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Neutron-induced cross section measurements

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Abstract. Neutron-induced cross sections represent the main nuclear input to models of stellar and Big-Bang nucleosynthesis. While (n,γ) reactions are relevant for the formation of elements heavier than iron, (n,p) and (n,α) reactions can play an important role in specific cases. The time-of-flight method is routinely used at n_TOF to experimentally determine the cross section data. In addition, recent upgrades of the facility will allow the use of activation techniques as well, possibly opening the way to a systematic study of neutron interaction with radioactive isotopes. In the last 20 years n_TOF has provided a large amount of experimental data for Nuclear Astrophysics. Our plan is to carry on challenging measurements and produce nuclear data in the next decades as well.

1 Introduction

The prominent role of neutron-induced reactions in the nucleosynthesis of isotopes with A>60 is well-established. In particular, the slow neutron capture process (the *s* process, see, e.g., [1] and [2]) is responsible for the formation of approximately half of the elemental abundances heavier than iron. It consists of a sequence of neutron radiative captures and β-decays. Starting from a seed distribution around iron, the *s* process builds up elements up to Bismuth. Overall, β-decay rates are faster than neutron capture rates, which means that reactions proceed along the valley of β stability. The *s* process is thought to take place in 2 different scenarios:

- the main component takes place during the asymptotic giant branch (AGB) phase [3–6] of low mass stars ($1.5 \leq M/M_\odot < 4.0$) and, to a lower extent, intermediate mass stars ($4.0 \leq M/M_\odot < 7.0$). Here, a sequence of short convective He-burning runaways (thermal pulses, TPs) and long periods of quiescent H-burning (interpulses) take place.
- the weak component, activated during the core He-burning and C-shell burning of massive stars ($M/M_\odot > 10.0$) largely contributes to abundances between Fe and Zr (e.g. [7]).

Together with β-decay rates, neutron capture cross sections are the basic nuclear physics input to the slow neutron capture process. However, to a minor extent (n,p) and (n,α) reactions on a few light elements can play some role as neutron poisons.

Experimentally, neutron-induced cross section data are determined in two ways:

- time-of-flight (TOF); energy-dependent cross sections $\sigma(E_n)$ are deduced by inferring the neutron energy from the time of flight of the neutron over a certain flight path length. $\sigma(E_n)$ is then averaged over the thermal energy distribution of neutrons inside stars, so to be used in stellar models.
- activation technique; the sample of interest is first irradiated with a continuous neutron beam, and subsequently the activity of the resulting product nucleus is counted. Clearly, this method can be applied only with radioactive products, i.e. provided that neutron captures result in unstable isotopes.

In both cases, the astrophysical reaction rate is extracted, i.e. the number density of interacting particles times the reaction rate per particle pair $\langle \sigma v \rangle$. Since the interacting particles are in thermodynamic equilibrium in a stellar plasma, the relative velocity v can be described by a Maxwell-Boltzmann distribution. Consequently, the reaction rate per particle pair can be expressed in terms of the Maxwellian-averaged cross section (MACS):

$$\mathrm{MACS} = \frac{\langle \sigma v \rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2} \int_0^\infty E\sigma(E) e^{-\frac{E}{kT}dE}, \tag{1}$$

If a cross section can be determined with the TOF method, it is possible to calculate MACSs at all relevant stellar temperatures, i.e from $kT = 8$ keV to $kT = 90$ keV. On the other hand, in case of rare and/or short-lived isotopes it is unlikely to collect few milligrams of mass (i.e., the minimum quantity required for a TOF measurement) as the activity of the sample pose severe constraints. In these cases, an alternative to TOF measurements is the activation method.

2 The n_TOF Facility at CERN

n_TOF is a white spallation neutron source based on the CERN proton synchrotron (PS) accelerator. In particular, neutrons are produced by 20 GeV/c protons impinging onto a massive Pb block, surrounded by a water layer acting as moderator of the initially fast neutron spectrum. The neutron-producing target [8] was conceived to produce a wide neutron energy spectrum at experimental areas [9, 10], ranging from meV to GeV. Two beam lines, EAR1 located at 185 m and EAR2 at 19 m from the neutron-producing target are equipped with detection systems for TOF measurements. In addition, an irradiation station named NEAR was recently built at 3 m from the spallation target. The high peak current of the PS accelerator, with nearly 10^{13} protons per pulse, results in 5×10^5 and 2×10^7 neutrons per pulse delivered to EAR1 and EAR2. In addition to the high instantaneous neutron flux, another important feature is the high resolution in neutron energy (reconstructed from the time of flight). The 185 m long flight path, in combination with the narrow proton-bunch width of 6 ns FWHM, result in an energy resolution $\Delta E/E \approx 10^{-4}$ in the eV region and $\Delta E/E \approx 10^{-3}$ in the keV region.

The n_TOF project has benefited from the close collaboration with other neutron facilities, in particular GELINA [11], at the European Commission Joint Research Center in Belgium and SARAF [12] in Israel. In fact, several cooperative projects were carried out in order to improve the quality of the cross-section data (see for example, the case of ^{197}Au [13–16] or ^{171}Tm [17].)

3 n_TOF: 20 years of nuclear data

In addition to some relevant cases not directly related to the s-process - as for example ^{7}Be(n,α) and ^{7}Be(n,p) [18, 19] of interest to Big Bang Nucleosynthesis, or ^{26}Al(n,p) and ^{26}Al(n,α) [20, 21] essential for understanding the observation of the ^{26}Al γ-ray emitter in our Galaxy - the n_TOF collaboration has investigated different aspects of the s-process: (i) the main neutron sources in Red Giants stars (e.g. [22–25]); (ii) The seeds nuclei for the s-process (e.g.^{58}Ni [26] and ^{62}Ni [27, 28]); (iii) end-point and isotopes with a closed shell configuration (^{204,206,207}Pb [29–31] and ^{209}Bi [32]); (iv) isotopes whose production is entirely ascribed to the s process (e.g. ^{58}Ni [26], ^{70}Ge [33], ^{154}Gd [34] and ^{186}Os [35, 36]); unstable isotopes where β decay competes with neutron capture (e.g.^{63}Ni [37] and ^{171}Tm [17]).

These examples represent a non-exhaustive overview of the n_TOF contribution to nucleosynthesis studies (for more details see [38]). In the near future, n_TOF will perform challenging cross-section measurements exploiting the improved characteristics of the renovated experimental areas EAR1 and EAR2, as well as the new irradiation station NEAR. The recent upgrade of the spallation target, has improved the energy resolution at EAR2 while increasing the instantaneous neutron flux. Therefore (n,γ) cross sections on radiositopes with very short half-life could become feasible either via TOF or activation. In addition, the possibility to produce rare isotopes at other facilities such as ISOLDE and PSI could lead to fruitful collaborations between these different facilities in the future.

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