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Referee report on the doctoral thesis of M.Sc. Aleksandra Gawlik,
Radiative neutron capture cross section measurement of ^{70}Ge at the n_TOF CERN *facility and its relevance for stellar nucleosynthesis*

The understanding of the origin of the heavier elements is one of the key aspects of modern nuclear astrophysics. Elements heavier than iron/nickel are produced mostly in a network of neutron-capture reactions starting with a seed nucleus. In stellar environments with relatively-low neutron densities, i.e. such that the lifetime for capturing a neutron is longer than that for the competing beta-decay, nucleosynthesis beyond iron proceeds through a network of neutron-capture and subsequent beta decay, in the so-called slow (s-) process. The modelling of the s-process and determination of the abundances for the various elements and isotopes, requires as input a wealth of data on the properties of the nuclei involved. Such data, like e.g. neutron-capture probabilities, half-lives, nuclear masses, etc., should be obtained experimentally, where possible.

The work presented in the doctoral thesis under evaluation here was conducted in the framework of a large international effort to provide astrophysicists with reliable experimental information to serve as input for their modelling of astrophysical/nucleosynthesis processes. The n_TOF facility at CERN, where these studies were performed, has been providing crucial data on (n,γ) reactions for astrophysics since its coming into operation almost 20 years ago. In general, considerable progress has been made in recent years, both from the experimental and theoretical point of view. Nevertheless, several important open problems remain, which present intriguing challenges for theory and experiment. The work described by M.Sc. Aleksandra Gawlik in her doctoral thesis addresses one of these open questions. It presents in fact the detailed study of the radiative neutron-capture reaction ^{70}Ge(n,γ)^{71}Ge for a broad range of neutron energies, ranging from thermal to 300 keV, hence covering the whole energy interval of astrophysical interest, study that was performed at n_TOF. Radiative neutron-capture on ^{70}Ge has a significant role on the production of elements from germanium to strontium. Another interesting aspect of this isotope of germanium is that it is an "s-only" nucleus, i.e. it is produced only by the s-process and not by the competing rapid (r-) process, which takes place in those stellar environments in which the neutron density is large. Until this study was performed, not much was known about this reaction.

The doctoral thesis of M.Sc. A. Gawlik is composed of 95 pages and is subdivided into 6 chapters, an abstract, conclusions, the bibliography and the list of publications of the Author.

In chapter 1 the author presents a comprehensive introduction on the physics context for her studies, namely nucleosynthesis in stars and the origin of the elements in the Universe, in particular those heavier than iron,

In chapter 2 an exhaustive summary on the physics of neutron-induced reactions is given, with a focus on those of relevance in this work, i.e. radiative neutron-capture. Radiative neutron-capture reactions are introduced and the mathematical formulation used to deduce the capture cross-section is detailed. The principles of R-matrix formalism, which is used to describe the interaction of the neutron with the nucleus, are clearly explained. The same holds for the formalism to determine the (Maxwellian-) averaged capture cross-section, which is later used for expressing the main results of the Author's work.

In chapter 3 the experimental facility and set-up are introduced. The chapter commences with a brief description of the CERN accelerator complex, with the localisation of n_TOF within it. The production method at n_TOF spallation source is described and the experimental areas available at n_TOF are described. Particular accent is given to the experimental hall EAR-1, where the experiment subject of this work took place. The chapter continues with a detailed description of how the neutron flux is obtained and monitored during the months-long data taking phases. The description of the neutron beam characteristics includes the explanation of the energy-resolution function for the n_TOF spectrometer. This is a crucial property to be understood when determining cross-sections, in particular for resonance-type behaviour. Last but not least, the detection set-ups available at n_TOF for both beam monitoring and for the actual measurement are described and the choice of C_6D_6 detectors for the ^{70}Ge(n,γ) experiment is well motivated.

In chapter 4 a description of the ^{70}Ge(n,γ) measurement is presented. The chapter starts with an exhaustive motivation for choosing to investigate this particular reaction. After this the target sample composition and preparation are presented and a description of the measurement details, including the set-up, is given.

In chapter 5 a thorough description of the data analysis procedure is given. It starts with a detailed presentation of the detector calibration procedure and meticulous explanation of the analysis techniques, weighting function and time-of-flight. A crucial aspect of the data analysis is the issue of background determination. A comprehensive analysis of the background was performed. After this more "preparatory" aspect, though essential, of the data analysis, the steps between neutron-capture yield and cross-section determination are detailed, ranging from a clear description of the formalism to the normalisation and neutron-capture yield determination. The chapter is concluded by a presentation of the SAMMY fitting software, used to evaluate the neutron cross-sections over a broad range of energies, from resonances in the resolved-resonance region for lower neutron-energies to the unresolved resonance region at higher neutron energies.

In chapter 6 the final results obtained by the Author in her work for ^{70}Ge(n,γ) cross-sections are presented. The data collected for the broad neutron-energy range between thermal and 300 keV are subdivided into two groups: resolved resonance region (thermal to 25 keV incident neutron energies), for which the the cross section is given in terms of the calculated resonance parameters, and unresolved resonance region (25 keV to 300 keV), for which the Maxwellian averaged cross-section was determined, corresponding to the energies of astrophysical interest from 5 $k_B T$ to 100 $k_B T$. Before M.Sc. Aleksandra Gawlik's work the data available in literature for the ^{70}Ge(n,γ) reaction were very limited and the experimental information on the cross sections has been significantly increased by her work.

The thesis is completed by a concise but exhaustive summary and conclusions, a rich bibliography comprising 67 items and a list of publications for M.Sc. Aleksandra Gawlik. It is important to note that the work presented in her doctoral dissertation has been submitted for publication in Physical Review C with M.Sc. Aleksandra Gawlik as main author.

The thesis is written in good English, with proper choice of vocabulary.

I have some comments/questions to the work presented by the Author, which I would like to propose for discussion during the defence of the thesis. These do not influence my very good opinion on the work presented by M.Sc. A. Gawlik in her doctoral thesis.

In section 3.1, at page 29, the two experimental areas at n_TOF are described. It would be interesting to know the energy range and resolution for both EAR-1 and EAR-2.

Figure 3.3 shows the simulated flux for different particles produced in the spallation of the proton beam. Was the simulation done for 20 GeV protons?

At page 30 collimators and the filtering station are introduced. What are the materials used for collimation? Black resonances are also mentioned for the first time, in the important context of the filtering station. They are well explained in chapter 5, nevertheless a brief definition is missing at this point.

Table 3.1. reports the neutron time-of-flight facilities operating worldwide and their main characteristics. The ORELA facility at Oak Ridge National Laboratory (USA) is no longer in operation, it was closed several years ago (Ref. [23] was probably published earlier).

Since the neutron flux (and the data) is normalised to the proton pulse, I am curious on how is the proton-beam pulse-intensity at the target (and its uncertainty) determined and whether it is provided by CERN or measured by the n_TOF collaboration.

Page 34 (Sec. 3.2), end of page, "next section" is actually Section 3.4. Similarly, at page 53, "next section" (Sec. 5.2.2) refers to section 5.5.

The broadening of the time distribution for the neutrons described in Sec. 3.4 due to the moderator at the target and the doppler effect is explained and determined through Monte Carlo simulations. Are these included in the neutron-flux shape uncertainty (Table 6.4)?

Table 5.1 summarises the resolution and energy coefficients, but does not give any uncertainty on them.

The SiMon detector is placed in the beam at which distance from the set-up? Are neutrons scattered off the SiMon detector influencing the background at the C_6D_6 measuring station?

As far as the editorial aspects of M.Sc. A. Gawlik's dissertation thesis are concerned, the text is aided by abundant number of figures and tables. The figures are large, easily readable and clear, with a good choice of fonts and colour schemes. There are a couple of exceptions to this: Figure 5.8 displays apparently the same colours for *Ge dedicated (parasitic)* and *beamoff dedicated (parasitic)* curves, while Figures 5.7, 5.11 and 5.16 are unnecessarily split over two pages.

Acronyms should be defined once, when first met and later be used exclusively in the text. An example is the proton synchrotron (PS) met for the first time at page 27 and defined later in more than one place.

I found some typos and language imperfections, which I don't find necessary listing, that do not impact/affect the reception/quality of the work.

Summarising, the work presented in M.Sc. Aleksandra Gawlik's thesis comprises original results on radiative neutron-capture cross-section measurements of ^{70}Ge at n_TOF. The measurement spanned over a wide range of energies, covering the whole energy range of astrophysical interest within the framework of the *s*-process nucleosynthesis, much broader than the energy range investigated in previous experiments. Many new resonances ($\sim$70) were observed and described in her work between thermal energies and 25 keV, where the resonances are well resolved, in addition to the few already known, and many also in the less resolved region up to 40 keV. Prior to her work no resonances were observed above 10 keV, and only unresolved cross-section was given for energies larger than 10 keV. Moreover, she determined the Maxwellian averaged cross-section for the neutron-energy range 25-300 keV extending the previously studied range by several tens of keV. It will be very interesting to see the impact of the ^{70}Ge(n,γ) cross-sections on the s-process abundance predictions.

The doctoral thesis "Radiative neutron capture cross section measurement of ^{70}Ge at the n_TOF CERN facility and its relevance for stellar nucleosynthesis" presented by M.Sc. Aleksandra Gawlik fulfils the requirements for doctoral thesis and I therefore ask for admission of M.Sc. Aleksandra Gawlik to the next steps of the doctoral dissertation.

Chiara Mazzocchi