

Nuclear astrophysics at FRANZ

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Abstract. The neutron capture cross section of radioactive isotopes for neutron energies in the keV region will be measured by a time-of-flight (TOF) experiment. NAUTILUS will provide a unique facility realizing the TOF technique with an ultra-short flight path at the FRANZ setup at Goethe-University Frankfurt am Main, Germany. A highly optimized spherical photon calorimeter will be built and installed at an ultra-short flight path. This new method allows the measurement of neutron capture cross sections on extremely small sample as needed in the case of ⁸⁵Kr, which will be produced as an isotopically pure radioactive sample. The successful measurement will provide insights into the dynamics of the late stages of stars, an important independent check of the evolution of the Universe and the proof of principle.

1. Introduction

The general features of the FRANZ facility, which is currently under construction, are already reported [1]. The FRANZ facility was developed to measure (n,γ) cross sections of astrophysically interesting isotopes with unprecedented sensitivity [2]. Recently also a program for (p,γ) experiments at FRANZ has been developed [3, 4]. This article concentrates on a new technique, which will be developed to determine neutron capture cross sections using the time-of-flight technique in combination with extremely small samples. This is beyond the standard program of FRANZ.

2. The origin of the elements

The synthesis of the naturally occurring chemical elements of mass equal or heavier than carbon started about 500 million years after the Big Bang - the beginning of our Universe. Apart from the primordial H, He and Li abundances the elements were and still are synthesized in stars. A clear and quantitative picture of nucleosynthesis in the different stages of stellar evolution constitutes the basis for our understanding of the chemical history of the Universe. Furthermore, understanding the chemical history leads to strong constraints on the age of the Universe.

The solar abundances distribution of the chemical elements can be explained by different processes, which contribute to the overall nucleosynthesis and occur during different stages of a star's life. The lightest elements - hydrogen, helium and traces of lithium - are produced in the Big Bang while the elements up to iron are synthesized during stellar burning phases by



charged-particle induced fusion reactions. During the extremely hot last stellar burning phase - the silicon burning - the isotopes around iron, which are most tightly bound, are produced in the nuclear statistical equilibrium, forming the famous iron peak around mass number 56. Almost all the elements with higher proton numbers than iron are produced through neutron-induced processes [5]. There are two major processes, the rapid neutron-capture process (*r* process) and the slow neutron capture process (*s* process). The *s* and *r* processes are reflected in the solar abundance distribution of the elements as a double-peak structure occurring at mass numbers corresponding to closed neutron shells. Only a few isotopes on the proton-rich side of the valley of stability get significant contributions from other processes.

3. Beyond iron - Neutron capture processes

The *r* process, producing about half of the elemental abundances, takes place in explosive scenarios such as supernovae. The neutron flux is so high and the neutron capture times are so short that a nucleus will almost always capture several neutrons before it undergoes β -decay. Thus, the *r* process follows a path that is shifted far towards the neutron-rich isotopes. Here, the β -decay half-lives are much shorter for isotopes very rich in neutrons, so that shortly after the neutron source terminates, the products of the *r* process will β -decay back to the valley of stability.

In contrast, the main component of the *s* process takes place in thermally pulsing Red Giant stars (T-AGB). These stars have left the main sequence after finishing hydrogen core burning. They are about 50 to 100 times bigger and cooler than our sun while their masses are comparable. The *s* process [6, 7] starts with an iron seed exposed to free neutrons. Since the neutron densities are low, an unstable isotope produced by a series of neutron capture reactions will almost always β -decay back to its stable isobar before capturing another neutron. Thus, the *s* process builds up the elements following the neutron-rich side of the nuclear valley of stability until it terminates in the lead-bismuth region.

4. The *s*-process branching at ^{85}Kr

The exact pathway of the *s* process depends on the conditions in the star. Starting at the very abundant iron group, all elements up to bismuth could, in principle, be produced by a sequence of reactions in which a series of neutron captures produces an unstable isotope that quickly decays to the next higher element through β -decay and then waits for the next neutron capture. If, however, conditions in the star make the rates for neutron capture comparable to the rate of β -decay for a particular isotope, the *s*-process path branches at that isotope: a fraction of the isotope transforms via neutron capture, while the other fraction β -decays.

The branching ratio, or relative likelihood, for the different reactions depends on the physical conditions in the interior of the star - temperature, neutron density and electron density. At higher neutron densities with all other conditions equal, more nuclei of a given isotope capture a neutron before having the chance to β -decay. Thus, the branching ratios deduced from the isotopic ratios observed in stellar material could provide the tools to effectively constrain modern models of the stars where the nucleosynthesis occurs. Therefore the fundamental rates, or cross sections, for neutron capture and β -decay are essential.

A particularly interesting branching of the *s* process occurs in the region around ^{85}Kr (Figure 1). The *s*-process path indicated by gray arrows has branch points at the unstable isotopes (blue squares). ^{85}Kr has an isomeric state, ^{85m}Kr , which always decays before neutron capture - either through β -decay or through internal conversion to the ground state. If the $^{85}\text{Kr}(n,\gamma)$ cross section is increased, the neutron capture occurs with enhanced probability and ^{86}Kr is produced more abundantly. This would therefore affect the abundance ratio of ^{84}Kr to ^{86}Kr . During *r*-process nucleosynthesis very neutron-rich isotopes are produced that decay back to the valley of stability. Stable isotopes (black squares) end these β -decay chains so that the

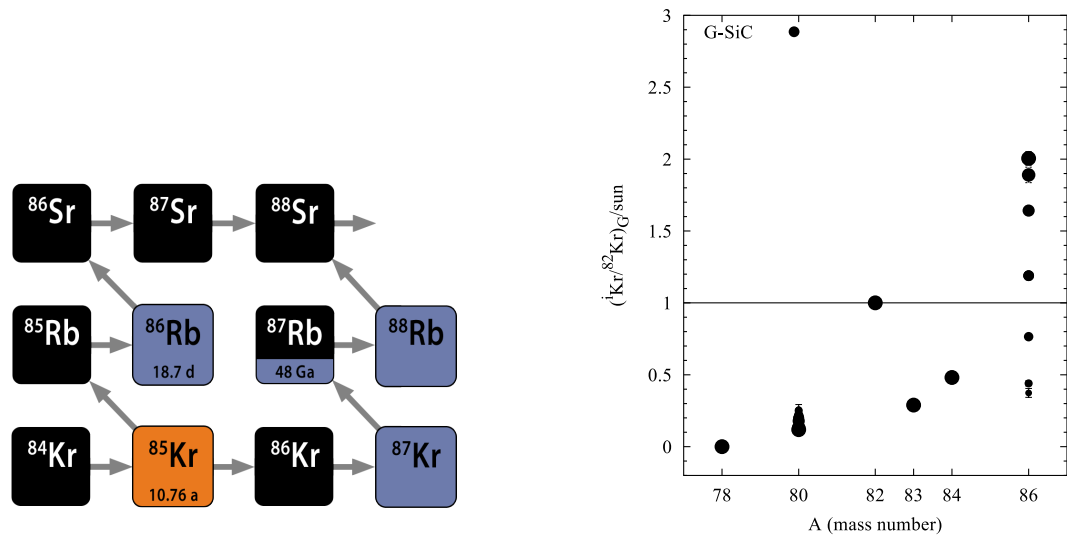


Figure 1. Left: Reaction network during *s*-process nucleosynthesis around the important branch point ^{85}Kr (10.76 yr). Right: Distribution of Kr isotopes in presolar grains [8].

stable isotope ^{86}Sr is produced only in the *s* process (*s*-only isotope). If the very long-lived ^{87}Rb were stable, ^{87}Sr would also be a *s*-only isotope.

5. $^{85}\text{Kr}(n,\gamma)$ cross section - Constraining stellar parameters

An additional exciting aspect of this region is the availability of observational data of the stellar abundances of those isotopes from stardust. These extremely small diamond-like grains are known to be formed in the outer regions of Red Giant stars. Under certain circumstances, such grains survive their long journey through interstellar space and participate in the formation of new stars and their planets. Therefore we can find them nowadays on earth. Since the grains are extremely small - only a few micrometers in diameter - it was necessary to develop greatly improved experimental equipment to reach the sensitivity needed for isotopic-abundance measurements of several isotopes from a single grain. It is possible to extract information about all stable isotopes of krypton from a single grain - hence, from a single star. Therefore the interesting $^{84}\text{Kr}/^{86}\text{Kr}$ ratio can be observed in presolar SiC grains originating from T-AGB stars [8] as shown in the right part of Figure 1. The competition between β -decay and neutron capture at ^{85}Kr is reflected in the observed $^{84}\text{Kr}/^{86}\text{Kr}$ ratio. The interpretation of the observed ratio as a measure of stellar parameters is currently hampered by the only very poorly known $^{85}\text{Kr}(n,\gamma)$ cross section [9, 10, 11].

6. $^{85}\text{Kr}(n,\gamma)$ cross section - calibrating a nuclear cosmochronometer

The decay of the long-lived ^{87}Rb (48 Gyr) affects the solar abundance ratio of the otherwise *s*-only isotopes $^{86,87}\text{Sr}$. While the small *r*-process contribution to the solar abundance of ^{87}Rb can be determined by a comparison with the stable, close-by *r*-only nuclei ^{96}Zr and ^{100}Mo , the by far more important contribution from the *s* process crucially depends on the $^{85}\text{Kr}(n,\gamma)$ cross section. If this cross section is smaller than assumed in the models, ^{87}Rb is less produced, and, hence, the ratio of ^{86}Sr to ^{87}Sr is less influenced - the Universe appears to be younger. If the $^{85}\text{Kr}(n,\gamma)$ cross section is bigger than assumed, the ^{86}Sr to ^{87}Sr ratio is strongly modified by the decays of ^{87}Rb - the Universe appears older. A detailed understanding of the *s*- and *r*-contribution to the ^{87}Rb abundance would therefore allow the determination of the onset of

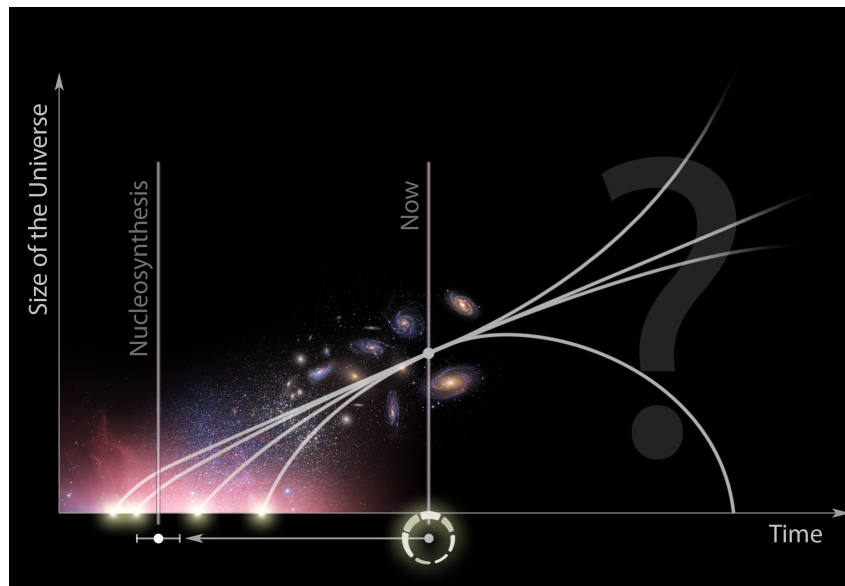


Figure 2. Starting with the big bang, the Universe is expanding ever since. Depending on the parameters of current models, the future could be accelerated expansion, the asymptotic stand still or even a collapse. Cosmological models help to couple the past (age of the Universe) with the future destiny. The exact knowledge of the time since the onset of the synthesis of the heavy elements allows to constrain the age of the Universe.

the *s*- and *r* process in the history of the Universe [12]. Similarly to the determination of the age of the solar system based on isotopic ratios, nuclear cosmochronometers offer a constraint of the age of the Universe (14 Gyr), which is completely independent of astronomical observations. Also here, the biggest remaining uncertainty of this Rb/Sr clock is the $^{85}\text{Kr}(n,\gamma)$ cross section.

The age of the Universe has been determined by the Re/Os clock [13] with the method described. The result has an overall uncertainty of about 1 Gyr. The unsatisfying outcome stems from major uncertainties of theoretical estimates. On the one hand, the neutron capture cross section of a low-lying nuclear state in ^{187}Os cannot be measured directly, but is extremely important at stellar temperatures. On the other hand, the nuclear clock itself induces problems: the β -decay half-life of ^{187}Re is about 109 times shorter under stellar conditions than under terrestrial or interstellar conditions. The reason for this dramatic change of the β -decay half-life is the bound-state β -decay in stellar interiors. In the hot plasma ^{187}Re may be fully ionized so that the decay electron remains in a bound state instead of being emitted into the continuum, drastically increasing the decay probability [14].

Both nuclear effects are not relevant in the case of the Rb/Sr clock [9, 15]. If the uncertainty of the value for the neutron capture cross section of ^{85}Kr is reduced to around 10% or less, the age determined by the Rb/Sr clock should result in a final uncertainty of less than 0.5 Gyr. This would put strong constraints on the different scenarios for the expansion of the Universe (Figure 2), possibly deciding on the models for a closed, flat or open Universe.

7. Measuring (n,γ) reactions with very short flight path and radioactive samples

The present layout of the FRANZ facility barely provides the high neutron fluxes needed to perform measurements on radioactive isotopes with comparably hard γ -ray emission like ^{85}Kr [2, 16]. Since the neutron production is already at the limits of the current technology, one option is to get closer to the neutron production target to increase the solid angle covered by

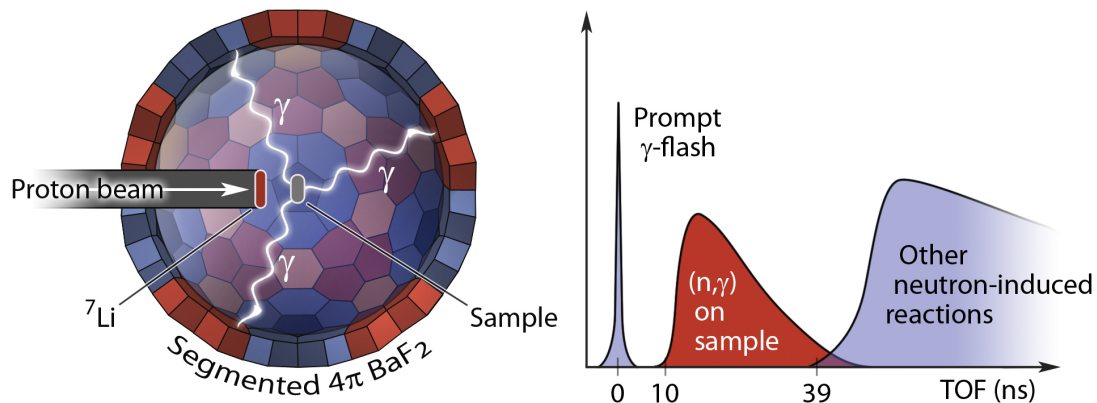


Figure 3. Left: Schematic setup of the planned neutron capture experiment with an ultra-short flight path of only 4 cm. Right: Anticipated time-of-flight spectrum [17].

the sample material. It is possible to perform a TOF measurement with sufficient accuracy even with a flight path as short as a few centimeters (Figure 3, left).

The only feasible solution is to produce the neutrons inside a spherical γ -detector and distinguish between background from interactions with the detector material and the signal from neutron captures on the sample based on the time after neutron production as illustrated in Figure 3, right. First, an initial γ -flash, occurring when the protons hit the neutron production target, is detected. Then the prompt γ -rays produced in the (n,γ) reaction at the sample induce a signal in the detector. Later, the neutrons from other reactions, such as scattering in the detector material, arrive in the detector with large time of flights, travelling at much slower speed than the γ -rays, and produce background.

A detailed investigation of the geometry of the setup at an ultra-short flight path has been performed. In contrast to the calorimeters used in such TOF experiments so far [5, 18, 19], the calorimeter shell has to be much thinner in order to allow the neutrons to escape quick enough. The geometry is based on the DANCE array [18, 20], which was designed as a high efficiency, highly segmented 4π BaF₂ array. It consists of up to 162 crystals of 4 different shapes, each covering the same solid angle. The high segmentation distributes the envisaged high count rate over many channels, leading to a significant increase of the maximal tolerable total count rate that can be processed by the DAQ. The DANCE array has an inner radius of 20 cm and a thickness of 12 cm. The combination of the fastest decay component of any scintillator known so far, very low neutron sensitivity and high γ -ray detection efficiency makes BaF₂ by far the best suited scintillator material for this purpose.

The advantage of this setup is the greatly enhanced neutron flux. Because of the reduction of the flight path from 1 m to 4 cm, the neutron flux will be increased by almost 3 orders of magnitude. The reduced time-of-flight resolution resulting in a reduced neutron-energy resolution is still sufficient for astrophysical and applied purposes. A comparison to the DANCE setup at the Los Alamos Natl. Laboratory shows that, despite the much shorter flight path (4 cm vs. 20 m), a much better time resolution (1 ns vs. 125 ns) will be achieved at the proposed setup. Because of the different time structure of the proton beam at the FRANZ facility the energy resolution will almost be the same for both setups.

8. Summary and Outlook

Radioactive isotopes become more and more in reach of current experimental research. Proton induced reaction studies on unstable nuclei are important and are being addressed also with

new techniques [21]. Neutron induced reaction studies are difficult on stable, very difficult on unstable nuclei [5]. FRANZ is designed to address many of those requirements. The NAUTILUS project aims at determining the neutron capture cross section of ^{85}Kr in the astrophysically important energy regime. Current and future ring designs promise breakthroughs in experimental techniques even for the determination of neutron-induced reaction cross sections [22].

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