# Experimental study of the $^{14}N(p,\gamma)^{15}O$ reaction

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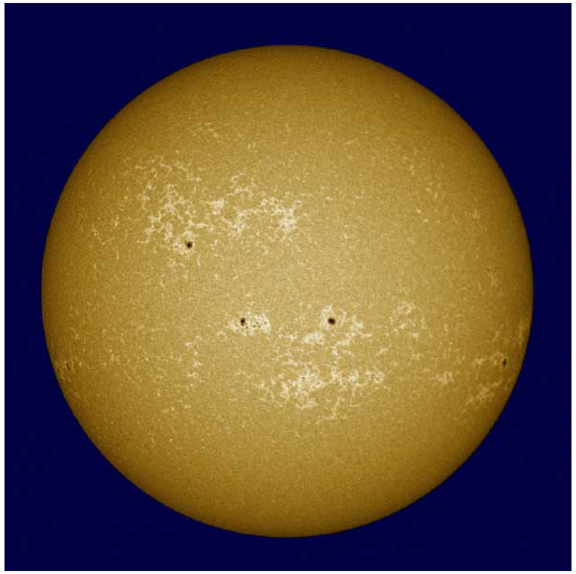
# Outline



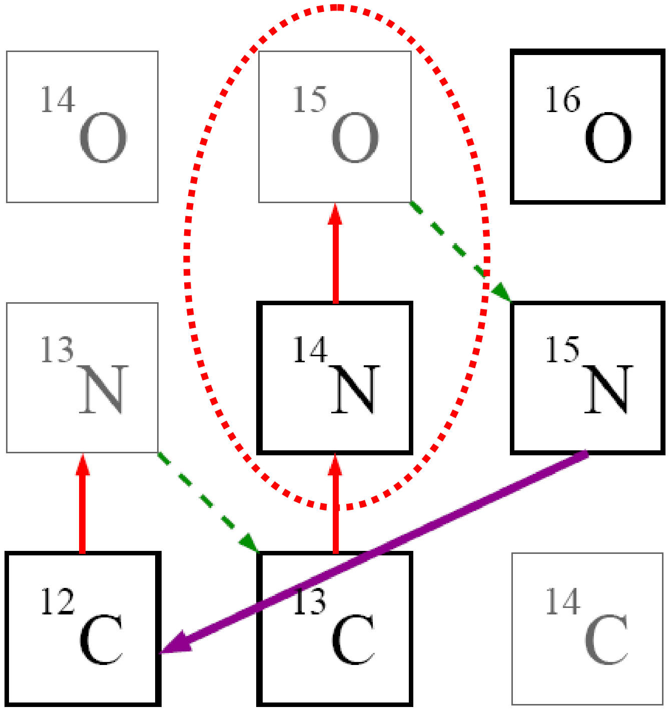
1. Motivation

2. Recent LUNA data (2008), $E_p = 0.36 – 0.4$ MeV

3. Experiment and results at Dresden Tandetron:
   - $E_p = 1058$ keV resonance
   - Off resonance $E_p = 0.6 – 2.0$ MeV

4. Summary and outlook

# Hydrogen burning: the Carbon-Nitrogen-Oxygen (CNO) cycle




Bottleneck reaction, determining the rate of the cycle: $^{14}N(p,\gamma)^{15}O$

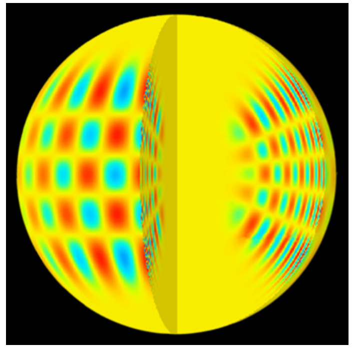
Astrophysical sites:

- Massive Stars: CNO more efficient than pp cycle (A. Heger's talk)
- Stars at the turn-off from the main sequence in the Hertzsprung-Russell diagram (age of globular cluster)
- Sun: CNO contributes only 0.8% to energy, but produces detectable neutrino flux (A. Ianni's talk)

# Astrophysics: our Sun

Observables:

- Luminosity
- Chemical abundances in the photosphere (absorption lines)
- Neutrino fluxes
  - Corrected for oscillation and detection efficiency
- Helioseismology
  - Density and sound velocity profiles, depth of the convective zone…



STANDARD SOLAR MODEL (SSM)

- Known physics: gravity, thermo-fluidodynamics, opacity, reaction cross sections…
- Assumptions: homogenous metallicity at the early stage of formation

# Our Sun: Solar abundance problem

- New results for chemical composition of the photosphere (M.Asplund et al.)
- Updated solar model predictions strongly disagree with measurements from helioseismology, whereas previous models agreed

STANDARD SOLAR MODEL A. M. Serenelli et al., Astrophys.J.Lett. 705, L123-L127 (2009)

| | Model | $(Z/X)_{surf}$ | $Z_{surf}$ | $Y_{surf}$ (He) | $R_{CZ}/R_{\odot}$ (Convection Zone) |
|---|---|---|---|---|---|
| old | GS98 | 0.0229 | 0.0170 | 0.2423 | 0.713 |
| new | AGSS09 | 0.0178 | 0.0134 | 0.2314 | 0.724 |
| HELIOSEISMOLOGY | | | | 0.2485 ± 0.0035 | 0.713 ± 0.001 |

- What is wrong? Metallicity in the solar core?

⬇

C+N abundance in solar core can in principle be measured by: CNO neutrino flux (Borexino, SNO+), solar core temperature (from $^{8}B$ neutrino flux), nuclear reaction rates

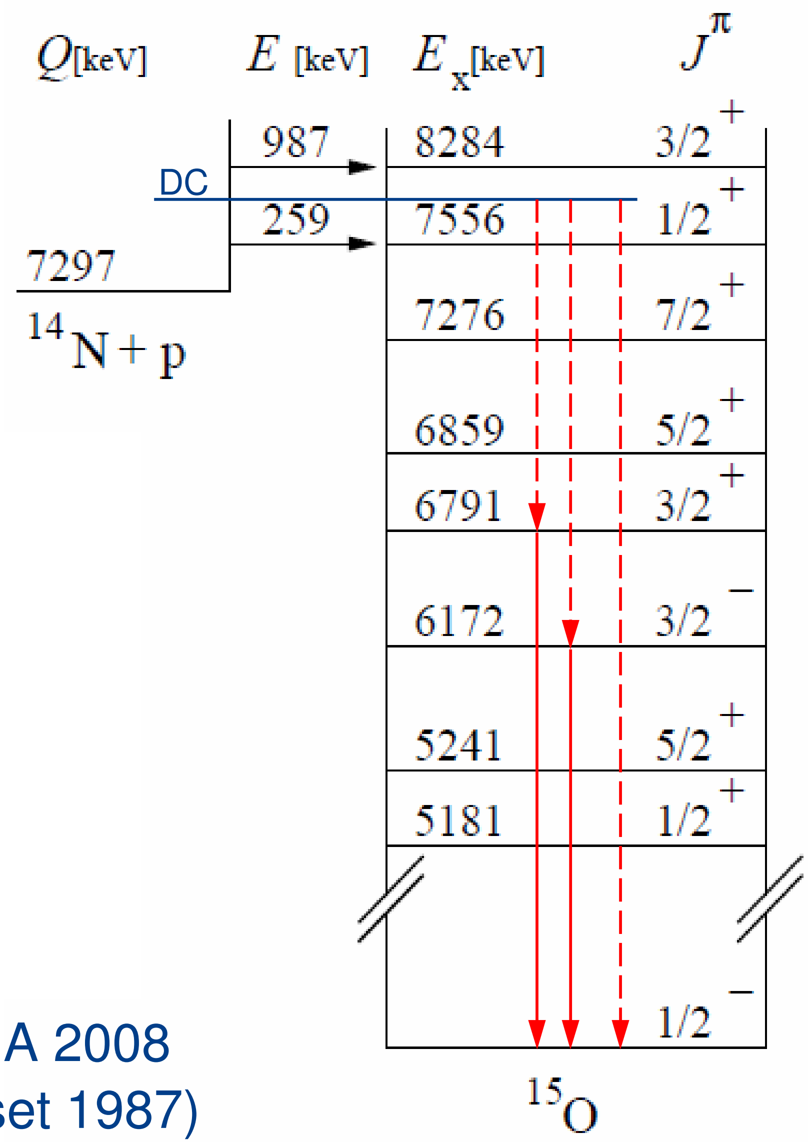
W. C. Haxton and A. M. Serenelli, Astrophys.J. 687, 678-691 (2008)

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

- Captures to different excited states in $^{15}O$ contribute to cross section

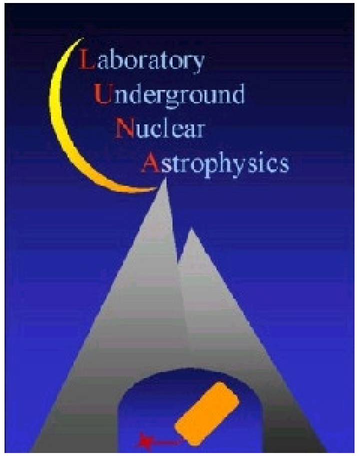
- Systematic uncertainty: true coincidence summing-in

| Capture to the state.. | LUNA 2005 (Imbriani et al.) | TUNL 2005 (Runkle et al.) |
|---|---|---|
| 0 | 0.25 ± 0.06 | 0.49 ± 0.08 |
| 6172 | 0.08 ± 0.03 | 0.04 ± 0.01 |
| 6792 | 1.20 ± 0.05 | 1.15 ± 0.05 |
| Other | 0.08 ± 0.04 | |
| total | 1.61 ± 0.08 | 1.68 ± 0.09 |

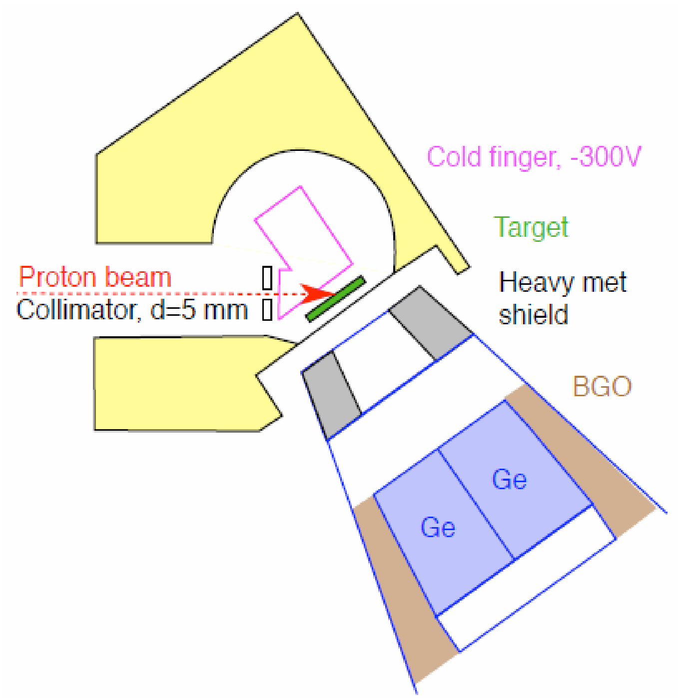


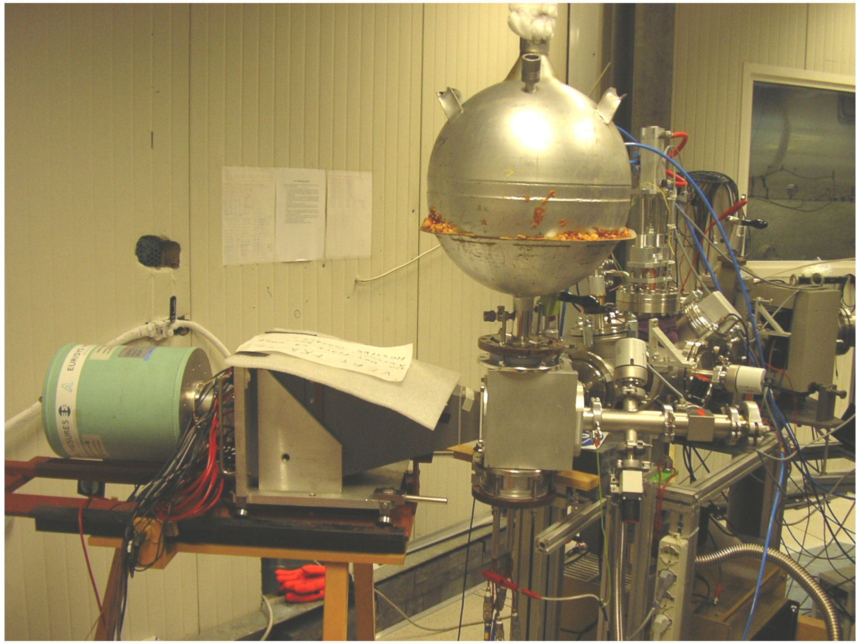

Improve #1: ground state discrepancy ⟶ LUNA 2008
Improve #2: data at higher energy (only data set 1987)

# Clover experiment at LUNA (C. Broggini's talk)




- Underground facility: reduced cosmic background
- $E_p$ = 360, 380, 400 keV, $I_p$ = 300 µA
- Solid TiN targets (55 keV thick) on Ta backing
- Eurisys clover detector: 4 single HPGe crystals closely packed
  - Addback mode and 4 single spectra → check summing effect
  - Surrounding BGO for anti-Compton shielding

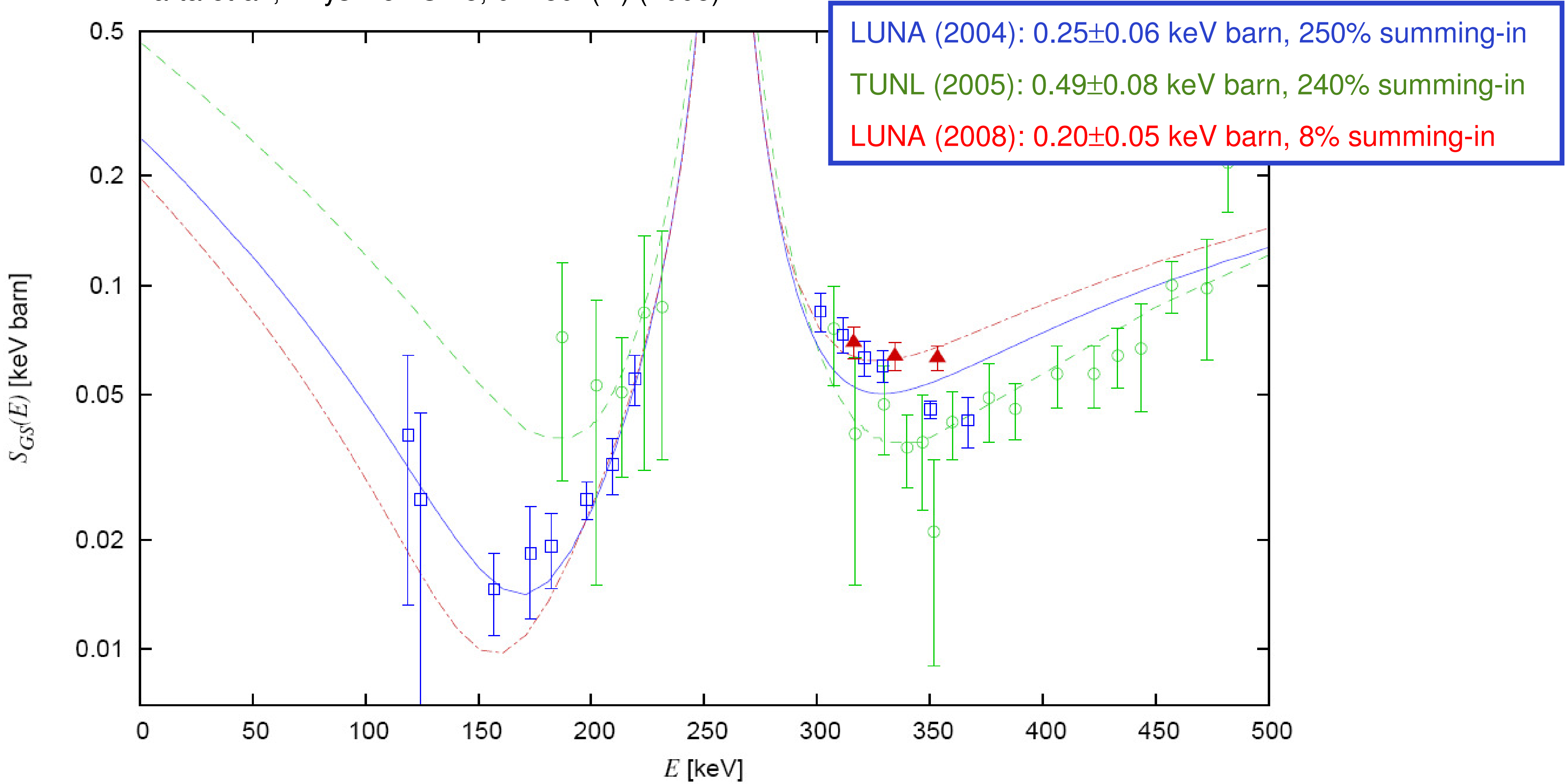


# S-factor capture to ground state $^{14}N(p,\gamma)^{15}O^{GS}$

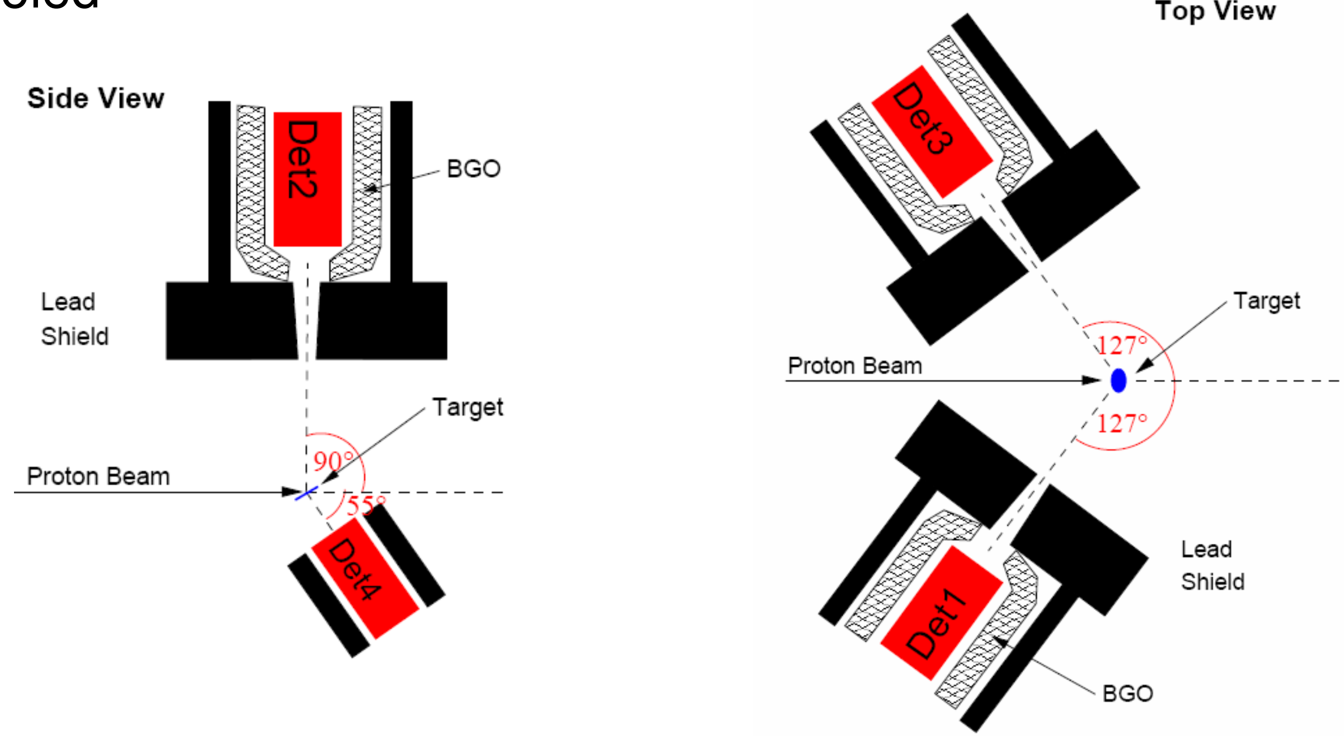
- At three energies, precise ratio of cross sections: ground state / 6.79MeV
- Updated R-matrix fit, new recommended $S_{GS}(0)=0.20\pm0.05$ keV barn

Marta et al., Phys.Rev.C 78, 022802(R) (2008)



# Experimental set up in Dresden ($E_p$ = 0.6 – 2 MeV)

- 3 MV Tandetron, Cs sputter ion source (10 - 40 µA), 1 - 15 µA on target
- 150µg/cm² TiN solid targets (reactive sputtering) on Ta backing, directly watercooled




- three 100% HPGe detectors (90°, +127°, -127°) BGO suppressed, at 30cm +
- one 60% HPGe detector at 55°, in close distance (4 cm)

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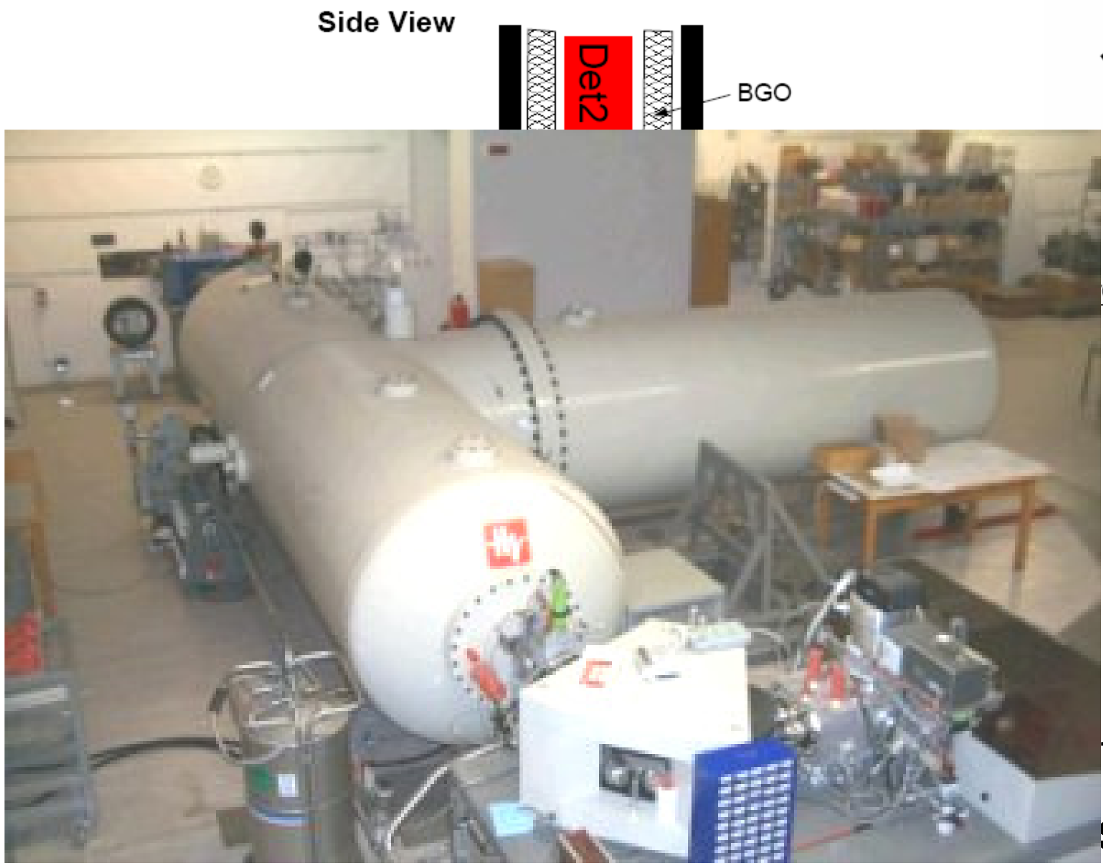
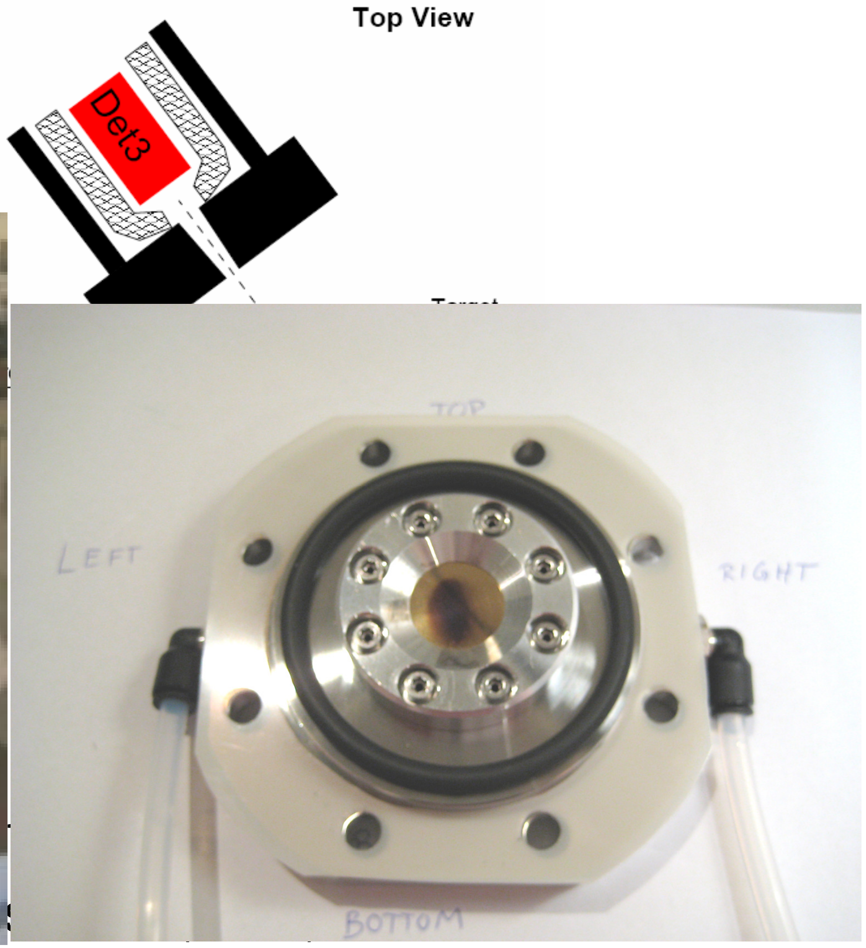
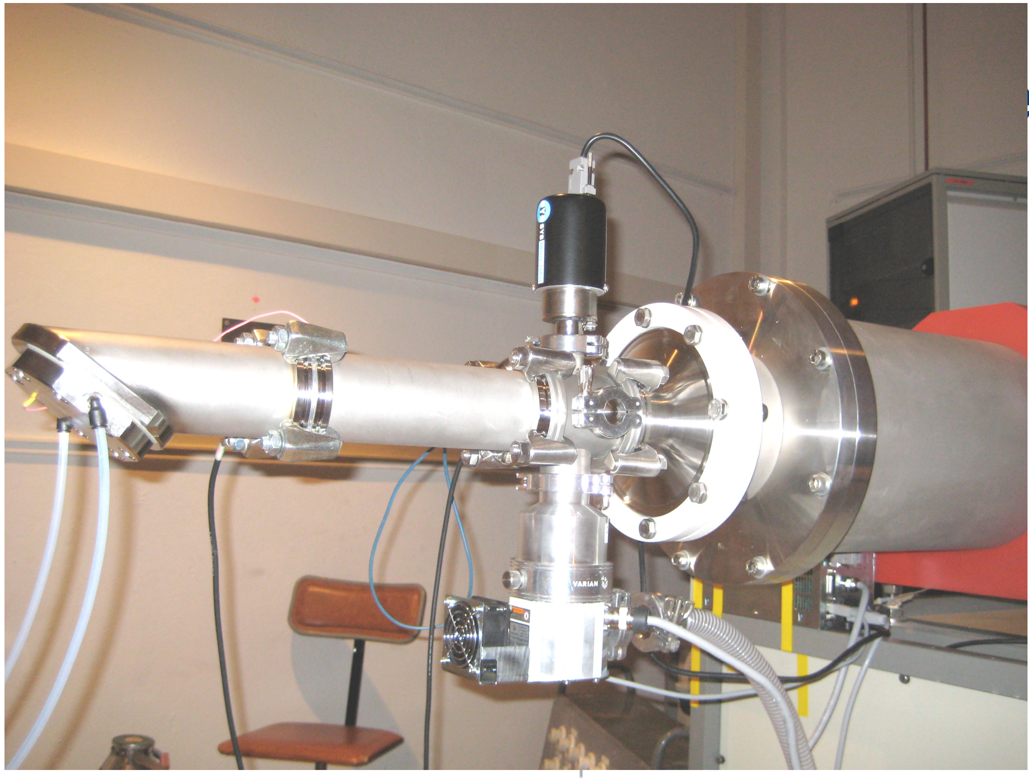
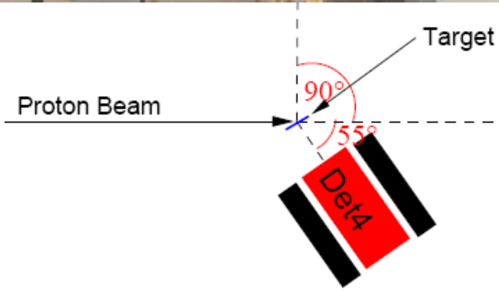
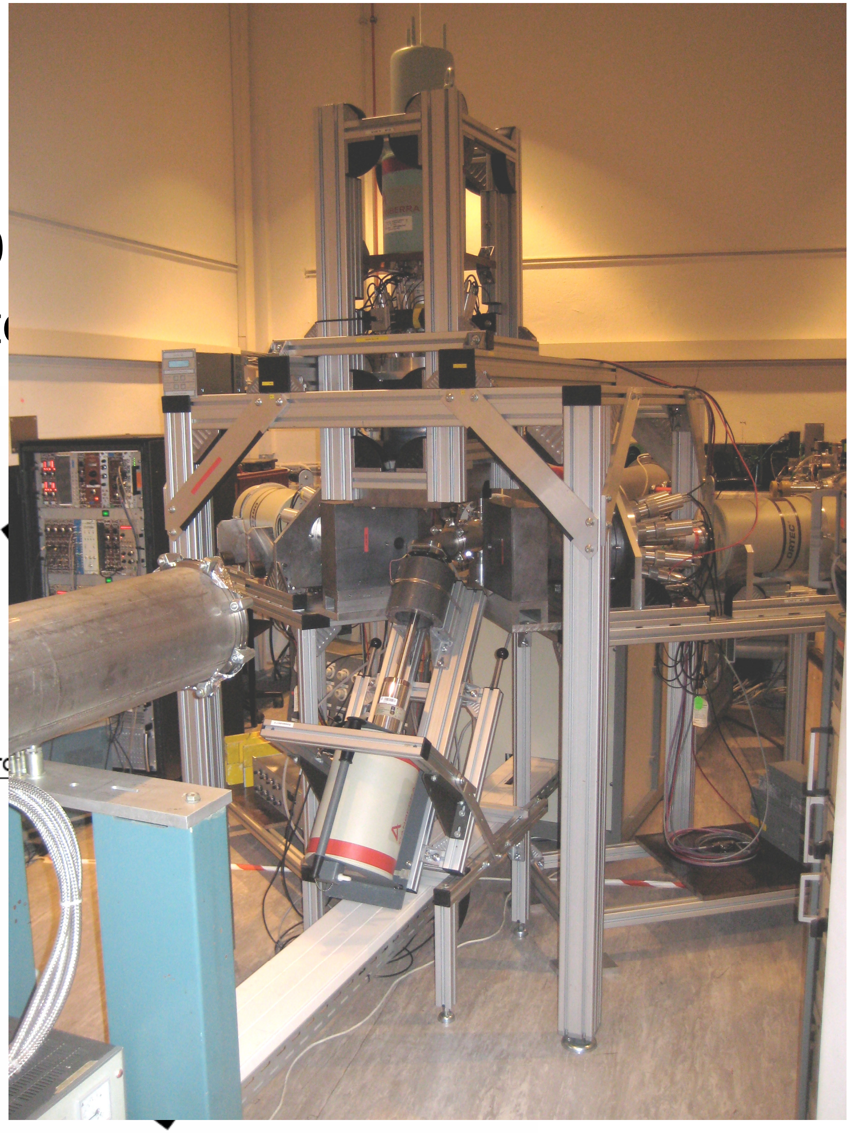


# EXPERIMENT in DRESDEN





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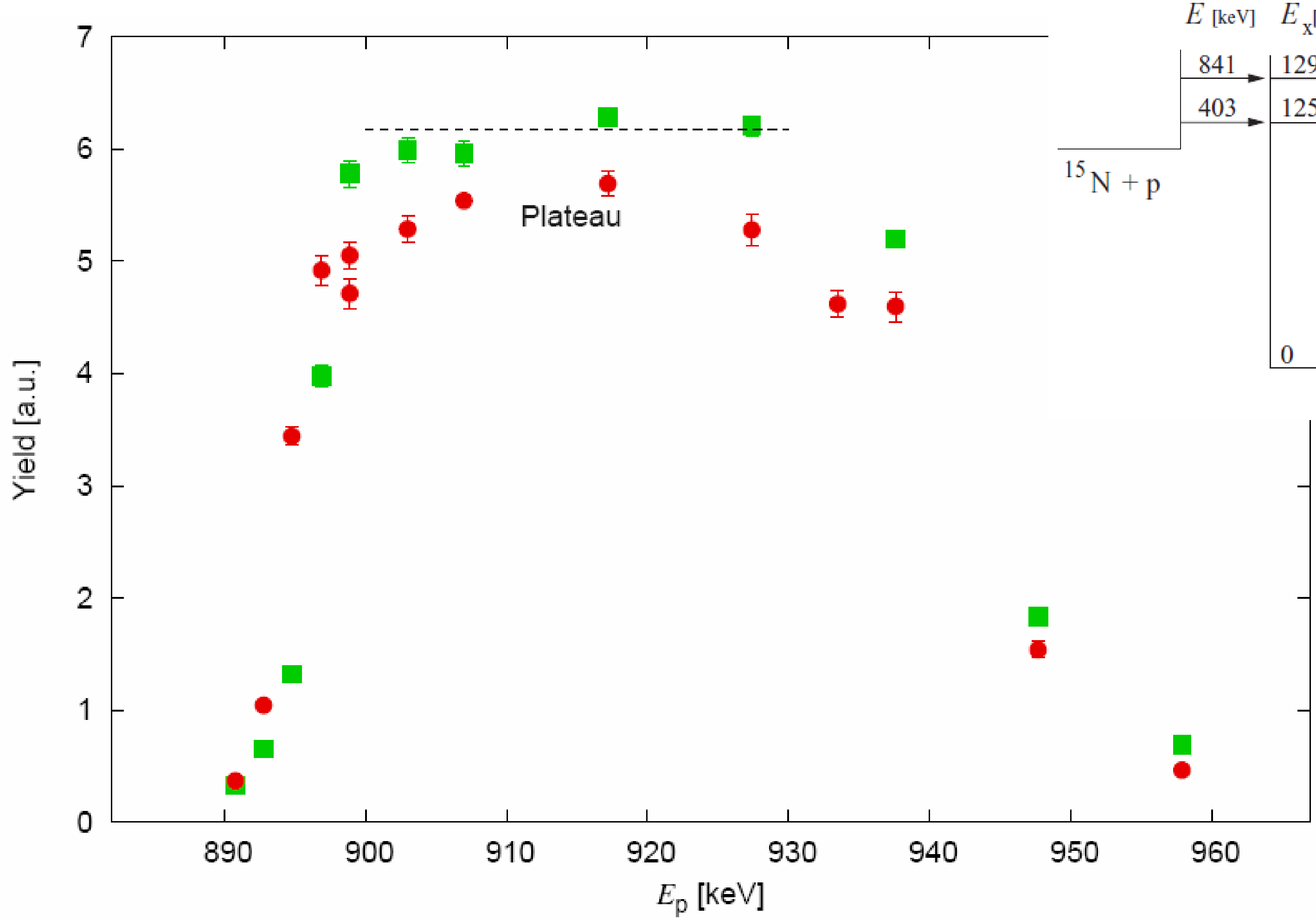
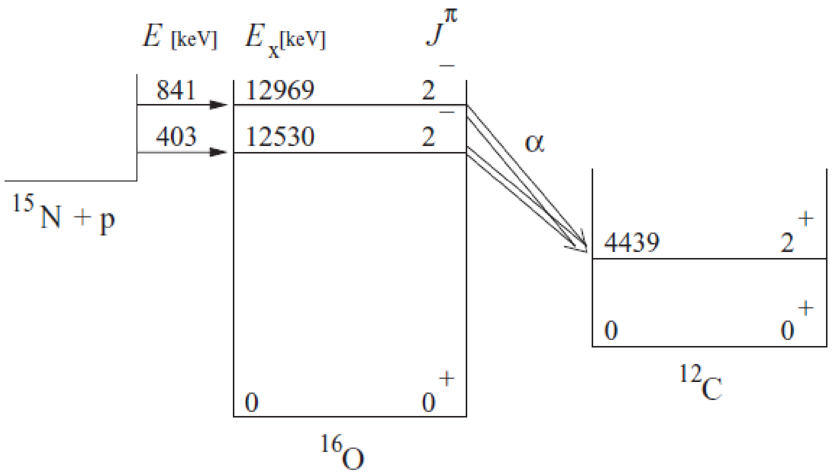
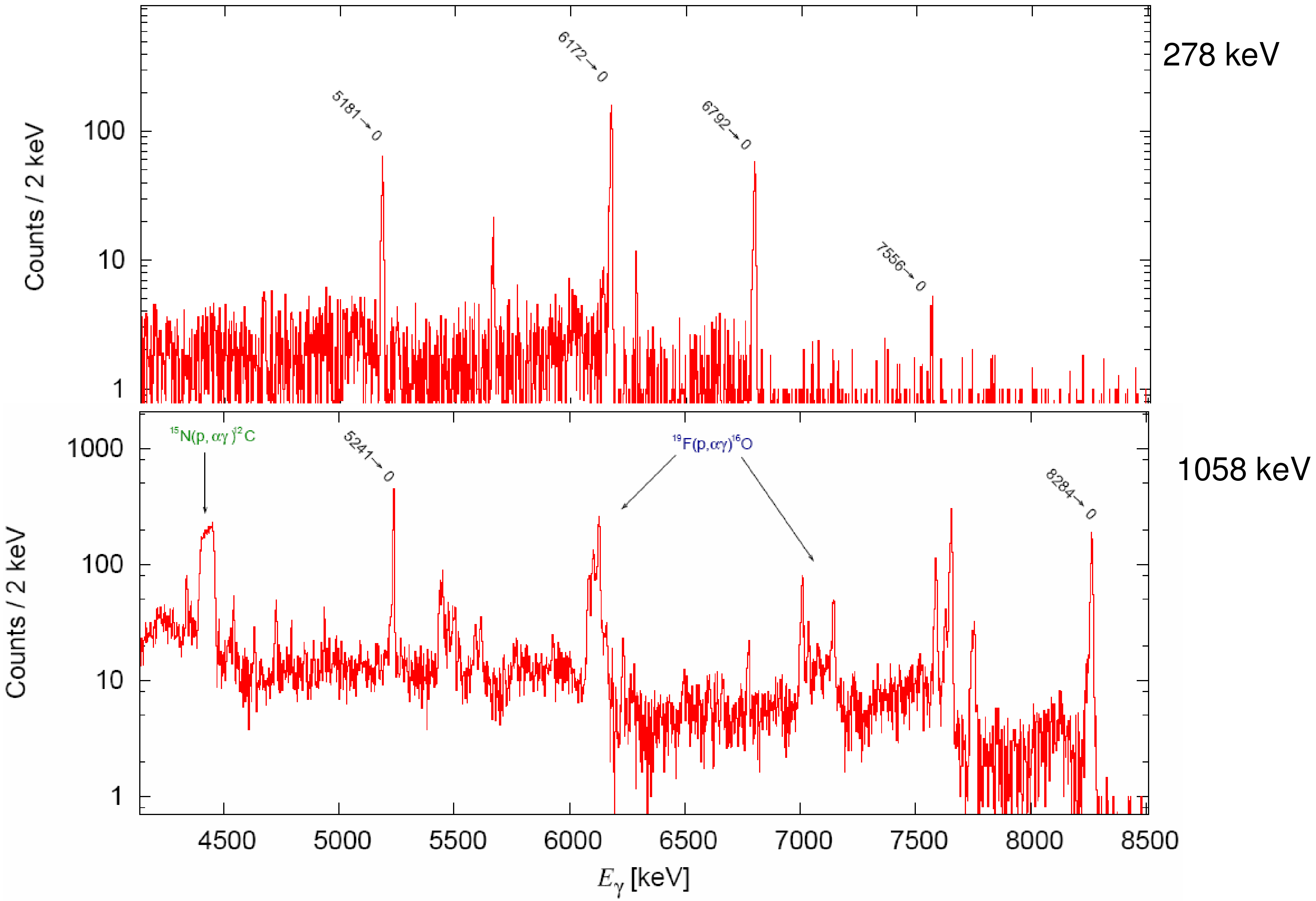
# Target profile: $^{15}N(p,\alpha\gamma)^{12}C$ resonance scan

- $^{15}N$ isotope is present in the target with 0.37% natural abundance
- Daily scan on the $E_p$=897keV resonance, observing the yield of the 4.4MeV γ-ray (first excited state of $^{12}C$)

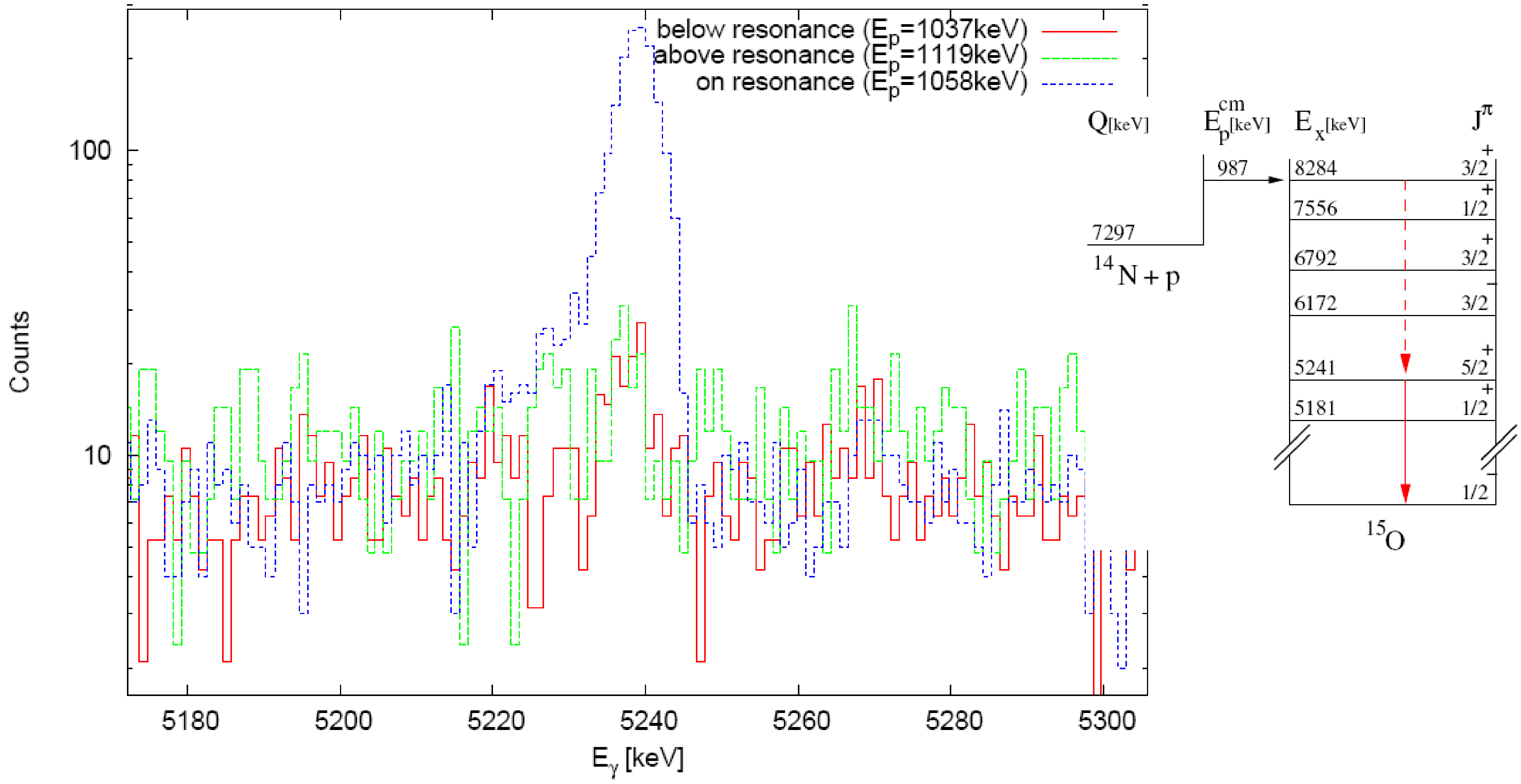


# γ-spectra on the 278 and 1058 keV resonances



# γ-spectra on the 278 and 1058 keV resonances



# 1058keV resonance strength ωγ, relative to 278keV strength

278 keV resonance:
- counts (secondary γ-rays)
- efficiency
- branching ratios (literature)
- ωγ = (13.1 ± 0.6) meV

→ Effective stopping power ε (278keV)

↓ Target history + stopping power ratio

ε (1058keV) →

1058 keV resonance:
- counts (secondary γ-rays)
- efficiency
- branching ratios (present)

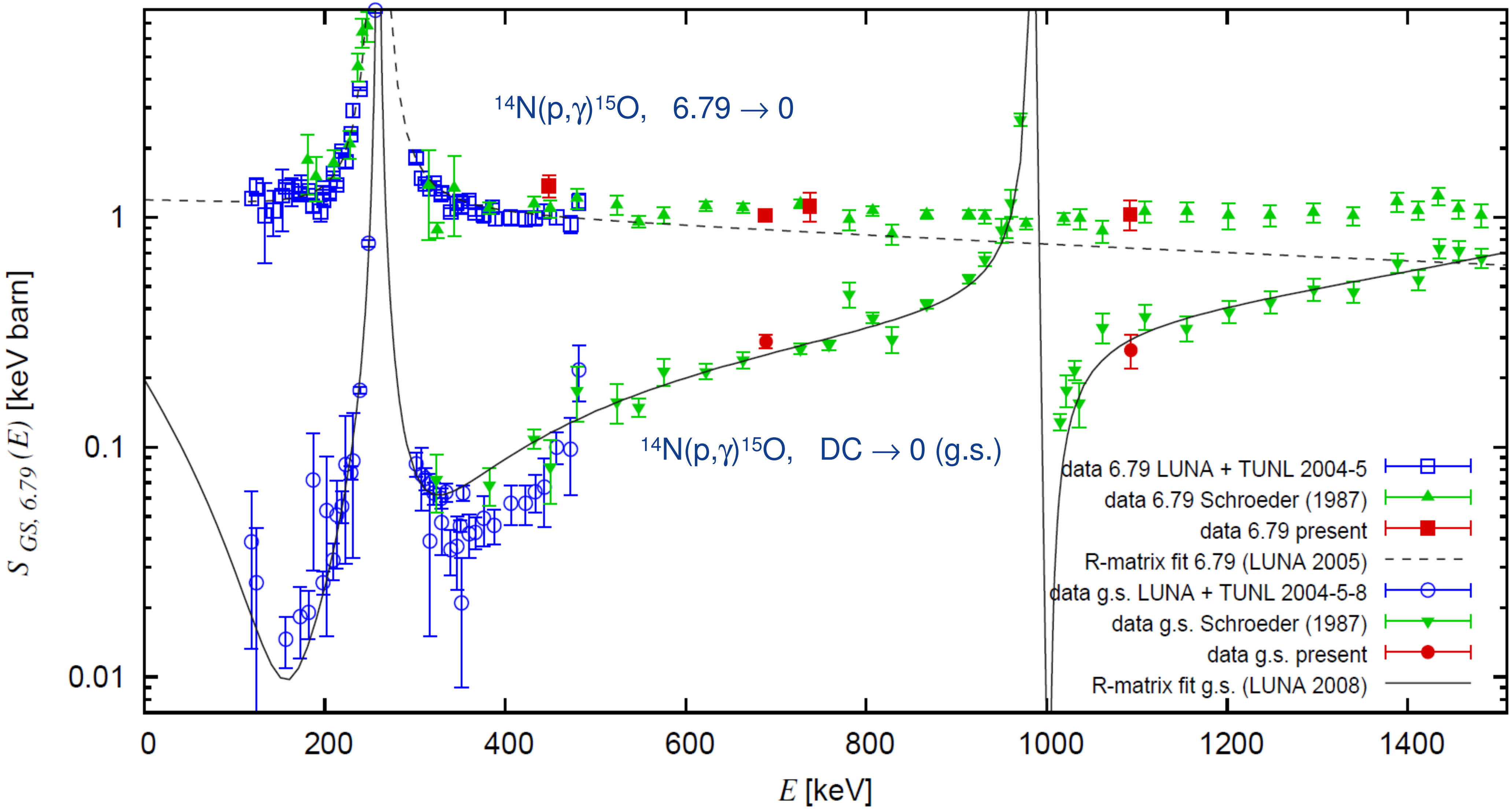
Infinite thick target Yield

$$Y_\infty = \frac{\lambda^2}{2}\frac{M+m}{M}\frac{1}{\varepsilon}\omega\gamma$$

M. Marta *et al.*: Phys. Rev. C 81, 055807 (2010)

| Reaction | Literature $E_p$ [keV] | Literature $\Gamma_{lab}$ [keV] | Present $\omega\gamma_n/\omega\gamma_{278}$ | Present $\omega\gamma$ [eV] | Literature $\omega\gamma$ [eV] |
|---|---|---|---|---|---|
| $^{14}N(p,\gamma)^{15}O$ | 278 | 1.12 | $\stackrel{Def}{=}1$ | — | 0.0131±0.0006 |
| $^{14}N(p,\gamma)^{15}O$ | 1058 | 3.8 | 27.8±0.9 | 0.364±0.021 | 0.31±0.04 |
| $^{15}N(p,\alpha\gamma)^{12}C$ | 430 | 0.1 | $(1.73\pm0.07)\cdot10^3$ | 22.7±1.4 | 21.1±1.4 |
| $^{15}N(p,\alpha\gamma)^{12}C$ | 897 | 1.57 | $(2.77\pm0.09)\cdot10^4$ | 362±20 | 293±38 |

# Off resonance S-factors (preliminary):
## capture to 6792 keV and ground state (g.s)



# Summary and Outlook

- Renewed interest in $^{14}N(p,\gamma)^{15}O$ reaction rate due to Solar composition problem
- Recent data at LUNA: 8% precision on $S_{tot}$
- Experiment in FZ Dresden (at high energy):
  - More precise strength for the 1058 keV resonance
  - Off resonance data (preliminary)

Improvements?

- Off resonance data at high-energy to improve the fit constraints $\rightarrow$ work in progress
- Measure the $\Gamma\gamma$ of 6.79 MeV subthreshold state, which influences the S-factor at very low energy (INFN - Legnaro National Laboratories)

# The LUNA collaboration

| | |
|---|---|
| Bochum (Germany): | C.Rolfs, F.Strieder, H.-P.Trautvetter |
| Debrecen (Hungary): | Z.Elekes, Zs.Fülöp, Gy.Gyürky, E.Somorjai |
| Dresden (Germany): | M.Anders, D.Bemmerer, M.Marta |
| Genoa (Italy): | P.Corvisiero, H.Costantini, A.Lemut, P.Prati |
| Gran Sasso (Italy): | A.Formicola, C.Gustavino, M.Junker |
| Milan (Italy): | A.Guglielmetti, C.Mazzocchi |
| Naples (Italy): | G.Imbriani, B.Limata, V.Roca, F.Terrasi |
| Padua (Italy): | C.Broggini, A.Caciolli, M.Erhard, R.Menegazzo, C.Rossi Alvarez |
| Teramo (Italy): | O.Straniero |
| Turin (Italy): | G.Gervino |

# Collaborators for measurement in Dresden:

| | |
|---|---|
| Dresden FZD (Germany): | D.Bemmerer, R.Beyer, E.Grosse, R.Hannaske, A.R.Junghans, M.Marta, C.Nair, R.Schwengner, E.Trompler, A.Wagner, D.Yakorev |
| Debrecen (Hungary): | Zs.Fülöp, Gy.Gyürky, T.Szücs |
| Padua (Italy): | C.Broggini, A.Caciolli, M.Erhard, R.Menegazzo |

## Thank you for your attention!