlhofer [2]. The RCS in Fig. 1 was developed using the Groote–Hilf–Takahashi mass model; isotopes of Pr, Ce, and La in the $A = 125$–134 region are displayed. Comparing the calculated RCS

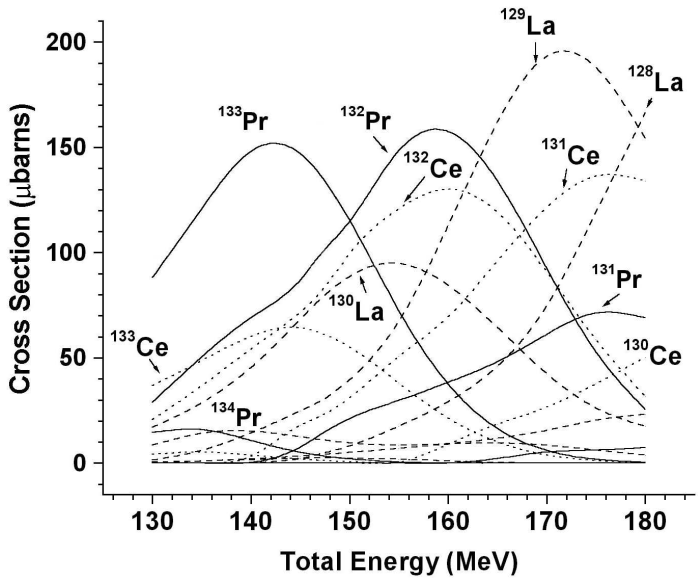

Fig. 1. Cross sections calculated with the CASCADE code using the Groote–Hilf–Takahashi nuclear mass model NM3 at 130–180 MeV for Pr (solid), Ce (dots), and La (dash) isotopes created during the reaction: ^{37}Cl on ^{100}Mo.

with the experimental excitation functions showed a greater amount of ^{133}Pr than anticipated and a totally unexpected presence of ^{134}Pr. This prompted an investigation into the effects of different nuclear mass models on these calculations.

1.1. Nuclear mass models

There are four nuclear mass models available in the CASCADE code: Myers–Swiatecki–Lysekil (NM0); Myers liquid droplet (NM1); Groote–Hilf–Takahashi (NM3); and Seeger (NM5) models. In addition, the last three are available with a Wigner term which corrects for a ∨-shaped deviation in a plot of mass number versus mass defect. This term is attributed to neutron–proton pairing correlations in nuclei occupying the same shell-model orbitals [3]. NM0 calculates masses by extrapolating nuclear properties, such as: (1) the nonuniformity in neutron and proton densities induced by electric forces and (2) the dependence of the neutron skin thickness on the position on the nuclear surface [4]. NM1 assumes that the nucleus has properties of a liquid droplet and accounts for shape permutations in ground state deformations and fission barriers. It contains an even–odd term that adjusts for the fact that separation between odd and odd-A mass surfaces is slightly smaller than the separation between the even and odd-A surfaces [5]. NM3 uses a unique bunching technique that simulates 'magic' gaps in the energy levels and appropriate sub-shell behavior [6]. NM5 is a combination of a smoothly varying droplet model plus a fluctuating shell correction term which involves the determination of Nilsson levels and ground states [7].

2. Discussion

2.1. Comparison of mass distributions

We obtained atomic mass distributions with the CASCADE code using NM0–NM6 and present the results in the bargraphs of Fig. 2. Each of the seven sets of mass distributions shows a similar fluctuating pattern with the relative ratios of the RCS differing for each model. In order to distinguish trends among the various isotopes for each atomic mass, a portion of the RCS from each set of calculations was selected for analysis. The segment that we analyze is in the range $A = 128$–134 at 160 MeV. To make a direct

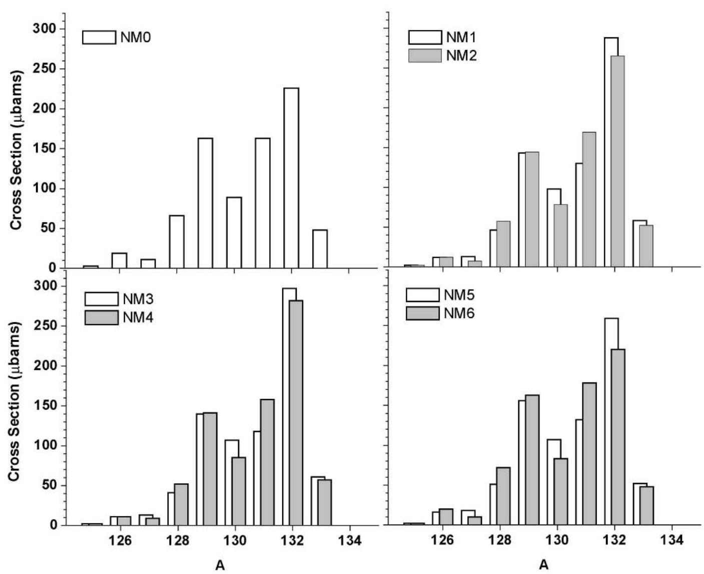

Fig. 2. A comparison of atomic mass distributions calculated for each model NM0–NM6 for the reaction 160 MeV ^{37}Cl on ^{100}Mo. The shaded bargraph represents the corresponding model with Wigner term.

comparison of the nuclear mass model contribution, RSC values for each isotope are normalized to NM0 (at 100 %) and listed as a percentage of this value. This is shown in Fig. 3. There are nine sets of data: ^{128,129,130}La; ^{131,132,133}Ce; and ^{131,132,133}Pr. Compared with NM0, the RSC is lowered by 11–42 % for ^{128,129}La, ^{131}Ce, and ^{131}Pr. The RSC for ^{130}La, ^{132,133}Ce, and ^{132,133}Pr (except for NM5) are all increased by 12–56 %.

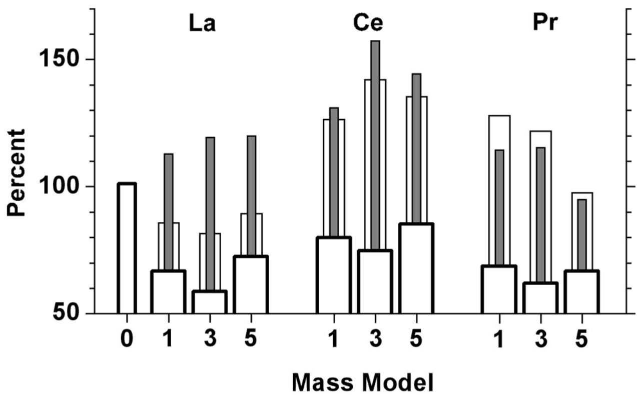

Fig. 3. A comparison of nuclear mass models, NM0,1,3,5 for isotopes of La, Ce, Pr. Cross sections are normalized to NM0 and listed as a percentage of its value. (^{128}La, thick line; ^{129}La, thin line; ^{130}La, filled bar; ^{131}Ce, thick line; ^{132}Ce, thin line; ^{133}Ce, filled bar; ^{131}Pr, thick line; ^{132}Pr, thin line; ^{133}Pr, filled bar.)

2.2. Effects of the Wigner term

The shaded bargraphs of Fig. 2 represent the atomic mass distributions calculated with the mass models containing the Wigner term. When this term is added to the nuclear mass model, the atomic mass distributions are consistently decreased for: $A = 127$ by 31–47 %; $A = 130$ by 20–22 %; $A = 132$ by 5–15 %; and $A = 133$ by 7–10 %. From the data segment chosen for analysis, we obtained the RCS ratio of each model with Wigner term compared with the corresponding model without Wigner term and plotted this ratio *versus* atomic mass. The effects that the Wigner term has on the RCS can be expressed as a function, linear with respect to atomic mass. The nine sets of data converge onto three groups of lines. Linear regression analysis yields a general expression relating the Wigner term results, $C_{\mathrm{NM}\omega}$, to atomic mass, A, and to the RCS without the Wigner term, $C_{\mathrm{NM}\iota}$.

$$C_{\mathrm{NM}\omega} = (b - mA)C_{\mathrm{NM}\iota}$$

The results for this equation are valid for the $A = 125$–134 region at 160 MeV and are listed in Table I.

TABLE I

Linear regression results correlating Reaction Cross Sections calculated using a mass model with Wigner term, ($NM\omega$), and the corresponding model without Wigner term, ($NM\iota$). NM0 = Myers–Swiatecki–Lysekil; NM1 = Myers Liquid Droplet; NM2 = NM1 + Wigner term; NM3 = Groote–Hilf–Takahashi; NM4 = NM3 + Wigner term; NM5 = Seeger; NM6 = NM5 + Wigner term.

Nucleus	NMω	b	m	NMι	r
La	6	35.631	−0.26714	5	−0.97959
	4	32.155	−0.24071	3	−0.98421
	2	32.233	−0.24143	1	−0.98452
Ce	6	35.904	−0.26600	5	−0.93729
	4	35.557	−0.26300	3	−0.95769
	2	33.810	−0.25000	1	−0.95187
Pr	6	45.543	−0.33500	5	−0.86603
	4	42.903	−0.31500	3	−0.91225
	2	48.187	−0.35500	1	−0.88410

2.3. Use of dual targets

With each mass model, the RCS at 160 MeV for ^{132}Pr is calculated to be greater than the RCS for ^{133}Pr; however, experimentally, ^{133}Pr appears to predominate. The RCS does not account for the presence of ^{134}Pr in the experimental data. All calculations yield a zero or near zero RCS for this isotope at the experimental beam energy. We suggest that the beam attenuation through the second foil in the target, which is directly related to the target thickness and, therefore, the stopping power of the foil, was great enough to shift the main, residual-product production at the second target from ^{132}Pr to ^{133}Pr. This would also explain the presence of ^{134}Pr, which is produced at a lower beam energy (see Fig. 1). The experimental results observed at 160 MeV, may be better represented by a combination of the RCS at 160 MeV plus a RCS at a lower beam energy, closer to the resonance energy for ^{133}Pr. Since the exact target thickness is unknown, an approximate calculation yields a beam energy of about 140 MeV at the second foil. By summing the results at 160 MeV plus 140 MeV, more reasonable correlations with the experimental data are obtained. Fig. 4 represents these summations. With this calculation, the presence of ^{134}Pr is accounted for.

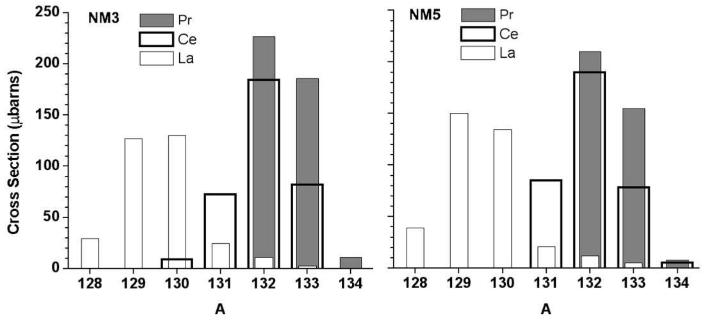

Fig. 4. Mass distributions calculated for individual Pr, Ce, and La nuclei with models NM3 and NM5. Cross sections at 160 MeV and 140 MeV are summed to approximate dual target contributions.

3. Conclusion

We have presented an empirical expression relating the effects of the Wigner term on calculations with three nuclear mass models and have shown the extent to which four nuclear mass models influence the reaction cross sections. In addition, this study led to the observation that reactions at the second foil in the target, which was exposed to an attenuated beam energy, produced a different ratio of residual products than initially calculated by the CASCADE code.

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