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Study of entrance channel effects on pre-equilibrium emissions in proton and alpha induced reactions on ^{64}Ni: Basic pre-equilibrium parameters

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The effect of entrance channel on the relative strength of pre-equilibrium emission, basic pre-equilibrium parameters, excitation functions for proton and alpha induced reactions on ^{64}Ni have been analyzed over the energy range from threshold up to 40 MeV. The results have been compared with the theoretical cross-sections calculated by means of the code EMPIRE3.2.3-MALTA and TALYS 1.6

Keywords: Pre-equilibrium emission, Excitation functions, Exciton number, Transition matrix element, Charge factor, EMPIRE 3.2.3-MALTA, TALYS 1.6

1 Introduction

As a part of continuous program of systematic study of nuclear reactions at low and intermediate energies we have calculated the pre-equilibrium cross section and the adopted input parameters are reported here. The process of ^{64}Cu radio isotope via (p,n) reaction on ^{64}Ni over the energy range from 0–40 MeV have been compared with the nuclear model codes EMPIRE-3.2.3-MALTA[1] and TALYS 1.6[2]. Experimentally measured cross sections for the reactions ^{64}Ni(p,n)^{64}Cu over the energy range 2.5 to 21 MeV, have been used as the standard reference for evaluating cross sections up to 40 MeV. Pre-equilibrium calculations depend on a wide set of parameters specific for the pre-equilibrium stage of the reaction. The important pre-equilibrium parameters are

Initial exciton number: One of the most important quantities or parameters in pre-equilibrium models is the initial exciton number.

Charge factor: The charge factor has been introduced into pre-equilibrium decay as a compensation for replacing its two-component (proton-neutron) nature with a one component formalism.

Intranuclear transition matrix element: The emission rates can be expressed in an unique way, the strength of the equilibration process, which competes with the emission. Very often a value corresponding to the average transition matrix element of the residual interaction is employed as a parameter. In principle, some functional dependence of such a parameter can be derived, and only the proportionality constant remains as a free parameter, which is obtained from systematics. As slight variations among different formulae yield similar behaviour of the squared matrix these slight differences among various functional dependences are in practice compensated by altering the value of the corresponding proportionality constant. Therefore, the exact form of the dependence is usually not essential for calculations of a specific reaction.

Level densities: The level densities have been adopted according to the RIPL (Reference Input Parameter Library)[3] for the general case of nuclear reactions.

Parameters specific to gamma emission: Mainly focus on photoabsorption cross section processes. The ^{64}Cu isotope is mainly used for medical purpose, mainly Positron Emission Tomography (PET). The significance of PET in diagnostic nuclear medicine is increasing and today this non-invasive technique is routinely used in neurology, cardiology, oncology and several other areas. The positron emitters used in preparing the suitable radiopharmaceuticals are of organic nature and are generally short-lived. For studying slow metabolic processes, however, some longer lived positron emitters (half-life between a few hours and a few days) are needed. Their use could extend to labeling of organic compounds leading to analogue tracers (e.g. with halogens) or to preparation

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of metal complexes (e.g. with copper). Several important or potentially important longer lived positron emitters, now termed as non-standard positron emitters, have been developed, and recently a whole workshop was devoted to their study. In general, the major constraint on PET imaging with non-standard positron emitters is the high end-point positron energy and the emission of several γ - rays during the decay. These may cause reduction of spatial resolution and blurring of the image.

The radioisotopes of copper are used for preparing metal-chelates for medical use. In particular the radionuclide ^{64}Cu is very well suited: it has appropriate half - life, a low β^+ end - point energy of 0.65 MeV and half-life 12.7 h. The decay properties are almost ideal for imaging. The radionuclide ^{64}Cu ($T_{1/2}$ = 12.7 h) is an important non - standard positron emitter, suitable for combining PET imaging and targeted therapy.

2 Evaluation Procedure for Nuclear Model Calculations

The normalized experimental data were compared with the results of nuclear model calculations using two codes, EMPIRE 3.2.3 - MALTA and TALYS 1.6. The nuclear reaction code, EMPIRE3.2.3-MALTA, has been designed to perform nuclear reaction calculations over a wide range of energies and incident particles. The covered energy range is from resonance region (~keV) to several hundreds of MeV, and the projectile could be nucleons, ions (including heavy ion) or a photons. EMPIRE3.2.3-MALTA is equipped with a complex system of codes to describe all the important nuclear reaction mechanisms. The optical model and the direct reaction calculations were performed by the ECIS-03 code [4].

The optical model, discrete levels and deformation parameters were retrieved from the RIPL-2 library[5]. The direct reaction calculations were performed by using the coupled channels model or the distorted wave Born approximation (DWBA) method. EMPIRE 3.2.3 - MALTA contains both the quantum mechanical (MSD/MSC) and classical models (DEGAS, PCROSS, HMS) to describe pre-equilibrium reactions. TALYS 1.6, a nuclear reaction software developed at NRG Petten[6] and CEA Bruyres - le – Chtel[7], provides a continuous and smooth description of nuclear reactions over a wide energy and mass range. Nuclear reactions induced by neutrons, protons, deuterons, tritons, helions, alphas and photons can be simulated in the 1 keV to 200 MeV energy range. TALYS 1.6 contains a vast database for nuclear structure and model parameters, mostly based on the IAEA Reference Input Parameter Library[8].

TALYS 1.6 incorporates a number of nuclear models to analyze all the significant nuclear reaction mechanisms. The ECIS06 code[9] was used to perform the optical model and direct reaction calculations. The default optical model potentials (OMPs) of TALYS for neutrons and protons are from the local and global parametrizations by Koning and Delaroche[10], whereas OMPs for deuterons, tritons, helions and alpha particles are based on the folding model approach. Depending on the structure of the nuclei, calculations for direct reactions can be performed by the coupled channel method, the distorted wave Born approximation (DWBA), the weak-coupling model, and a phenomenological model for the giant resonances description. In all the calculations the default options for the direct reactions were used. The compound nucleus was treated within the frame work of Hauser Feshbach model along with the width fluctuation correction model of Moldauer [11]. The pre-equilibrium reaction calculations were performed by the exciton model [12]. The model parameters were adjusted to get a better agreement between the experimental and calculated cross section values.

3 Results and Discussion

The EMPIRE 3.2.3 - MALTA code calculations for the direct reactions were performed by the DWBA model with slight modification of the local optical model potential. The options of multi- step direct (MSD) and multi-step compound (MSC) were executed for pre-equilibrium emission of protons. For neutron and cluster emission in pre-equilibrium reactions the value of PCROSS was set as 1.5, and the single particle level density parameter (GTILNO) was multiplied by 0.7. The calculations by the TALYS 1.6 code were invoked by the default optical model potential (OMP) for proton. However, to get a better agreement between the experimental and calculated cross sections some parameters were adjusted. The average effective matrix element was adjusted by setting M2constant = 0.6. The excitation function of the ^{64}Ni(p,n)^{64}Cu reaction compared with EMPIRE3.2.3-MALTA and TALYS 1.6 nuclear reaction model code are shown in Fig. 1. Good agreement could be achieved between calculated and measured ex-citation functions by a careful choice of nuclear model parameters. In general, the model

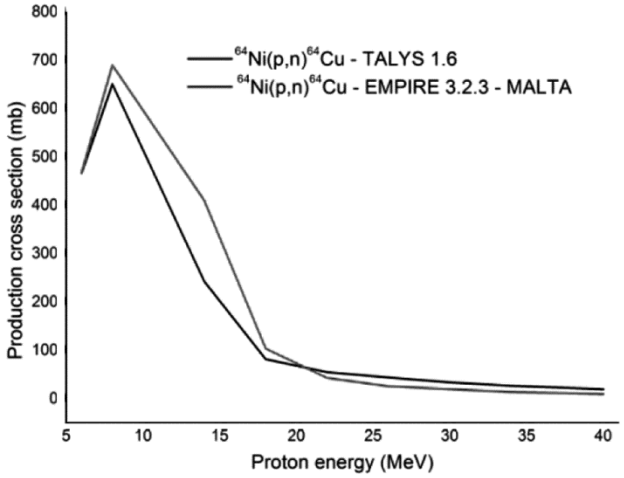

Fig. 1 — Excitation function of the ^{64}Ni(p,n)^{64}Cu reaction compared with EMPIRE3.2.3-MALTA and TALYS 1.6

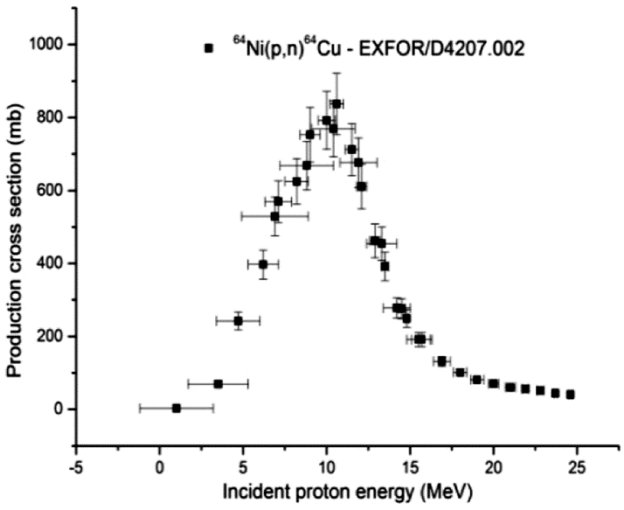

Fig. 2 — Normalized experimental data for the reaction ^{64}Ni(p,n)^{64}Cu

calculations did not validate the absolute values of experimental data, but were able to validate the consistency of different experiments in different energy ranges. Good experiments indirectly help to refine nuclear models, particularly in depicting the significance of various model parameters. The normalized experimental data for the ^{64}Ni(p,n)^{64}Cu reaction is shown in Fig. 2. Pre-equilibrium cross section of the ^{64}Ni(p,n)^{64}Cu, ^{64}Ni(α,n)^{67}Zn reaction is evaluated from TALYS 1.6 nuclear reaction code is shown in Fig. 3. and selected experimental data along with the results of calculations using the nuclear model codes EMPIRE 3.2.3 - MALTA and TALYS 1.6 for the ^{64}Ni(p,n)^{64}Cu reaction is shown in Fig. 4.

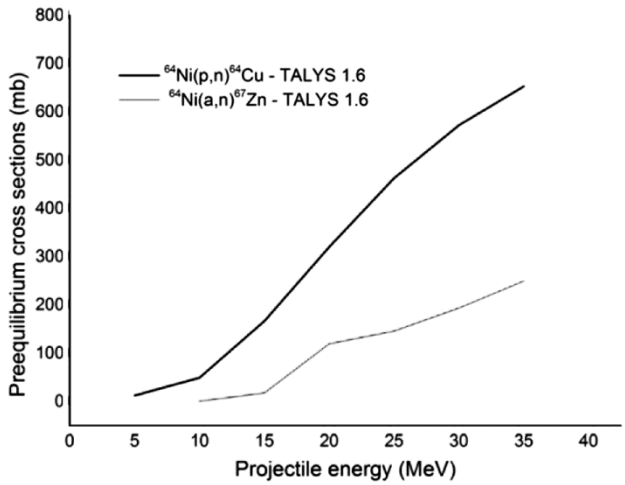

Fig. 3 — Pre-equilibrium cross section of the ^{64}Ni(p,n)^{64}Cu, ^{64}Ni(α,n)^{67}Zn reaction is evaluated from TALYS nuclear reaction code.

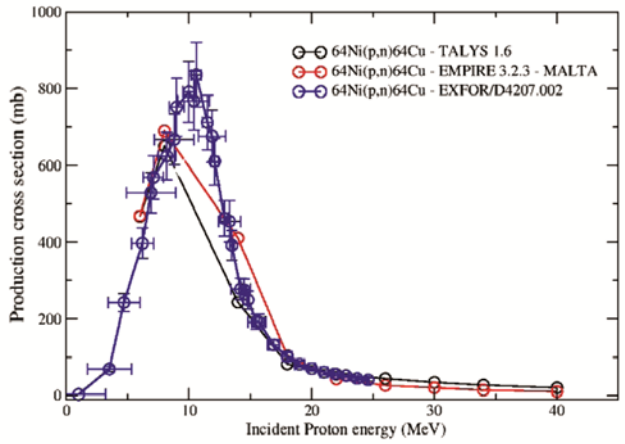

Fig. 4 — Selected experimental data along with the results of calculations using the nuclear model codes EMPIRE3.2.3-MALTA and TALYS1.6 for the ^{64}Ni(p,n)^{64}Cu reaction

4 Conclusions

The experimental cross sections for the reaction were compared with nuclear model calculations. Good agreement could be achieved between calculated and measured excitation functions by a careful choice of nuclear model parameters. Of particular importance was the choice of optical model parameters (OMPs), nuclear structure and level densities. In general, the model calculations did not validate the absolute values of experimental data, but were able to validate the consistency of different experiments in different energy ranges. The recommended sets of data should be useful for optimizing various routes for the production of ^{64}Cu using accelerators.

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