Direct neutron capture of ^{48}Ca at $kT=52$ keV

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The neutron capture cross section of ^{48}Ca was measured relative to the known gold cross section at $kT=52$ keV using the fast cyclic activation technique. The experiment was performed at the Van de Graaff accelerator, Universität Tübingen. The new experimental result is in good agreement with a calculation using the direct capture model. The $1/v$ behavior of the capture cross section at thermonuclear energies is confirmed, and the adopted reaction rate which is based on several previous experimental investigations remains unchanged. [S0556-2813(97)06608-9]

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The neutron capture cross section of the neutron-rich and doubly magic nucleus ^{48}Ca is dominated by the direct capture (DC) mechanism at thermonuclear energies [1,2]. This capture mechanism has to be well understood for the analysis of neutron-induced nucleosynthesis in the vicinity of ^{48}Ca which is also of relevance for the Ca-Ti isotopic abundance anomalies in certain primitive meteorites [3–5].

The nonresonant DC cross section of ^{48}Ca(n,γ)^{49}Ca was measured by Beer *et al.* [2] and Käppeler *et al.* [6] at thermonuclear energies using activation techniques. Weak resonances were found by Carlton *et al.* [7] using the time-of-flight (TOF) technique, and the thermal capture cross section was measured by Beer *et al.* [2] and Cranston and White [8]. Summarizing the previous experiments, in the experimentally analyzed energy range the ^{48}Ca(n,γ)^{49}Ca cross section shows an almost pure $1/v$ behavior which is typical for s-wave capture. However, there is some evidence for a deviation from the $1/v$ law at $kT=25$ keV in Ref. [2] where the experimental value is roughly 25% smaller than the calculated cross section (corresponding to 2.8 times the uncertainty of the experiment). This behavior can be explained either by the uncertainty of the experiment or by a destructive interference between the nonresonant DC and a hypothetical $1/2^+$ s-wave resonance at $E\approx 1.5$ keV [2] which should have been observed in the TOF experiments of Ref. [7].

The most important energies for astrophysical scenarios are in the order of 10–100 keV. Therefore we measured the neutron capture cross section of ^{48}Ca using a quasi-Maxwellian neutron energy spectrum with $kT=52$ keV which is obtained by bombarding a thick tritium target with protons at $E_p=1091$ keV [72 keV above the T(p,n) threshold at $E_p=1019$ keV] [9].

The experimental setup using the fast cyclic activation technique is close to the one described in Refs. [2,10]. The sample is irradiated for a period $t_b=149.15\pm 0.01$ s; after this irradiation time the sample is moved to the counting position in front of a high-purity germanium (HPGe) detector ($t_{w_1}=0.80\pm 0.01$ s). The γ rays following the β decay of ^{49}Ca are detected for a time interval $t_c=149.20\pm 0.01$ s, and finally the sample is moved back to the irradiation position ($t_{w_2}=0.85\pm 0.01$ s). The whole cycle with duration $T=t_b+t_{w_1}+t_c+t_{w_2}=300$ s is repeated many times to gain statistics.

The sample material consisted of $CaCO_3$ powder enriched by 77.87% in ^{48}Ca. Two samples were available with a diameter $d=6$ mm and masses of 48.83 mg and 49.06 mg. The samples were sandwiched between two thin gold foils ($m\approx 16$ mg per foil), and both the sample and the two gold foils were put into a cylindrical polyethylene container with an inner diameter of 6 mm.

The experiment was performed at the 3.0 MV Van de Graaff accelerator ROSENAU at the University of Tübingen where a tritium target with a total activity of about 5 Ci is available for the neutron production with the ^{3}H(p,n)^{3}He reaction. The thickness of the titanium layer which contains the tritium is about 150 keV at $E_p=1091$ keV which is at least twice the requested thickness of 72 keV.

The neutron flux was limited by the relatively low beam current of about 15 μA. Using this current the temperature of the tritium target remained below 40 °C, and a constant ratio between the neutron flux and the proton beam current could be observed during the whole experiment. Furthermore, the depth profile of the tritium target was constant during the experiment. This was controlled by measuring the neutron yield at different energies between the (p,n) threshold and $E_p=1091$ keV. Changes in the depth profile would affect the neutron energy spectrum. The resulting uncertainty of the capture cross section is estimated to be smaller than 5%.

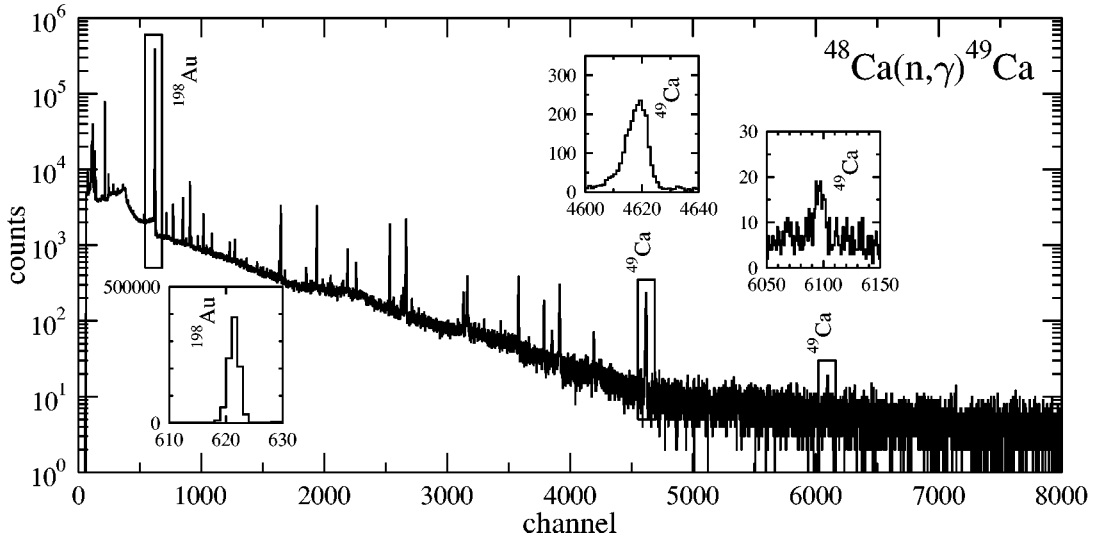

FIG. 1. Energy spectrum of the HPGe detector measured during the activation of ^{48}Ca. In the insets the relevant areas around 411.8 keV (decay of ^{198}Au), and 3084.4 and 4071.9 keV (decay of ^{49}Ca) are shown. Note the logarithmic scale of the full spectrum and the linear scale of the three insets.

Because of the relatively low neutron flux several improvements had to be achieved compared to our previous experiment [2]. The improvements are (i) better detection efficiency using a HPGe detector with 98.6% relative efficiency (compared to a 3×3 in. NaI detector) and (ii) longer distance (1 m) between irradiation and detection position which is used for a better shielding of the HPGe detector (75-cm lithium-loaded paraffin between the neutron source and the HPGe detector, and 0.3 cm cadmium and 15 cm lead around the HPGe detector). A typical spectrum is shown in Fig. 1. In the insets the relevant areas around 411.8 keV (decay of ^{198}Au) and 3084.4 and 4071.9 keV (decay of ^{49}Ca) are shown.

The accumulated number of counts from a total of N cycles, $C=\Sigma_{i=1}^{n}C_i$, where C_i, the counts of the ith cycle, are calculated for a chosen irradiation time t_b, which is short enough compared with the fluctuations of the neutron flux, is [10]

$$C=\epsilon_\gamma K_\gamma f_\gamma \lambda^{-1}[1-\exp(-\lambda t_c)]\exp(-\lambda t_{w_1}) \times\frac{1-\exp(-\lambda t_b)}{1-\exp(-\lambda T)}N\sigma_\gamma[1-f_b\exp(-\lambda T)]\sum_{i=1}^{n}\Phi_i, \quad (1)$$

with

$$f_b=\frac{\Sigma_{i=1}^{n}\Phi_i\exp[-(n-i)\lambda T]}{\Sigma_{i=1}^{n}\Phi_i}.$$

The following additional quantities have been defined: ϵ_γ is the detection efficiency, K_γ the γ-ray absorption, f_γ the γ-ray intensity per decay, λ the decay constant, N the thickness (atoms per barn) of target nuclei, σ_γ the capture cross section, and Φ_i the neutron flux in the ith cycle. The quantity f_b is calculated from the registered flux history of a ^{6}Li glass monitor.

The efficiency of the HPGe detector was determined by a calculation using the computer code GEANT [11]. The results of the detector simulation were tested experimentally by measuring the relative intensities of γ rays following the decays of ^{115,117}Cd. For this purpose a sample of ^{nat}Cd with the same geometry as the calcium samples (diameter $d=6$ mm, mass $m=343.47$ mg) was mounted exactly in the same way as for the calcium experiment. Additionally, the capture γ rays of ^{27}Al$(p,\gamma)^{28}$Si at the resonance at $E_p=1317$ keV which are well known in the literature [12,13] were measured using a thick ^{27}Al target and a ''D''-shaped scattering chamber which was especially designed for the detection of capture γ rays [14]. The γ-ray absorption coefficients in the sample and in the gold foils were calculated using the tables provided by National Nuclear Data Center, Brookhaven National Laboratory, via the World Wide Web, and based on Ref. [15]. These corrections are in the order of a few % or even less for the γ lines from the ^{49}Ca decay. The half-lives and the γ-ray intensities per decay of ^{49}Ca and ^{198}Au are given in Table I.

Using Eq. (1) the neutron capture cross section of ^{48}Ca can be determined relative to the known activation cross sec-

TABLE I. Sample characteristics and decay properties of the product nuclei ^{49}Ca and ^{198}Au.

Isotope	Chemical form	Isotopic composition (%)	Residual nucleus	$T_{1/2}$ (min)	E_γ (keV)	Intensity per decay (%)
^{48}Ca	$CaCO_3$	77.87±1.90	^{49}Ca	8.716±0.011	3084.4	92.1±1.0
					4071.9	7.0±0.7
^{197}Au	metallic	100	^{198}Au	2.69 d	411.8	95.50±0.096

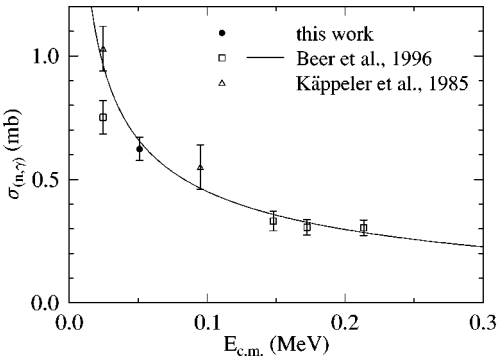

FIG. 2. Experimental neutron capture cross section of ^{48}Ca (●, this work; □, Ref. [2]; △, Ref. [6]) compared to a DC calculation (solid line, Ref. [2]).

tion of ^{197}Au which was calculated at $kT=52$ keV in Ref. [9] based on experimental data of Ref. [16]: $\sigma(^{197}\mathrm{Au})=431\pm15$ mb. The experimental result for ^{48}Ca at $kT=52$ keV is $\sigma_{\mathrm{expt}}(^{48}\mathrm{Ca})=623\pm47$ μb. The following uncertainties were taken into account: statistical (1.5%), neutron energy variations due to tritium density changes in the target ($<5\%$), enrichment of ^{48}Ca in the $CaCO_3$ sample (2.4%), γ branching ratios (1% for the 3084.4 keV line, 10% for the 4071.9 keV line), calculated efficiency of the HPGe detector (3%), monitoring of neutron flux using the ^{6}Li glass monitor (1%), corrections of the divergence of the neutron beam (2%), and cross section of the gold reference (3.4%). Minor uncertainties from the mass determination of the $CaCO_3$ sample and the gold reference ($<0.1\%$), from the half-lives of ^{49}Ca and ^{198}Au ($<0.1\%$) and from the measuring and waiting times $T=t_b+t_{w_1}+t_c+t_{w_2}=300$ s ($<0.1\%$) can be neglected. The total uncertainty of about 7.5% is given by the quadratic sum of the above uncertainties.

The experimental value is in good agreement with our theoretical prediction based on a DC calculation: $\sigma_{\mathrm{calc}}(^{48}\mathrm{Ca})=655$ μb [2]. In Fig. 2 the new experimental result is shown together with previous experiments [2,6] and our DC calculation [2].

In conclusion, the $1/v$ behavior of the neutron capture cross section of ^{48}Ca at thermonuclear energies was confirmed. At $kT=52$ keV the measured capture cross section agrees very well with the calculated value. No sign of a destructive interference between the nonresonant DC and a hypothetical $1/2^+$ s-wave resonance at $E\approx1.5$ keV suggested in Ref. [2] that should also show up in an experimental measurement at $kT=52$ keV was found. The energy-independent reaction rate factor $N_A\langle\sigma v\rangle=1.19\times10^5$ cm^3 mol^{-1} s^{-1} given in Ref. [2] remains unchanged.

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