Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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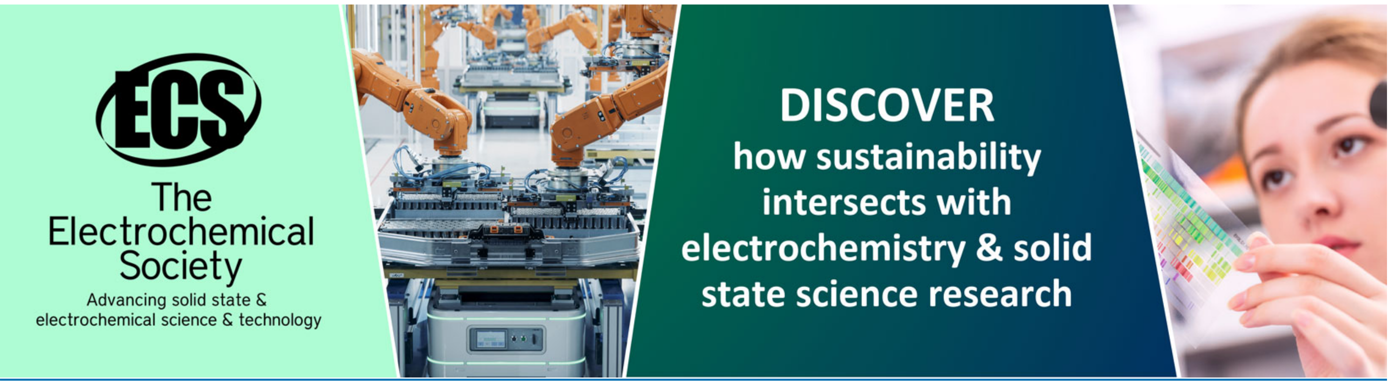
To cite this article: J L Rodríguez-Sánchez *et al* 2018 *J. Phys.: Conf. Ser.* **1024** 012002



IOP Conf. Series: Journal of Physics: Conf. Series **1024** (2018) 012002 doi:10.1088/1742-6596/1024/1/012002

Excitation of baryon resonances in charge-exchange reactions of heavy nuclei

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Abstract. The Liège intranuclear-cascade model (INCL) has been improved using a refined description of the matter and energy densities in the nuclear surface. Hartree-Fock-Bogoliubov calculations with the Skyrme interaction were used to obtain a more realistic description of the proton and neutron density profiles. We find that the new approach, together with a realistic modeling of the de-excitation process of the nuclear pre-fragments, improves the description of the production cross sections of the heaviest nuclear residues produced by charge-exchange processes in spallation reactions, where the excitation of baryonic resonances plays an important role.

1. Introduction

In the last decade, different experiments were performed at GSI using the fragment separator FRS to study the production of charge-exchange residues in spallation reactions [1]. A spallation reaction is a process in which a projectile (proton or neutron) with a kinetic energy from $\sim$100 MeV to several GeVs interacts with a heavy nucleus (e.g. lead) and causes the emission of a large number of hadrons (mostly neutrons) or some light fragments. In these reactions, the charge-exchange residues are populated when the projectile exchanges one proton or one neutron with the target. This charge-exchange process can be produced by quasi-elastic nucleon-nucleon interactions exciting electromagnetic transitions, such as the Gamow-Teller, or by inelastic nucleon-nucleon collisions where baryonic resonances, e.g. the Δ resonance, play an important role [2].

The structure of baryons, such as the Δ and Roper (N*) resonances, and their excitation spectrum is one of the unsolved issues of strong interaction physics. Recently, the early appearance of Δ-isobars in dense nuclear matter has inspired many studies relevant to neutron stars [3] and heavy-ion collisions [4]. In particular, very compact stellar configurations are reached due to the introduction of Δ-isobars [3]. However, the in-medium properties of baryon resonances are not well understood. Up to now, the in-medium effects of Δ-isobars have been studied in heavy-ion collisions at kinetic energies above the production threshold using pion-nucleus and nucleon-nucleus reactions in direct kinematics [5, 6], where there is not a good control over the production of residual fragments and thus over the number of collisions. The production of these resonances is also very important to understand the pion production in heavy-ion collisions [7] because their main decay channel is going into a nucleon and a pion.

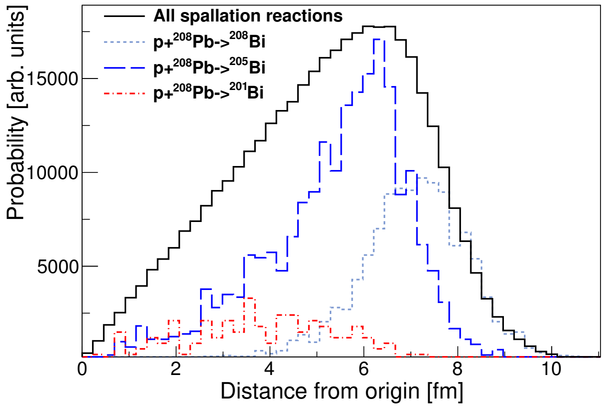

Figure 1. Radial distributions calculated with the INCL model for different nuclear residues produced in proton-induced charge-exchange reactions on ^{208}Pb at 1 GeV. The solid line represents the radial distribution for all possible interactions. The probability for the charge-exchange residues indicated in the figure were multiplied by a factor of 150.

Charge-exchange collisions produced in proton-induced reactions on nuclei are found as an optimum tool to investigate the in-medium properties of baryonic resonances [8]. Recently, it has been demonstrated that the use of the inverse kinematics technique, together with state-of-the-art detection systems, allows a full identification in atomic and mass number of the nuclear residues produced by charge-exchange reactions [1]. In addition, the measurement of the momentum distributions permits the separation of the quasi-elastic and inelastic contributions, as observed in the investigation of isobaric charge-exchange reactions [2, 9], providing a complete identification of the baryonic resonances excited in the nuclear collision. This kind of measurement could be extended to other nuclear residues produced by charge-exchange reactions to investigate the in-medium properties of the baryonic resonances as illustrated in Fig. 1, where the radial distribution calculated with the Liège intranuclear-cascade model (INCL) [10] is displayed for different nuclear residues. As can be seen, the heaviest residues are produced at the nuclear periphery (low nuclear density) while the lighter ones are excited with smaller impact parameters almost in the center of the nucleus (high nuclear density). Therefore, the investigation of the momentum distributions of these nuclear residues could help to understand how the excitation of the baryonic resonances changes with the nuclear density.

In this work, we will present some of the first steps performed in INCL to improve the description of this kind of reaction.

2. Model description

Spallation reactions at high energy ($\geq$ 100A MeV) are commonly described by the coupling of intranuclear cascade (INC) and de-excitation models [11, 12, 13, 14], where the first stage of the reaction can be described as an avalanche of independent binary collisions. The INC scheme can be derived from the usual nuclear transport equations under suitable approximations [15] and its numerical solution can be efficiently tackled on today's computers. The INC model is essentially classical, with the addition of a few suitable ingredients that mimic genuine quantum-mechanical features of the initial conditions and of the dynamics: for instance, target nucleons are endowed with Fermi motion, realistic space densities are used, and elementary nucleon-nucleon collisions are subject to Pauli blocking.

In this work we use the latest C++ version of the Liège intranuclear-cascade code (INCL) [10], which is equivalent to the reference fortran INCL4.6 version [16]. In this model the hadronnucleus or nucleus-nucleus reactions are modelled as a sequence of binary collisions between the nucleons (hadrons) present in the system. The nucleus is represented by a potential well according to the Woods-Saxon distribution [17]. Nucleons move along straight trajectories until they undergo a collision with another nucleon or until they reach the surface, where they eventually escape. The latest version of the INCL also includes isospin- and energy-dependent nucleon potentials calculated according to optical models [16], isospin-dependent pion potentials [7], and the Pauli principle is considered by means of statistical blocking factors [17]. Cluster emission is also possible via a dynamical phase-space coalescence algorithm [16]. Pions and Δ resonances are supposed to appear and disappear through the $NN \Leftrightarrow N\Delta$ and $\Delta \Leftrightarrow \pi N$ reactions. For πN interactions, we use experimental cross sections including the resonant and nonresonant contributions while the cross sections for $N\Delta$ interactions are taken as for nucleon-nucleon collisions with some correction factors in order to describe pion absorption on nuclei (see Ref. [17] for more details).

In previous studies using INCL, the authors were interested in the isotopic spallation production cross sections [16, 17], where the neutron and proton densities were taken as Woods-Saxon profiles with parameters set to reproduce the charge density measured by electron scattering. However, peripheral reactions, where a few number of nucleons are removed, are expected to be more sensitive to the relative densities of neutrons and protons at the surface of the nucleus. Therefore, in the present manuscript, the neutron and proton densities are taken from microscopic single-particle wave functions from Hartree-Fock-Bogoliubov calculations performed with the HFBRAD code [18], considering the Skyrme Sly5 interaction [19] since it provides a reasonable description of the proton and neutron density radii [20]. The HFBRAD calculations were performed for all nuclei between the proton and neutron drip lines and were included in INCL following our previous work using a basic shell model [21].

At the end of the intranuclear cascade process, an excited remnant is left. This nucleus typically relaxes by emitting low-energy particles or, if possible, by fissioning. The time scale for the second stage is typically much longer than that for the first one, which justifies the fact that de-excitation is not described by INC but by a different class of models which rely on statistical assumptions about the properties of the excited remnant. It is required to couple INC to a de-excitation model if one wishes to describe the production of reaction residues.

For the de-excitation step, we use the ABLA07 model [22], which describes the de-excitation of a nucleus emitting γ-rays, neutrons, light-charged particles, and intermediate-mass fragments (*IMFs*) according to Weisskopf's formalism [23]. For a more realistic description of the de-excitation, the separation energies and the emission barriers for charged particles are considered according to the atomic mass evaluation from 2003 [24] and the Bass potential [25], respectively. In addition, de-excitation by fission is also included according to a dynamical picture described in Ref. [26].

3. Comparison with experimental data

The new ingredients of INCL should only affect the production of nuclear fragments close to the projectile, in particular, those produced by charge-exchange reactions at the surface of the nucleus where the excitation of resonances plays an important role [1, 2, 8]. In Fig. 2 we compare our standard INCL calculations (solid lines) with experimental data (solid circles) of nuclear residues produced by charge-exchange collisions in proton-induced reactions on ^{136}Xe (a) and ^{208}Pb (b) at kinetic energies of 1 GeV per nucleon. Calculations based on the new approach considering HFBRAD density profiles are also shown (dashed lines). In both calculations we assume only the excitation of Δ resonances which is a good approximation at energies of 1 GeV per nucleon because the probability of exciting other resonances is lower. As can be seen in the figures, the new approach improves the description of the production cross sections of intermediate nuclear residues produced through charge-exchange reactions. In addition, we also

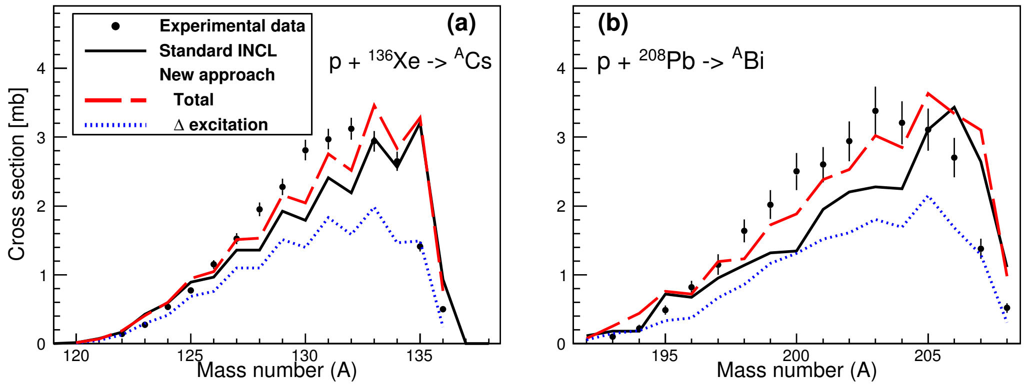

Figure 2. Isotopic distributions of nuclear residues produced in charge-exchange reactions by the excitation of baryonic resonances: p + ^{136}Xe → ^{A}Cs [27] (a) and p + ^{208}Pb → ^{A}Bi [1] (b) at 1 GeV. The experimental data is compared with the standard INCL (solid lines) and HFBRAD (dashed lines) calculations. The contribution from Δ excitation is also shown (dotted lines).

show the contribution from the excitation of Δ resonances (dotted lines), which corresponds to 50% of the total distribution.

In Fig. 3 we also compare our calculations with experimental data of total charge-exchange cross sections that correspond to the sum over all the nuclear residues produced by charge-exchange reactions that lead to fragments with atomic number $Z = Z_{projectile} + 1$. As can be observed, the new approach (dashed line) increases the total cross sections and brings the prediction in a better agreement with the experimental data. The cross sections from the excitation of Δ resonances are also displayed (dotted line). In this case, one can note that the probability of exciting the Δ resonance increases with the kinetic energy, going from ∼15% at 0.5 GeV/A to ∼60% at 1.4 GeV/A. This tendency is expected because at low kinetic energies the inelastic collisions disappear [7]. In general, the refined treatment of the surface considerably improves the predictions for these cross sections.

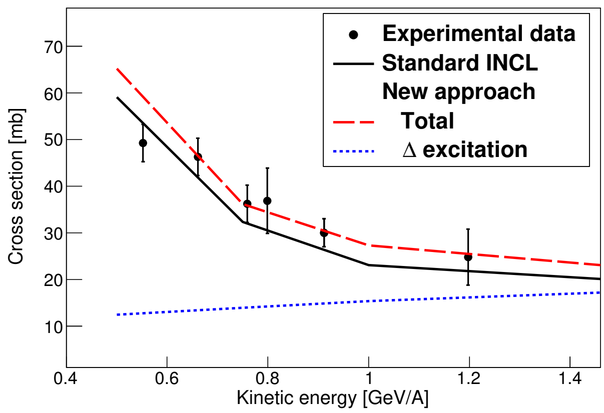

Figure 3. Total production of Hg in the spallation reaction p + ^{197}Au as a function of the projectile kinetic energy per nucleon. Experimental data taken from Ref. [28]. The solid line corresponds to standard INCL calculations while the dashed line represents INCL calculations using the Hartree-Fock-Bogoliubov calculations to define the surface of the nucleus. The contribution from Δ excitation is also shown (dotted line).

4. Conclusions

The initial conditions of the Liège intranuclear-cascade model (INCL) have been improved within Hartree-Fock-Bogoliubov calculations to take into account the presence of proton and neutron skins following the prescriptions given in our previous work [21]. In order to obtain a realistic description of the final nuclear residues produced by charge-exchange reactions, INCL was coupled to the de-excitation model ABLA07. The use of Hartree-Fock-Bogoliubov calculations to shape the surface of the nucleus, together with the capacity of INCL model to describe nucleon-nucleon collisions, allows us to reproduce better the cross sections of the heaviest nuclear residues produced in proton-induced reactions on medium and heavy targets. In particular, we have seen that the new approach improves the description of the cross sections of nuclear residues produced in charge-exchange reactions in which baryonic resonances, e.g. the Δ resonance, are excited with a probability around 50% at projectile energies of 1 GeV per nucleon.

5. Acknowledgments

This work has been partially supported by the project EU-ENSAR2-FP7-654002.

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