Investigation of the $^{37}$Ar(n,p)$^{37}$Cl and $^{37}$Ar(n,α)$^{34}$S reactions as a function of the neutron energy

CYRIEL WAGEMANS¹, GERT GOEMINNE¹, JAN WAGEMANS², RONALD BIEBER², MARC LOISELET³, MICHEL GAELENS³, BRUNO DENECKE², PETER GELTENBORT⁴, FILIP KOLEN¹

¹ Dept. of Subatomic and Radiation Physics, RUG, B-9000 Gent, Belgium
² EC, JRC, Institute of Reference Materials and Measurements, B-2440 Geel, Belgium
³ Cyclotron Research Center, UCL, B-1348 Louvain-la-Neuve, Belgium
⁴ Institute Laue-Langevin, B.P.156, F-38042 Grenoble, France

Abstract. The energy dependent $^{37}$Ar(n,p)$^{37}$Cl and $^{37}$Ar(n,α)$^{34}$S reaction cross sections were determined for the first time in an experimental effort involving three large facilities: the cyclotron of the UCL (Louvain-la-Neuve, Belgium) where implanted $^{37}$Ar samples were produced; the high flux reactor of the ILL (Grenoble, France) where thermal (n,p), (n,α0) and (n,α1) cross sections of $(37±4)$ b, $(1070±80)$ b and $(290±50)$ mb respectively could be determined, and the GELINA neutron time-of-flight facility of the IRMM (Geel, Belgium) where strong resonances were observed in the keV region.

1 Introduction

Neutron induced reactions on $^{37}$Ar occur in the weak component of the s-process, where the most relevant neutron energies are situated in the keV range. In order to calculate the Maxwellian averaged cross section in this energy region, the reactions under investigation have to be studied with thermal as well as with resonance neutrons. The thermal value is often used to normalise the higher energy values and besides it is needed in the calculation of the Maxwellian averaged cross section as a summation of the thermal and resonance components[2].

2 Sample Preparation

Samples with a well-defined mass are of great importance to perform reliable reaction cross section measurements, so a lot of effort was put in the preparation and characterisation of suited samples. A detailed description of the procedure is given in[3].

$^{37}$Ar atoms were produced via the $^{37}$Cl(p,n)$^{37}$Ar reaction by bombarding a NaCl target with 30 MeV protons from a cyclotron of the UCL at Louvain-la-Neuve (Belgium). These atoms were then ionised to the $1^+$ state and implanted at 8 keV in a 20 μm thick Al-foil. Different samples were produced, containing $10^{14}$ up to $5 \times 10^{15}$ atoms. These numbers were determined at the IRMM in Geel via the detection of the 2.6 keV KX-rays (emitted in the decay of $^{37}$Ar) with a gas flow proportional counter.

3 Measurements with thermal neutrons

The experiments with thermal neutrons were performed at the end of the 87m curved neutron guide H22 of the High Flux Reactor at the ILL in Grenoble (France). A well-thermalised flux of about $5 \times 10^8$ neutrons/cm$^2$ was available at the sample position.
Figure 1: Measurement of the $^{37}$Ar(n,$\alpha_0$)$^{34}$S reaction with a sample containing $1.84 \times 10^{15}$ $^{37}$Ar atoms.

The $^{37}$Ar samples were mounted in a vacuum chamber together with suited surface barrier detectors, placed outside the neutron beam. A typical charged particle spectrum obtained during a 62 h neutron irradiation of one of the $^{37}$Ar samples is shown in figure 1. The results of these measurements are summarised in table 1. Comparison of our results with those obtained by Ashgar et al. shows that our values for both the (n$_{th}$,α0) and (n$_{th}$,p) cross sections are about two times smaller, which indicates that the discrepancy most likely lies in the determination of the number of $^{37}$Ar atoms in the sample or in the neutron flux determination.

Table 1.

| Reaction             | Q-value (MeV) | Cross section (b) |
|----------------------|---------------|-------------------|
| $^{37}$Ar(n$_{th}$,α0)$^{34}$S | 4.63          | 1070 ± 80         |
| $^{37}$Ar(n$_{th}$,α1)$^{34}$S | 2.50          | 0.29 ± 0.05       |
| $^{37}$Ar(n$_{th}$,γα)$^{34}$S | ≤ 6           |                   |
| $^{37}$Ar(n$_{th}$,p)$^{37}$Cl | 1.60          | 37 ± 4            |

4 Measurements with resonance neutrons

The measurements with resonance neutrons were carried out at a 9 m long flight path of the linear accelerator GELINA of the IRMM in Geel (Belgium), covering a neutron energy range from 10 meV up to 70 keV. The flux determination was done via the well known $^{10}$B(n,α)$^7$Li reaction. An overview of the characteristics of the measurements is given in table 2. In none of the three measuring cycles the (n,p), (n,γα) or (n,α1) reactions were observed, as could be expected from their small thermal values.
In the 100 Hz measuring campaign a 1/v shape of the $^{37}$Ar(n,α0) cross section could be established (figure 2).

A second measuring cycle, with the linac operating at 800 Hz, provided us with cross section data for neutron energies up to 15 keV (figure 2). Two strong resonances were observed at 1.6 keV and at 2.5 keV, with resonance areas of (4 3 ± 9) b.keV and (33 ± 7) b.keV. In a third measuring cycle we used a surface barrier detector mounted in a vacuum chamber and realised good experimental conditions up to 70 keV neutron energy. Here, two smaller resonances were observed at 25 keV and at 40 keV. Resonance areas are in the order of 12 b.keV and 15 b.keV respectively.

5 Maxwellian averaged cross section

The determination of the Maxwellian averaged cross section is based on a formula which calculates the Maxwellian averaged cross section as a sum of the $1/v$ extrapolation of the thermal value and the contributions of the resonances[2]:

$$\langle \sigma \rangle_{kT} = \sigma_{th} \sqrt{\frac{25.3 \times 10^{-6}}{kT}} + \frac{2}{\sqrt{\pi}} \sum_{res} A_{res} \frac{E_{res}}{(kT)^2} \exp \left( -\frac{E_{res}}{kT} \right).$$

In eq. (1) $\sigma_{th}$ is the thermal cross section value in mb, $kT$ the stellar temperature in keV, $E_{res}$ the resonance energy in keV and $A_{res}$ the resonance area in (mb.keV).

Our data result in very large values for the Maxwellian averaged cross section, e.g. 19 b at 2 keV which is 7 times larger than the theoretically calculated one (figure 3).
Figure 3: The Maxwellian averaged cross section for the $^{37}$Ar(n,α)${}^{34}$S reaction

### 6 Conclusion

For the first time neutron induced reactions on $^{37}$Ar were performed, covering a neutron energy range from thermal energy up to 70 keV. Measurements with thermal neutrons were performed at the high flux reactor of the ILL, leading to cross section values for the (n,p), (n,α₀) and (n,α₁) reactions of $(37 \pm 4)$ b, $(1070 \pm 80)$ b and $(290 \pm 50)$ mb respectively. For the (n,α₀) reaction, measurements at the neutron spectrometer GELINA of the IRMM gave evidence for a perfect 1/v shape of the cross section in the low energy region and moreover revealed the existence of four resonances in the region up to 70 keV. The obtained resonance parameters combined with the thermal cross section value lead to very large values of the Maxwellian averaged cross section.

### References

[1] Ashgar M., Emsallem A., Hagberg E., Jonson B. and Tidemand-Petersson P., *Z. Phys* A288 (1978) 45.

[2] Bao Z. and Kappeler F., *Atomic Data and Nuclear Data Tables* 36 (1987) 411.

[3] Wagemans C., Loiselet M., Bieber R., Denecke B., Reher D. and Geltenbort P., *Nucl. Instr. and Meth. A397* (1997) 22.