PROCEEDINGS OF SCIENCE

PoS(NIC-IX)089

First measurements of the total and partial stellar cross section to the *s*-process branching-point ^{79}Se

Iris Dillmann[*]
Forschungszentrum Karlsruhe, Institut für Kernphysik, Postfach 3640, D-76021 Karlsruhe and
Departement Physik und Astronomie, Universität Basel, Klingelbergstrasse 82, CH-4056 Basel
E-mail: `iris.dillmann@ik.fzk.de`

Michael Heil[†] **and Franz Käppeler**

Forschungszentrum Karlsruhe, Institut für Kernphysik, Postfach 3640, D-76021 Karlsruhe

Thomas Faestermann, Gunther Korschinek, Klaus Knie[‡] **Michail Poutivtsev, and Georg Rugel**
Fakultät für Physik, Technische Universität München, D-85747 Garching

Anton Wallner
Vienna Environmental Research Accelerator, Institut für Isotopenforschung und Kernphysik,
Universität Wien, A-1090 Wien

Thomas Rauscher

Departement Physik und Astronomie, Universität Basel, Klingelbergstrasse 82, CH-4056 Basel

Although ^{79}Se represents an important branching in the weak *s* process, the stellar neutron capture cross sections to this isotope have not yet been measured experimentally. In this case, experimental data is essential for evaluating the important branching in the *s*-process reaction path at ^{79}Se. The total cross section of ^{78}Se at a stellar energy of kT = 25 keV has been investigated with a combination of the activation technique and accelerator mass spectrometry (AMS), since offline decay counting is prohibitive due to the long terrestrial half life of ^{79}Se ($2.80\pm0.36 \times10^5$ y [1]) as well as the absence of suitable γ-ray transitions. The preliminary result for the total Maxwellian averaged cross section is $<\sigma>_{30\ keV}$= 60.1±9.6 mbarn, significantly lower than the previous recommended value. In a second measurement, also the partial cross section to the 3.92 min-isomer was determined via γ-spectroscopy and yielded $<\sigma>_{30\ keV}$(part.)= 42.0±2.0 mbarn.

International Symposium on Nuclear Astrophysics — Nuclei in the Cosmos — IX
June 25-30 2006
CERN, Geneva, Switzerland

---

[*] Speaker.
[†] Now at Gesellschaft für Schwerionenforschung, Darmstadt/ Germany
[‡] Now at Vienna Environmental Research Accelerator, Wien/ Austria

1. Introduction

The origin of the elements heavier than iron can be almost completely ascribed to neutron capture processes characterized by much longer and much shorter time scales compared to average β-decay half-lives. The respective nucleosynthesis processes, known as the slow (s) and the rapid (r) neutron capture process, contribute in approximately equal parts to the total elemental abundances in the mass range above iron. The s process can be subdivided into two fractions, corresponding to different mass regions, temperature ranges and neutron exposures. The "weak" component, responsible for the elements with A$<$90, is driven by the neutron production via the ^{22}Ne$(\alpha,n)^{25}$Mg reaction at temperatures of T= 2-3 $\times 10^8$ K. The "main" component is mainly based on the ^{13}C$(\alpha,n)^{16}$O reaction, which operates at temperatures of 10^8 K. In this case the ^{22}Ne$(\alpha,n)^{25}$Mg contributes only a small part of the total exposure, but affects the final abundance pattern. This main component is producing the s abundances in the region A$\leq$90$\leq$A$\leq$208. The astrophysical environment for the weak s process are massive stars with core He and shell C burning, whereas the main component needs He shell flashes in low mass TP-AGB stars.

Our measurements refer to the region of the "weak" s process. Among the nuclei involved, the long-lived radioactive isotopes ^{63}Ni, ^{79}Se, and ^{85}Kr assume key positions, because the β-decay rate becomes comparable to the neutron capture rate ($\lambda_\beta \approx \lambda_n$). This competition leads to branchings of the synthesis path, as sketched in Fig. 1. The branching point isotopes are important, since they can be used for a diagnosis of the temperature and neutron density by comparing the ratios of isotopes at masses above and below the respective branching with observations.

The split of the reaction path at ^{79}Se causes part of the flow to bypass ^{80}Kr, whereas at ^{82}Kr both flows merge back. The strength of the resulting branching is reflected in the abundance of the s-only isotopes ^{80,82}Kr, which are shielded from the decay chains of the r process by ^{80,82}Se. Analysis of the local abundance pattern in the mass region 80$\leq$A$\leq$82 yields the effective half-life of ^{79}Se at the s-process site.

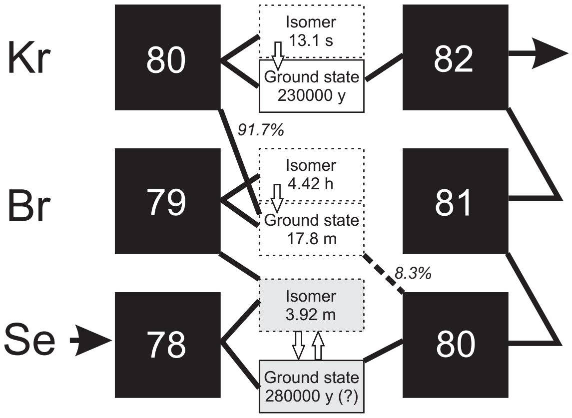

Figure 1: Sketch of the s-process flow in the Se-Br-Kr region. The half-lives given here are terrestrial half-lives.

It was noticed that the effective branching ratios for ^{79}Se and ^{85}Kr are almost equal. This leads to a conflict, since the terrestrial half-life of both isotopes differ by roughly four orders of magnitude. The solution of this puzzle is due to β decays from thermally populated excited states.

The ground state β-decay of ^{79}Se is first-forbidden unique, but allowed decays are possible from the isomer at 95.7 keV, and from states at 128 keV and 137 keV, which are populated to 1.0%, 0.4% and 1.2%, respectively, at kT=30 keV [2, 3]. Apart from this, stellar decay rates are also influenced by the high degree of ionization in the hot stellar plasma. This allows "bound-state" β-decays (Q_β<300 keV), which contribute ≈25% to the stellar rate [4]. It was shown for ^{79}Se (see Fig. 7 in [5]), that the β-decay rate is almost constant for $T<10^8$K, but drops quickly to the order of a few years when low-lying first excited states become thermally populated. Since the temperature dependence of the half-life is well known from calculations (see [5] and [4]), the branching at ^{79}Se can be interpreted as an *s*-process thermometer [6]. Nevertheless, this leads to the uncommon fact that the temperature dependence is better known than the terrestrial half-life.

For ^{78}Se, no experimental information on its stellar (n,γ) cross section to the ground and isomeric state in ^{79}Se existed so far. Both cross sections were determined by means of the activation technique. In combination with AMS this technique can be extended to hitherto inaccessible cases, e.g. to reactions producing very long-lived nuclei with very weak or completely missing γ transitions. The application of AMS counting in stellar neutron reactions, which has been demonstrated recently for ^{62}Ni [7] and also ^{58}Ni [8], has the further advantage of being independent of uncertain γ-ray intensities or half-lives.

2. Experimental technique

The activation measurements were carried out at the Karlsruhe 3.7 MV Van de Graaff accelerator. Neutrons were produced with the $^7\text{Li}(p,n)^7\text{Be}$ source by bombarding 30 μm thick layers of metallic Li on a water-cooled Cu backing with protons of 1912 keV, 30 keV above the reaction threshold. The angle-integrated neutron spectrum imitates almost perfectly a Maxwell-Boltzmann distribution for kT = 25.0±0.5 keV with a maximum neutron energy of 108 keV [9]. Hence, the proper stellar capture cross section at kT= 25 keV can be directly deduced from our measurement. For an extrapolation to higher and lower temperatures we make use of either energy-dependent cross section data, as available from the libraries JEFF, JENDL and ENDF-B, or normalize the semi-empirical cross section and energy-dependence of Bao et al. [10] to our experimental result.

The neutron flux is kinematically collimated in a forward cone with 120° opening angle. Neutron scattering through the Cu backing is negligible since the transmission is about 98 % in the energy range of interest. To ensure homogeneous illumination of the entire surface, the beam with a DC current of ≈100 μA was wobbled across the Li target. Thus, the mean neutron flux over the period of the activations was $\approx 1.5\text{-}2\times10^9$ *n*/s at the position of the samples, which were placed in close geometry to the Li target. A ^{6}Li-glass monitor at 1 m distance from the neutron target recorded the time-dependence of the neutron yield in intervals of 1 min as the Li target degrades during the irradiation. This allows for the later correction of the number of nuclei, which decayed during the activation. This correction is small for very long half-lives like the ground state of ^{79}Se, but becomes important for the short-lived isomeric state.

Samples of selenium metal and cadmiumselenide (CdSe) with natural isotopic abundance (23.77% ^{78}Se) were used in the measurements. The sample material was pressed to thin pellets, which were enclosed in a 15 μm thick aluminium foil and sandwiched between 10-30 μm thick gold foils of the same diameter. In this way the neutron flux can be determined relative to the well-known capture cross section of ^{197}Au [9].

For the determination of the partial cross section to the 3.92 min isomer, we irradiated several thin Se metal samples for 600-710 s, corresponding to a time-integrated total neutron flux of Φ_{tot}= 1.2-2.9$\times 10^{12}$ n. The induced γ-ray activity of the 95.7 keV transition (I_γ=9.62$\pm$0.28% [11]) was afterwards counted off-line in a well defined geometry of 76.0$\pm$0.5 mm distance using a shielded HPGe detector in a low background area. Since we recorded several 120 s spectra, we were also able to measure the half-life of the isomer to be 3.90$\pm$0.14 min, in perfect agreement with the literature value of 3.92$\pm$0.01 min [11].

For the AMS measurement one CdSe sample was irradiated for 13d (Φ_{tot}= 1.96$\times 10^{15}$ n). The number of produced ^{79}Se nuclei was measured at the Munich 14 MV tandem accelerator using the gas-filled analyzing magnet system (GAMS) [12]. The AMS system at Munich consists of a sputter ion source, a 90° mass analyzer, an 18° electrostatic deflection, a 14 MV tandem accelerator and a Wien filter. To separate the radioisotopes from the stable isobars we use the sensitive combination of a gas-filled magnet with a multi-ΔE ionization chamber. Since AMS determines the concentration ratio of a radioisotope to a stable isotope, [^{79}Se]/[^{78}Se], relative to a standard of known isotopic ratio, we can easily deduce our experimental cross section from the equation $\sigma = \frac{[^{79}Se]}{[^{78}Se]} \times \frac{1}{\Phi_{tot}}$. The biggest challenge in our case was the suppression of isobaric contaminations from the stable neighbor ^{79}Br (49.31%), since Bromine is rather volatile and readily forms negative ions. The contamination of ^{79}Br is reduced by means of the gas-filled magnet in front of the ionization chamber by roughly two orders of magnitude. We chose a rather high charge state of 15^+ (stripping yield: 0.64%) at a terminal voltage of 12.55 MV. For a more detailed description of the ^{79}Se AMS measurement, refer to [8].

3. Preliminary results

From the activity measurement of the isomeric state, we can deduce a partial Maxwellian averaged cross section of $<\sigma>_{30\ keV}$(part.)= 42.0$\pm$2.0 mbarn. With AMS we determined for the total cross section a ratio of [^{79}Se]/[^{78}Se]= (1.19$\pm$0.19)$\times 10^{-10}$, corresponding to $<\sigma>_{30\ keV}$= 60.1$\pm$9.6 mbarn. Following these results, the isomeric ratio (IR), which should – according to Hauser-Feshbach theory – show no energy-dependence, decreases from 0.88$\pm$0.06 at kT=25 meV to 0.70$\pm$0.11 at kT=30 keV.

The rather high uncertainty of the AMS measurement is due to the high background from ^{79}Br, and the uncertainty in the used ^{79}Se standard. This standard was produced using the thermal cross sections, which themselves exhibit rather large uncertainties (σ_{th}(^{79}Se^g)= 50$\pm$10 mbarn; σ_{th}(^{79}Se^m)= 380$\pm$20 mbarn [13]). Thus, one requirement to reduce the uncertainty is the (chemistry-free) preparation of an independent standard, e.g. via the reaction ^{82}Se$(p,\alpha)^{79}$As(β^-, 8.2m)^{79}Se. The amount of ^{79}Se atoms can then be easily measured with γ spectroscopy. With this new standard, a re-measurement of the thermal and stellar total neutron cross sections is planned.

4. Astrophysical implications

Our result for the total cross section of ^{78}Se is by a factor of 2 lower than the previous recommended semi-empirical cross section from Bao et al. (109±41 mbarn [10]). Additionally, a recent remeasurement of the total ^{81}Br cross section showed the same trend [14], the cross section being a factor of ≈1.4 lower than than the previous recommended value.

Adding up these two significantly lower cross sections, we expect in future stellar model calculations a weaker reaction flux across the ^{79}Se branching, which shifts the ^{80}Kr/^{82}Kr ratio to larger values due to the larger ^{80}Kr abundances.

5. Acknowledgments

The authors would like to thank E.P. Knaetsch, D. Roller and W. Seith for their help and support during the irradiations at the Karlsruhe Van de Graaff accelerator. We gratefully acknowledge the excellent operation of the Munich MP tandem by the staff during our experiment. This work was supported by the Swiss National Science Foundation Grants 2024-067428.01 and 2000-105328, and by the "Sonderforschungsbereich 375-95 für Astro-Teilchenphysik" der Deutschen Forschungsgemeinschaft.

References

[1] M. He, S.-S. Jiang, S. Jiang, L.-J. Diao, S.-Y. Wu, C. Li, Nucl. Instr. Meth. B **194**, (2002) 393.

[2] G. Walter and H. Beer, Kernforschungszentrum Karlsruhe, Report KfK-3327 (1982).

[3] F. Käppeler, H. Beer, and K. Wisshak, Rep. Prog. Phys. **52**, (1989) 945.

[4] K. Takahashi and K. Yokoi, Nucl. Phys. A **404**, (1983) 578.

[5] N. Klay and F. Käppeler, Phys. Rev. C **38**, (1988) 295.

[6] G. Walter, H. Beer, F. Käppeler, G. Reffo, F. Fabbri, Astron. Astrophys. **167**, (1986) 186.

[7] H. Nassar et al., Phys. Rev. Lett. **94**, (2005) 092504.

[8] G. Rugel, I. Dillmann, T. Faestermann, M. Heil, F. Käppeler, K. Knie, G. Korschinek, W. Kutschera, M. Poutivtsev, A. Wallner, Proceedings "AMS 10", Berkeley, CA/ USA, Sept. 5-10, 2005, submitted to Nucl. Instr. Meth. B (2006).

[9] W. Ratynski and F. Käppeler, Phys. Rev. C **37**, (1988) 595.

[10] Z. Bao, H. Beer, F. Käppeler, F. Voss, K. Wisshak, and T. Rauscher, At. Data Nucl. Data Tables **76**, (2000) 70.

[11] B. Singh, Nucl. Data Sheets **96**, (2002) 1.

[12] K. Knie, T. Faestermann, G. Korschinek, G. Rugel, W. Rühm, and C. Wallner, Nucl. Instr. Meth. B **172**, (2000) 717.

[13] S. Mughabghab, M. Divadeenam, and N.Holden, *Neutron Cross Sections*, BNL-325, 1st ed., Vol. 1 (1981).

[14] M. Heil, private communication (2006).