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The s-process - overview and selected developments

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Abstract. Almost all of the heavy elements are produced via neutron capture reactions in a multitude of stellar production sites. The predictive power of the underlying stellar models is currently limited because they contain poorly constrained physics components such as convection, rotation or magnetic fields.

Neutron captures measurements on heavy radioactive isotopes provide a unique opportunity to largely improve these physics components, and thereby address important questions of nuclear astrophysics. Such species are branch-points in the otherwise uniquely defined path of subsequent neutron captures along the s-process path in the valley of stability. These branch points reveal themselves through unmistakable signatures recovered from pre-solar meteoritic grains that originate in individual element producing stars.

Measurements on radioactive isotopes for neutron energies in the keV region represent a stringent challenge for further improvements of experimental techniques. This holds true for the neutron sources, the detection systems and the technology to handle radioactive material.

1. Introduction

About 50% of the element abundances beyond iron are produced via slow neutron capture nucleosynthesis (s process). Starting at iron-peak seed, the s-process mass flow follows the neutron rich side of the valley of stability via a sequence of neutron captures and β^- decays (see Figure 1) synthesizing the elements between iron and bismuth.

If different reaction rates are comparable, the s-process path branches and the branching ratio reflects the physical conditions in the interior of the star. Such nuclei are most interesting, because they provide the tools to effectively constrain modern models of the stars where the nucleosynthesis occurs. As soon as the β^- decay is significantly faster than the typically competing neutron capture, no branching will take place. Therefore experimental neutron capture data for the s process are only needed, if the respective neutron capture time under stellar conditions is similar or smaller than the β^- decay time, which includes all stable isotopes. Depending on the actual neutron density during the s process, the "line of interest" is closer to or farther away from the valley of stability.

The modern picture of the main s-process component refers to the He shell burning phase in AGB stars [1]. Nuclei with masses between 90 and 209 are mainly produced during the main component. The highest neutron densities in this model occur during the ^{22}Ne(α,n) phase and are up to 10^{12} cm^{-3} with temperatures around $kT = 30$ keV. The other extreme can be found during the ^{13}C(α,n) phase where neutron densities as low as 10^7 cm^{-3} and temperatures around $kT = 5$ keV are possible. Similarly to the main component, also the weak component referring to different evolutionary stages in massive stars has to phases [2, 3]. Mainly nuclei with masses

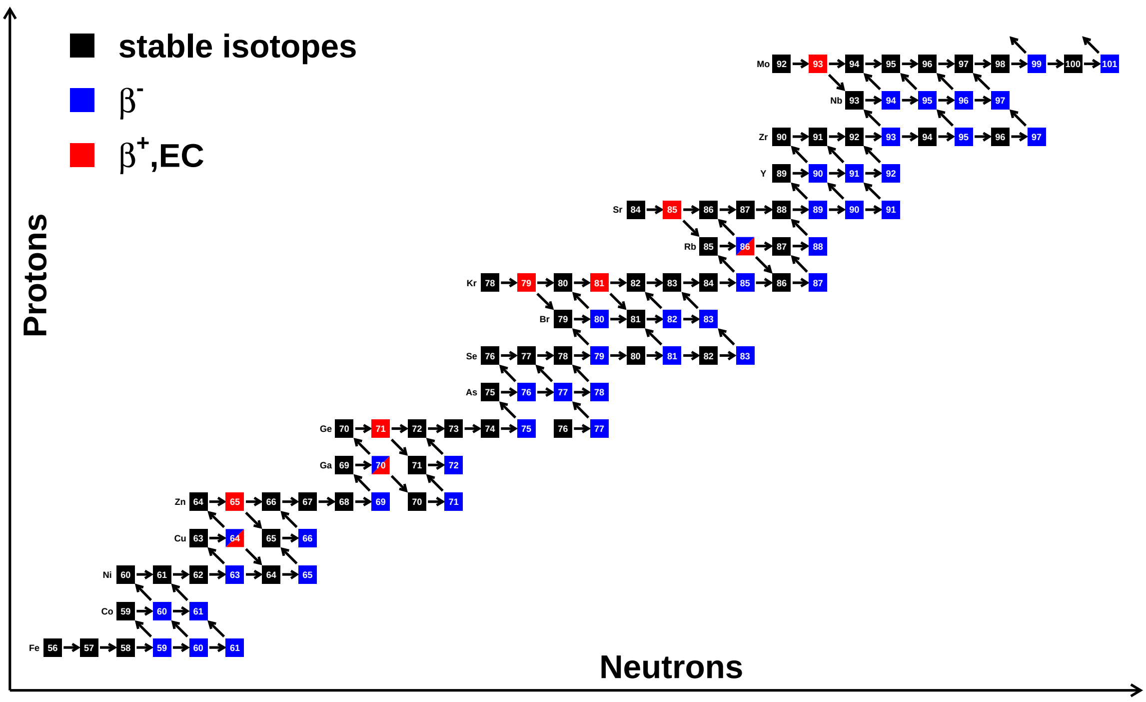

Figure 1. The *s*-process path between Fe and Mo, the domain of the weak component.

between 56 and 90 are mainly produced during the weak component. The first phase occurs during the helium core burning with neutron densities down to 10^6 cm^{-3} and temperatures around $kT = 25$ keV. The second phase happens during the carbon shell burning with neutron densities up to 10^{12} cm^{-3} at temperatures around $kT = 90$ keV.

The left part of Figure 2 shows a summary of the neutron capture and β^- decay times for radioactive isotopes on the neutron rich side of the valley of stability, under the condition that the neutron capture during the ^{13}C(α,n) occurs faster than than the β^- decay at stellar temperature. Obviously the vast majority of isotopes, where an experimental neutron capture cross section is desirable, have terrestrial β^- half-lives of at least thousands of days. The right part Figure 2 shows the same as the left part, but for the higher neutron density and temperature. Now isotopes with half-lives down to a few days can be of interest for the *s*-process reaction network.

Improved experimental techniques, especially as far as the neutron source and sample preparation are concerned, are necessary to perform direct neutron capture measurements on such isotopes [6]. Though the activation method or accelerator mass spectroscopy of the reaction products could be applied in a limited number of cases, experimental facilities like DANCE at LANL (USA) [7], n-TOF at CERN (Switzerland) [8] and the upcoming projects like SARAF (Israel) [9] and FRANZ at the Goethe University in Frankfurt (Germany) [10] are addressing the need for such measurements on the basis of the more universal method of detecting the prompt capture γ-rays, which is required for the application of the neutron time-of-flight (TOF) technique. In particular the FRANZ facility, which will be located close to the new FAIR facility might allow the investigation of radioactive isotopes with half-lives down to tens of days, while present facilities require half-lives of a few hundred days.

In section 2 the time-of-flight method is explained at the example of the DANCE facility,

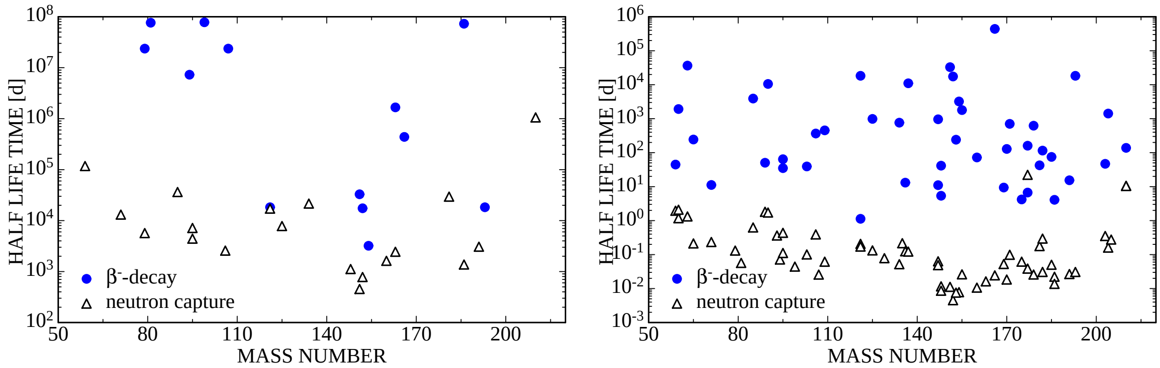

Figure 2. Left: Half life times with respect to neutron capture (open triangles) for a neutron of density 10^7 cm^{-3} and terrestrial β^- half life times (filled circles) for unstable isotopes on the s-process path as a function of mass number. Shown are only isotopes where the neutron capture is faster than the β^--decay at $kT = 5$ keV. The neutron capture cross sections are taken from [4] and the half lives under stellar conditions from [5]. Right: Same as left, but for a neutron of density 10^{12} cm^{-3} and β^--decays at $kT = 30$ keV

the currently most sensitive facility for (n,γ) experiments and a new approach (FRANZ) currently realized at the Goethe University Frankfurt, Germany is described. The FRANZ facility will allow energy-dependent neutron capture cross section and activation experiments in the astrophysically interesting energy region with significantly higher neutron fluxes then currently available elsewhere [11]. In section 3 alternative approaches like the activation or indirect methods are described.

2. The time-of-flight method

2.1. DANCE

The Detector for Advanced Neutron Capture Experiments (DANCE) is designed as a high efficiency, highly segmented 4π BaF_2 detector for calorimetrically detecting γ-rays following a neutron capture. DANCE is located on the 20 m neutron flight path 14 (FP14) at the Manuel Lujan Jr. Neutron Scattering Center at the Los Alamos Neutron Science Center (LANSCE). The design of the detector is such that a full 4π array would consist of 162 crystals of four different shapes, each shape covering the same solid angle [12]. Two of the 162 crystals are left out in order to leave space for the neutron beam pipe, see Figure 3.

Depending on the experiment, one crystal can be replaced by a sample changer mechanism, which makes it possible to exchange up to 3 samples without closing the beam shutter and breaking the vacuum of the beam pipe. Thus the full array is designed to host 159 or 160 out of 162 possible BaF_2 crystals. The dimensions of the bare crystals are designed to form a BaF_2 shell with an inner radius of 17 cm and a thickness of 15 cm. Thanks to the fairly low repetition rate of 20 Hz, measurements can be carried out over the whole energy range from 10 meV to 500 keV. This combination of a strong neutron source and a high efficiency γ-ray detector allows to measure (n,γ) cross sections of radioactive isotopes down to a few hundred days half-life. Further details on the overall performance of the array can be found in [7]. For details on the analysis and the neutron flux see [13]).

One of the first reactions investigated at DANCE was the neutron capture on ^{62}Ni, which is related to the weak s-process component during helium burning in massive stars of 10 to 25 $M_\odot$ [14]. The production of ^{62}Ni in a 25 $M_\odot$ stellar model [15] motivated a closer investigation of

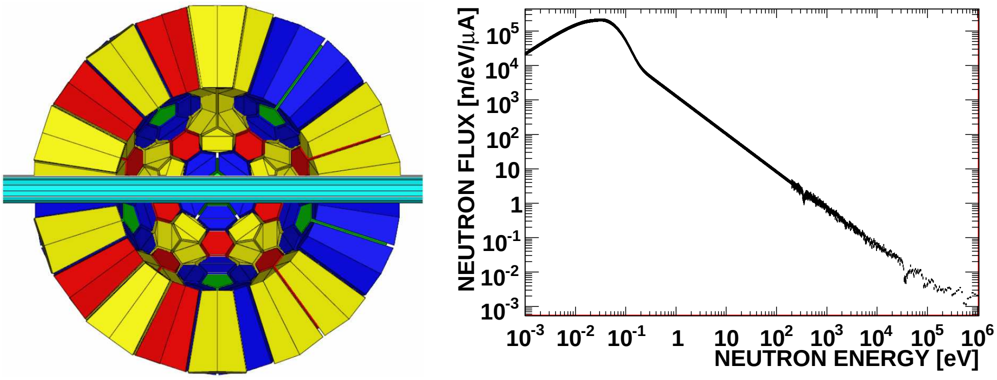

Figure 3. Left: Schematic drawing of one half of in total 160 crystals of the DANCE array including the neutron beam pipe. Right: The neutron flux given per μA at DANCE. Typically 100 μA of beam are available during experiments.

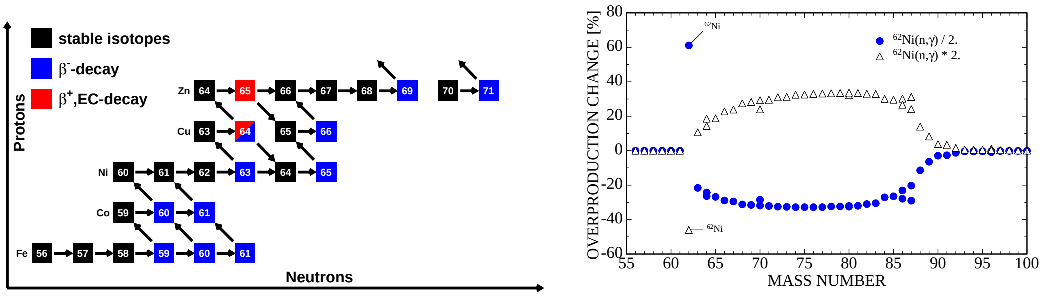

Figure 4. Left: s-process nucleosynthesis in the region between iron and tin with the important branching at ^{63}Ni. Right: Example of the effect of changing one cross section in the weak s-process path. The standard case was calculated for a $25 M_{\odot}$ star using the cross section data from [16]. The two curves show the relative change in overproduction after changing this cross section by a factor of two down (blue, filled circles) or up (open, black triangles). Changing one cross section in the weak s-process path affects the production of the respective isotope and all following ones.

the neutron capture rates involved (see Figure 4). Details can be found in Ref. [16]. The derived Maxwellian averaged cross section at $kT = 25$ keV ($31.5 \pm 2.5_{stat} \pm 2.2_{sys}$ mb) is in agreement with recently performed activation measurements (see section 3), but seems to disagree with a recent TOF measurement [17]. One reason for the disagreement could be the determination of the efficiency for detecting the γ-cascades after the neutron capture on ^{62}Ni in the recent TOF measurment [17]. A new measurement in this interesting mass region around nickel is scheduled for 2009. The DANCE array will be used to investigate the radioactive branch point nucleus ^{63}Ni, which has an half life of 100 years.

2.2. FRANZ

The Stern-Gerlach-Zentrum SGZ, recently founded at the University of Frankfurt, allows to build and operate larger experiments now in accelerator physics, astrophysics and material science research. It was decided to develop an intense neutron generator, the "Frankfurter

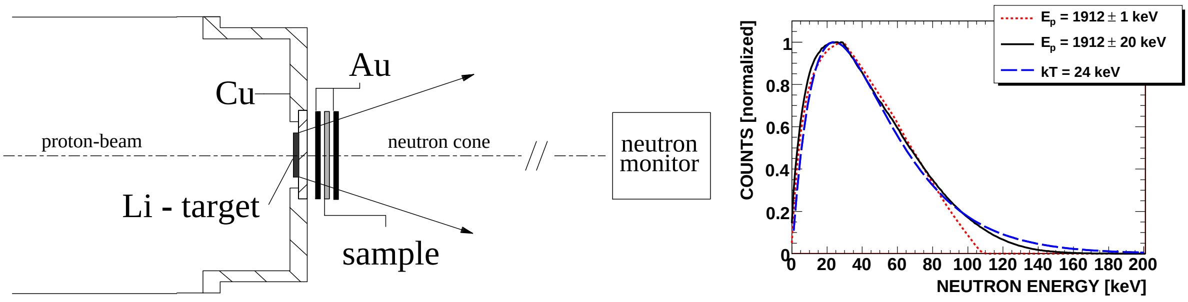

Figure 5. Left: Typical activation setup at the Forschungszentrum Karlsruhe. Neutrons are produced via the ^{7}Li(p,n) reaction just above the production threshold. The emitted neutrons are then kinematically focussed into a cone with an opening angle of 120°. The sample is usually sandwiched by two gold foils in order to determine the neutron flux just before and behind the sample. Right: Comparison of simulated activation spectra including two gaussian proton energy profiles with a theoretical spectrum corresponding to neutron fluxes at $kT = 24$ keV [25].

Neutronenquelle am Stern-Gerlach-Zentrum" (FRANZ). The planned proton driver LINAC consists of a high voltage terminal already under construction to provide primary proton beam energies of up to 150 keV. A volume type ion source will deliver a DC beam current of 100-250 mA at a proton fraction of 90%. A low energy beam transport using four solenoids will inject the proton beam into an RFQ, while a chopper at the entrance of the RFQ will create pulse lengths in the range of 100 ns at a repetition rate of up to 250 kHz. A drift tube cavity, which delivers variable end energies between 1.9 and 2.1 MeV will be installed downstream of the RFQ. Finally a bunch compressor of the Mobley type forms a proton pulse length of 1 ns at the Li target, where neutrons will be produced via the ^{7}Li(p,n) reaction. The maximum energies of the neutrons are then be adjustable between ≈30 keV and ≈500 keV by varying the primary proton beam energy (for details see also [18]).

3. Alternative methods

3.1. The activation method

If the product of the neutron capture is radioactive, the freshly produced nuclei can be detected after an extended period of irradiation either via their unique decay signatures (if the half life time is rather short) or by applying accelerator mass spectroscopy (AMS).

While other neutron-energy distributions were used on occasion [19, 20], the quasi-stellar neutron spectrum, which can be obtained by bombarding a thick metallic Li target with protons of 1912 keV, slightly above the reaction threshold at 1881 keV, was the working horse at the Forschungszentrum Karlsruhe [4]. Under such conditions, the ^{7}Li(p,n)^{7}Be reaction yields a continuous energy distribution with a high-energy cutoff at $E_n = 106$ keV. The produced neutrons are emitted in a forward cone of 120° opening angle. The angle-integrated spectrum closely resembles a distribution necessary to determine the Maxwellian averaged cross section (MACS) for a thermal energy of kT = 25 keV [21]. The samples are typically sandwiched between gold foils and placed directly on the backing of the lithium target. A typical setup is sketched in Fig. 5.

Triggered by the significant uncertainty for the (n,γ) cross section of ^{62}Ni [4, 22], two activation experiments have been carried out detecting the number of produced ^{63}Ni nuclei via AMS [23, 24]. The activation measurements agree with the TOF measurement carried out at DANCE within the quoted uncertainties.

3.2. Indirect methods
Indirect methods play an important role in the determination of nuclear reaction cross sections that are hard to measure directly. There are two main approaches in this context. The first is the determination of the desired A(n,γ)B via the inverse reaction B(γ,n)A. If the product of the neutron capture B is itself radioactive, the Coulomb dissociation (CD) method can be applied at radioactive beam facilities [26, 27]. If the product is stable or very long-lived real photons can be used is addition to the CD method [28]. Another method that is used successfully for neutron-induced fission cross sections is the surrogate method. So far, no successful proof of principle could be performed for neutron capture cross sections, but it might be an interesting additional approach [29].

4. Summary
Nowadays, the s-process as a nucleosynthesis process is well understood and established. Current research uses the s-process as a link between abundance observations and stellar models. Data on radioactive branch point nuclei are urgently needed to enhance the reliability of that approach. Current facilities can measure some, upcoming facilities will investigate a suite of radioactive isotopes. There will always be the need for other than TOF methods, especially for isotopes with short half lives.

Acknowledgments
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