EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

The $^{140}\text{Ce}(n,\gamma)^{141}\text{Ce}$ reaction at n_TOF-EAR1: a litmus test for theoretical stellar models

08 January 2018

S. Amaducci$^{1,2}$, L. Cosentino$^1$, S. Cristallo$^{1,3}$, P. Finocchiaro$^1$, M. Igashira$^4$, T. Katabuchi$^4$, A. Manna$^{1,5}$, C. Massimi$^{1,3}$, A. Mengoni$^{1,6}$, L. Piersanti$^{1,3}$, G. Vannini$^{1,3}$, I. Roederer$^7$ and the n_TOF Collaboration

1 National Institute for Nuclear Physics - INFN, Italy
2 University of Catania, Italy
3 National Institute for Astrophysics, Italy
4 Tokyo Institute of Technology, Japan
5 University of Bologna, Italy
6 Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile - ENEA, Italy
7 Department of Astronomy, University of Michigan 1085 S. University Ave., Ann Arbor, MI 48109, USA

Spokesperson(s): S. Cristallo (sergio.cristallo@inaf.it), C. Massimi (massimi@bo.infn.it) and A. Mengoni (alberto.mengoni@cern.ch)

Technical coordinator: O. Aberle (oliver.aberle@cern.ch)

Abstract

Evolutionary stellar models need nuclear input data as much accurate as possible. This holds in particular for nucleosynthesis calculations involving the production of nuclei heavier than iron. The case of $^{140}\text{Ce}$ (88% of solar cerium) is particularly interesting, because of its very small neutron capture cross section, due to its closed shell nuclear structure. Cerium is mostly synthesized by the slow neutron capture process (the s-process). It has been carefully characterized in laboratory and observed in almost all stellar evolutionary phases. Currently, stellar models and observations of s-process enriched stars belonging to galactic globular clusters well agree for elements belonging to the 2nd s-process peak (Ba-La-Ce-Pr-Nd), except for cerium. The re-evaluation of its neutron capture cross section is needed to verify the robustness of theoretical predictions, possibly solving the only remaining discrepancy.

Requested protons: $2.9 \times 10^{18}$ protons on target

Experimental Area: EAR1
SCIENTIFIC MOTIVATIONS

Stars were recognized since sixty years ago as the cauldrons where matter becomes complex, starting with the light nuclei left by the Big Bang [1,2]. Stellar nucleosynthesis has then developed into a sophisticated discipline at the crossing of Nuclear Physics, Chemistry and Astronomy, exploiting results from theoretical stellar models with growing complexity.

![Figure 1. Observed isotopic solar distribution (upper panel) and corresponding neutron capture cross sections (lower panel). The three s-process peaks are indicated. Previous n_TOF measurements are also highlighted.](image)

The chemically enriched winds of Asymptotic Giant Branch (AGB) stars, together with Supernovae and neutron mergers events, are the major polluters of the Inter-Stellar Medium [3]. The AGB evolution is characterized by a sequence of alternate burning and mixing episodes, which carry to the stellar surface the nuclear products freshly synthesized in the interiors. In those objects, isotopes heavier than $^{56}$Fe are synthesized via the slow neutron capture process (the so-called s-process), whose path extends up to lead and bismuth [4]. In order to verify the robustness of nucleosynthesis stellar models, the uncertainties deriving from input nuclear physics have to be minimized. Thus, neutron capture cross sections are of paramount importance to this end. In the upper panel of Fig. 1 we report the isotopic observed solar abundances distribution: beyond $A=80$ many peaks are clearly visible. Three of them are related to the s-process and correspond to nuclei with a magic number of neutrons (50, 82 and 126). Due to their particularly stable nuclear configurations, those isotopes have very small neutron capture cross sections (see the lower panel). They are bottlenecks along the s-process path and, therefore, a precise knowledge of their neutron capture cross sections is mandatory in order to accurately model their synthesis and reproduce the observed abundances. At n_TOF, the neutron cross sections of two magic nuclei, $^{90}$Zr [5] and $^{139}$La [6], have already been studied and results are published. In addition, the cross sections of two additional isotopes, $^{88}$Sr and $^{89}$Y, are currently under investigation. We propose to continue this program with the measurement of $^{140}$Ce$(n,\gamma)^{141}$Ce cross-section. Note that its neutron capture cross section has recently been shown to be among the most influent nuclear reactions for the s-process nucleosynthesis [7]. Moreover, cerium is of particular interest because its abundance has been measured by different groups [8,9], together with other s-process dominated elements, in representative samples of stars belonging to the galactic globular clusters M4 and M22 (14 and 6 stars, respectively). Those stars have been polluted in the past by a population of already extinct AGBs. The comparison between observations and theoretical models has been presented by [10]. Their analysis found a very good agreement for elements belonging to the 2nd s-process peak (Ba-
La-Pr-Nd), with the notable exception of cerium (Ce, Z=58), whose theoretical surface prediction is lower than observed data (see Fig. 2). Cerium has been carefully characterized in laboratory [11]; therefore, its measurement and, in particular, its differential abundance with respect to neighboring elements, is trustworthy. A possible solution for the discrepancy between observations and models rely in the nuclear destruction/production channels of $^{140}\text{Ce}$, which represents 88% of the solar cerium. The production channel, i.e. the neutron capture on $^{139}\text{La}$ (together with the following $\beta$ decay) has already been explored by the n_TOF collaboration [6]. Here, we propose to study its destruction channel, i.e. the neutron capture on $^{140}\text{Ce}$. The precise knowledge of this neutron capture cross section and of the corresponding uncertainties is fundamental to (possibly) solve the afore-mentioned discrepancy. Preliminary AGB nucleosynthesis calculations indicate that a reduction of 50% of the $^{140}\text{Ce}$ neutron capture cross section would lead to a 50% enhancement of its surface abundance. This variation would completely remove the discrepancy between theory and observations.

Cerium isotopes with mass number around 140 are fragments largely produced in fission processes. In the thermal fission of $^{235}\text{U}$, the $^{140}\text{Ce}$ cumulative yield exceeds 6%. In case of $^{239}\text{Pu}$ fission induced by fast neutrons, the $^{140}\text{Ce}$ cumulative yield is in excess of 5% and this isotope has been considered a candidate for fission monitoring. In addition, Cerium isotopes are involved in feasibility studies of transmutation systems where rare-earth elements are difficult to separate from minor actinides (Am, Cu and higher elements) and, therefore, their neutron capture cross sections become increasingly important for design studies of minor actinides burning reactor cores.

Research and development in the field of nuclear instrumentation and detection techniques is focusing on CeBr$_3$ and LaBr$_3$ (5% Ce) scintillators because of their good energy resolution and high detection sensitivity to $\gamma$-ray.

Both nuclear technological applications can benefit from a better and more precise knowledge of the interaction between neutrons and $^{140}\text{Ce}$, as its cross section determines the destruction rate of $^{140}\text{Ce}$ and the background induced by $\gamma$-rays originating from the neutron-capture in Cerium-based scintillator respectively.
STATUS OF THE DATA

As $^{140}$Ce is a neutron-magic nucleus, the level density observed just above the neutron separation energy at 5.428 MeV is extremely low, with a level spacing of the order of 3 keV for s-wave and 1.2 keV for p-wave states. The neutron-capture cross section for energies of interest here is very low and strongly influenced by individual resonances. For instance, as illustrated in Fig. 3, the contribution of the first resonance at 2.5 keV neutron-kinetic energy to the stellar cross section is sizable, and can be as high as 20% at the temperature of $kT = 8$ keV.

Experimental data on this isotope are scarce. Capture data below $E_n=3$ keV are only reported as private communication in evaluated nuclear data files. At higher neutron energies, a time-of-flight measurement by Musgrove and collaborators [12] at the ORELA facility is present in literature. In this measurement $C_6F_6$ detectors were used. It is now well known that this scintillator detector is not particularly suited for $(n, \gamma)$ measurements on isotopes characterized by very high elastic-to-capture cross section ratio. Another capture measurement in the keV region [13] was performed at the Research Laboratory for Nuclear Reactors at the Tokyo Institute of Technology. The energy resolution of the facility did not resolve resonance structures. The main information on the resonance cross section is provided by transmission experiments i) on a $^{141}$Ce sample [14], although the signal is dominated by the abundant $^{142}$Ce isotope, since its total cross section is higher and ii) by Camarda [15] in a limited energy region ($20$ keV $< E_n < 240$ keV) and using a $^{140}$CeO$_2$ powder sample. It is worth noticing that activation measurements on $^{140}$Ce are reported in literature, but they were measured only for neutron spectra corresponding to temperatures of around $kT=25$ keV (see for instance Ref. [16] and references therein) and extrapolations at lower temperatures largely differ from the stellar cross section deduced from resonance parameters.

![Figure 3. Contribution of the first resonance at $E_n=2.5$ keV to the MACS as a function of the stellar temperature.](image)

PROPOSED $^{140}$Ce$(n,\gamma)^{141}$Ce MEASUREMENT AT THE n_TOF EAR-1

For the detection of the prompt $\gamma$-rays resulting from the capture events, i.e. the electromagnetic cascade produced in the de-excitation of the compound nucleus formed in $(n, \gamma)$ reactions, we propose to use the optimized $C_6D_6$ liquid scintillator detector, described in ref. [17]. They are characterized by lower neutron sensitivity than the alternative capture detector available at n TOF, i.e. the 4π BaF$_2$. This is a main advantage when the elastic channel dominates over the reaction channel, as in the case of $^{140}$Ce where the capture cross section is about 4 orders of magnitude lower than the elastic one. In addition, the $C_6D_6$ detector does not suffer from the so-called $\gamma$-flash (the prompt signal caused in the detector by spallation $\gamma$-rays and relativistic particles), which blinds the detector for few microseconds. Therefore, the proposed measurements can be safely carried out in the energy
region of interest (eV to MeV). This is an important aspect since the $\gamma$-flash in the $4\pi$ BaF$_2$ detector currently limits the energy range up to less than 100 keV.

The capture cross-section of the stable $^{140}$Ce isotope will be measured with an array of 4 C$_6$D$_6$ scintillators at the n TOF EAR-1, exploiting the total energy system based on the so-called pulse height weighting technique. The only drawback is that the reduced energy resolution of the C$_6$D$_6$ detector does not permit to distinguish capture events by their different binding energies and, therefore, the measurement on a highly-enriched sample becomes fundamental for the accuracy of the final result.

As in many of the n_TOF experiments, the availability, preparation and characterization of suitable samples is rather important for the success of the measurement. In the present case we can profit from the capabilities of the National Isotope Development Center – USA, which has demonstrated to be able to prepare highly-enriched samples (abundance > 99%) in the form of self-sustaining metallic disc, thus reducing the impact of the background introduced by the sample container. In alternative, the same oxide sample used in the measurement described in Ref. [13] can be used, after appropriate studies for the estimation of the background induced by the canning will be performed.

In addition to the cerium sample, a gold sample, a graphite sample and a lead sample will be used for normalization purposes, and to study the background. All samples must have the same dimension, and will be prepared as discs of 1.5 cm radius. As the $^{140}$Ce isotope is characterized by a very small capture cross-section, a challenging signal to background ratio is expected from the proposed measurement. The expected counting rate for a mono-isotopic cerium sample of 4 grams is shown in Fig. 4. The calculation is based on the capture cross section retrieved from JEFF-3.2 [18] and considering a neutron irradiation corresponding to $2\times10^{18}$ protons on the $^{140}$Ce sample.

The quantity of cerium in the samples results from a compromise between the cost of the sample and the need of characterize the resonances with an adequate number of data points (i.e. energy bins per decade).

As in previous C$_6$D$_6$ measurements, the estimation of the different components of the background for the proposed measurement is based on an empty-sample, $\text{nat}^\text{Pb}$ and $^{12}$C measurement. This background study requires a total number of $0.6\times10^{18}$ protons. The normalization of capture data, the validation of the measurement at high energy and the cross-check of the flux stability is achieved by a cyclic measurement of a gold sample with 500 mg. This further study requires a neutron intensity corresponding to $0.3\times10^{18}$ protons. In summary, the total proton request is $2.9\times10^{18}$ protons on target. The final beam share can undergo small changes depending on the preliminary results of the measurement.
CONCLUSIONS

We propose to measure the capture cross section of $^{140}$Ce isotope because of its astrophysical relevance. Cross section data are present in literature in a limited energy region, and no capture data is reported below the neutron energy of 3 keV. This lack makes particular uncertain the MACS at low temperatures and calls for a systematic and accurate study. In this view, a measurement on enriched Cerium sample is proposed at the n_TOF EAR-1 making use of an array of 4 $^{12}$C$_6$D$_6$ detectors. The main objective is study the cross section in order to provided capture data conclusive enough to determine stellar cross sections at kT=8 keV with overall uncertainty below 5%. 2.9x10$^{18}$ protons are requested to successfully complete the measurement.

Summary of requested protons: 2.9x10$^{18}$

References: