Experimental study of the ^{14}N(p,γ)^{15}O reaction for solar fusion at 0.5-1.5 MeV

Louis Wagner[1,2]

[1] *TU Dresden*
[2] *Helmholtz-Zentrum Dresden-Rossendorf*

16th December 2013

Motivation – The Standard Solar Model (SSM)

- framework of calculations and data for our sun
- based on known physics:
  - thermodynamics
  - gravitation
  - interaction of radiation and matter
  - nuclear reactions
- predicts solar properties:
  - surface chemical composition
  - luminosity
  - neutrino fluxes
  - internal structure
- observations can test reliability
- ⇒ new 3D models like AGSS09 in good agreement with observables

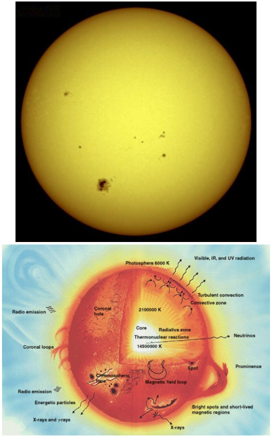


Figure: Top: sunspots bottom: section of sun

The CNO cycle

- SSM proportion of Elements heavier then He in disagreement with helioseismology
- $\Rightarrow$ need better knowledge of nuclear reactions of those elements
- CNO-cycle net result: $4\ \mathrm{H} \rightarrow {}^4\mathrm{He} + 2\ e^+ + 2\ \nu_e + 3\ \gamma + 26.8\ \mathrm{MeV}$
- catalytic cycle using solar abundance of C, N and O
- dominant source of energy in stars with mass $m \geq 1.3 \cdot m_\odot$
- temperature dependency of reaction rate $\sim T^{18}$
- 0.8% of Sun energy

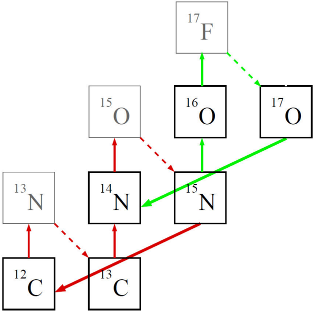


Figure: (p,γ) solid line, $(p,\alpha\gamma)$ bold and β^+ decay dashed line

The reaction $^{14}N(p,\gamma)^{15}O$

- third proton capture in CNO cycle with energy release of at least 7.3 MeV
- resonant or nonresont (Direct Capture)
- followed by emmision of 1 or 2 promt γ-rays
- lowest reaction rate of cycle for $T < 0.1\,GK$
- ⇒ “bottleneck reaction” determines CNO cycle rate
- low cross-section makes observation in laboratory at astrophysical energies difficult
- ⇒ high uncertainty for resonance strenght $\approx 5\%$ (Marta 2010)

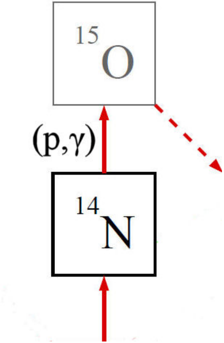


Figure:
$^{14}N + p \rightarrow ^{15}O + \gamma$

The astrophysical S factor

- nuclear cross section σ characterizes probability if nuclear reaction occurs
- $\sigma(E)$ depends strongly on projectile energy because of coulomb barrier to target atom
- common parametrization of $\sigma(E)$ in nuclear astrophysics is astrophysical S factor

$$S(E) = \sigma(E) \cdot E \cdot \exp\left(\frac{2\pi Z_1 Z_2 e^2}{\hbar \nu} \sqrt{\frac{\mu}{E}}\right)$$

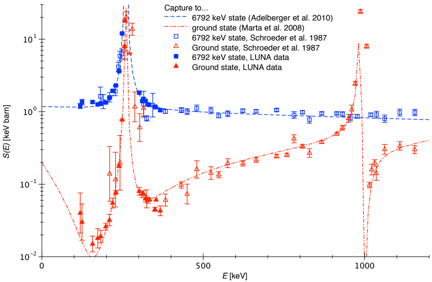


Figure: S factors of $^{14}N(p,\gamma)^{15}O$ for ground state (red) and 6792 keV excited state

R-matrix fit

- R-matrix framework rely on theory and experimental data
- experimental input:
    - properties of poles (resonance strength and width)
    - S factors of direct captur (DC)
- necessary to extrapolate to low stellar energies
- energy range for fusion at solar core temperatures: gamow-window

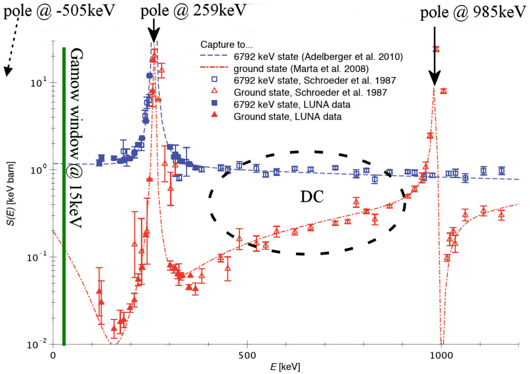


Figure: Important poles and direct capture (DC) for R-matrix fit and postion of gamow window

Monte Carlo simulations with Geant4

- first step to prepare experiment was MC simulation
- powerful tool to simulate passage of particles through matter
- software and source code (c++) freely available, used version 9.5p1
- can be used to determine detector efficiencies above γ-energies of radioactive sources
- good check whether one understands the detector if compared to real data
- for comparison used data of last experiment on ^{14}N(p,γ)^{15}O in 2009 by Michele Marta et al.

Experimental efficiency 2009

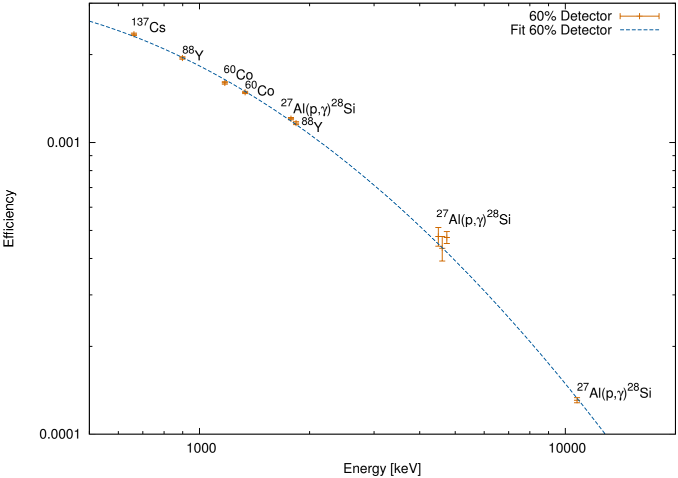


Figure: Detector efficiency curve from rad. sources ^{60}Co, ^{137}Cs and ^{88}Y and reaction ^{27}Al(p,γ)^{28}Si

Simulated and experimental efficiency 2009

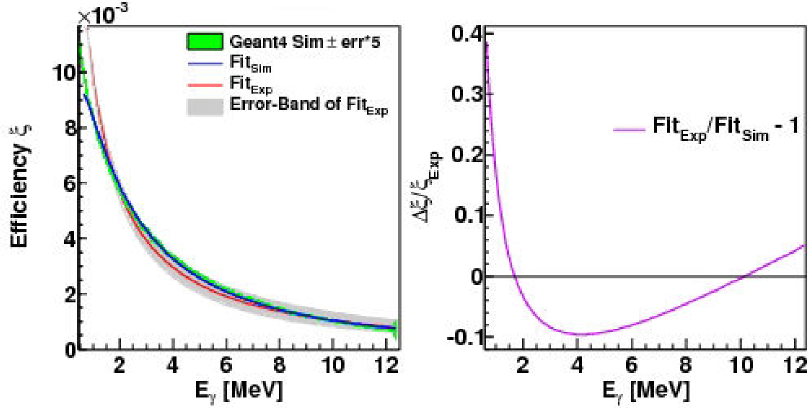
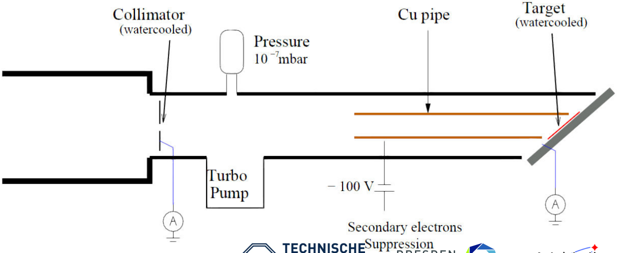


Figure: Comparison of the simulated and experimental efficiency curves of the detector with 60% rel. efficiency

The experimental setup 2013

- experiment about $^{14}N(p,\gamma)^{15}O$ done at HZDR's 3.3 MV Tandem accelerator in January 2013
- two HighPurityGermanium Detectors with BGO shielding
- ⇒ high resolution γ-spectroscopy with Compton veto
- detectors placed at angles of 55° and 90° to beam-axis
- target in vacuum chamber with water cooling and secondary electron suppression



Setup

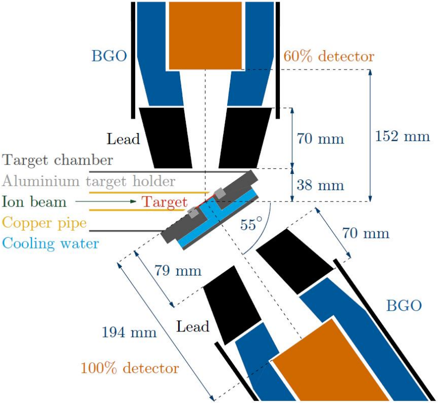


Figure: Layout and photo of setup from top

Experimental efficiency

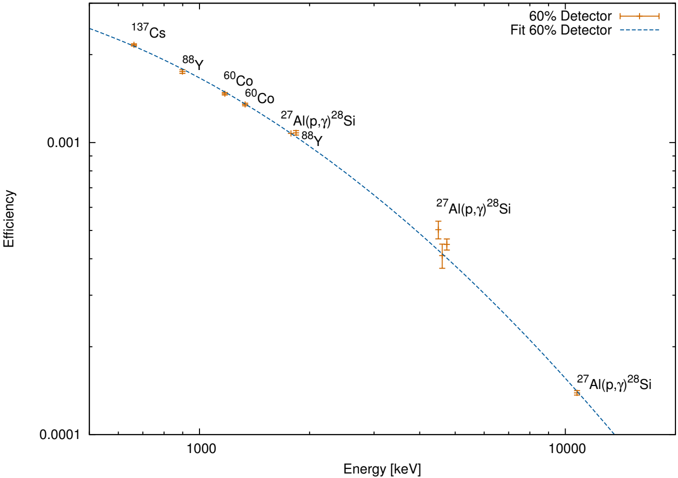


Figure: Detector efficiency curve from rad. sources ^{60}Co, ^{137}Cs and ^{88}Y and reaction ^{27}Al(p,γ)^{28}Si

TitaniumNitride Target

- extremely hard ceramic material
- often used as coating on aluminium, alloys and steel tools
- improve the substrate's surface properties
- Targets consists of TiN about 120 nm-170 nm thick
- reactive sputtering on 0.22 mm thick Tantalum backing 27 mm in diameter

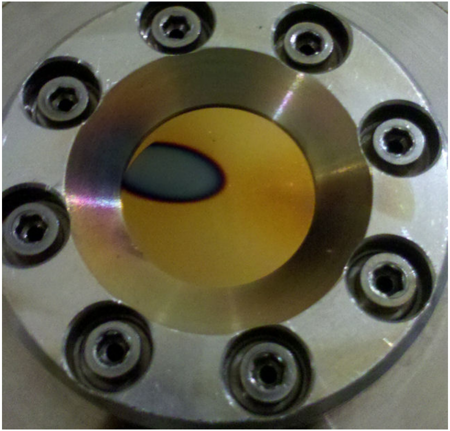


Figure: Target St-TiN-1 after irradiation

Target scan

- to measure energy loss of p in TiN-layer scanned with E_p around 897keV resonance ($\Gamma_R = 1\,\mathrm{keV}$)
- high yield of 4439 keV γ's from $^{15}\mathrm{N}(\mathrm{p},\alpha\gamma)^{12}\mathrm{C}$
- useful to check stoichiometry and target degradation
- isotopic abundance:
  - $^{14}\mathrm{N}$=99.6%
  - $^{15}\mathrm{N}$=0.4%
- but reaction rate at resonace of $^{15}\mathrm{N}(\mathrm{p},\alpha\gamma)^{12}\mathrm{C}$ much higher then any of $^{14}\mathrm{N}$

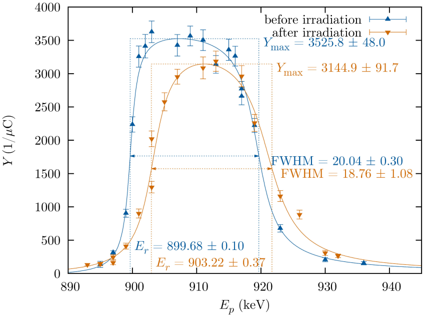


Figure: Scan of target before irradiation and after accumulated charge of $Q = 0.87\,\mathrm{C}$ in 22 h

proton energies for $^{14}N(p,\gamma)^{15}O$

- interested in p-capture to: ground state of ^{15}O and excited state at 6792 keV (primary and secondary γ's)
- eight runs with different p-energies
- $E = \{497; 597; 698; 800; 892; 1040; 1112; 1215\}$ keV
- away from resonant energies at $E = 259$ keV and $E = 987$ keV
- required beam-time decreases with energy because cross-section rises

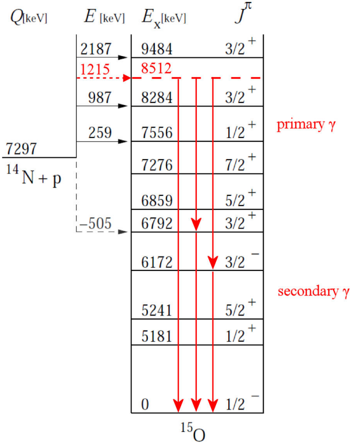


Figure: ^{15}O level scheme

Gamma-Spectra

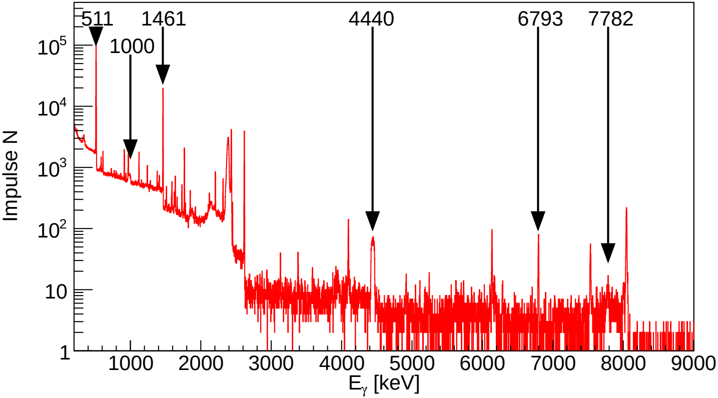


Figure: spectra of lowest proton energy $E_{CM} = 485\,\text{keV}$

Gamma-Spectra

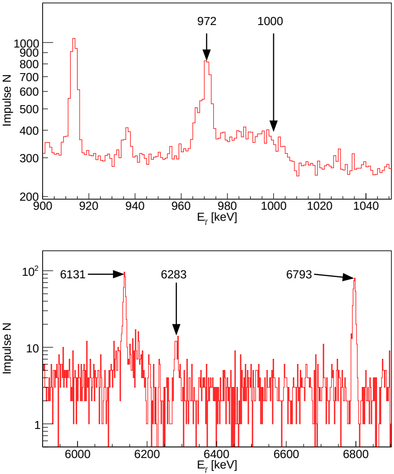


Figure: spectra of $E_p = 525\,\text{keV}$; zoom to the regions of interest

Gamma-Spectra

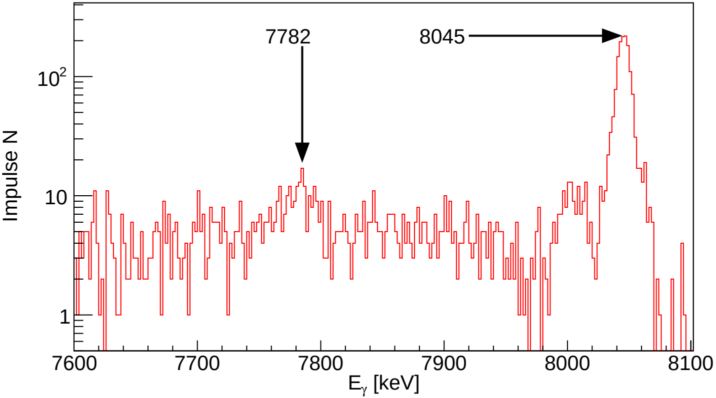


Figure: spectra of $E_p = 525$ keV; zoom to GS and $^{13}C(p,\gamma)^{14}N$ at 7968 and 8068 keV

Gamma-Spectra

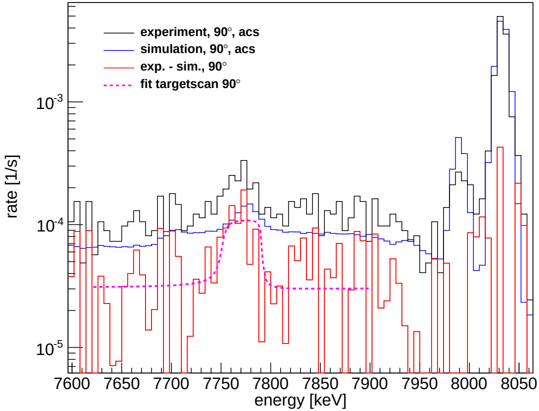


Figure: location of GS peak after subtraction of simulated spectra

Yield

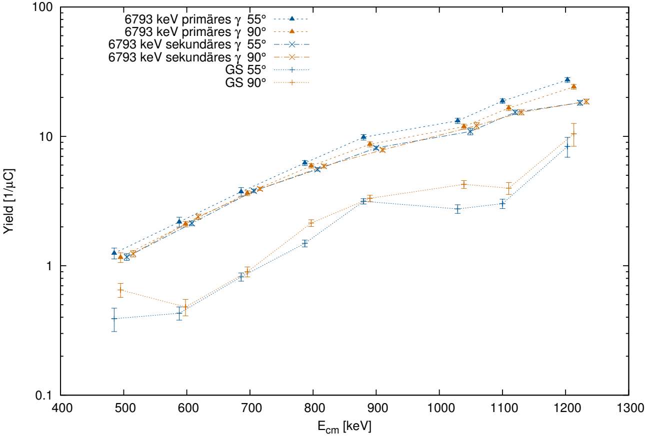


Figure: Yield $Y = \frac{N \cdot W(\Theta)}{\varepsilon_{\mathrm{Det}} \cdot Q \cdot \left(1 - \frac{t_T}{t_R}\right)}$ of primary and secondary γ of 6793 keV excited state and the γ of ground state

weighted S Factor

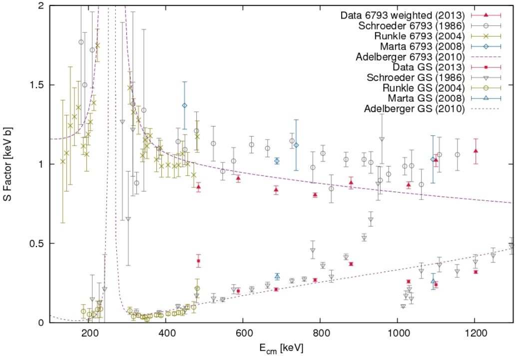


Figure: Resulting S Factors as weighted average of four measurments at the 6793 keV excited state and two at the ground state compared with literature values

Summary / Outlook

- off-resonance runs covered energy range from 500 keV to 1300 keV
- useful and important region for S Factor calculation and solar reaction rates of CNO-cycle
- can improve R-Matrix fits for total S Factor extrapolation to Gamow-window
- new S Factors seem to be lower then previous data by Schroeder (1987)
- but have lower uncertainty except for lowest $E_p = 520\,\text{keV}$ which is to close to resonance of $^{13}\text{C}(\text{p},\gamma)^{14}\text{N}$ ($E_R = 557\,\text{keV}$)
- need additional measurement at 400 and 500 keV for alignment with data of lower energy
- improve targets by lowering fluorine contamination to see 6.17 MeV level

Acknowledgment

Thank you for your attention!

Co-workers

Daniel Bemmerer[1], Michael Anders[1,2], Zoltán Elekes[1], Arnd Junghans[1], Michele Marta[3], Tobias Reinhardt[2], Stefan Reinicke[1,2], Konrad Schmidt[1,2], Marko Röder [1,2], Ronald Schwengner[1], Andreas Wagner[1], Kai Zuber[1], Marcell Takács[1] and Tamás Szücs[1,4]

[1] Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Dresden
[2] TU Dresden, IKTP
[3] Helmholtz-Zentrum für Schwerionenforschung (GSI), Darmstadt
[4] ATOMKI, Debrecen
supported by "Nuclear Astrophysics Virtual Institute (VH-VI-417)" of Helmholtz Association