PROCEEDINGS OF SCIENCE

Direct measurement of stellar neutron capture rates of ^{14}C and comparison with the Coulomb breakup method

---

R. Reifarth,[a] **M. Heil,**[b] **R. Plag,**[b] **U. Besserer,**[c] **A. Couture,**[a] **S. Dababneh,**[b] **L. Dörr,**[c] **C. Forssén**[d] **J. Görres,**[e] **R.C. Haight,**[a] **A. Mengoni,**[f] **S. O'Brien,**[e] **N. Patronis,**[g] **R.S. Rundberg,**[a] **E. Uberseder,**[b] **M. Wiescher,**[e] **J.B. Wilhelmy**[a]
E-mail: `reifarth@lanl.gov`
[a] *Los Alamos National Laboratory, Los Alamos, New Mexico, 87545, USA*
[b] *Forschungszentrum Karlsruhe, IK, P.O. Box 3640, D-76021 Karlsruhe, Germany*
[c] *Forschungszentrum Karlsruhe, Tritiumlabor, P.O. Box 3640, D-76021 Karlsruhe, Germany*
[d] *Lawrence Livermore Laboratory, Livermore, California, 94550, USA*
[e] *University of Notre Dame, Physics Department, Notre Dame, IN 46556, USA*
[e] *CERN, CH-1211 Geneva 23, Switzerland*
[f] *Nucl. Phys. Lab., Department of Physics, The University of Ioannina 45110 Ioannina, Greece*

The neutron capture cross section of ^{14}C has been shown to be important for several neutron driven nucleosynthesis scenarios. Due to the high neutron abundance it is expected that the ^{14}C(n,γ) reaction competes strongly with other neutron-induced reactions on ^{14}C. The ^{14}C(n,γ) reaction is also important to validate (n,γ) cross sections obtained via the inverse reaction by the Coulomb breakup method. In principle, ^{14}C belongs to the few cases where this correspondence can be validated in a convincingly clean way. So far, the example of ^{14}C is obscured, however, by discrepancies between several experiments and theory. In this contribution we report on a re-analysis of the direct measurements of the ^{14}C(n,γ) reaction presented on the last NIC conference (Vancouver, 2004). The neutron energies used during the experiment ranged from 30 to 800 keV. The earlier presented disagreement between the direct measurements and the Coulomb breakup method has been resolved.

International Symposium on Nuclear Astrophysics — Nuclei in the Cosmos — IX
June 25-30 2006
CERN, Geneva, Switzerland

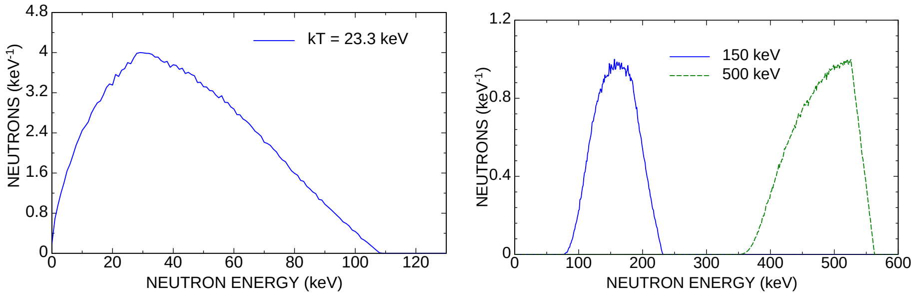

Figure 1: Neutron spectra during the cyclic activations in arbitrary scaled units. The distribution in the left panel can be approximated by a Maxwellian averaged distribution for kT=23.3 keV. The distributions in the right panel are typical for a mono-energetic experiment with a wide energy uncertainty.

1. Introduction

Inhomogeneous big bang models [1] offer a possibility to bridge the mass gaps at $A = 5$ and 8 via the reaction sequence ^{7}Li(n,γ)^{8}Li(α,n)^{11}B(n,γ)^{12}B(β^{-})^{12}C [2, 3]. Subsequent neutron captures on ^{12}C and ^{13}C will then lead to the production of ^{14}C, which has a half-life of 5730±40 yr [4]. On the time scale of big bang nucleosynthesis ^{14}C can be considered as stable and further proton, alpha, deuteron, and neutron capture reactions on ^{14}C will result in the production of heavier nuclei $(A > 20)$ [2]. Due to the high neutron abundance it is expected that the ^{14}C(n,γ)^{15}C reaction competes strongly with the other reactions. The ^{14}C(n,γ) reaction is also important to validate (n,γ) cross sections obtained via the inverse reaction by the Coulomb breakup method (see e.g. [5], [6], [7]). Other estimates are given in [8], [9].

^{14}C is one of the few nuclei, where the (n,γ) reaction can be measured directly and compared with results of Coulomb breakup experiments, in this case ^{15}C(γ,n)^{14}C. Preliminary data have been presented at the last Nuclei in the Cosmos Meeting [10]. In this article we present a re-analysis of these data, which became necessary because of huge dead-time corrections in the Germanium detectors used for determining the induced ^{15}C-activity. We present the data with the smallest uncertainties.

2. Experiment

A first important step was the independent determination of the sample mass by a calorimetric measurement of the decay heat. This measurement was carried out at the Tritium Labor of Forschungszentrum Karlsruhe. The heat production was determined to be 370 $\pm$ 4 μW, corresponding to 1.25 $\pm$ 0.01 Ci or 0.282 $\pm$ 0.03 g of ^{14}C. This is more than a factor of 2 less than the specified value, which had been adopted in the previous activation [11].

Neutrons of different energy distributions were produced by bombarding a metallic ^{7}Li target with protons of different energies above the (p,n) threshold. The proton beam was provided by the Karlsruhe 3.7 MV Van de Graaff accelerator. The different neutron energy distributions are shown in Figure 1. The corresponding neutron fluxes ranged between 10^{7} and 10^{9} cm^{-2}s^{-1}.

The short half-life of ^{15}C of only 2.449 ± 0.005 s implied the use of the fast cyclic activation technique [12]. The induced activity during each cycle was detected via the characteristic 5.297 MeV line (intensity I_γ = 0.68) in the ^{15}C decay using a HPGe detector with a relative efficiency of 100%.

The detector efficiency was determined with a set of calibration sources and via the ^{27}Al(p,γ)^{28}Si reaction as described in Ref. [13]. The results are shown in Figure 2. Simulations of the γ-ray efficiency using GEANT showed that the energy dependence is slightly different for the setup used during the activation (6 mm distance) and during the ^{27}Al(p,γ)^{28}Si experiment (50 cm). This effect was considered in the analysis. The main difference to our previous analysis was the discovery of a huge dead time effect during the experiment. Even though the detector was shielded from the neutron production target to reduce radiation damage, enough neutrons reached the detector to produce unstable germanium isotopes in the detector. The ^{14}C powder was previously used during experiments with high-energy protons, which activated the thin nickel container. One of the reaction products in the container is the long-lived ^{44}Ti, which decays to ^{44}Sc. During the decay of ^{44}Sc a γ-ray of 1.15 MeV is emitted. We used the independently measured activity of ^{44}Sc to determine the necessary dead time corrections of about a factor of 3.

Each cycle consisted of an activation time of t_{beam} = 10 s, the γ-ray detection time $t_{detector}$ = 10 s (during which the proton beam was switched off), and twice the time for moving the sample between detector and neutron production target t_{wait} = 0.8 s. The sample was sandwiched between two thin gold foils, allowing a measurement relative to the well known ^{197}Au(n,γ)^{198}Au cross section. At the end of each run the activity of the gold foils was determined via the 412 keV γ-ray from the ^{198}Au decay ($t_{1/2}$ = 2.7 d).

Figure 3 shows a typical γ-ray spectrum taken during the experiment. Full energy, single escape as well as double escape peaks of the 5.3 MeV line are clearly visible above the background. In order to reduce systematic uncertainties, the time dependence of the ^{15}C decay during the 10 s counting period, has been monitored. The decay curve is compared in Figure 4 with a fit of a constant background and the exponential decay law with 2.449 s half-life. Within the statistical uncertainties the measured activity follows the expected time dependence.

3. Results

The results and a preliminary comparison with results from Coulomb-breakup experiments are shown in Table 1 and Figure 5. The results of this measurement are not for mono-energetic neutrons, but for a broad distribution of neutron energies. This holds true in particular for the 23.3 keV cross section measured, which is in fact a Maxwellian Averaged Cross Section (MACS) at $kT = 23.3$ keV. The position of this point in Figure 5 however is at 23.3 keV. A more realistic comparison between the methods is done in Table 1, which contains a comparison done by folding the differential cross sections derived from the RIKEN data [7] (solid line in Figure 5) with the neutron spectra shown in Figure 1.

The determining contributions to the uncertainty estimation come from counting statistics (2-8%), the γ-ray detection efficiency (5%), and the determination of the neutron flux (2-10%). All other uncertainties are smaller than 2%.

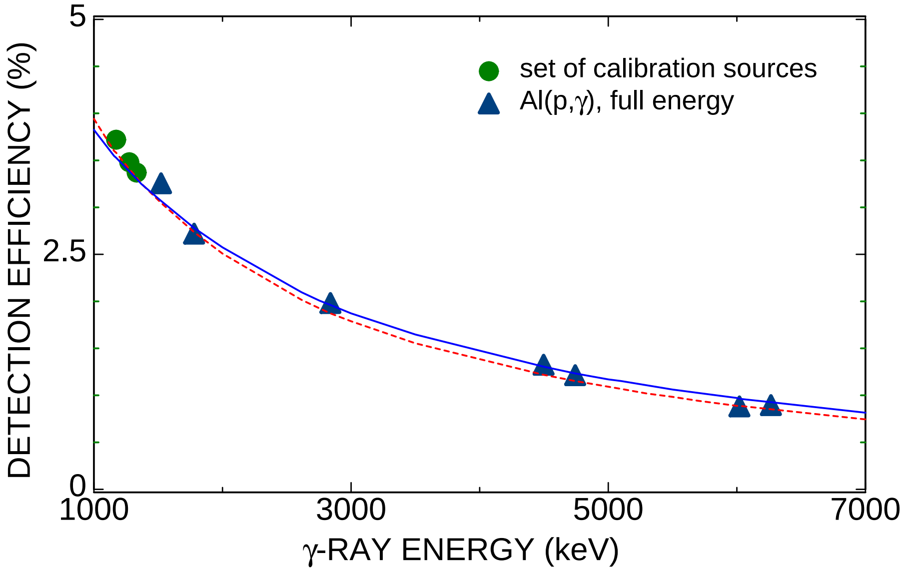

Figure 2: The γ-ray efficiency of the HPGe detector used during the cyclic activation. The efficiency was measured using calibration sources and the ^{27}Al(p,γ)^{28}Si reaction. The red and blue solid curves correspond to normalized efficiency simulations using GEANT with 50 cm and 6 mm distance between sample and detector. The extrapolation from low to high energies is slightly smaller for the 6 mm case.

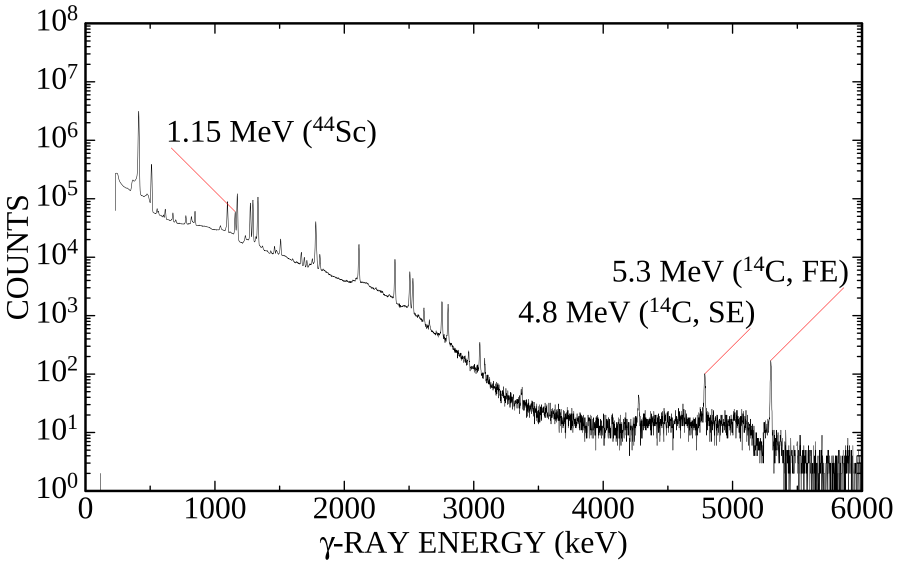

Figure 3: Measured γ-ray spectrum after 22 h of cyclic activation during the run corresponding to neutron energies of kT = 23.3 keV. Clearly visible above the background are the 3 peaks corresponding to the decay of ^{15}C at 5.3 MeV (full energy peak), 4.8 MeV (single escape peak), and 4.3 MeV (double escape). The peak from the decay of ^{44}Sc at 1.15 MeV is also marked.

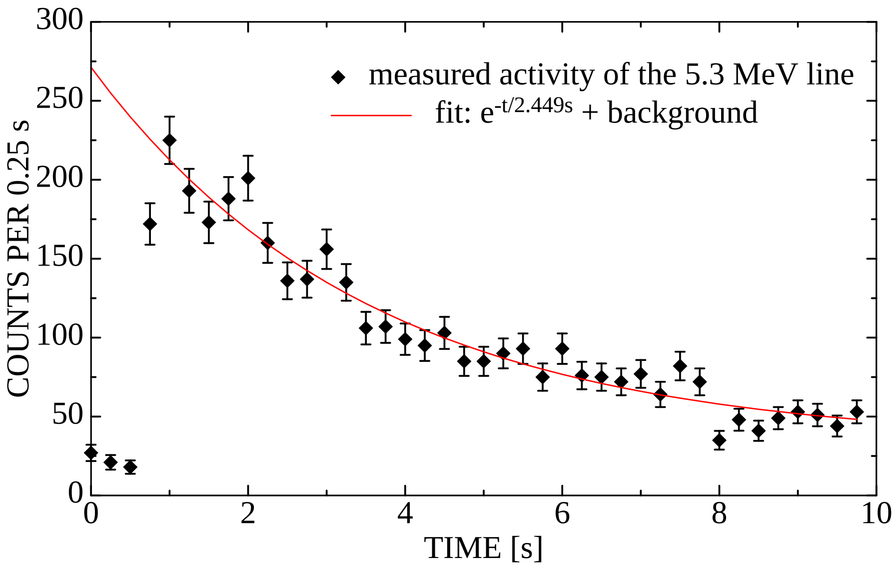

Figure 4: Activity of the 5.297 MeV line from the decay of ^{15}C as a function of time. The solid line corresponds to the half-life of ^{15}C. The first four points, which are below the fit, were take while the sample was not yet in front of the detector and are not included in the actual fit.

Compared to the result of the previous activation with $kT = 23.3$ keV [11] we find agreement only if if the new sample mass is taken into account and a similar dead-time problem like during our experiment is assumed. The present values are in agreement with data from two Coulomb breakup studies [6], [7]), while they disagree from a third study ([5]. A more comprehensive comparison with the available data will be published in a separate paper.

Table 1: Cross sections of the ^{14}C(n,γ)^{15}C reaction measured via activation technique. The last column shows a preliminary comparison with the results from the Coulomb breakup method.

Energy (keV)	cross section (μb)	Uncertainty (%)	Ratio CD / Activation
23.3 (MACS)	7.1	7	1.01
150	10.7	11	1.05
500	17.0	9	1.01

Acknowledgments

We would like to thank E.-P. Knaetsch, D. Roller, and W. Seith for their support at the Karlsruhe Van de Graaff accelerator. This work was partly supported by the Joint Institute for Nuclear Astrophysics (JINA) through NSF Grants Nos. PHY-0072711 and PHY-0228206.

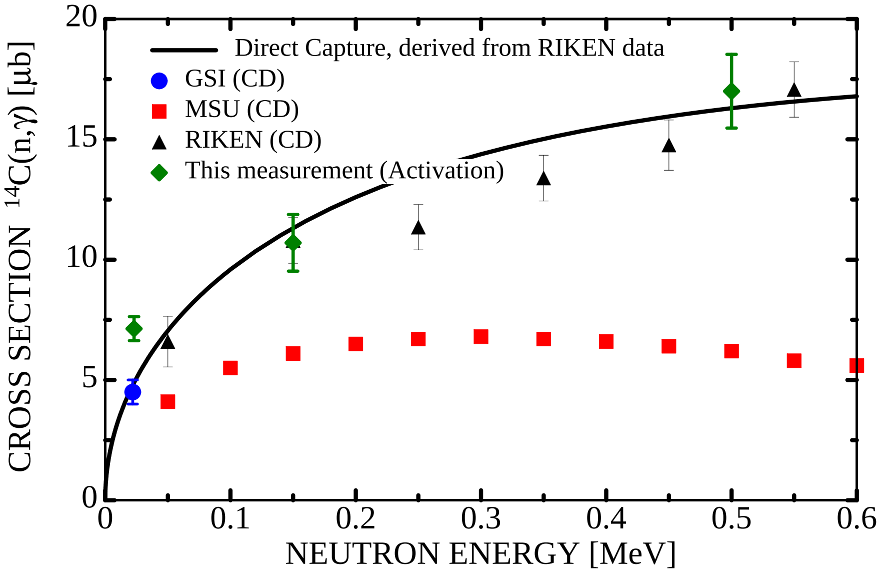

Figure 5: Comparison between this measurement and cross section estimates based on Coulomb dissociation experiments (CD) on ^{15}C. The results of this measurement are not for mono-energetic neutrons, hence the quite large deviation at 23.3 keV.

References

[1] J. H. Applegate, C. J. Hogan. *Relics of cosmic quark condensation. Physical Review D (Particles and Fields)* **31**(12) (1985) 3037.

[2] J. H. Applegate, C. J. Hogan, R. J. Scherrer. *Cosmological quantum chromodynamics, neutron diffusion, and the production of primordial heavy elements. Astrophysical Journal* **329**(2) (1988) 572.

[3] R. A. MALANEY, W. A. FOWLER. *LATE-TIME NEUTRON DIFFUSION AND NUCLEOSYNTHESIS IN A POST-QCD INHOMOGENEOUS OMEGAB=1 UNIVERSE. ASTROPHYSICAL JOURNAL* **333**(1) (1988) 14.

[4] F. Ajzenberg-Selove. *Energy levels of light nuclei A=13-15. Nucl. Phys. A* **449** (1986) 1.

[5] A. Horváth, J. Weiner, A. Galonsky, F. Deák, Y. Higurashi, K. Ieki, Y. Iwata, A. Kiss, J. Kolata, Z. Seres, J. Schwarzenberg, H. Schelin, S. Takeuchi, S. Typel, R. Warner. *CROSS SECTION FOR THE ASTROPHYSICAL 14C(n,g)15C REACTION VIA THE INVERSE REACTION. Ap. J.* **570** (2002) 926.

[6] U. Datta Pramanik, T. Aumann, K. Boretzky, B. Carlson, D. Cortina, et al. *Coulomb breakup of the neutron-rich isotopes 15C and 17C. Phys. Lett. B* **551** (2003) 63.

[7] T. Nakamura. *Neutron Capture Cross Section of ^{14}C Studied by Intermediate-Energy Coulomb Dissociation.* In M. Terasawa, S. Kubano, T. Kishida, T. Kajino, T. Motobayashi, K. Nomato, eds., *Origin of Matter and Evolution of Galaxies* (2005), 155.

[8] M. Wiescher, J. Görres, F.-K. Thielemann. *Capture Reactions on ^{14}C in Nonstandard Big Bang Nucleosynthesis. Ap. J.* **363** (1990) 340.

[9] N. K. Timofeyuk, D. Baye, P. Descouvemont, R. Kamouni, I. J. Thompson. *C-15-F-15 charge symmetry and the C-14(n,gamma)C-15 reaction puzzle*. *PHYSICAL REVIEW LETTERS* **96**(16) (2006) 162501.

[10] R. Reifarth, M. Heil, R. Plag, U. Besserer, S. Dababneh, L. Dörr, J. Görres, R. C. Haight, F. Käppeler, A. Mengoni, S. O'Brien, N. Patronis, R. S. Rundberg, M. Wiescher, J. B. Wilhelmy. *Stellar neutron eapture rates of C-14*. *NUCLEAR PHYSICS A* **758** (2005) 787C.

[11] H. Beer, M. Wiescher, F. Käppeler, J. Görres, P. E. Koehler. *A Measurement of the $^{14}C(n,\gamma)^{15}C$ Cross Section at a Stellar Temperature of kT = 23.3 keV*. *Ap. J.* **387** (1992) 258 .

[12] H. Beer. *Capture cross section measurements of krypton and xenon isotopes and the fundamental parameters of the s-process*. *Ap. J.* **375** (1991) 823.

[13] A. Anttila, J. Keinonen, M. Hautala, I. Forsblom. *Use of the 27Al(p,g) 992 keV resonance as a g-intensity standard*. *NIM* **147** (1977) 501.