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Abstract. The FRANZ facility is currently under construction at Goethe Universität Frankfurt a.M., Germany. It is designed to produce the world’s highest neutron intensities in the astrophysically relevant energy range between 10 keV and 1 MeV and consists of a high-intensity proton linac providing energies close to the threshold of the $^7$Li(p,n) reaction at $E_p = 1880$ keV. The high intensities of both the proton and the neutron beam allow the investigation of reactions of unstable target isotopes since the needed amount of target material is significantly reduced. We will present two examplary reactions relevant for the $s$ process and the nucleosynthesis of $p$ nuclei, respectively.

1. Introduction

The study of nuclear reactions relevant for stellar evolution or the nucleosynthesis of elements is often hampered by very low reaction yields due to low reaction cross-sections and/or small amounts of target material especially in case of radioactive samples [1]. To overcome these limits, it is mandatory to develop high-intensity beams and enable their usage by sophisticated cooling methods of the targets. The FRANZ facility is currently under construction at Goethe Universität Frankfurt a.M., Germany, and aims to produce highest neutron intensities in the astrophysically relevant energy range of about 10 keV to 1 MeV. Therefore, it will provide a high-intensity proton beam with energies close to the reaction threshold of $E_p = 1880$ keV of the reaction $^7$Li(p,n) [2]. In addition to the neutron production, the beam can be used directly to study proton-induced reactions.

A schematic layout of the FRANZ facility is shown in Fig. 1 [3]. After the production in a volume-type ion source, the protons are transported via the Low Energy Beam Transport (LEBT) section which ends in a chopper device to impose a suitable time structure on the beam for the further processing. The acceleration to an energy of $E_p = 2$ MeV is realized with a combination of RFQ and IH structure. This solution is very space saving and can handle the aspired high intensities up to beam currents of 20 mA. After this acceleration, a CH rebuncher is foreseen to tune the beam energy without losses in intensity within $\pm 10\%$ to allow a specific modulation of the energy spectrum of the produced neutron beam.
Figure 1. Schematic layout of the FRANZ facility at Goethe Universität Frankfurt a.M., Germany. A high-intensity low-energy proton beam will produce neutrons with the world’s highest intensities in the keV energy-range. For details, see text.

At the FRANZ facility, different intensities of the neutron beam will be available. Using a fast calorimeter [4] at the experimental position labeled (a) in Fig. 1, the time-of-flight (TOF) technique provides the energy of the neutrons in an in-beam experiment. The bunch compressor samples nine of the proton bunches provided by the accelerating structures at the neutron-production target. Therefore, the lithium target deals with a proton beam of a mean current of 2 mA but with a very pronounced time structure: bunches with a length of 1 ns are repeated with a rate of 250 kHz and contain a current of 8 A. The resulting neutron beam has the world’s highest intensity of $10^7$ neutrons s$^{-1}$cm$^{-2}$.

Figure 2. Simulation of beam transport at FRANZ. The transport from the CH rebuncher to experimental position (c) in Fig. 1 is shown in the left panel. The envelope of the beam passing a quadrupole doublet, a deflecting dipole magnet, and a quadrupole triplet is depicted. The right panel illustrates the dimension of the beam at target position (c) in Fig. 1. For details, see text.

For the activation technique realized at position (b) in Fig. 1, the proton beam need not to be shaped by the bunch compressor. Hence, the beam is used in the quasi-continuous wave mode as provided by the accelerating structures. Mean currents of up to 20 mA provide a neutron beam in the keV energy-range with intensities of up to $10^{12}$ neutrons s$^{-1}$. Position (c) in Fig. 1 is dedicated to the investigation of proton-induced reactions. Again, the proton beam is used in
the quasi-continuous wave mode in combination with a $4\pi\text{ BaF}_2$ detector for $\gamma$ calorimetry [4].

Fig. 2 shows the results of a simulation of the beam transport behind the bunch compressor towards position (c). A focusing quadrupole doublet, a deflecting dipole magnet, and a focusing and aligning quadrupole triplet are implemented in the simulation software TraceWin [5]. The left panels indicate the envelope of the beam in $x$ and $y$ direction, respectively. The right panel depicts the dimension of the beam at position (c). The quadrupole triplet yields an almost circular and homogeneous distribution with a diameter of about 4 cm. While a broad distribution is desirable to reach a reduced areal power density and prevent the samples from damage, further optimization of the components of the beam line is needed as the envelope is partly to close to the limiting diameter of the beam pipe [6].

Figure 3. Sketch of a prototype of a neutron converter target. The protons are converted to neutrons by the $^7\text{Li}(p,n)$ reaction. The deposited power is carried away by a high-pressure water-cooling. Neutrons emitted in a cone with opening angle 120° are used for activation experiments. For details, see text and [7].

The high proton current provided by the linear accelerator at FRANZ is transformed to a high-intensity neutron beam by the $^7\text{Li}(p,n)$ reaction. The lithium is evaporated as a thin layer on a backing material with high thermal conductivity, e.g., copper. In a prototype design (compare Fig. 3 and [7]), the copper backing is 1 mm thick and a $\mu$m layer of lithium fluoride (LiF) or lithium oxide (Li$_2$O) serves as neutron converter target. The melting temperatures of LiF and Li$_2$O are $T_M = 1118.15$ K and $T_M = 1843.15$ K, respectively, exceeding the one of metallic lithium ($T_M = 453.69$ K) by far [8]. As the loss of neutron conversion due to the stoichiometry remains small and the spectral composition of the neutrons remains shapeable by the thickness of the lithium layer, these chemical compounds might be a good alternative compared to a liquid lithium target [9]. A primary cooling of high-pressure water-flow carries away the heat from the power deposited by the proton beam. To avoid modulation of the neutron spectrum towards lower energies, the water layer is restricted to a thickness of 0.2 mm. A secondary cooling circle prevents the mounting structure from heating. First tests at IRMM,
Geel, Belgium, proved the vacuum-tightness and water-proofness of the prototype. In addition, the influence of the water cooling on the neutron spectrum was examined [7].

The high intensities of both the neutron and proton beams allow the investigation of reactions with very low yields as in the case of a radioactive probes [1]. The FRANZ facility will be one of the scarce accelerators worldwide where this is possible in standard kinematics and provides a remarkable alternative to experiments in inverse kinematics at large-scale facilities providing radioactive ion beams.

2. Investigation of the \(^{85}\text{Kr}(n,\gamma)\) reaction

The cross section of the \(^{85}\text{Kr}(n,\gamma)\) reaction is one of the important ingredients to understand the wide range of isotopic ratios \(\delta^{86}\text{Kr}/^{82}\text{Kr}\) as found in silicon carbide grains [10]. While the observed spread might be caused in a temperature dependent half-life of \(^{85}\text{Kr}\) due to transitions between the ground-state and the isomeric state at \(E = 304.87\text{ keV}\) [11] the absolute value depends critically on the cross section of the \(^{85}\text{Kr}(n,\gamma)\) reaction. There are attempts to derive this cross section from the inverse \(^{86}\text{Kr}(\gamma,n)\) reaction [12]. However, the transition matrix elements connect very different levels in both cases and the uncertainty of the extracted neutron-capture cross section is still very large. Therefore, it is desired to attempt the direct measurement of the neutron-capture cross section at FRANZ [13] to clarify the nuclear physics of the branching point isotope \(^{85}\text{Kr}\) (compare Fig. 4).

![Figure 4. The s-process branching at \(^{85}\text{Kr}\). The situation is complicated by an isomeric state at \(E = 304.87\text{ keV}\) with a very short half-life of 4.48 h compared to the ground-state of \(^{85}\text{Kr}\) with \(t_{1/2} = 10.76\text{ a}\). The red arrows indicate the main reaction path connecting the isotopes \(^{84}\text{Kr}, \(^{86}\text{Kr}, \(^{87}\text{Kr}, \(^{87}\text{Rb}, \(^{88}\text{Rb}, \(^{88}\text{Sr}, \text{ and } ^{89}\text{Sr}. The blue arrows between ^{85m}\text{Kr} \text{ and } ^{85}\text{Kr} \text{ indicate the temperature dependent excitation and de-excitation reactions of the two nuclear levels. The orange arrows show alternative reactions paths due to the branching at ^{85}\text{Kr}.](image)

An important step towards such an experiment is the production of a sufficient amount of target material in a suitable chemical form. The unstable isotope \(^{85}\text{Kr}\) is produced by the \(^{82}\text{Se}(\alpha,n)\) reaction as well as by \(^{82}\text{Se}(\alpha,p)\) reaction and the subsequent \(\beta\) decay of \(^{85}\text{Br}\). This allows the almost isotopically pure production of \(^{85}\text{Kr}\) by the irradiation of an isotopically enriched metallic \(^{82}\text{Se}\) with \(\alpha\) particles of energies between 6 MeV and 10 MeV (compare Fig. 5). If the temperature during the irradiation is below 50°C the krypton gas remains trapped in the selenium [14].

At a sample preparation site, the \(^{85}\text{Kr}\) can be released from the selenium if the sample is heated beyond its melting point. A spherical container cooled by liquid-nitrogen can be used to condensate the krypton gas. An experiment with neutron intensities as provided by FRANZ requires an amount of at least \(10^{17}\) atoms of \(^{85}\text{Kr}\). This number can be reached if the total amount of \(\alpha\) particles impinging on the selenium target is about \(2.5 \cdot 10^{18}\) projectiles [13].

Since \(^{85}\text{Kr}\) emits a non-negligible amount of \(\gamma\) radiation after the \(\beta\) decay of both the isomeric and the ground-state, the amount of sample material to be placed inside a high-efficiency \(\gamma\) calorimeter without causing non-manageable background is limited. Therefore, an increase of the neutron intensity beyond the current design value of FRANZ is favourable for the measurement.
of the $^{85}$Kr(n,γ) reaction. This can be achieved by a reduced flight path of the neutrons provided by an optimized γ calorimeter as described in [13].

3. Investigation of the $^{91}$Nb(p,γ) reaction

The most abundant p nucleus $^{92}$Mo ($f_{s^+} = 14.84\%$) can be produced by the so-called γ process [15] or a series of subsequent proton capture reactions on stable or long-lived isotopes of the N = 50 closed neutron shell starting from $^{86}$Kr (compare Fig. 6 and [16, 17]). The $^{91}$Nb(p,γ) reaction is not experimentally studied so far since a direct measurement requires the availability of a radioactive target sample of $^{91}$Nb isotopes. Due to the increasing Coulomb barrier, the proton-capture cross sections on $^{90}$Zr and $^{91}$Nb decrease compared to the other semi-magic isotopes at N = 50. Thus, these cross sections determine how much $^{92}$Mo can be produced in the explosive scenario of a type Ia supernova. As an unstable isotope, $^{91}$Nb is not available in the seed distribution. Thus, every $^{91}$Nb atom has to be produced before it can capture a proton to become $^{92}$Mo. Therefore, the cross sections of the $^{90}$Zr(p,γ) and $^{91}$Nb(p,γ) reactions are the most important ones to understand the production of $^{92}$Mo. Besides the production of $^{92}$Mo via proton-capture reactions its destruction by the same reaction type has to be taken into account, too. However, the produced $^{92}$Mo will not be destroyed directly because of the low cross section of the reaction $^{92}$Mo(p,γ) [18].

The fundamental difficulty of the measurement of the $^{91}$Nb(p,γ) reaction is the instability of the $^{91}$Nb isotope. At the FRANZ facility, a small amount of $^{91}$Nb is sufficient to determine the cross section of interest. The $^{91}$Nb sample will be produced by irradiating a molybdenum target enriched in $^{92}$Mo with protons of energies of 25 MeV energy. Due to the closed neutron shell, the dominating reaction channels in this energy range are $^{92}$Mo(p,2p), $^{92}$Mo(p,3p), and $^{92}$Mo(p,2n). Since $^{91}$Nb is either produced directly or via subsequent electron capture decays, the produced niobium is almost isotopically pure. An amount of $1.2 \times 10^{16} \,$ $^{91}$Nb nuclei yields after the irradiation of 300 mg sample material enriched to 95% in $^{92}$Mo with a current of about 80 μA for about 24 hrs. This can be realized for example at the Oslo Cyclotron Laboratory, Norway. Prior to that production run, the cross sections shown in Fig. 7 will be experimentally determined at the same facility [20].

As can be seen from Fig. 7, the production of $^{93}$Nb by the $^{92}$Mo(p,γ) reaction is hampered by the much lower reaction cross section as well as by the very large half-life of $^{93}$Mo ($t_{1/2} = 4000$ a). The chemical purification of the sample material has to be optimized for the reduction of molybdenum in the sample. However, even if some $^{92}$Mo remains in the sample material the contribution from the $^{92}$Mo(p,γ) reaction to the measured spectra can be easily separated because of its different Q value ($Q = 4087$ keV) compared to the $^{91}$Nb(p,γ) reaction.

Figure 5. Production of target sample of $^{85}$Kr. The irradiation of an enriched $^{82}$Se target with α particles between 6 MeV and 10 MeV leads to the almost isotopically pure production of $^{85}$Kr. For details, see [13].
$Q = 7462$ keV).

The cross section of the $^{91}$Nb(p,$\gamma$) reaction is predicted to amount about $10\ \mu$b at $E_p = 2$ MeV. An amount of $10^{16}$ $^{91}$Nb nuclei yields a count rate of approximately 1.5 kHz using the $4\pi$ BaF$_2$ calorimeter available at FRANZ. This rate is clearly above the expected background and can be processed by the data acquisition system. Therefore, a sample of suitable size can be produced by the proposed procedure.

4. Summary and outlook

The Frankfurt neutron-source FRANZ will provide the world’s highest neutron intensities for both activation and TOF experiments in the keV energy-range. The study of key reactions for s-process nucleosynthesis is foreseen at this facility. In addition, the high-intensity low-energy proton beam will serve as a source to study proton-induced reactions related to the production of the $p$ nuclei. The study of reactions on unstable isotopes necessitates the production of radioactive samples. For each case, as shown exemplarily for $^{85}$Kr and $^{91}$Nb, a special production mechanism leading to isotopically pure samples has to be developed.
Short half-lives or high intrinsic activities prevent a measurement in standard kinematics. Then, experiments in inverse kinematics can be performed as explained, e.g., in the contributions of A.M. Laird and R. Reifarth to this volume.

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