Simulation of multi-step γ cascade spectra from ^{59}Fe(d,pγ) reaction

S. Ota,[1] M. Krticka,[2] A. Abott,[1] E.A. Bennett,[1] A. Couture,[3] J. Gauthier,[1] K. Hagel,[1]
A.B. McIntosh,[1] A. Simon,[4] M. Sorensen,[1] and S.J. Yennello[1]
[1]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843,*
[2]*Charles University in Prague, Prague, Czech Republic*
[3]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545,*
[4]*University of Notre Dame, Notre Dame, Indiana 46556*

Cosmic γ rays from long-lived (τ (1/2) ~ Myrs) unstable nuclei such as ^{26}Al and ^{60}Fe are observed overall in the Galactic disk [1]. Understanding the origin of these nuclei will lead to greatly constrain and improve models of galactic chemical evolution and stellar nucleosynthesis.

These ^{60}Fe are believed to be produced by the ^{59}Fe(n,γ) reaction, e.g., in the He burning stage of massive stars. It is therefore important to determine the reaction cross sections at the stellar temperature (neutron energy (E_n) ~30 keV). However, since ^{59}Fe is short-lived (τ (1/2) = 44 days), indirect methods must be taken to determine the cross sections. We are developing a method using the ^{59}Fe(d,pγ)^{60}Fe reaction to indirectly constrain the ^{59}Fe(n,γ) cross sections. A charged particle detector with high energy-resolution (for ejectile protons) and a large γ-detector array with high detection efficiency are demanded for the method. Thus, a detector system composed of a Si detector and 128 BaF_2 crystals [2] is under development at the TAMU Cyclotron Institute [3].

Data analysis from the present method is highly similar to the one employed for (n,γ) experiments with the DANCE BaF_2 array at Los Alamos National Laboratory (LANL) [4]. In our case, highly excited states of a nucleus of interest are populated by (*d, p*) reactions instead of neutron capture reactions. Populated states and underlying states of a nucleus, ^{60}Fe in our case, are simulated by a Monte Carlo Simulation code named DICEBOX [5]. The simulation process, "Nuclear Realization", involves multiple nuclear realizations to accommodate the fact that many energy levels and decay properties of ^{60}Fe are not known in details. Realistic energy levels of ^{60}Fe from the ground state to a certain excitation energy (usually set to the neutron separation energy, 8.8 MeV for ^{60}Fe), with e.g., given spins, parities, γ partial width, are thus generated based on a nuclear level density model and photon strength function models provided in the input file. The multi-step (MS) γ cascades from the excitation energy to ground state are incorporated in our GEANT4 simulation in which the TAMU BaF2 array is built. The obtained GEANT4 spectra will be eventually compared with our experimental (*d,pγ*) spectrum. By iterating the simulation varying the models used, we will find the "best-match" level density and PSF models with the experimental spectra. ^{59}Fe(n,γ) cross sections can be determined using these models, e.g., with the TALYS code [6].

Figs. 1 show examples of simulated (generated) MS γ cascade spectra for ^{58}Fe, which were made to study data from the test experiments with the ^{57}Fe(d,pγ) reaction to benchmark the method. Note no detector responses have been included in the present simulations yet. The simulations are made from a nuclear level density available from [7] and PSFs theoretically calculated by Goriely *et al.* [8]. Each panel presents the overlaid spectra from different nuclear realizations for the cases of γ decay multiplicity

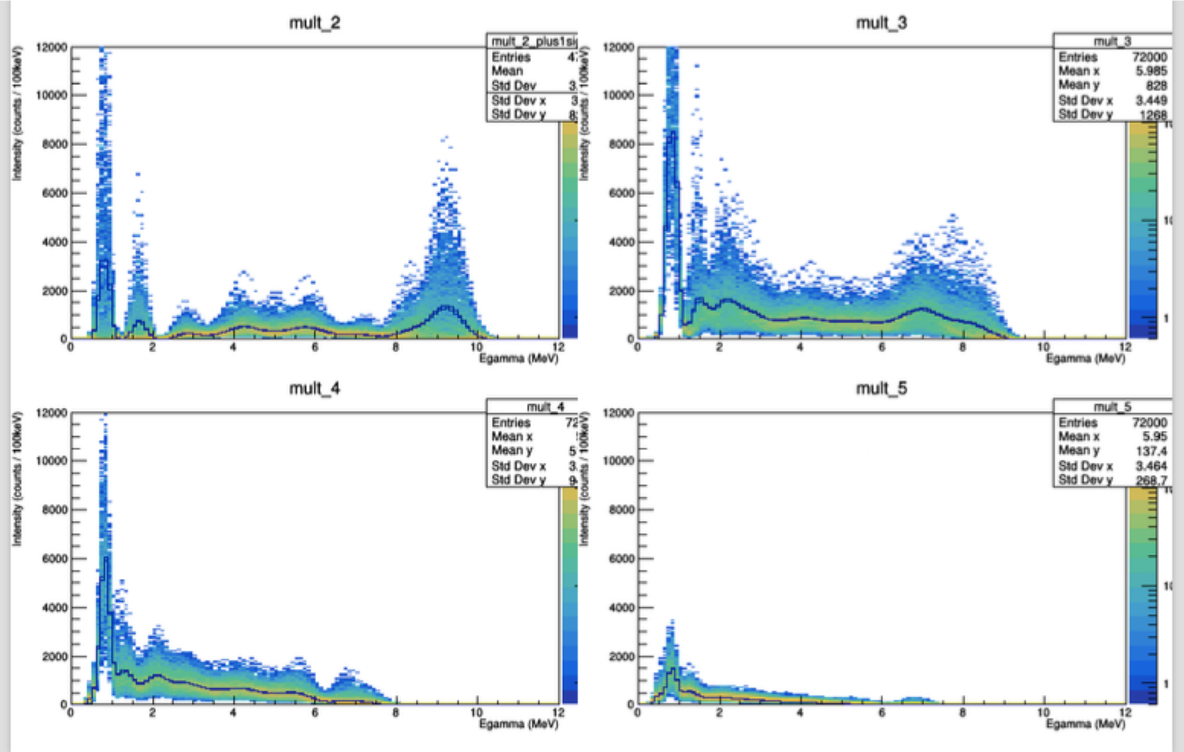

Fig. 1. Multi step γ cascade spectra from E_x=10 MeV ^{58}Fe J=2^+ state. Each panel shows a different γ source multiplicity.

equal to 2, 3, 4, and 5, respectively (see e.g., [9]). The lines in the panels correspond to average values at respective γ energies. It is clear the MS γ cascade spectra have intrinsic fluctuations derived from quantum mechanics (more specifically, e.g., the Porter-Thomas distribution). Therefore, a band corresponding to 66% (1 sigma) of the data will be extracted from each spectrum and then compared with the experimental data.

Fig. 2 shows the ^{57}Fe(n,γ) cross sections calculated using the models above with TALYS in comparison to past measurements [10, 11]. The calculations are preliminary, given no appropriateness of models used have been discussed yet. It can be seen, however, the (n,γ) cross sections can vary by a factor of two easily depending on models used. Thus, it is essential for the TAMU BaF_2 array to have the capability to distinguish different nuclear level density models and PSF models from the measured spectra. It is also noteworthy that the experimental cross-sections in the energy range of astrophysical interest (the range shown in the Fig. 2) have some discrepancies from different measurements. PSFs of ^{58}Fe currently being studied at LANL [12] may instead be a better guide for us to benchmark our method instead.

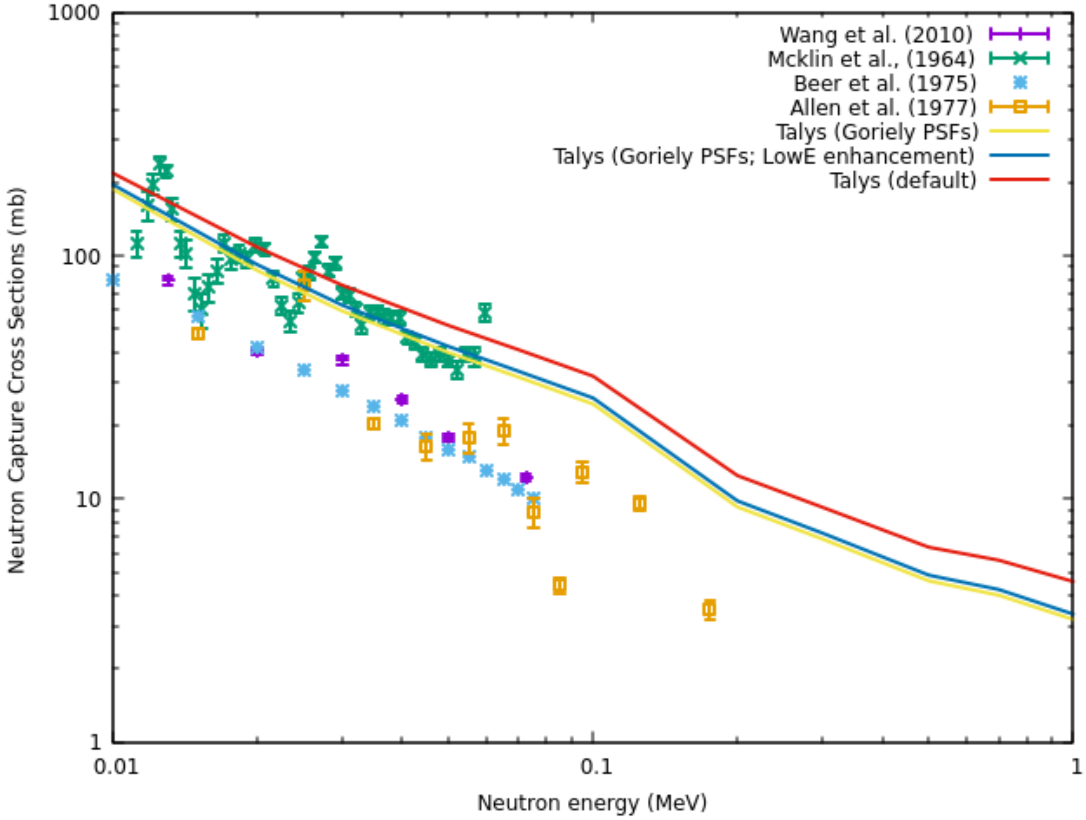

Fig. 2. ^{57}Fe(n,γ) cross sections from the past measurements and preliminary TALYS calculations.

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