PROCEEDINGS OF SCIENCE

Production of ^{91}Nb for a measurement of the ^{91}Nb(p,γ) reaction at FRANZ

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In order to answer open questions about the production mechanisms of the p nucleus ^{92}Mo, the cross section of the ^{91}Nb(p,γ) reaction must be known precisely. The challenge in measuring this reaction is the instability of ^{91}Nb. However, it will be possible to perform measurements in standard kinematics in combination with the summing crystal technique using the high proton current FRANZ (Frankfurter Neutronen Quelle am Stern-Gerlach-Zentrum) will deliver. To perform this measurement, it is necessary to produce ^{91}Nb. One possible way is to activate ^{92}Mo with protons at $E_p \approx 20$ MeV. A first step towards the production run has been done by measuring the cross sections of the reactions ^{nat}Mo(p,x) around this energy.

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1. Motivation

The origin of the elements from hydrogen to iron can be explained by the primordial nucleosynthesis and by fusion reactions during the different burning stages in stars. The synthesis of the elements heavier than iron can be explained by neutron capture processes, namely the *s* and *r* processes [1]. However, there are around 35 proton-rich isotopes, which cannot be produced by neutron capture processes. These isotopes are called the *p* nuclei [2]. Nowadays, it is assumed that these *p* nuclei are produced during core-collapse supernovae or type Ia supernovae by a series of photo-disintegration reactions – the so called γ process [3]. Network simulations of these scenarios showed that the γ process could not reproduce the expected abundance ratios [4]. The *p* isotopes of Mo and Rb were in particular underproduced by several orders of magnitude (compare Fig. 1). However, simulations showed, that the experimentally observed abundance ratios may be reproduced by including a series of proton capture reactions [5,6]. To confirm this assumption, the cross sections of the crucial reactions (see Fig. 1) have to be known with precision.

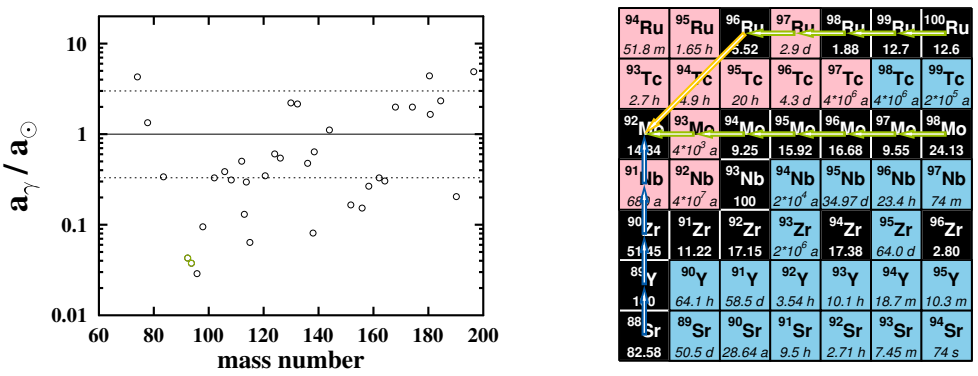

Figure 1: The figure on the left shows the normalized abundances a_γ of the *p* nuclei from a Type II supernova network simulation relative to their normalized solar abundances $a_\odot$. Data taken from [7]. Most of the ratios are within a factor of 3 (dashed lines). The highly underproduced ^{92,94}Mo isotopes are marked green. The figure on the right shows a part of the reaction network of the γ process with (γ, n) and (γ, α) reactions leading to ^{92}Mo. Also shown is the possible proton capture path with (p, γ) reactions leading to ^{92}Mo.

For the *p* nucleus with the highest relative isotopic abundance, ^{92}Mo, these reactions are the radiative proton captures of ^{90}Zr and ^{91}Nb, due to the fact that these are the last two steps in this production path and ^{91}Nb is unstable. The reaction ^{90}Zr(p,γ) was recently remeasured [8] and is under investigation. Details on the studies of this cross section can be found in the contribution by K. Sonnabend in this volume. In contrast, there is no experimental data for the cross section of the ^{91}Nb(p,γ) reaction. Due to the instability of ^{91}Nb , the common way would be an experiment in inverse kinematics, *e.g.*, with a proton gas-jet target as shown in the contribution by J. Glorius in this volume. Due to the half-life of ^{91}Nb of 680 yr [9], it seems feasible to produce a ^{91}Nb target to perform a measurement in standard kinematics. Radioactive targets suffer three challenges: Firstly, a sufficient amount of target material must be produced with as few impurities as possible. Secondly, the small amount of target material results in a low reaction yield. And at last, the decay radiation from the target must be handled.

2. Production of ^{91}Nb

A possible way to produce ^{91}Nb is to irradiate ^{92}Mo with protons above an incident energy of 15 MeV. Theoretical calculations with TALYS 1.6 [10] show that, above this energy, the reaction channels ^{92}Mo(p,pn) and ^{92}Mo(p,2n) are open leading to ^{91}Mo and ^{91}Nb. The subsequent decay of ^{91}Mo will also produce ^{91}Nb. Figure 2 shows these production paths and the calculated cross sections. Other niobium isotopes in the target would lead to a high background and could not be separated chemically. But all other open reaction channels will not efficiently produce any other stable or long-lived niobium isotope directly. Any production through subsequent decays is shielded by stable or long-lived molybdenum isotopes. This allows the production of a high-purity ^{91}Nb sample after chemical separation of the ^{91}Nb from the molybdenum. Using the theoretical cross sections, 1.2×10^{16} ^{91}Nb nuclei can be produced by irradiation of 300 mg sample material enriched to 95 % in ^{92}Mo with a total charge of about 7 C. This can be realized for example with the Cyclotron at Physikalisch Technische Bundesanstalt, Braunschweig, Germany, in four days or at the Oslo Cyclotron Laboratory, Norway in one day. After the chemical separation of ^{91}Nb from the ^{92}Mo matrix at Paul Scherrer Institut, Villingen, Switzerland, it is estimated that 50 % of the produced ^{91}Nb can be recovered. With this ^{91}Nb material, one could perform a ^{91}Nb(p,γ) experiment around 2 MeV using the high proton current of 2 mA soon available at FRANZ, Frankfurt a. M., Germany. With the theoretical cross sections of ^{91}Nb(p,γ), a count rate of 60 Hz is expected in a 4π BaF_2 calorimeter [11]. The radiation from the active target will be on the order of 1 MBq. Under these conditions, an experiment using the summing crystal technique should be possible.

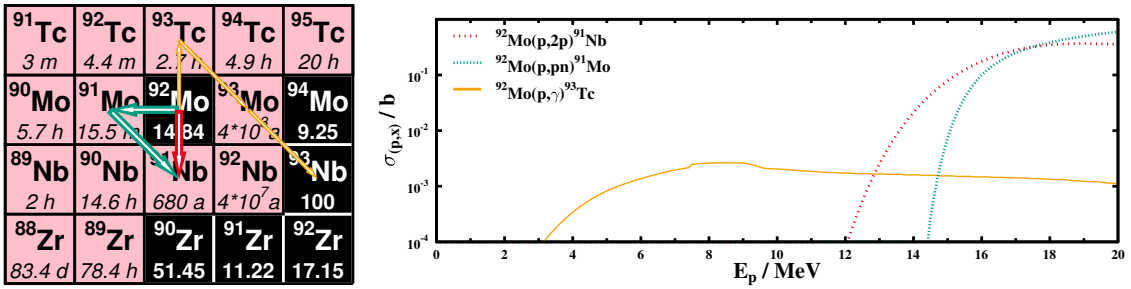

Figure 2: Relevant reaction channels for ^{92}Mo + p around 15 MeV and their subsequent decays. The cross sections were calculated using TALYS [10]. The production of ^{93}Nb is suppressed by a small cross section and shielded by the long-lived ^{93}Mo (yellow arrows).

3. Determination of the production yields of ^{92}Mo + p

The first step in the sample production was the experimental check of the predicted cross sections. In cooperation with the PTB, Braunschweig, Germany, the PTB cyclotron was used to irridate molybdenum foils of natural isotopic composition. The thickness of the foils was approximately 10 µm, confirmed by RBS measurements using the Van-de-Graaff accelerator at Goethe Universität Frankfurt a. M., Germany, as well as at PTB, Braunschweig, Germany, at proton energies of 2.4 MeV and 3.0 MeV, respectively. Five different energies $E_p = 15 - 19$ MeV and currents

of approximately 500 nA were used. At each energy, there was an activation of 15 minutes to determine the cross section of the reaction ^{92}Mo(p, pn) leading to ^{91}Mo with a half-life of 15.49 minutes. Between the end of the activations and the beginning of γ-ray spectroscopy with a large volume high purity germanium detector there was a delay of approximately 6 minutes. A layer of 2.5 cm lead between the target and the detector was reducing the rate in the detector by the low energy γ and X-rays. Figure 3 shows a measurement after an irridation at $E_p = 19$ MeV. Due to the long half-lives of ^{91}Nb (680 yr) and its isomer (60.86 d) an eight-hour activation was performed at each energy as well to gain higher yields. The spectroscopic analysis of these activation runs is currently carried out using a LEPS (Low Energy Photon Spectrometer) at Goethe Universität Frankfurt a. M., Germany. A first spectrum of the target irridated with protons of $E_p = 15$ MeV for 8 h is depicted in Fig. 4. The first preliminary spectra show the expected counts in the peaks and it should, therefore, be possible to produce the needed amount of ^{91}Nb.

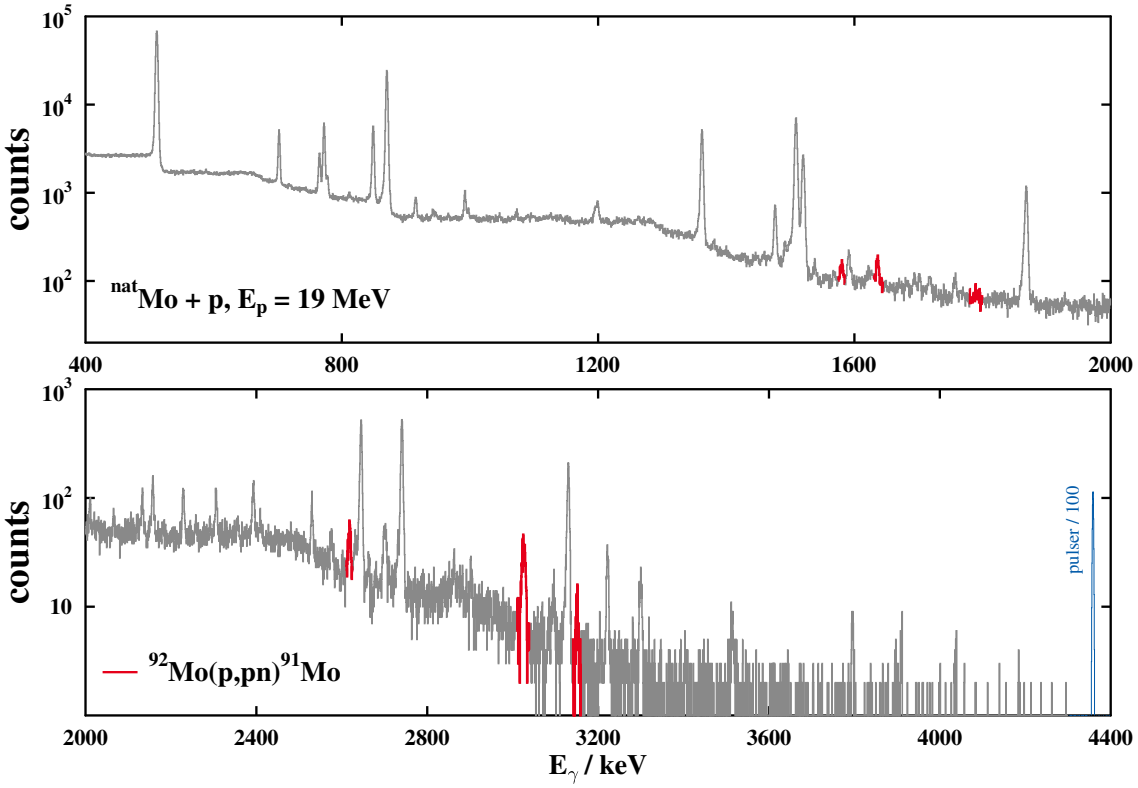

Figure 3: Spectrum of a naturally composed molybdenum target shortly after the 15 minutes proton irradiation with $E_p = 19$ MeV. Red marked peaks correspond to the decay of ^{91}Mo. Most of the other peaks result from the decay of ^{94}Tc, produced, *e.g.*, by the ^{94}Mo(p, n) reaction.

4. Outlook

After the determination of the production cross sections, the next step will be the production of ^{91}Nb. In parallel, the investigation of a way to separate the niobium from the molybdenum matrix takes place at PSI, Villingen, Switzerland. At the same time the FRANZ facility at Frankfurt

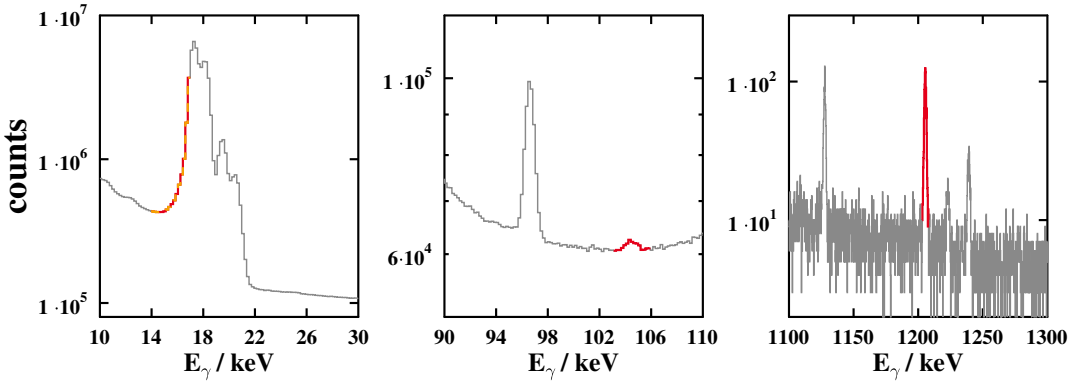

Figure 4: Details of the spectrum of a naturally composed molybdenum target two months after the activation with $E_p = 15\,MeV$. Red marked peaks correspond to the decay of the isomer, while the yellow range indicates the energy range which shows the decay of the ground state of ^{91}Nb. The other peaks mainly result from the decays of the long-lived technetium isotopes. This spectrum was measured for 72 hours.

a. M., Germany, is finalized. Aspects of focusing the high-current beam, cooling the target and beam diagnostics are currently studied to optimize the experimental area. For more details, see the contribution by K. Sonnabend in this volume.

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