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The half-life of the doubly-magic r-process nucleus ^{78}Ni

H. Schatz[1,2,3,a], P.T. Hosmer[1,2], A. Aprahamian[3,4], O. Arndt[5], R.R.C. Clement[1,2,b], A. Estrade[1,2], K.-L. Kratz[5], S.N. Liddick[1,6], P.F. Mantica[1,6], W.F. Mueller[1], F. Montes[1,2], A.C. Morton[1,c], M. Ouellette[1,2], E. Pellegrini[1,2], B. Pfeiffer[5], P. Reeder[7], P. Santi[1,d], M. Steiner[1], A. Stolz[1], B.E. Tomlin[1,6], W.B. Walters[8], and A. Wöhr[4]

[1] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA
[2] Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
[3] Joint Institute for Nuclear Astrophysics, USA[e]
[4] Department of Physics, University of Notre Dame, Notre Dame, IN 46556-5670, USA
[5] Institut für Kernchemie, Universität Mainz, Fritz-Strassmann Weg 2, D-55128 Mainz, Germany
[6] Department of Chemistry, Michigan State University, East Lansing, MI 48824, USA
[7] Pacific Northwest National Laboratory, MS P8-50, P.O. Box 999, Richland, WA 99352, USA
[8] Department of Chemistry and Biochemistry, University of Maryland, College Park, MD 20742, USA

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Abstract. Despite a lot of experimental and theoretical progress the question of the r-process site and the origin of the heavy elements in nature remains one of the biggest open questions in nuclear astrophysics. We report first results from experiments with rare isotope beams of r-process nuclei at Michigan State University's National Superconducting Cyclotron Laboratory. This includes a first measurement of the half-life of the doubly-magic waiting point nucleus ^{78}Ni, which serves as a major bottle-neck for the synthesis of heavy elements in many r-process models.

PACS. 21.10.Tg Lifetimes – 23.40.-s β decay; double β decay; electron and muon capture – 26.50.+x Nuclear physics aspects of novae, supernovae, and other explosive environments

1 Introduction

The r-process is one of the major nucleosynthesis processes in the universe producing roughly half of all elements heavier than iron [1,2]. One of the biggest problems in nuclear astrophysics remains the question of the site of the r-process. The proposed scenarios include the neutrino-driven wind off the newborn neutron star in core-collapse supernovae [3,4], prompt supernova explosions induced by the collapse of a ONeMg core in 8–10 $M_\odot$ stars [5], accretion and jets from core-collapse supernovae [6,7], and neutron star mergers [8,9]. Currently none of the proposed models can synthesize self-consistently all r-process nuclides. Observations of r-process elements in very old stars together with Galactic chemical evolution models do provide some constraints. These studies seem to rule out neutron star mergers as a dominant source of r-process nuclei due to their low frequency that cannot explain the observed gradual enrichment of the Galaxy in r-process elements [10].

In the end, observations and experiments will have to solve the problem and address the theoretical ambiguities. In the case of the r-process, the only direct empirical constraint on the process itself and its immediate astrophysical environment are observations of the detailed pattern of the resulting nuclear abundances, together with a thorough understanding of the underlying nuclear physics. Without the latter, observations cannot be connected to r-process models in a quantitative way.

On the observational side tremendous progress has been made in recent years. With the availability of detailed and accurate abundance data from r-process enhanced ultra metal poor halo stars, the operation of individual r-process events in the early galaxy can now be observed. (see Truran *et al.* [11] for a recent review). For example, for the star CS 22892-052 accurate abundances of 28 neutron capture elements have been obtained [12]. The analysis of the handful of such stars currently known shows a fairly stable r-process abundance pattern from event to event, with some variations for very light r-process elements,

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[a] Conference presenter; e-mail: `schatz@nscl.msu.edu`

[b] *Present address*: Lawrence Livermore National Laboratory, 7000 East Ave. Livermore, CA 94550, USA.

[c] *Present address*: TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3 Canada.

[d] *Present address*: Los Alamos National Laboratory, TA 35 Bldg. 2 Room C-160, USA.

[e] `http://www.jinaweb.org`

and possibly also for uranium and thorium [13,14,15,16]. This already provides some important new insights into the r-process mechanism. For example, the event to event consistency requires tightly constrained astrophysical conditions. The deficiencies between observed "single" event patterns and the solar r-process abundances for very light r-process elements have been interpreted as a hint for the existence of a second "r-process" producing the missing amount of lighter r-process elements with $A < 130$ [17,18]. Facilities and programs are now in place to dramatically increase the available observational data by identifying possibly hundreds of r-process enriched metal poor halo stars in future large scale surveys and their higher resolution follow ups [19].

Similar progress is now needed in experimental nuclear physics. Connecting abundance observations with r-process models in a quantitative way requires an understanding of the structure of the extremely neutron rich heavy nuclei participating in the r-process [20]. This will not only be important for identifying and understanding the site of the r-process. In the future, once the r-process is on a solid nuclear physics basis, it could be used as a probe for the physics of the extreme astrophysical environments it takes place in.

2 Nuclear physics needs for r-process calculations

The nuclear physics needed to model the r-process includes β-decay half-lives, branchings for β-delayed neutron emission, neutron separation energies, fission rates and fragment distributions, and to some extent neutron capture rates [1,20]. β-decay half-lives are among the most important quantities, especially at neutron shell closures where the r-process path is shifted towards stability and where therefore the slowest β-decay rates are encountered. Slow β-decay rates serve as bottle-necks that control the synthesis of all heavier elements and therefore play a critical role in constraining the astrophysical parameters of the r-process. β-decay rates also determine directly the local abundance pattern with fast decay rates leading to low abundance and slow decay rates leading to high abundance along the r-process path.

The mass range of the r-process is delineated by the distribution of seed nuclei at the low mass end, and by the onset of fission at the high mass end, probably around $A \approx 250$. The seed distribution depends largely on the particular r-process model. Two classes of models can be distinguished. In scenarios where the seeds are produced by a full α-rich freezeout (standard neutrino driven wind in core collapse supernovae, neutron star mergers, etc.) seed nuclei beyond iron in the $A = 90$ region are formed. On the other hand, there is a number of scenarios where the r-process sets in at lighter nuclei. These include models of a neutrino driven wind from a relatively massive neutron star where neutron capture starts already in the CNO region [21] and ONeMg core collapse supernovae driven by prompt explosions [5]. In such models with lighter seeds the first critical bottleneck in the r-process flow is the $N = 50$ shell closure far from stability. In the initial phase of the r-process the neutron density is high. The r-process runs closer to the neutron drip line, and accelerated by the shorter β-decay half-lives most of the heavy element buildup occurs. Therefore, the half-lives of ^{79}Cu and ^{78}Ni set the processing timescale for the synthesis of elements beyond $A \approx 80$. As the neutron density drops the r-process path moves closer to stability and the longer-lived ^{80}Zn becomes an additional r-process waiting point shaping together with ^{78}Ni and ^{79}Cu the final $A \approx 80$ abundance distribution.

While the half-life of ^{79}Cu has been experimentally determined before to be 188 ms [22], theoretical predictions for the half-life of ^{78}Ni were ranging from 100 ms to 500 ms (see fig. 2 below) introducing a significant uncertainty in r-process models. We present here a first measurement of the half-life of ^{78}Ni, which puts these r-process model calculations on a considerably more solid experimental basis.

3 Experiment and results

Radioactive beams of r-process nuclei are produced at the NSCL by fragmentation of stable, neutron rich beams at typical energies of 120–140 MeV$/u$. Important factors for the high exotic beam production capabilities of the facility are high primary beam currents, high beam energy that allows for the use of thicker production targets, and the large momentum acceptance of 5.5% of the A1900 superconducting fragment separator. The A1900 produces a mixed radioactive beam that is transported to various experimental stations and typically contains on the order of a dozen species. Individual nuclei can then be identified event-by-event by measuring their momentum, charge, and velocity. Momenta are measured by tracking particles at the dispersive intermediate image of the A1900, charge numbers are obtained from energy loss measurements in Si PIN diodes, and velocities are determined from the time of flight between two plastic scintillators. For the β-decay experiments the identified nuclei are transported to the NSCL β counting system [23] and continuously implanted into a highly segmented (40×40 strips) double-sided silicon strip detector measuring time and location of the implantation. The same detector also registers the electrons emitted in the subsequent β-decay of the short-lived nuclei allowing one to determine the decay time. With this setup decay properties of all species in the radioactive beam can be determined simultaneously.

For the experiment reported here the β counting system was surrounded by the neutron detector NERO to measure branchings for β-delayed neutron emission. NERO is a neutron long counter using ^{3}He and BF$_3$ gas counters embedded in a polyethylene matrix that serves as a neutron moderator. The neutron detection efficiency is 30–40% for neutron energies up to 5 MeV.

In a first measurement we succeeded in measuring the half-life of the doubly-magic nucleus ^{78}Ni [24] —one of the last (besides ^{48}Ni) and most exotic of the 10 classical doubly-magic nuclei in nature with unknown properties.

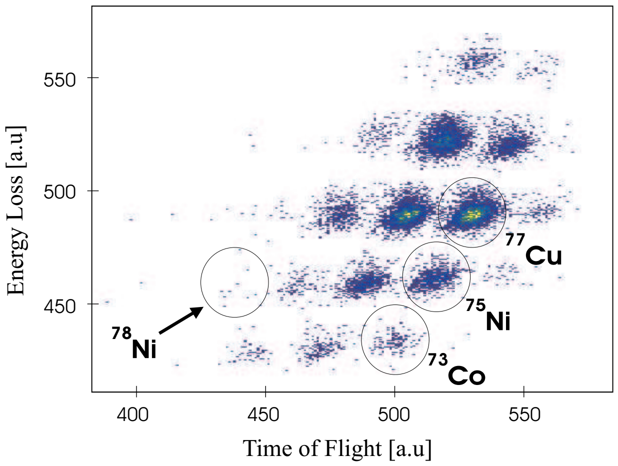

Fig. 1. Time of flight *versus* energy loss in a Si detector for each particle implanted in the double-sides Si strip detector. This information is used for particle identification.

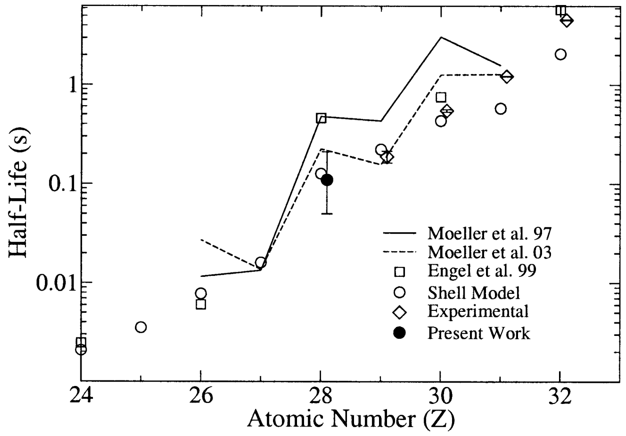

Fig. 2. The half-lives of neutron rich $N = 50$ isotones. Shown is our preliminary result for ^{78}Ni together with previous experimental data [25] (Experimental) for more stable isotones. In addition, we show theoretical predictions from Engel *et al.* 1999 [26], Langanke & Martinez-Pinedo 2003 [27] (Shell Model), Möller *et al.* 1997 [28], and Möller *et al.* 2003 [29].

Before just 3 ^{78}Ni nuclei had been identified in a pioneering experiment at GSI [30]. We detected a total of 11 ^{78}Ni events in 104 hours of beam time, using the fragmentation of a 15 pnA 140 MeV/u ^{86}Kr beam and taking advantage of the full momentum acceptance of the A1900. Figure 1 shows the particle identification of a subset of events. Figure 2 shows the experimental half-lives of $N = 50$ nuclei together with various predictions, including our preliminary result for ^{78}Ni. Our preliminary result seems to favor a lower half-live for ^{78}Ni in line, for example, with the predictions by the shell model calculations of Langanke and Martinez-Pinedo [27]. However, r-process calculations require predictions by global models that can be applied to all r-process nuclei in a consistent way. As fig. 2 shows, the overprediction of half-lives by older global models [28, 31] already observed for more stable nuclei persists up to ^{78}Ni. A more recent revision of the global QRPA model by Möller *et al.* [29] that takes into account first forbidden transitions and enforces zero defomation at shell closures clearly leads to some improvement. However, half-life comparisons can only be a first step in testing theoretical models. For example, deviations in excitation energies, transition strengths, and decay Q-value can in principle compensate each other. More stringent tests, for example through detailed decay spectroscopy as it might become possible at future facilities, are needed to clarify the reliability of the various theoretical models in describing the underlying nuclear structure.

The anlaysis of this experiment is still ongoing. Final results will be presented in a forthcoming publication. In addition, due to the mixed nature of the radioactive beam we expect to be able to also determine half-lives for ^{77}Ni, $^{73-75}$Co, and ^{80}Cu. Together with data on neutron emission they will be presented in a future publication.

4 Conclusions

With a new generation of rare isotope beam facilities such as the new Coupled Cyclotron Facility at Michigan State University there are now new opportunities to carry out experiments deep in the path of the r-process, at least below $A \approx 130$. This will put r-process model calculations in this region on a much more solid basis and will allow a quantitative interpretation of observational data. Here we reported on a first experiment determining the half-life of ^{78}Ni. First r-process model calculations with our new data confirm that indeed the smaller half-life leads to a considerable acceleration of the r-process requiring a significant readjustment of the astrophysical conditions needed for a successful r-process.

To extend such measurements in the heavier r-process region, in particular into the region around the $N = 126$ shell closure will require a next generation facility such as the Rare Isotope Accelerator RIA. With such facilities on the horizon there is now a real prospect to finally determine the nuclear physics of the r-process in the coming decade. Together with expected advances in astronomy we can hope that finally the problem of the origin of the r-process elements in nature will be solved.

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