EPJ Web of Conferences **93**, 02021 (2015)
DOI: 10.1051/epjconf/20159302021

Investigation of the reaction ^{90}Zr(p,γ) with in-beam γ-ray spectroscopy

Philipp Erbacher[1,a], A. Endres[1], J. Glorius[1,3], L. Netterdon[2], K. Sonnabend[1], B. Thomas[1], and A. Zilges[2]

[1] Institut für Angewandte Physik, Goethe Universität Frankfurt am Main, D-60438 Frankfurt a. M., Germany
[2] Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany
[3] GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany

Abstract. The *p* nucleus ^{92}Mo is believed to be mainly produced through photodisintegration reactions in type II supernovae. However, this production scenario cannot solely account for the observed solar relative isotopic abundance of ^{92}Mo. Additional production scenarios have been suggested to explain this discrepancy. One of these scenarios could be the production of ^{92}Mo in type Ia supernovae via a chain of proton-capture reactions. To verify this scenario, an accurate knowledge of the involved reaction rates is important. We measured the cross section of ^{90}Zr(p,γ) reaction using an enriched ^{90}Zr target by means of in-beam γ-ray spectroscopy in the energy range between 3.6 MeV and 5.1 MeV. Since the reactions ^{90}Zr(p,γ) and ^{91}Zr(p,n) produce the same nucleus, the contributions of both reactions have to be disentangled. This procedure is explained in this contribution in detail.

1 Introduction

The elements heavier than iron are mainly produced by neutron-capture reactions within the *s* and *r* processes [1, 2]. Even so there are about 35 isotopes, called the *p* nuclei, that are shielded from the *s* and *r* processes by stable or long lived isotopes which have to be produced by other processes [3]. These nuclei are believed to be produced by a number of processes including the so-called γ process [4]. While the relative abundances of most *p* nuclei can be explained by the γ process, it cannot explain the high isotopic abundance of $I_{\%} = 14.84\%$ of the *p* nucleus ^{92}Mo [5]. Depending on the network calculations, the prediction for the production of ^{92}Mo is more than one magnitude below the expected value. To explain this discrepancy, an additional production mechanism in type Ia supernovae was proposed [6, 7]. ^{92}Mo is produced via a chain of proton-capture reactions including the reaction ^{90}Zr(p,γ). The in-beam γ-ray spectroscopy technique was used to measure the corresponding cross section.

2 In-beam γ-ray spectroscopy of ^{90}Zr

The radiative proton-capture cross section of ^{90}Zr was measured using high-resolution in-beam γ-ray spectroscopy. In order to determine the production cross section for an energy level *i* in ^{91}Nb, the γ-yield for all transitions feeding level *i* has to be determined. Since ^{91}Nb has an isomeric state at 104.62 keV [8], the total cross section for the reaction ^{90}Zr(p,γ) can be obtained by summing up all transitions feeding the ground and isomeric state (except the transition from the isomeric state to the ground state).

The target was enriched to 97.65(10)% in ^{90}Zr. It contained 0.96(5)% of ^{91}Zr. Above a proton energy of 2 MeV [8], the reactions ^{90}Zr(p,γ) and ^{91}Zr(p,n) produce ^{91}Nb nuclei. In order to disentangle the contribution of these reactions, a second target with different enrichments (^{90}Zr: 5.99(10)%, ^{91}Zr: 89.20(10)%) was investigated at each proton energy. All emitted photons in an in-beam experiment follow an angular distribution. In order to obtain the number of γ-rays emitted in 4π, the γ-yield was measured at five angles ϑ relative to the proton-beam axis.

3 Disentangling the contributions of the reactions ^{90}Zr(p,γ) and ^{91}Zr(p,n)

The measured counts $N^{j\to i}_{\mathrm{p}\gamma+\mathrm{pn}}(\vartheta)$ for a transition from energy level *j* to energy level *i* in ^{91}Nb, containing contributions from the reactions ^{90}Zr(p,γ) and ^{91}Zr(p,n) is given by the expression:

$$\begin{aligned} N^{j\to i}_{\mathrm{p}\gamma+\mathrm{pn}}(\vartheta) &= N^{j\to i}_{\mathrm{p}\gamma}(\vartheta) + N^{j\to i}_{\mathrm{pn}}(\vartheta) \\ &= (\sigma^{j\to i}_{\mathrm{p}\gamma} W^{j\to i}_{\mathrm{p}\gamma}(\vartheta) I^{1}_{\mathrm{p}\gamma} + \sigma^{j\to i}_{\mathrm{pn}} W^{j\to i}_{\mathrm{pn}}(\vartheta) I^{1}_{\mathrm{pn}}) \epsilon_\gamma(E) m_{\mathrm{T}} N_{\mathrm{p}} \\ &= (\sigma^{j\to i}_{\mathrm{p}\gamma}(\vartheta) I^{1}_{\mathrm{p}\gamma} + \sigma^{j\to i}_{\mathrm{pn}}(\vartheta) I^{1}_{\mathrm{pn}}) \epsilon_\gamma(E) m_{\mathrm{T}} N_{\mathrm{p}} \qquad (1) \end{aligned}$$

$W^{j\to i}_{\mathrm{p}\gamma}(\vartheta)/W^{j\to i}_{\mathrm{pn}}(\vartheta)$: angular distribution
$\sigma^{j\to i}_{\mathrm{p}\gamma}/\sigma^{j\to i}_{\mathrm{pn}}$: cross section of the transition $j\to i$
$I^{1}_{\mathrm{p}\gamma}/I^{1}_{\mathrm{pn}}$: relative isotopic abundance of ^{90}Zr and ^{91}Zr
$\epsilon_\gamma(E)$: detector efficiency
m_{T}: area density of the Zr target.

Since this equation contains two unknown parameters, $\sigma^{j\to i}_{\mathrm{p}\gamma}(\vartheta) = \sigma^{j\to i}_{\mathrm{p}\gamma} W^{j\to i}_{\mathrm{p}\gamma}(\vartheta)$ and $\sigma^{j\to i}_{\mathrm{pn}}(\vartheta) = \sigma^{j\to i}_{\mathrm{pn}} W^{j\to i}_{\mathrm{pn}}(\vartheta)$, the cross section for the transition $\sigma^{j\to i}_{\mathrm{p}\gamma}(\vartheta)$ cannot be

---

[a] e-mail: philipp.erbacher@stud.uni-frankfurt.de

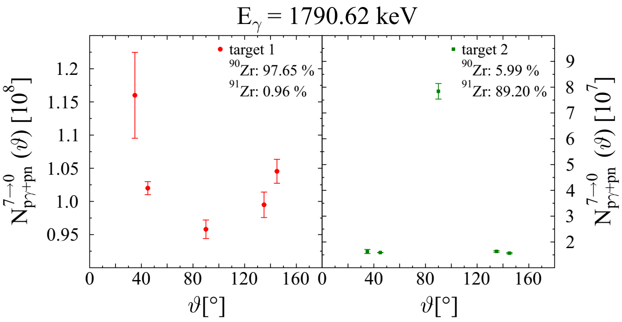

Figure 1. Two targets with different enrichments were measured. The efficiency-corrected γ-yields are depicted in ^{90}Zr and ^{91}Zr, respectively. The angular distribution differs exceedingly between both targets due to different entry states of the reactions.

obtained from one measurement alone. For this reason, a second target with different enrichments $I^2_{p\gamma}$ and I^2_{pn} was measured. The observed γ-yields for the transition from the seventh excited state of ^{91}Nb to the ground state with a γ-ray energy $E_\gamma = 1790$ keV are shown for both targets in Fig. 1. The angular distribution varies vastly between both targets due to the population of different entry states of both reaction resulting from their different Q-values. Using Eq. (1) for both measurements, an equation for $\sigma^{j\to i}_{p\gamma}(\vartheta)$ can be derived for all observed transitions:

$$\sigma^{j\to i}_{p\gamma}(\vartheta) = \frac{N^{x\to i,1}_{p\gamma+pn}(\vartheta)}{\epsilon_\gamma m^1_T N^1_p} - \frac{N^{j\to i,2}_{p\gamma+pn}(\vartheta) I^1_{pn}}{\epsilon_\gamma m^2_T N^2_p I^2_{pn}} \Big/ \left(I^1_{p\gamma} - \frac{I^2_{p\gamma}}{I^2_{pn}} I^1_{pn} \right). \quad (2)$$

Equation (2) was used to obtain the contribution $\sigma^{j\to i}_{p\gamma}(\vartheta)$ of the reaction ^{90}Zr(p,γ) for all transitions. Figure 2 shows the result again for the transition from the seventh excited state of ^{91}Nb to the ground state. The cross section $\sigma^{7\to0}_{p\gamma}$ can be obtained by fitting a sum of Legendre polynomials:

$$\begin{aligned}\sigma^{7\to0}_{p\gamma}(\vartheta) &= \sigma^{7\to0}_{p\gamma} W^{7\to0}_{p\gamma}(\vartheta)\\ &= \sigma^{7\to0}_{p\gamma}\left[1 + \sum_k \alpha_k P_k(\cos\vartheta)\right] \quad (k = 2, 4...) \quad (3)\end{aligned}$$

to the data to account for the angular distribution $W^{7\to0}_{p\gamma}(\vartheta)$ of the emitted γ-rays [9]. The maximum value of k depends on the multipolarity of the γ-rays. Electromagnetic transitions in atomic nuclei are generally dominated by dipole and quadrupole transitions, hence, $k = 4$ was chosen as maximum value for k. It can be shown that the integral of $W^{7\to0}_{p\gamma}(\vartheta)$ over the whole solid angle is one. Therefore, the equation

$$\sigma^{7\to0}_{p\gamma} = \sigma^{7\to0}_{p\gamma} \underbrace{\int_0^\pi [1 + \alpha_2 P_2(cos\vartheta) + \alpha_4 P_4(cos\vartheta)]\, d\vartheta}_{=1} \quad (4)$$

yields $\sigma^{7\to0}_{p\gamma}$. Fig. 2 shows the result for this fit to the data. This method was used for all transitions with contributions of both reactions.

The total cross sections for all measured proton energies are shown in the contribution of A. Endres *et al.* in this volume.

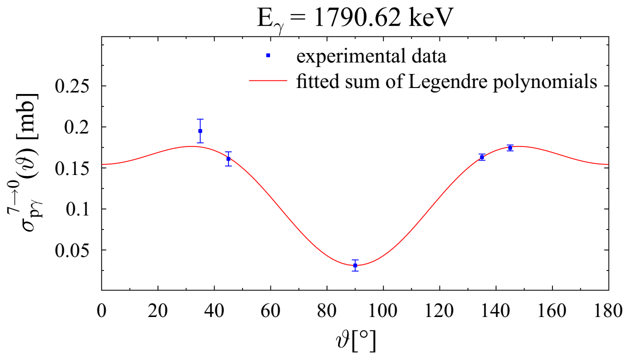

Figure 2. The contribution of the reaction ^{90}Zr(p,γ) for the transition $\sigma^{7\to0}_{p\gamma}$ from the seventh excited state to the ground state was calculated using Eq. (2). Fitting the data by a sum of Legendre polynomials yields the cross section for the transition.

Acknowledgments

We thank the group of A. Zilges and the accelerator staff at the Institute for Nuclear Physics of the University of Cologne, Germany for their enormous support during the beam time. This work is supported by Deutsche Forschungsgemeinschaft (SO907/2-1) and by the HIC for FAIR within the framework of LOEWE. J. G. acknowledges support by Nautilus.

References

[1] F. Käppeler, R. Gallino, S. Bisterzo, W. Aoki, Rev. Mod. Phys. **83**, 157 (2011)
[2] M. Arnould, S. Goriely, K. Takahashi, Phys. Rep **450**, 97 (2007)
[3] D. Lambert, Astron. Astroph. Rev. **3**, 201 (1992)
[4] M. Arnould, S. Goriely, Phys. Rep. **384**, 1 (2003)
[5] P. De Bièvre, P. Taylor, Int. J. Mass Spectrom. Ion Phys. **123**, 149 (1993)
[6] M. Kusakabe, N. Iwamoto, K. Nomoto, Astrophys. J. **726**, 25 (2011)
[7] C. Travaglio, F. Röpke, R. Gallino, W. Hillebrandt, Astrophys. J. **739**, 93 (2011)
[8] C.M. Baglin, Nuclear Data Sheets **114**, 1293 (2013), online version (http://www.nndc.bnl.gov, July 23, 2014)
[9] H. Morinaga, T. Yamazaki, *In-beam gamma-ray spectroscopy* (North-Holland Publishing Company, 1976)