Measurement of $^{59}Fe(n,\gamma)^{60}Fe$ using the Coulomb Dissociation Method

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Introduction

One of the fundamental signatures for active nucleosynthesis in our Universe is the observation of long-lived radioactive elements in our galaxy using high-resolution satellite based gamma-ray observatories such as COMPTEL, RHESSI, and INTEGRAL. The use of these observatories allows detailed imaging simulations of the distribution of characteristic gamma decay radiation along the galactic plane [1]. The highest activity is clearly associated with the galactic center and with known supernova remnants and other explosive events. The observed activity provides important information about the distance of the source, the magnitude of the explosion and the associated nucleosynthesis pattern.

Long-lived radioactive isotopes such as ^{18}F, ^{22}Na, ^{26}Al, ^{44}Ti, and ^{60}Fe, are produced at different sites, such as novae and supernovae and are therefore associated with different nucleosynthesis processes [2]. Critical information for the analysis obviously comes from the exact knowledge of the life-times of the radioactive species which provide information about the amount of material observed. Particularly important are also the reaction rates of the production and depletion reactions of the radioactive isotope in the framework of the respective nucleosynthesis process.

Of particular importance are the two long-lived radioactive isotopes ^{26}Al and ^{60}Fe whose production is thought to be associated with the nucleosynthesis in hot carbon or oxygen shell burning in massive pre-supernova stars and in the subsequent shockfront driven explosive nucleosynthesis of type II supernovae [3,4]. RHESSI and INTEGRAL results [5,6] point to a fixed observational abundance ratio of the two radioactive isotopes, but model simulations seem to identify the origin of ^{60}Fe with neutron capture processes in shell carbon burning, while ^{26}Al is produced in explosive shockfront driven nucleosynthesis [4]. While the reactions associated with the nucleosynthesis of ^{26}Al have been studied extensively in the past using stable and radioactive ion beam techniques, very little is known about the reactions associated with the production of ^{60}Fe. The goal of this proposal is to receive experimental approval for a measurement of the Coulomb dissociation reaction ^{60}Fe(γ,n)^{59}Fe using the LAND/ALADIN setup at GSI. The experimental results will provide important information about the ^{59}Fe(n,γ_0)^{60}Fe reaction which contributes strongly to the production of the long-lived ^{60}Fe. This experiment complements a recent study of the depletion process ^{60}Fe(n,γ)^{61}Fe which was performed at the FZ Karlsruhe using the activation technique [7]. Both projects are part of the PhD thesis of Ethan Uberseder at the University of Notre Dame.

Physics Motivation

A particularly interesting case is the long-lived ^{60}Fe isotope. Its characteristic γ-radioactivity has been observed with the RHESSI [5] and INTEGRAL [6,8] gamma ray telescopes. The results indicate a smooth distribution of ^{60}Fe along the galactic plane [8]. Figure 1 shows the characteristic gamma signature as detected by INTEGRAL and the extrapolated galactic distribution of the radioactive isotope.

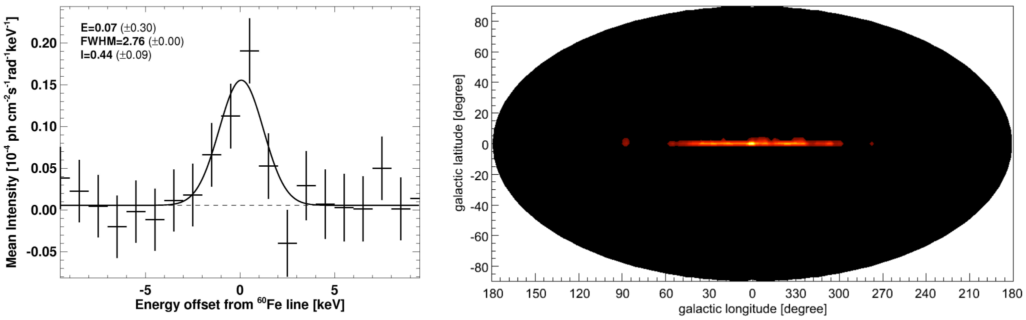

Fig. 1: Superimposed line spectrum from INTEGRAL observed for the characteristic ^{60}C decay lines a 1173 and 1332 MeV produced by beta-decay from ^{60}Fe [8]. Also shown is the modeled sky distribution of ^{60}Fe along the galactic plane [9].

Isotopic anomalies in Ni, in particular an enrichment in meteoritic inclusions [10,11] indicate that ^{60}Fe has been present in substantial amounts in the early solar system. These observations are complemented by recent AMS studies which suggest high ^{60}Fe abundance in deep sea ferromanganese sediments [12]. All this has been taken as evidence for early ^{60}Fe injection from a recent (≤3 million years) supernova event into the solar system [13,14]. A more quantitative interpretation of time and distance of the proposed supernova event requires a detailed knowledge of the lifetime and the nucleosynthesis history of ^{60}Fe. Recent lifetime measurements performed at the PSI, Switzerland and the TU Munich suggest a significantly longer lifetime for ^{60}Fe than previously claimed. New, independent measurements are presently being performed at the NSCL, Michigan State University [9].

Model predictions however claim that the ^{60}Fe is not exclusively produced in the supernova shock front but also in a hot s-process environment during carbon shell burning in the massive supernova progenitor star and is subsequently ejected in the supernova explosion. Figure 2 shows the predicted post-supernova profile of the iron isotope abundances plotted as function of the mass coordinate (radius), 25000 sec after the core-collapse of a 19 solar mass star [14]. The neutron rich iron isotopes are associated with the previous carbon burning layer of the star and are produced by a neutron capture reaction sequence shown on the right hand side of figure 2.

According to the nucleosynthesis simulations of shell carbon burning the radioactive ^{60}Fe isotope ($T_{1/2}$=1.5My) is produced by a sequence of neutron capture reactions of stable iron isotopes such as ^{58}Fe(n,γ)^{59}Fe(n,γ)^{60}Fe. Since ^{59}Fe is radioactive with a rather short half-life of $T_{1/2}$=44.5d the neutron capture has to be stronger than the decay rate to lead to a substantial production of ^{60}Fe. The final abundance of the long-lived ^{60}Fe therefore depends on the neutron capture rates of these feeding processes, on the rate of the ^{60}Fe(n,γ)^{61}Fe depletion reaction, and on the decay rates of the associated radioactive Fe isotopes. The reaction path feeding ^{60}Fe is shown in figure 2. No experimental information had been available about the associated cross sections except for the neutron capture reaction ^{58}Fe(n,γ)^{59}Fe. Present simulations of the ^{60}Fe nucleosynthesis rely entirely on statistical model predictions of the neutron capture rates [15]. Because of the

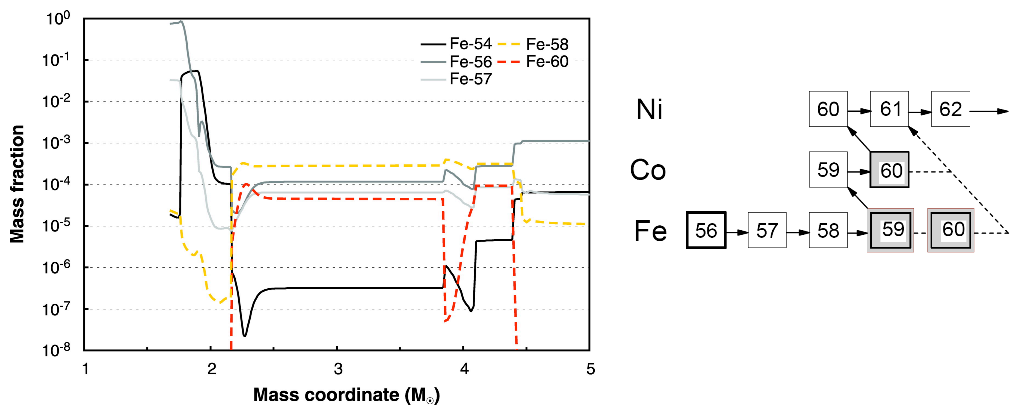

Fig. 2: Post-supernova profile of Fe isotope abundances as a function of the mass coordinate for a 19 solar mass SN progenitor star, 25,000 s after core bounce [14]. The neutron rich isotopes are produced by neutron capture reactions as shown on the right hand side.

relatively low level density in the associated ^{60}Fe, ^{61}Fe compound nuclei these model predictions are unreliable and need to be tested experimentally.

We just recently have completed successfully a direct measurement of ^{60}Fe(n,γ)^{61}Fe using the activation technique with a ^{60}Fe sample of $8x10^{15}$ atoms, provided by PSI Switzerland. The results show substantial deviation between the experimental data and the Hauser Feshbach model predictions for this reaction rate [7]. Such a deviation is also observed in the case of neutron capture on the stable isotopes ^{56}Fe, ^{57}Fe, and ^{58}Fe which were all measured through the neutron time-of-flight technique. The Hauser Feshbach predictions show considerable discrepancies in particular in the cases of ^{56}Fe(n,γ)^{57}Fe and ^{57}Fe(n,γ)^{58}Fe [16]. For ^{58}Fe(n,γ)^{59}Fe on the other hand , the agreement seems reasonable. The remaining link in this neutron capture chain is ^{59}Fe(n,γ)^{60}Fe, which has not yet been studied experimentally. All of the simulations of ^{60}Fe nucleosynthesis are based on "standard" Hauser Feshbach rates [15]. The ^{59}Fe(n,γ)^{60}Fe reaction represents the main uncertainty in the prediction of the ^{60}Fe abundance as shown in figure 3. This figure is based on a model simulation for nucleosynthesis in a 25 solar mass star at the end of carbon shell burning using the standard Hauser Feshbach rates for the associated neutron capture processes and the presently available experimental decay rates for the associated radioactive ^{59}Fe and ^{60}Fe isotopes. The capture and decay rates were varied by a factor of two to determine the impact of the particular process on the ^{60}Fe production. The figure clearly shows that the most sensitive reaction is the ^{59}Fe(n,γ)^{60}Fe capture process.

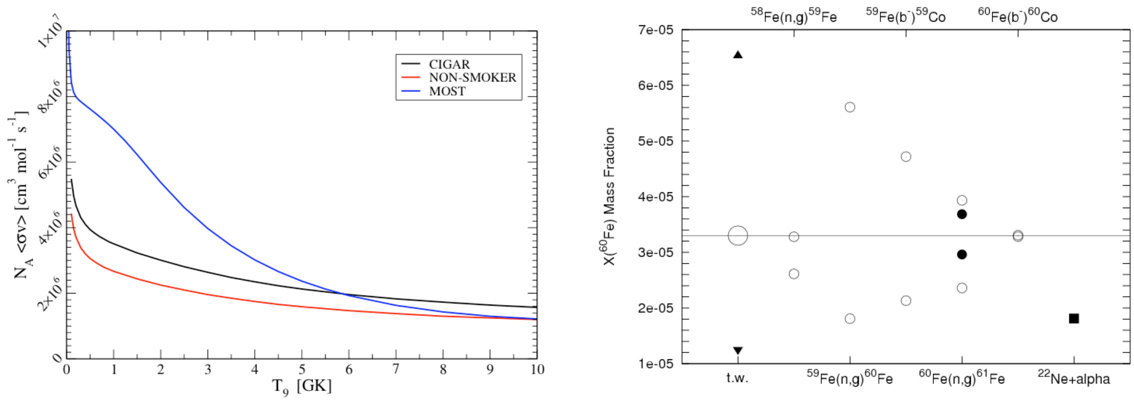

Fig. 3: The figure on the left demonstrates the theoretical discrepancies in the $^{59}Fe(n,\gamma)^{60}Fe$ cross section as determined by three different Hauser-Feshbach codes, NON-SMOKER [15], CIGAR [20], and MOST [21]. The results demonstrate the range of uncertainty within the framework of a statistical model prediction. This translates directly into the reliability for the ^{60}Fe abundance prediction. The figure on the right illustrates the sensitivity of the ^{60}Fe production to variation of the main reaction and decay rates of the associated Fe isotopes by a factor of two (open circles). The uncertainty associated with the experimental $^{60}Fe(n,\gamma)^{61}Fe$ rate is marked by the black circles [7]. According to these results, the most sensitive reaction rate is the one of $^{59}Fe(n,\gamma)^{60}Fe$.

Proposed Measurement

The direct laboratory investigation of the $^{59}Fe(n,\gamma)^{60}Fe$ is not possible because of the relatively short lifetime of ^{59}Fe isotope ($T_{1/2}$=44.5 d). We therefore intent to use Coulomb dissociation techniques to measure the cross section for the time-reversal reactions of $^{60}Fe(\gamma,n)^{59}Fe$ (Q = -8.82 MeV) and $^{59}Fe(\gamma,n)^{58}Fe$ (Q = -6.58 MeV) at GSI. The reaction cross sections of the corresponding inverse capture reactions will be calculated from detailed balance. This method was successfully employed at GSI in the past for the investigation of $^{7}Be(p,\gamma)^{8}B$ and $^{14}C(n,\gamma)^{15}C$ through Coulomb dissociation of the radioactive isotope ^{8}B [17] and ^{15}C [18], respectively, which were produced through heavy ion beam fragmentation. These particular cases, however, were ideal since the Q-values for the respective proton and neutron capture process were low and only single E1 ground state transitions were expected for the decay of the resonance states. In the case of the here discussed measurements on neutron rich Fe isotopes the analysis and direct comparison between Coulomb dissociation and neutron capture is more complex and may require substantial corrections for γ-cascade patterns of the various resonance states and possible higher order γ-multipoles contributions not included in the virtual Coulomb spectrum. For this particular reason we also propose the study of $^{59}Fe(\gamma,n)^{58}Fe$ to compare the results with the previous experimental results of the $^{58}Fe(n,\gamma)^{59}Fe$ measurements [19]. This will be important to test the reliability of the inverse approach for investigating neutron capture reactions on massive neutron rich isotopes.

The ^{59}Fe and ^{60}Fe beam can be produced by fragmentation of ^{64}Ni on a 4 g/cm^2 Be target at an energy of 500 MeV/u. This beam energy guarantees high efficiency at the LAND detector for neutron removal reactions and assures dominant dipole excitation. A beam intensity of more than 10^8 ^{64}Ni particles/s can be achieved and would provide Fe isotopes with intensities of 10^4 particles/s.

To estimate the ^{60}Fe Coulomb dissociation rate, we have applied the detailed balance theorem to a CIGAR Hauser-Feshbach ^{59}Fe(n,γ)^{60}Fe calculation [20] to yield the inverse reaction cross section

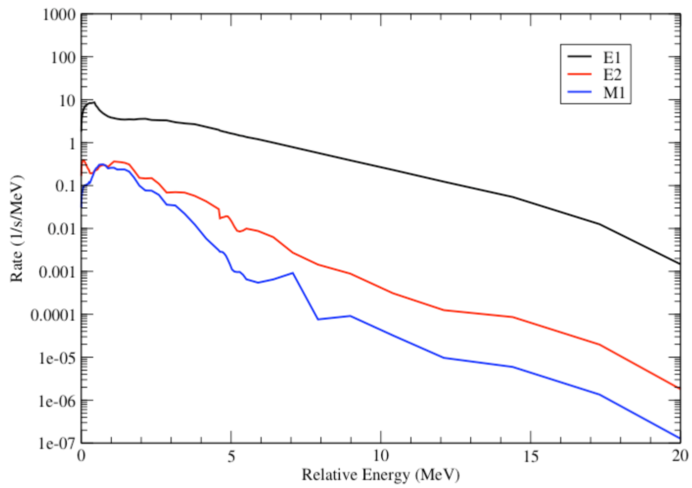

Fig. 4: Predicted Coulomb dissociation rates based on an incident ^{60}Fe beam of 500 MeV/u on a 500 mg/cm^2 lead target. The necessary ^{60}Fe(γ,n)^{59}Fe cross section has been determined using the detailed balance theorem from a Hauser-Feshbach ^{59}Fe(n,γ)^{60}Fe cross section [20].

of ^{60}Fe(γ,n)^{59}Fe. Shell model transition amplitudes have been used to separate this resulting (γ,n) cross section into specific E1, E2, and M1 components. Assuming bombardment of the incident ^{60}Fe beam on a 500 mg/cm^2 lead target, we expect Coulomb dissociation rates for E1 virtual photons of greater than 1 1/s/MeV in the energy range relevant to astrophysics. Figure 4 shows the expected ^{60}Fe Coulomb dissociation rates as a function of relative neutron energy. It should be noted that the E1 contribution is expected to dominate the E2 and M1 components by more than an order of magnitude, allowing for a clean separation of the dipole cross section. The Fe recoil products, the released reaction neutrons, as well as γ rays will be detected with using the ALADIN/LAND setup, which allows particle identification of all reaction products. The fragment-neutron relative energy can be reconstructed with a 200 keV resolution for energies close to the threshold.

Due to the close production cross sections and transition strengths for neighboring isomers, we expect a similar dissociation rate for ^{59}Fe(γ,n)^{58}Fe in comparison to the ^{60}Fe(γ,n)^{59}Fe reaction. Additionally, the nuclear component of the dissociation cross section will be evaluated using a ^{12}C target and duly subtracted from the yield obtained during the Pb measurement.

This experiment will provide detailed information about the strength of the ground state transition in the corresponding (n,γ) capture reaction measurement. To determine the strength of γ-transitions to higher excited states we need to investigate the characteristic γ-decay pattern of neutron unbound states in the respective compound nuclei using γ-spectroscopy techniques. The γ-decay of the unbound states in ^{60}Fe will be measured in a separate study using photo-excitation techniques at the DALINAC facility at the TU Darmstadt or the HIγS Facility at TUNL Duke University in collaboration with local groups.

Beam Time Request

Due to the relatively high predicted dissociation rate, and considering an overall efficiency of the LAND reaction setup of ~ 0.5, we estimate one day each will be needed to obtain sufficient statistics using the Pb target for incident ^{59}Fe and ^{60}Fe beams. Measurements with the ^{12}C target, and without a target, for the two respective settings will require another 2 days in total. Additionally, an estimated two days will be needed for the setup and calibration of FRS and LAND. We would prefer to have the beam time as early as possible as the project is part of the Ph.D. thesis of Ethan Uberseder at the University of Notre Dame.

Therefore we request a total of 6 days of beam time for this proposal.

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