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Cross-section measurements of the ^{94}Mo(γ,n) and ^{90}Zr(γ,n) reactions using real photons at the HIγS facility

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Abstract. The photodisintegration reaction cross-sections for ^{94}Mo(γ,n) and ^{90}Zr(γ,n) have been experimentally investigated with quasi-monochromatic photon beams at the High Intensity γ-Ray Source (HIγS) facility, Triangle University Nuclear Laboratory (TUNL). The measurements were focused primarily on studying the energy dependence of the photoneutron cross sections, which is the most direct way of testing statistical models, and were performed close to the respective neutron thresholds and above up to ~ 20 MeV. Neutrons from the (γ,n) reactions were detected using a 4π assembly of ^{3}He proportional counters developed at Los Alamos National Laboratory and presently available at TUNL. While the ^{94}Mo(γ,n) cross section measurement aims to contribute to a broader investigation for understanding the γ-process (the mechanism responsible for the nucleosynthesis of the so-called *p*-nuclei), the information from the ^{90}Zr(γ,n) data is relevant to constrain QRPA calculations of γ-ray strength functions in this mass region. In this contribution, we will present our preliminary results of the total (γ,n) excitation functions for the two photoneutron reactions on ^{94}Mo and ^{90}Zr.

1 Introduction

How nuclear reactions that occur in stars and stellar explosions have been forging the elements out of hydrogen and helium leftover from the Big Bang is a longstanding, still timely research topic in nuclear astrophysics [1]. Although there is fairly complete understanding of the production of elements up to iron by nuclear fusion reactions in stars, important details concerning the production of the elements beyond iron remain puzzling.

Current understanding is that the nucleosynthesis beyond iron proceeds mainly *via* neutron capture reactions and subsequent β^- decays in the *s*-process and *r*-process [2]. But some 35 *proton-rich stable* isotopes, between ^{74}Se and ^{196}Hg cannot be synthesized by neutron-capture processes since they are located on the neutron-deficient side of the valley of β-stability. These proton-rich nuclides are generally referred to as *p*-nuclei [3]. The mechanism responsible for their synthesis is termed the *p*-process. The astrophysical details of the *p*-process are still under discussion. So far it has been impossible to reproduce the solar abundances of all *p*-isotopes using a single process. Several different sites and (independently operating) processes seem to be required. However, the largest fraction of *p*-isotopes is created by sequences of photodisintegrations and β^+ decays. Because of the dominance of photodisintegrations, this mechanism of the *p*-process is referred to as the γ-process [4]. It is generally accepted that the γ-process occurs mainly in explosive O/Ne burning during supernova Type II explosions at temperatures in the range of $T \approx$ 2-3 GK, but supernovae Type Ia and Ib/c have also been considered [5]. Calculations based on the γ-process concept can produce the bulk of the *p*-nuclei within a factor of ≈ 3 [6]. However, the most abundant *p*-isotopes, ^{92,94}Mo and ^{96,98}Ru, as well as the whole region A < 124 are underproduced, making their nucleosynthesis one of the great outstanding mysteries in nuclear astrophysics. It is not yet clear whether the observed underproductions are due to deficiencies in the astrophysical models or in the nuclear physics input, *i.e.* the reaction rates used in the model.

Contrary to the *s*- or *r*-process, the concepts of steady flows or reaction rate equilibria cannot be applied to the *p*-process, which operates far from equilibrium. As a result, an extended network of some 20000 reactions linking about 2000 nuclei in the A ≤ 210 mass region must be computed in detail. It is impossible to measure all these reaction rates in the laboratory. Hence, it becomes obvious that the vast majority of reaction rates

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must be determined theoretically. Usually the missing reaction rates are calculated within the framework of Hauser-Feshbach (HF) statistical model [5] with typical uncertainties of about 20-30% [6]. The model requires input based on nuclear structure physics, optical model potentials, and nuclear level densities to calculate transmission coefficients (average widths) which, in turn, determine the reaction cross sections, and thus, the reaction rates. The uncertainties involved in any HF cross section calculation are not related to the model of formation and de-excitation of the compound nucleus itself, but rather to the evaluation of the nuclear quantities necessary for the calculation of the transmission coefficients. The photon transmission coefficient is particularly relevant in case of photonuclear reactions and is calculated assuming the dominance of dipole *E1* transitions. The transmission coefficient for γ emission with multipolarity *L* is related to the (downward) strength function *f* as follows:

$$T_{\gamma}^{L} = 2\pi E_{\gamma}^{2L+1} f\left(E_{\gamma}\right) \quad (1)$$

Much effort has been and it is still devoted to measuring and understanding the electric dipole strength function that exhibits a pronounce peak at the Giant Dipole Resonance (GDR) energy. There are many approaches to derive *f*, each leading to an energy dependence of the E1 transmission given by a Lorentzian, around the GDR energy. Experimental photoabsorptian data confirm the simple semi-classical prediction of a Lorentzian shape at energies around the resonance energy but this description is less satisfactory at lower energies, and especially near the reaction threshold [5]. Therefore, it is of substantial interest to develop models of the microscopic type which are expected to provide a reasonable reliability and predictive power for the *E1*-strength function. Attempts in this direction, such as QRPA calculations [7,8], have been applied successfully to several photoneutron cross section measurements carried out recently with quasi-monochromatic laser-Compton scattering γ rays [9-12].

Despite the endemic problem of reproducing the solar abundances of ^{92,94}Mo and ^{96,98}Ru, as well as the whole region A < 124, most recently a study performed by Travaglio *et al*. [13] in supernova Type Ia using both deflagration and detonation models achieved a remarkable breakthrough. For the first time, a stellar source has been shown to produce the solar abundances of both light and heavy *p*-nuclei almost at the same level as ^{56}Fe, including the so much debated isotopes ^{92}Mo and ^{96,98}Ru. And yet the isotope ^{94}Mo is obtained with a much lower abundance with respect to all the other light *p*-nuclei. Another remarkable finding of [13] points out that the γ-process can make important contributions to the production of the neutron magic ^{90}Zr, previously known as genuine *s*-process nuclide.

In light of the intriguing findings of [13], we were motivated to investigate ^{94}Mo and ^{90}Zr, and in this contribution, we will present our preliminary results of the total (γ,n) excitation functions for the two photoneutron reactions.

2 Experiment

The measurements of the ^{94}Mo(γ,n)^{93}Mo were performed at the γ-ray energy range from 9 MeV to ~20 MeV, in steps of 50-100 keV. In the case of ^{94}Mo(γ,n)^{93}Mo reaction, the unstable product ^{93}Mo besides having a long half-life of $T_{1/2}$ = 3500 y decays by electron capture without γ-ray emission. The only way to study ^{94}Mo(γ,n)^{93}Mo experimentally is by direct neutron counting. Neutrons from the (γ,n) reaction were detected using an assembly of 4π ^{3}He proportional counters [14], developed at Los Alamos National Laboratory and presently available at HIγS. The neutron array is readout by two TTL electronic output signals corresponding to the detected events in the inner and outer rings of the array that are recorded on a scaler in the local VM-USB based data acquisition system. Thus, neutron multiplicity of each neutron counter was not possible. The ^{94}Mo target was placed in the center of the ^{3}He counter array. A deuterated benzene target located downstream from the ^{94}Mo target and two liquid scintillator neutron detectors, each at 90° on either side of the target, were used to determine the γ-ray beam intensity event by event via the d(γ,n)p reaction.

The integrated photon flux was determined to high precision based on well-known total cross sections [15,16] and angular distributions [17] of the neutrons produced by deuteron photodisintegration. This procedure was cross-calibrated at a few γ-ray energies using the activation of a ^{197}Au target. The advantages of using ^{197}Au(γ,n) as a monitor reaction are threefold: (i) the cross section has smooth energy dependence even near the threshold region due to the high-level density of the resultant ^{196}Au reaction product; (ii) this reaction has one of the highest photoneutron cross sections; (iii) the half-life and decay energy of the reaction product nucleus are very convenient for off-line measurements. After the irradiation a low-background 60% HPGe detector, combined with a Canberra Multiport II multichannel analyzer, was used to count off-line the activity of the gold foil monitor. At each photon beam energy, the beam distribution and intensity was measured separately, at low flux, with a 123% HPGe detector positioned on/off along the beam axis. For this purpose precisely machined copper attenuators were remotely inserted into the beam.

Typical photon beam intensities were ~10^7 – 10^8 γ/s while a typical beam energy spread was ~4-5% (FWHM). The target thickness and enrichment were ~600 mg/cm^2, 98.97% for ^{94}Mo and ~1g/cm^2, 97.7% for ^{90}Zr.

3 Preliminary Results

In Figure 1 we present preliminary results for the measured excitation function in the case of the ^{94}Mo(γ,n) reaction.

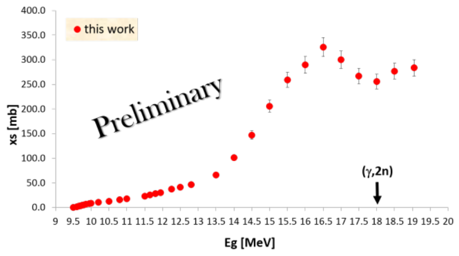

Fig. 1. Excitation function measured for the ^{94}Mo(γ,n) reaction.

In Figure 2 we present a comparison of our work with a recent measurement published by H. Utsunomiya *et al.* [10].

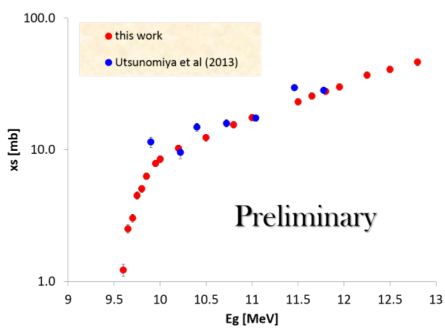

Fig. 2. Excitation function measured for the ^{94}Mo(γ,n) reaction (this work) illustrated in comparison with a recent work [10]; data is presented in logarithmic scale.

In Figure 3 we present preliminary results for the measured excitation function in the case of the ^{90}Zr(γ,n), shown in comparison with past work.

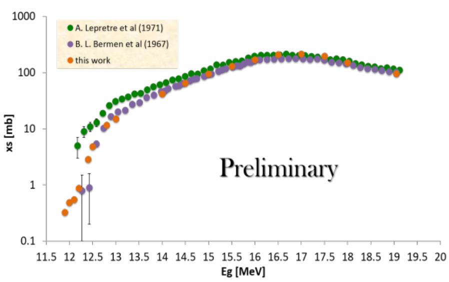

Fig. 3. Excitation function measured for the ^{90}Zr(γ,n) reaction (this work) illustrated in comparison with past work; data is presented in logarithmic scale.

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