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Neutron capture cross sections on light nuclei

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Abstract. The neutron capture cross sections on light nuclei (A<56) are important for *s* process scenarios since they act as neutron poisons. Although the cross sections of these nuclei are small, they can still have large effects on the neutron balance during the *s*-process because of their high abundances. Neutron capture cross sections of light nuclei play also a crucial role for the interpretation of abundance patterns in presolar grains. We report on cross section measurements on several light isotopes (^{23}Na, ^{27}Al, ^{41}K, ^{45}Sc), which were performed at the Karlsruhe 3.7 MV Van de Graaff accelerator via the activation method. The results are compared with previous measurements using the time-of-flight method.

Key words. Nuclear reactions, nucleosynthesis, abundances

1. Introduction

The cross sections of light elements are important because they affect the neutron balance inside stars during the *s* process. Although their cross sections are small these elements are much more abundant than those in the mass region above Fe. Therefore, light elements constitute potential neutron poisons and may consume neutrons, which are then not available for *s*-process nucleosynthesis. Especially important in this respect are neutron captures on the CNO elements and on the neon and magnesium isotopes, but also other light isotopes up to iron contribute as well. For many of these isotopes the neutron capture cross sections are not known with sufficient accuracy since they are small and difficult to measure.

Neutron capture cross sections of light isotopes play also an important role for analyses of presolar grains, which can provide stringent constraints on the *s*-process models (Zinner 1998). Because these grains are only a few μm in size and because the abundances of heavy elements are rather low, their isotopic abundance components in the grains are difficult to analyze. Lighter elements are more abundant and, therefore, easier to detect in these grains.

However, the quality of the available (n,γ) data for the light elements is not sufficient for a thorough discussion of these aspects of the *s* process. Fig. 1 shows the present uncertainties of Maxwellian averaged capture cross sections (MACSs) at kT=30 keV. While there are many accurate measurements for heavy nuclei, especially in the rare earth region, the uncertainties for practically all light nuclei are rather large. For some elements, e.g. for selenium and germanium, experimental information is not available at all. For the comprehensive interpretation of the isotopic patterns in presolar grains and for their role as neutron poisons accurate (n,γ) cross sections for light elements are mandatory. Therefore, a measuring campaign was launched at Forschungszentrum

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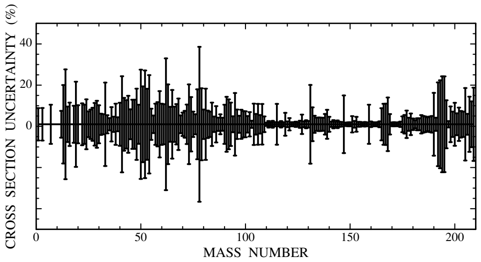

Fig. 1. Uncertainties of Maxwellian averaged neutron capture cross sections at a thermal energy of kT=30 keV.

Karlsruhe with the aim to improve the neutron capture cross sections in this region. In section 2 we describe the activation method, which was used to perform the experiments, and the various measurements. In chapter 3 the new results are compared with previous time-of-flight (TOF) experiments, and the discrepancies between the two methods are discussed before we conclude in chapter 4.

2. Activation measurements and results

A reliable and accurate approach to derive Maxwellian averaged cross sections at kT=25 keV is the activation method (Beer, & Käppeler 1980), where the ^{7}Li(p,n)^{7}Be reaction is used to produce a quasi-stellar neutron spectrum as sketched in Fig. 2. After irradiation in that spectrum the induced sample activity is counted in a low background environment. The proton beam with an energy of E_p=1912 keV and typical intensities of 100 μA was delivered by the Karlsruhe 3.7 MV Van de Graaff accelerator. The neutron production target consists of a metallic Li layer, which is evaporated onto a water cooled copper backing. The sample is placed inside the resulting neutron cone, which has an opening angle of 120 degrees. The neutron flux is monitored throughout the irradiation by means of a ^{6}Li glass detector, positioned at a distance of 83 cm from the target. After the irradiation the total number of activated nuclei A is given by

$$A=\Phi \cdot N \cdot \sigma \cdot f_b \qquad (1)$$

where Φ is the time integrated neutron flux, N the number of sample atoms per cm^2, and σ the spectrum averaged neutron capture cross section. In order to determine the neutron flux, the sample is sandwiched between gold foils. Since the gold cross section is well known, the total number of neutrons can be obtained by the intensity of the 412 keV line from the decay of ^{198}Au. The factor f_b accounts for the variation of the neutron flux and for the decay during activation. The cross section can then be calculated from the number of counts in a characteristic γ-ray line measured by means of HPGe detectors,

$$\begin{aligned} C_\gamma &= A \cdot K_\gamma \cdot \varepsilon_\gamma \cdot I_\gamma \cdot \\ &\quad (1 - exp(-\lambda t_m)) \cdot exp(-\lambda t_w) \qquad (2) \end{aligned}$$

where K_γ is a correction factor for γ-ray self-absorption, ε_γ the efficiency of the Ge-detector, I_γ the line intensity, t_w the waiting time between irradiation and counting, and t_m the duration of the activity measurement. In this way, we have measured the MACSs of ^{23}Na, ^{41}K, and ^{45}Sc at kT=25 keV. For each isotope various samples of different diameter and thickness but also different chemical compounds were used in order to derive reliable cross sections. The preliminary results are summarized in Table 2 together with the previously recommended values (Bao et al. 2000).

2.1. Activation measurements at kT=5 keV

Instead of the ^{7}Li(p,n)^{7}Be reaction, which closely simulates a Maxwellian neutron spectrum at a thermal energy of kT=25 keV, the ^{18}O(p,n)^{18}F reaction can be used as well. At a proton energy of E_p=2582 keV, just 8 keV above the reaction threshold, a Maxwellian neutron spectrum at kT=5 keV can be approximated by this reaction (Heil et al. 2005). Again a simultaneous irradiation of gold foils serves for the neutron flux measurement. The data analysis can be performed in the same way as described for the activation measurement with the ^{7}Li(p,n)^{7}Be reaction. With this technique

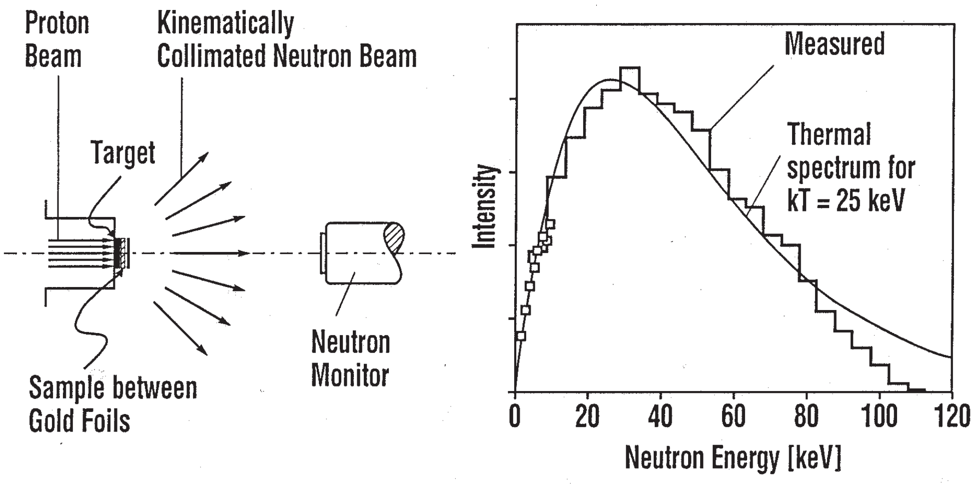

Fig. 2. The experimental setup for activation measurements (left), and a comparison of the produced neutron spectrum and a thermal neutron spectrum at kT=25 keV (right).

Table 1. Preliminary energy dependent MACSs of the ^{23}Na(n,γ) reaction.

Thermal energy (keV)	Bao et al. (mbarn)	This work (mbarn)
5	1.4	10.5
10	5.2	4.0
15	3.4	2.6
20	2.7	2.1
25	2.2	1.7
30	2.1	1.5
40	1.7	1.3
50	1.5	1.2
60	1.4	1.1
80	1.3	0.97
100	1.2	0.88

it was possible to determine the MACS of the ^{23}Na(n,γ)^{24}Na reaction at kT=5 keV to be 10.7±0.6 mbarn. One of the most important input parameters for stellar models of the main s process in thermally pulsing asympthotic giant branch (TP-AGB) stars are MACSs in the temperature range T_8=0.9-3 which corresponds to thermal energies of kT=8-25 keV. In the past, the temperature dependence of the MACSs had to be extrapolated to lower temperatures from the measured values at kT=25 keV. With the ^{18}O(p,n)^{18}F reaction it is now possible to determine the MACSs at kT=5 keV, much closer to the lower temperature limit of the models, thus providing an interpolation between kT=5 and 25 keV with greater reliability. This was especially helpful for ^{23}Na, where the cross section is dominated by three broad resonances at E_n=2.8, 35, and 53 keV. While the activation measurement at kT=25 keV gives constraints on the strength of the two higher lying resonances, the 5 keV value can be used to limit the resonance at 2.8 keV. In this way, temperature dependent MACSs could be calculated with improved accuracy (see Table 1).

2.2. Cyclic activation

For activation measurements with short half-lives of the product nuclei the cyclic activation technique can be applied (Beer et al. 1994). A shielded HPGe detector is positioned close to the neutron production target. The sample is transported from the irradiation position at the neutron production target to the measuring position in front of the HPGe detector with a pneumatic slide. In this way, transfer times

Table 2. Preliminary MACSs in mbarn at kT=25 keV.

Isotope	Bao et al.	This work
^{23}Na	2.2±0.2	1.74±0.08
^{27}Al	4.1±0.3	3.3±0.2
^{41}K	24.7±0.9	22.1±0.2
^{45}Sc	80±7	64±3

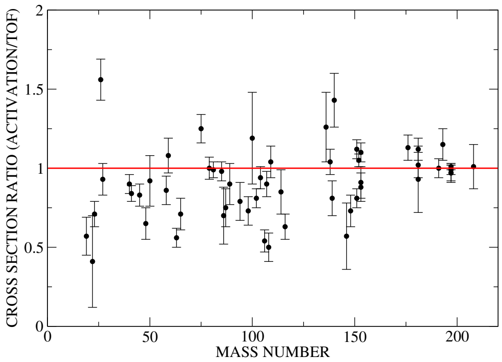

Fig. 3. Comparison of MACSs at kT=30 keV obtained by the activation and TOF method.

of <1 s can be realized and nuclei with short half-lives can be measured. This method was applied for the cross section measurement of ^{27}Al, where the half-life of ^{28}Al after neutron capture is only 135 s. The Al samples with different diameter and thickness were repeatedly activated and subsequently counted for 300 s, respectively.

With the activation methods described above we have measured the MACSs of the four isotopes, which are compared in Table 2 with the previously recommended values (Bao et al. 2000).

3. Discussion

It is striking that all new results are systematically smaller than the recommended cross sections from Bao et al. (2000), which are based on TOF measurements performed with C_6D_6 detectors in the late 70's and early 80's (Musgrove, Allen, & Macklin 1978; Macklin 1984; Kenny, Allen, & Macklin 1977). In fact, this trend is confirmed by a general comparison between MACSs obtained with the activation method and the TOF method performed with C_6D_6 detectors, which reveal large discrepancies on average. The cross sections obtained in activation measurements are consistently lower, often in complete disagreement with the quoted uncertainties. Fig. 3 shows a systematic comparison between MACSs at kT=30 keV obtained with the TOF and the activation method. A possible explanation could be the underestimation of background due to scattered neutrons in old TOF setups. Neutrons, which are scattered on the sample, can be captured in the detector and/or in surrounding materials. This background can be as high as 50% for light nuclei, where the scattering/capture ratio are large. Therefore, the corrections for background from scattered neutrons can introduce large systematic errors.

4. Conclusions

With the activation method we have measured the MACSs of several light isotopes, which constitute possible neutron poisons during *s*-process nucleosynthesis, by using different activation techniques. The obtained cross sections are systematically smaller than previously reported results using the TOF technique in combination with C_6D_6 detectors. It seems that older TOF measurements have underestimated the background due to scattered neutrons. Since this is a systematic effect, which applies to the (n,γ) cross sections of many light nuclei, it will have a strong, cummulative impact on the neutron balance during the *s* process. This problem underlines the urgent need for more accurate (n,γ) cross sections in the mass region A<120.

The implications of a systematic corection to older data needs to be further investigated with respect to the *s* abundances predicted in stellar model calculations of TP-AGB and of massive stars.

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