Measurement and analysis of neutron capture reaction rates of light neutron–rich nuclei

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Abstract

Several neutron capture cross sections of light neutron–rich nuclei were measured in the astrophysically relevant energy region of 5 to 200 keV. The experimental data are compared to calculations using the direct capture model. The results are used for the calculation of neutron capture cross sections of unstable isotopes. Furthermore, neutron sources with energies below $E_n \approx 10$ keV are discussed.

1 Introduction

Contrary to charged–particle reactions neutron–capture reactions can contribute to the nucleosynthesis of light and heavy elements. For the heavy elements $(n,\gamma)$–reactions are the basis of the s– and r–process. In the s–process nucleosynthesis of heavy elements neutron–capture is dominated by the compound–capture mechanism. However, in the r–process scenarios, in the $\alpha$–rich freeze–out, and in the s–process for light nuclei the direct–capture (DC) is important.

Presently the direct capture mechanism can be investigated experimentally only for light nuclei near the border of beta stability. For heavy nuclei direct capture is non–negligible only for nuclei near magic numbers. We have investigated neutron–capture reactions for many neutron–rich target nuclei in the mass region $A = 10–50$ (see Refs. [1]). The measurements were carried out in the thermonuclear energy region at the Karlsruhe 3.75 MV Van-de-Graaff accelerator. Neutrons were produced with the $^7$Li(p,n)–reaction near the reaction threshold giving a quasi–Maxwellian energy spectrum with $kT = 25$ keV and with thin Li–targets at higher energies. The cross sections were determined with the method of fast cyclic activation technique [2]. Additionally,
experiments at thermal energies were carried out at the reactor BR1, Mol, Belgium. In this case also the primary transitions and their branching could be measured.

2 Present Experiments

In this work we extend our studies to neutron energies which cannot be produced by the usual \(^7\)Li(p,n)–reaction. Because of the conservation of momentum lower neutron energies than about 20 keV can only be obtained for target nuclei with negative Q–values for the (p,n)–reaction which are much heavier than \(^7\)Li. We analyzed the (p,n)–reactions of \(^{65}\)Cu, \(^{51}\)V, and \(^{45}\)Sc using the pulsed proton beam and a flight path of 91 cm between the production target and the neutron detector. The neutrons are produced by the resonances close above the (p,n) threshold. For \(^{45}\)Sc we confirmed the result of Ref. [3] that one can obtain practically monoenergetic neutrons at \(E_n = 8.15\) keV at \(\vartheta_{\text{lab}} = 0^\circ\). For \(^{51}\)V we found a new resonance at \(E_n = 4.20\) keV (see Fig. 1) which is too weak to be used as neutron source but strong enough to disturb the monoenergetic spectrum from the \(E_n = 6.49\) keV resonance. For \(^{65}\)Cu the neutron yield is relatively small.

![Figure 1: Neutron TOF spectrum of the reaction \(^{51}\)V(p,n)\(^{51}\)Cr at \(E_p = 1592\) keV, \(\vartheta_{\text{lab}} = 0^\circ\). For the known resonances we agree with Ref. [4], and a new weak resonance was found \((E_n = 4.20\) keV).](image1)

Additionally, a quasi-Maxwellian energy spectrum at \(kT = 52\) keV can be obtained from the \(^3\)H(p,n)–reaction [5]. Recently we used this spectrum to complete our measurement of the neutron capture cross section of \(^{48}\)Ca (see Fig. 2) [7].

![Figure 2: Experimental neutron capture cross section of \(^{48}\)Ca compared to a calculation using the DC model (see Ref. [5]).](image2)

3 Direct Capture Calculations, Reaction Rates

The theoretical analysis was carried out in the framework of the DC formalism [8]. The capture cross section for each final state is determined by the overlap of the scattering wave function \(\chi_l(r)\), the electromagnetic transition operators \(O^{EC,MC}\) and the bound state wave function \(u_{NL}(r)\), and by the spectroscopic factor \(C^2S\) of the final state. The
total capture cross section is given by the sum of all partial capture cross sections:

$$\sigma^{DC} \sim \sum_i (C^2 S)_i \cdot \left| \int \chi_i(r) O^{EL,MC} u_{NL,i}(r) \, d^3 r \right|^2$$  \hspace{1cm} (1)

For the calculation of the relevant wave functions we used folding potentials: $$V(R) = \lambda V_{F}(R) = \lambda \int \rho_a(r_1) \rho_A(r_2) \psi_{\text{eff}}(E, \rho_a, \rho_A, s) \, dr_1 dr_2.$$ For the nucleus $^{48}\text{Ca}$ the depth of the potentials was adjusted to the scattering length (scattering wave) and to the binding energy (bound states) leading to $\lambda$ values very close to unity [5]. The spectroscopic factors can be derived from Eq. (1) with very small uncertainties by comparing the calculated and the experimental capture cross section at thermal energies [5].

For the calculation of the neutron capture cross sections of the unstable Ca isotope $^{50}\text{Ca}$ we can use the results derived for $^{48}\text{Ca}$. The density distribution for $^{50}\text{Ca}$ is obtained from a Hartree Fock calculation. The strength parameter $\lambda$ of the optical potential in the entrance channel is calculated using the same volume integral as for $^{48}\text{Ca}$. The spectroscopic factors of the isotopes $^{49,51}\text{Ca}$ are calculated from the shell model using the code OXBASH [3] and the interaction FPD6 [10]. The excitation energy of the $1/2^-$ state of $^{51}\text{Ca}$ is $E_x = 1.773$ MeV using this interaction.

In Tab. 1 we list spectroscopic factors of $^{51}\text{Ca}$ calculated from the above procedure, and we give reaction rate factors $N_A < \sigma v >$ calculated from the DC model. The calculation of the neutron capture cross section of $^{50}\text{Ca}$ gives somewhat smaller results than in a previous paper [11]. However, the conclusions given in Ref. [11] remain unchanged.

Table 1: Spectroscopic factors $C^2 S$ of $^{51}\text{Ca}$, and capture cross section $\sigma(30 \text{ keV})$ and reaction rate factor $N_A < \sigma v >$ of the reaction $^{50}\text{Ca}(n,\gamma)^{51}\text{Ca}$

| $J^\pi$ | $E_x$ (MeV) | $Q$ (MeV) | $C^2 S$ | $\sigma(30 \text{ keV})$ (mb) | $N_A < \sigma v >$ (cm$^3$ s$^{-1}$ mole$^{-1}$) |
|-------|-------------|-----------|---------|----------------------------|---------------------------------|
| $3/2^-$ | 0.0         | 4.400     | 0.47    | 0.43                       | $6.20 \times 10^4$               |
| $1/2^-$ | 1.773       | 2.627     | 0.82    | 0.18                       | $2.60 \times 10^4$               |
| sum    | 0.61        |           |         |                            | $8.80 \times 10^4$               |

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