Precise study of the supernova reaction $^{40}Ca(\alpha,\gamma)^{44}Ti$ in the Dresden Felsenkeller

EuroGENESIS Meeting

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Daniel Bemmerer (EuroGENESIS AP)

EuroGENESIS
Origin of the Elements and Nuclear History of the Universe

NAVI
Nuclear Astrophysics Virtual Institute

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Partner von DRESDEN concept exzellenz-dresden.de

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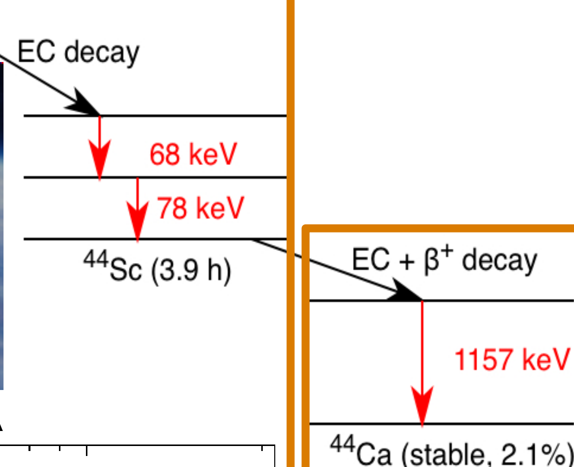
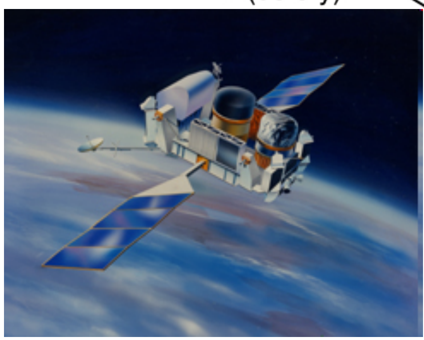
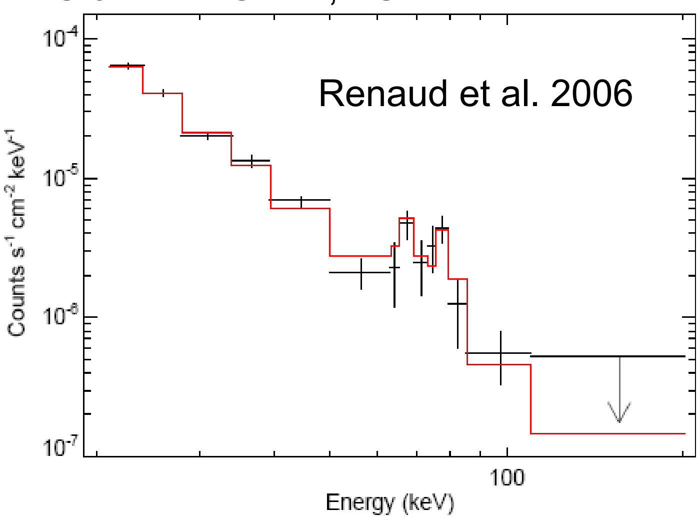
Supernova signal: ^{44}Ti in Cassiopeia A supernova remnant

- Decay of radioactive ^{44}Ti produces low-energy and high-energy γ-rays
- Half-life of just 59.6 years provides “smoking gun” for a supernova explosion
- Detectable by space-based γ-spectrometers

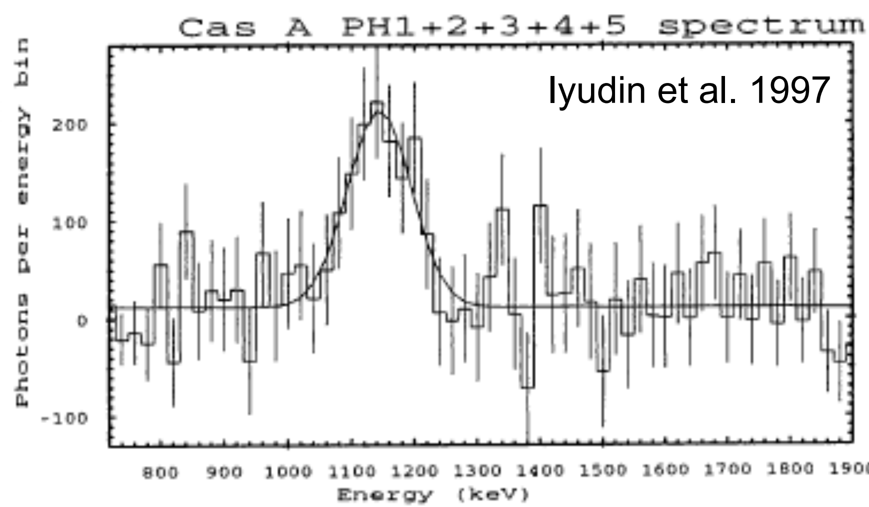




IBIS on INTEGRAL, ESA



COMPTEL on CGRO, NASA



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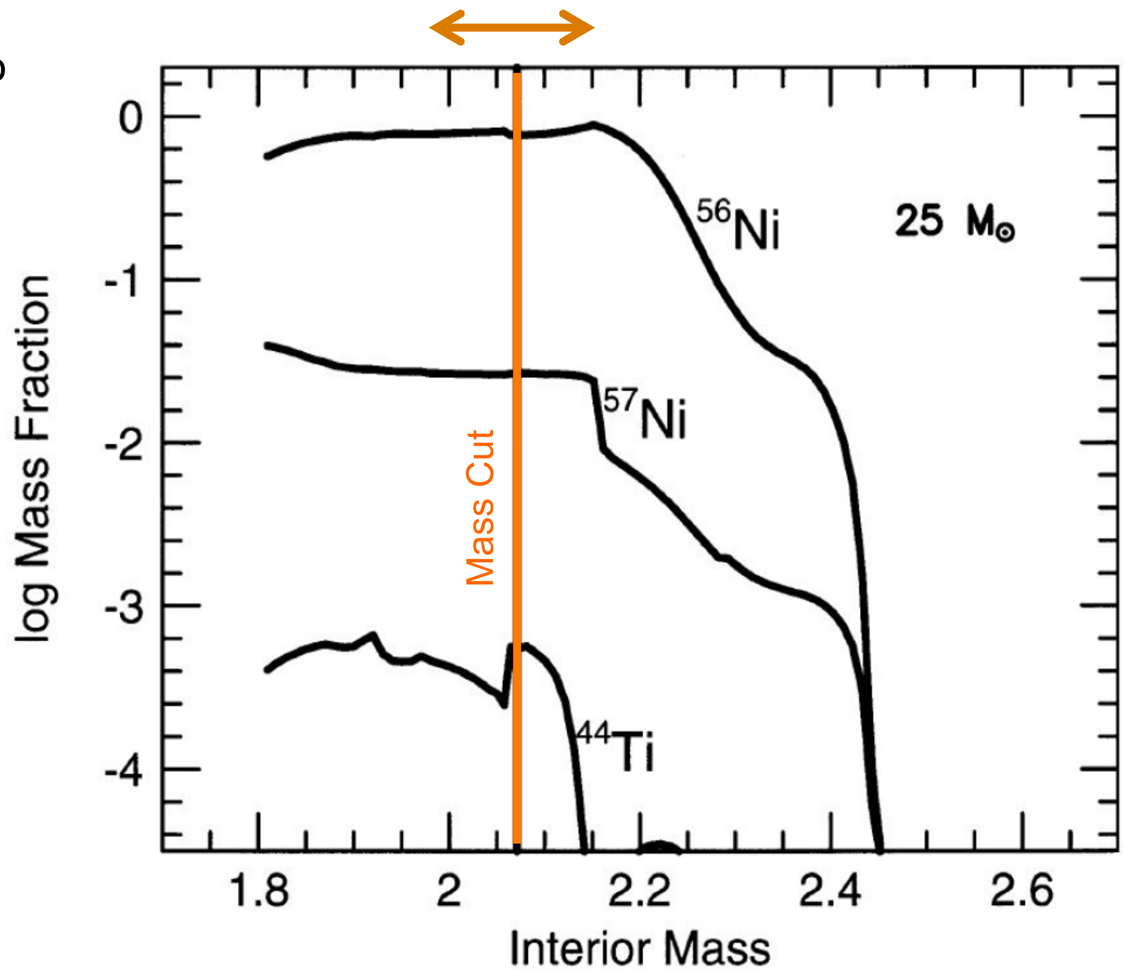
^{44}Ti and core collapse supernovae models

- Yields of ^{44}Ti and ^{56}Ni are sensitive to the explosion temperature, density and proton-to-neutron ratio Y_e
- ^{44}Ti/^{56}Ni abundance ratio in Cas A supernova remnant not well reproduced by models
- ^{44}Ti is produced close to the mass cut (if one is used)
- Nuclear uncertainties must be excluded:
  - ^{44}Ti-producing reaction **^{40}Ca(α,γ)^{44}Ti (results)**
  - ^{44}Ti-destroying reaction ^{44}Ti(α,p)^{47}V (feasibility study)



Mass profiles of ^{44}Ti and ^{56}Ni for a 25 $M_\odot$ core-collapse supernova model (Hoffman et al. 1995, Diehl et al. 1998)

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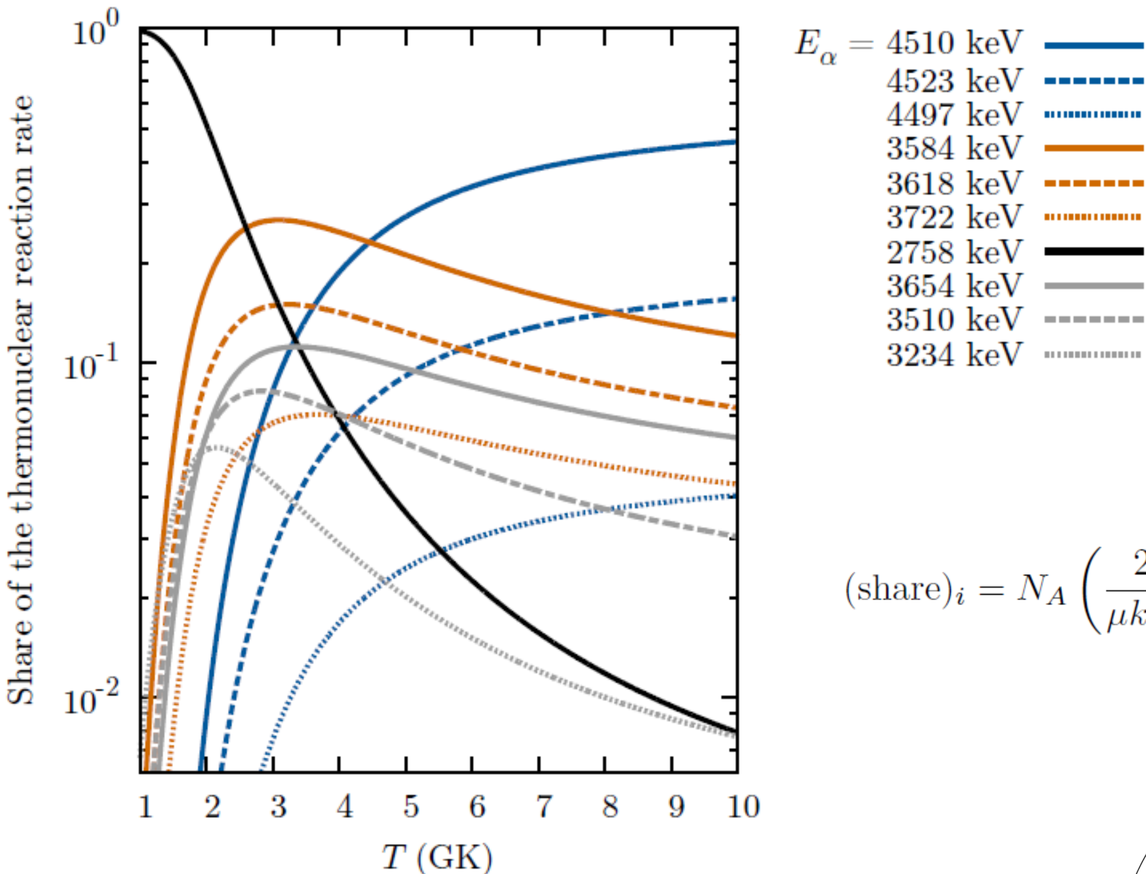
Most important resonances in the $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction

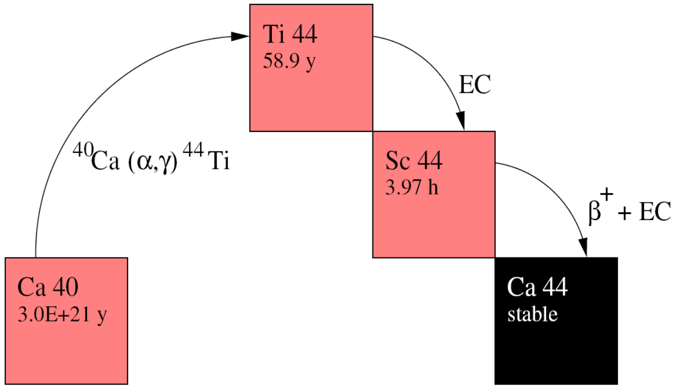


this talk

under analysis, γ-counting in Felsenkeller Dresden

under analysis, 2nd beam time planned for late 2013

$$(\mathrm{share})_i = N_A \left(\frac{2\pi}{\mu k_B T}\right)^{2/3} \hbar \frac{(\omega\gamma)_i \exp\left[-E^{\mathrm{lab}}_{\alpha,i}/(k_B T)\right]}{\sum_i (\omega\gamma)_i \exp\left[-E^{\mathrm{lab}}_{\alpha,i}/(k_B T)\right]}$$



Approach:

1. Activation at high-intensity 3 MV Tandetron
2. γ-counting in Felsenkeller Dresden
3. Determination of resonance strengths $\omega\gamma$

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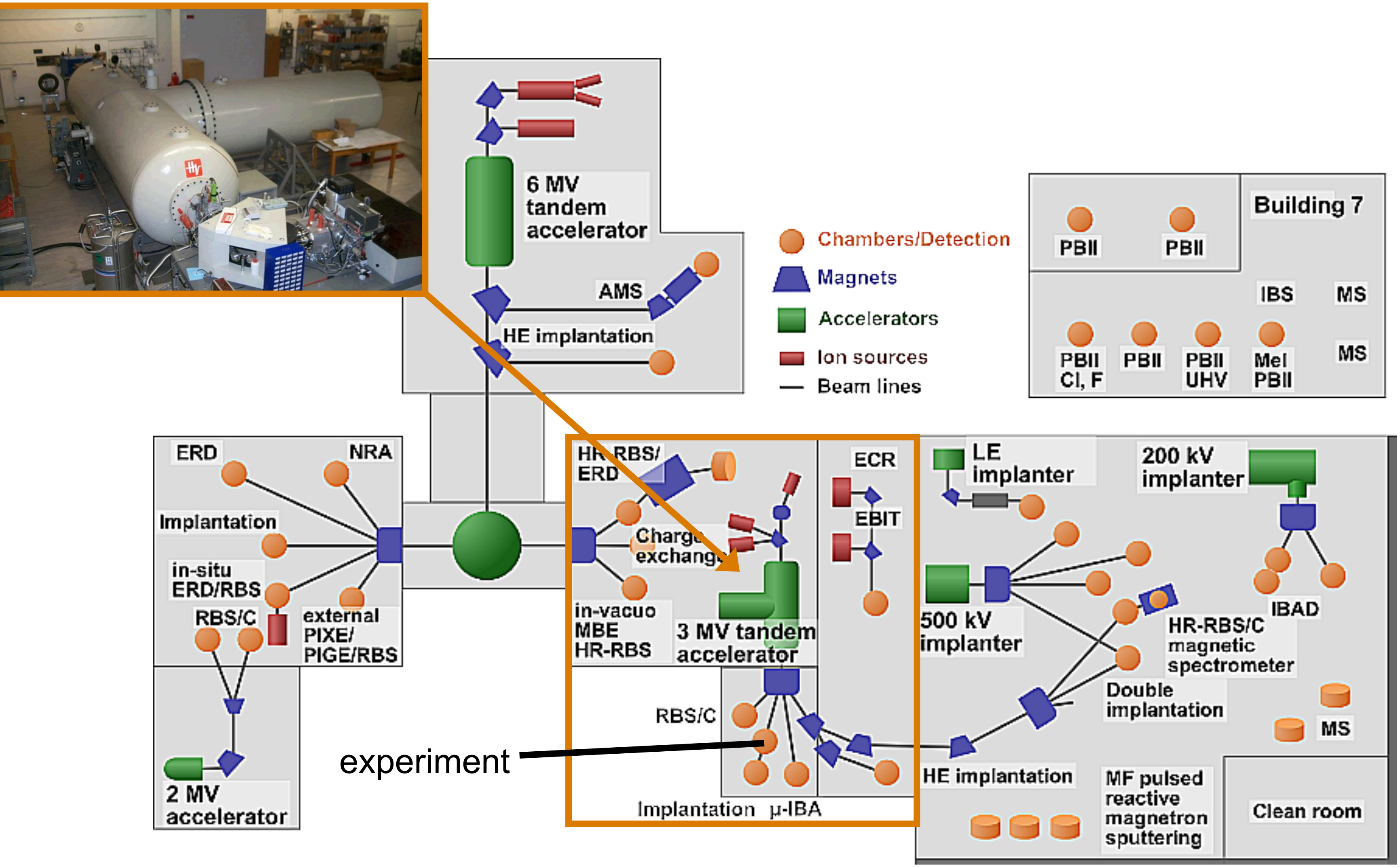
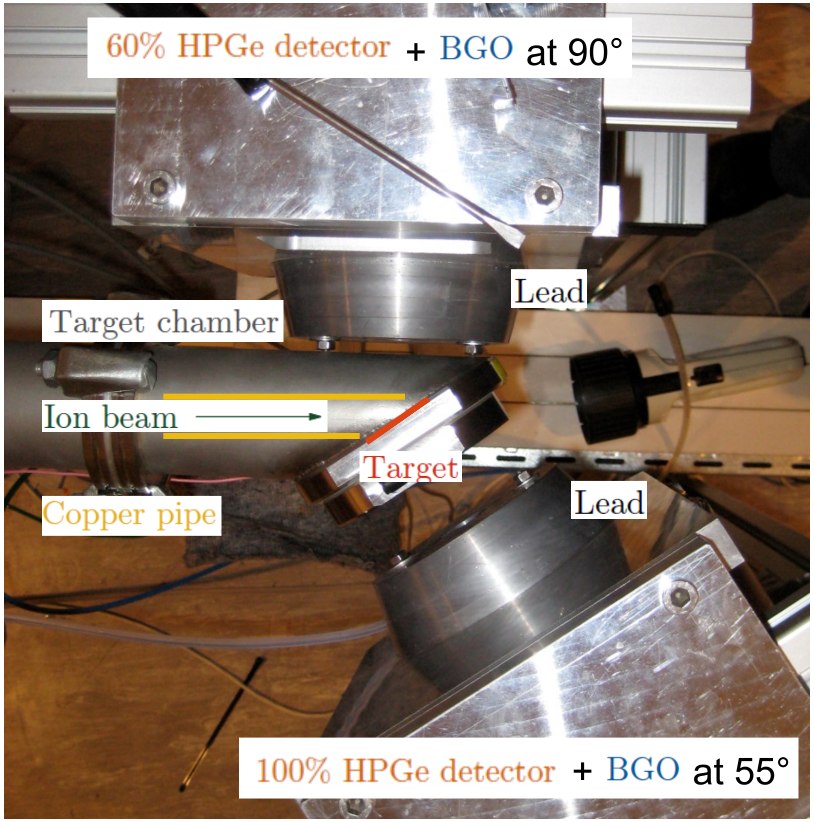
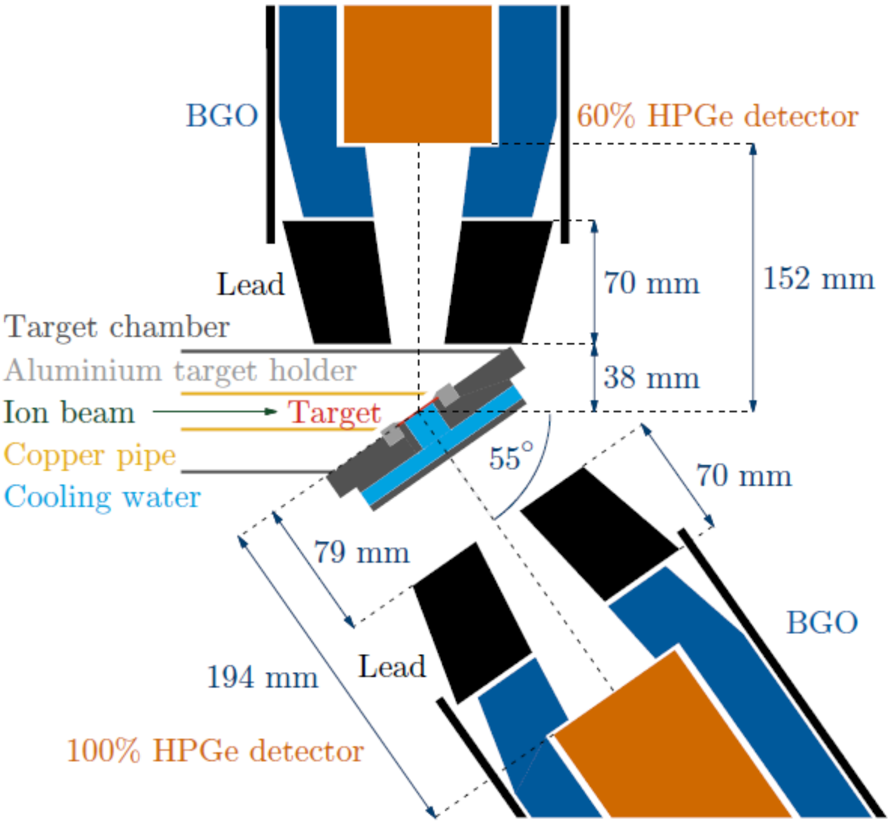
$^{40}Ca(\alpha,\gamma)^{44}Ti$ experiment at HZDR ion beam center



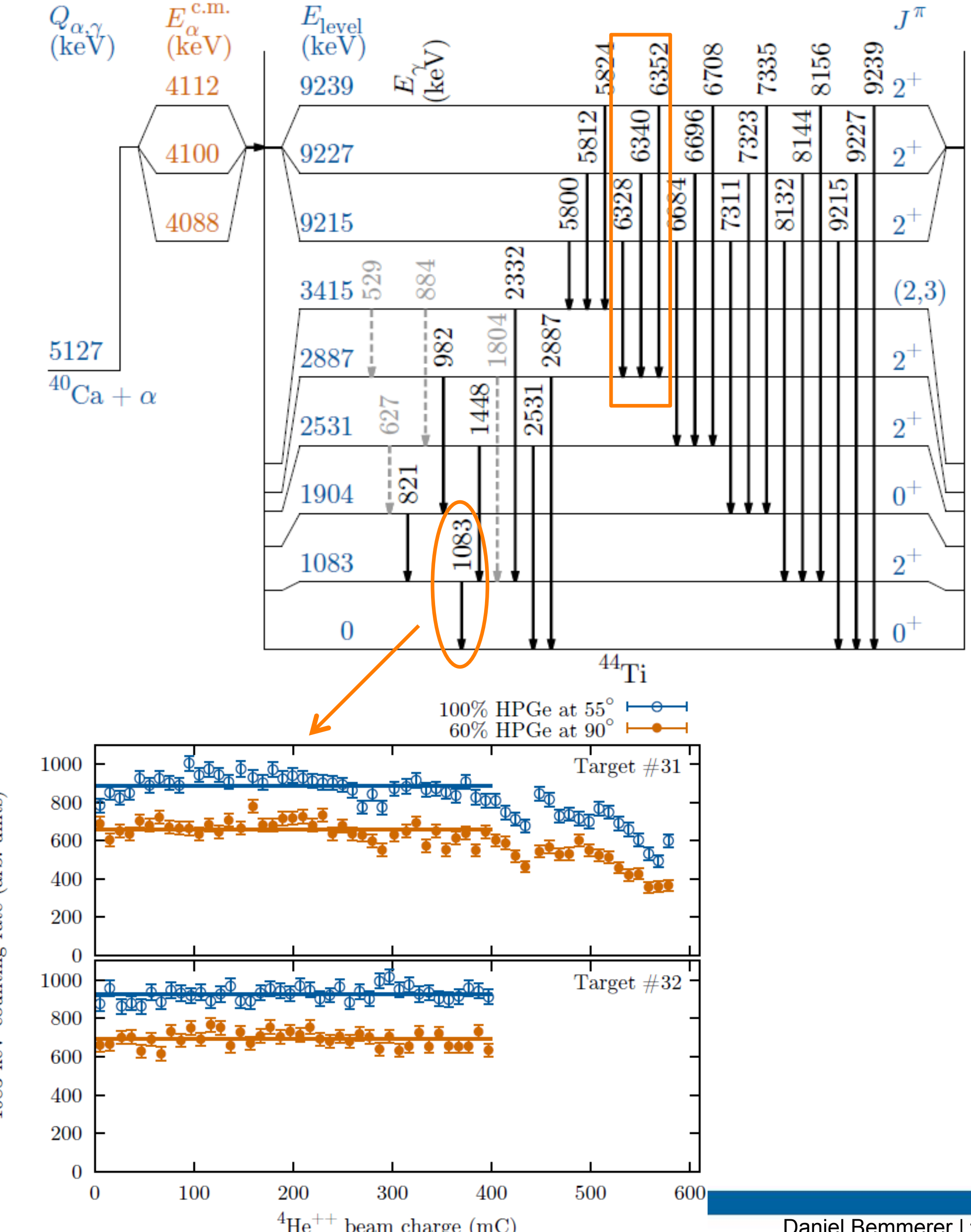
Setup at 3 MV Tandetron at HZDR





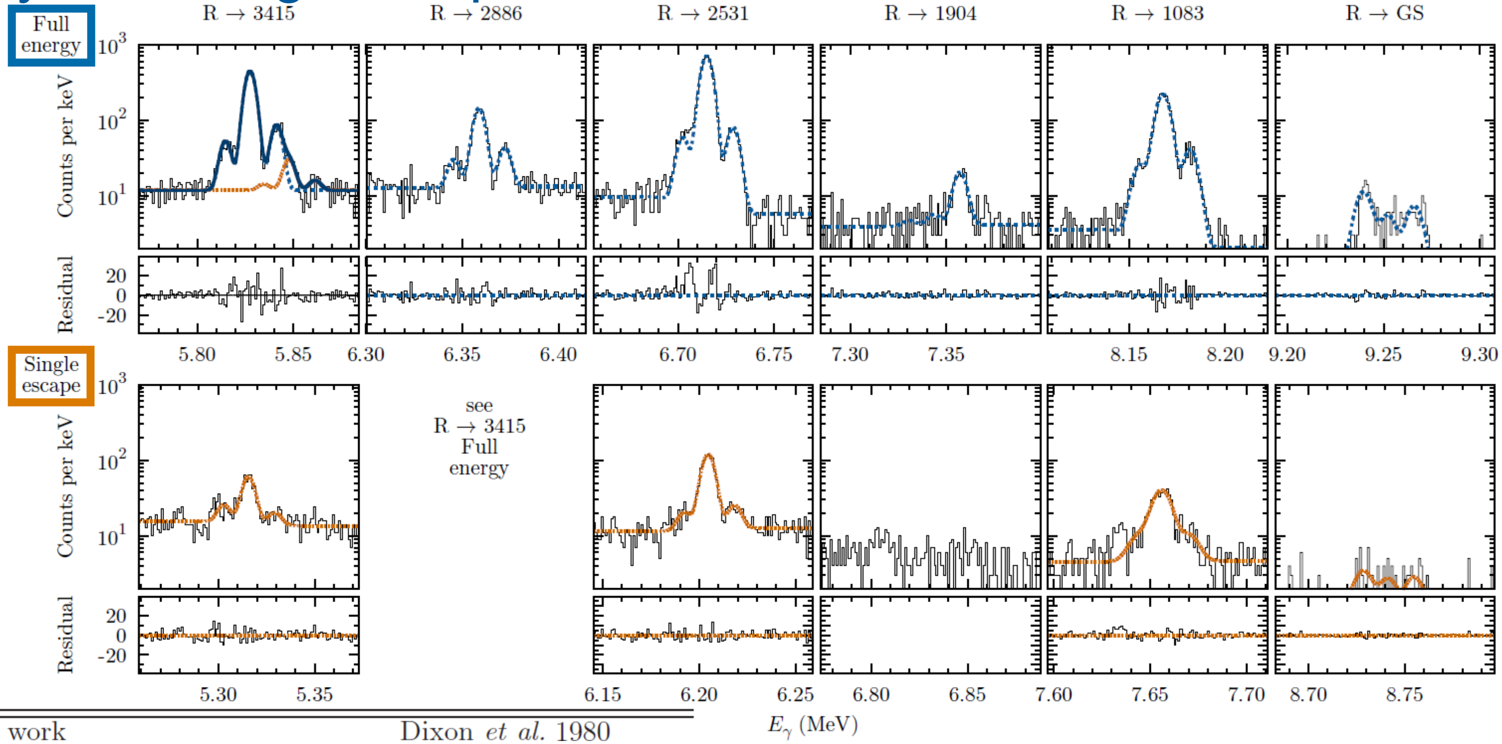
- 3 MV Tandetron provides up to 9 MeV, 3 μA He^{++} beam.
- $Ca(OH)_2$ target on Ta backing, directly water cooled.
- Irradiations at 4.5 MeV, three closely spaced resonances there

Reduced level scheme of ^{44}Ti and monitoring of the irradiations



- Three close-by resonances near E_{CM} = 4.1 MeV (E_α=4.5 MeV) activated together
- Triplet of resonances is apparent in high-energy γ ray groups of three
- Irradiation monitored using 1083 keV γ ray from decay of first excited state of ^{44}Ti

Primary γ-rays showing the triplet of resonances



Final level (keV)	Present work Initial level (keV) 9215 (%)	9227 (%)	9239 (%)	Dixon *et al.* 1980 Initial level (keV) 9215	9227	9239
0	12.9 ± 1.3	0.70 ± 0.08	6.1 ± 0.5	10 ± 1	0.6 ± 0.2	4.0 ± 0.5
1083	20.1 ± 2.3	21.4 ± 0.5	23.6 ± 1.4	16 ± 2	23 ± 2	27 ± 2
1904			7.7 ± 1.0	2 ± 1	< 1	5 ± 1
2531	34 ± 4	45.8 ± 0.7	28.3 ± 1.6	41 ± 2	45 ± 2	28 ± 2
2886	9.4 ± 1.7	7.7 ± 0.3	11.0 ± 0.8	11 ± 2	8 ± 2	11 ± 2
3415	21.2 ± 1.9	23.4 ± 0.6	23.3 ± 1.1	20 ± 2	23 ± 2	25 ± 2

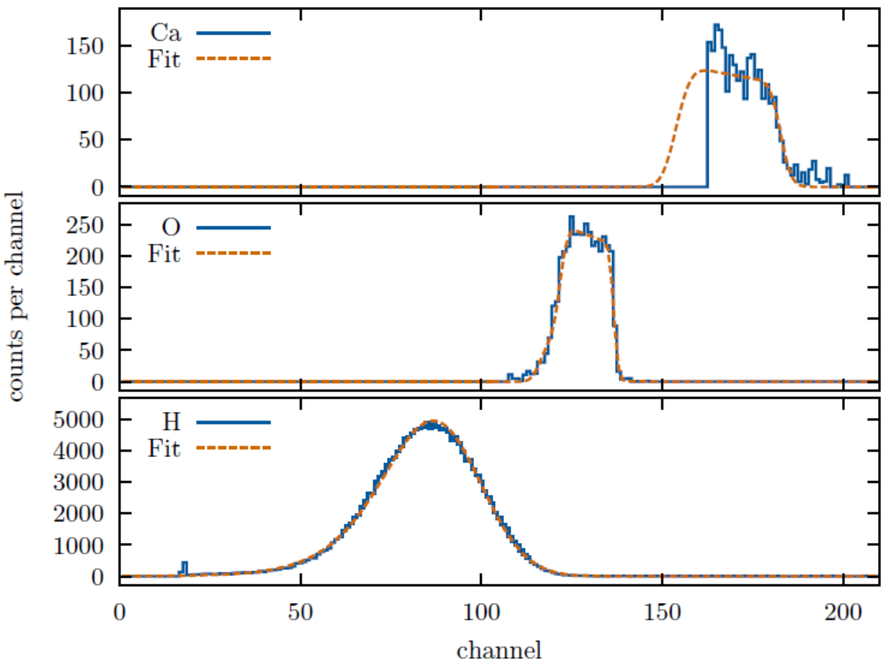
- γ-ray branching ratios observed at 55°.
- Improved precision with respect to literature.

W. R. Dixon, R. S. Storey, and J. J. Simpson, Can. J. Phys. **58**, 1360 (1980).

Stoichiometric ratio x in $Ca(OH)_x$

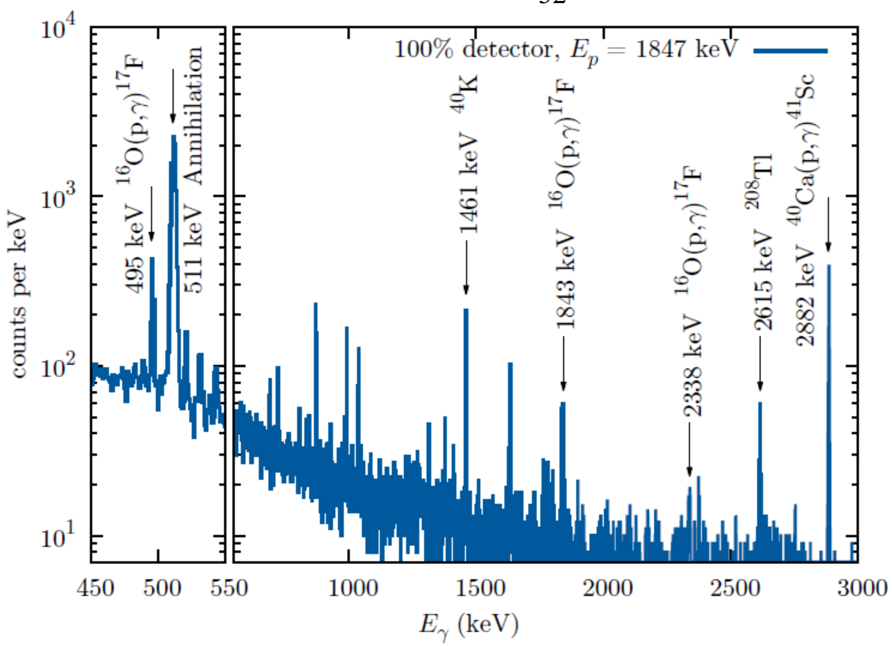
- Two independent methodes have been used to determine the stoichiometric ratio x in $Ca(OH)_x$:

1. Elastic Recoil detection Analysis (ERDA): $x_{30} = 1.88 \pm 0.21$



2. From proton induced in-beam γ-ray spectrum, using $^{16}O(p,\gamma)^{17}F$ reaction (with 6% uncertainty in σ by Mohr *et al.* 2012):

$$x_{31} = 1.9 \pm 0.6$$
$$x_{32} = 1.8 \pm 0.5$$



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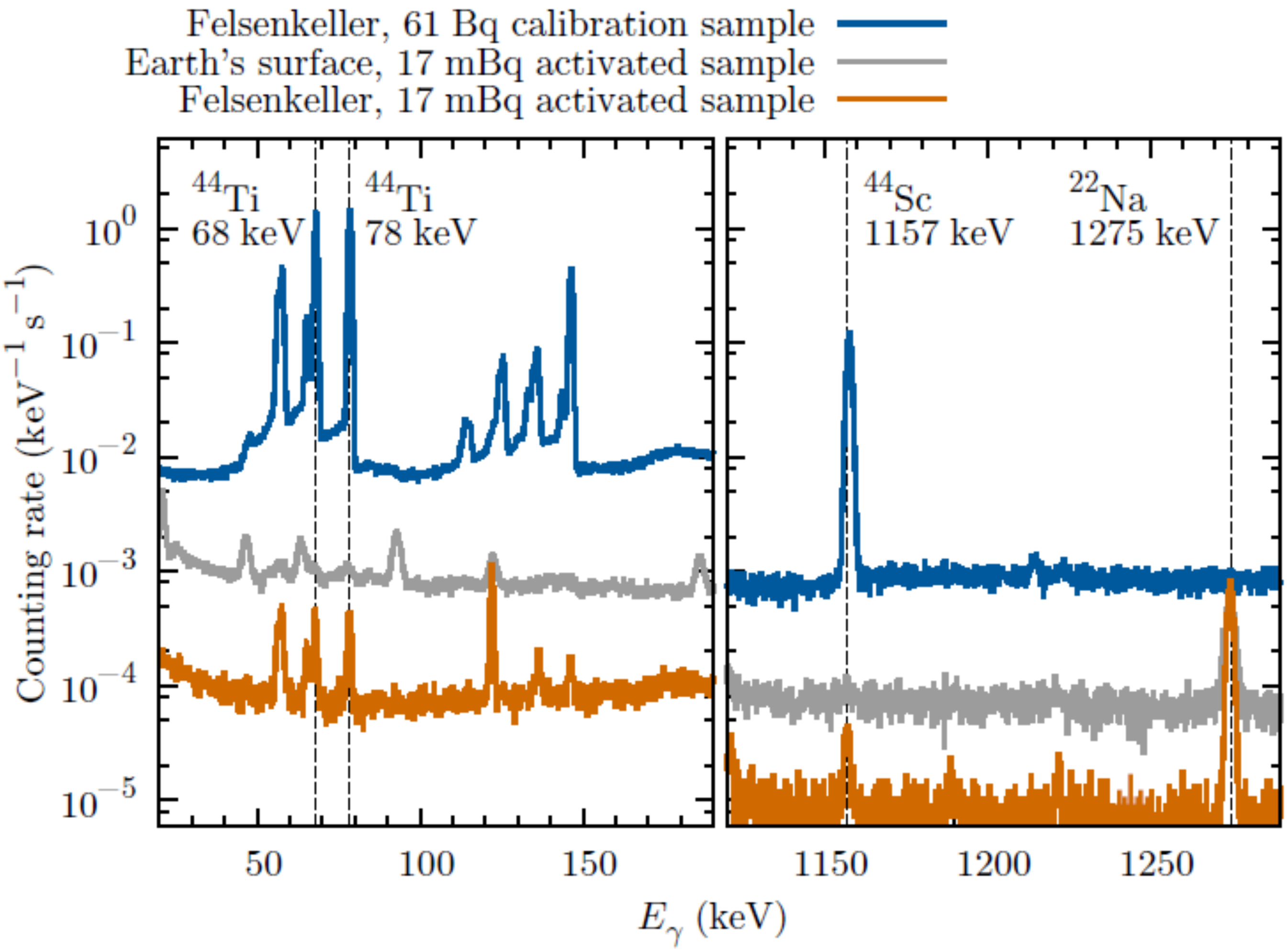
Offline spectra of activated ^{44}Ti samples



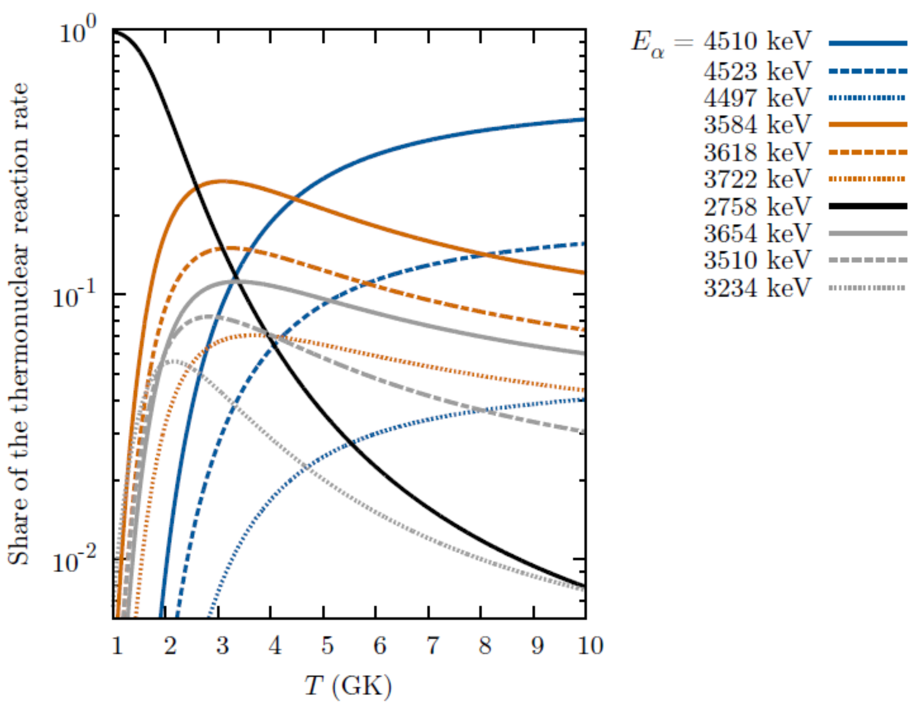
- Spectra of ^{44}Ti samples, measured in a low-background counting facility at earth's surface and in the ultra-low-background facility Felsenkeller Dresden.
- After 68.4 h activation and 7 days counting, an activity of 17.1 ± 0.5 mBq was determined.

Results: ^{40}Ca(α,γ)^{44}Ti resonance strengths

$\omega\gamma$ [eV]	Reference	Technique
8.3 ± 1.7	Dixon *et al.* 1980	in-beam γ spectroscopy
8.8 ± 3.0	Nassar *et al.* 2006	AMS
7.6 ± 1.1	Vockenhuber *et al.* 2007	recoil detection
9.0 ± 1.2	Robertson *et al.* 2012	in-beam γ spectroscopy
8.4 ± 0.6	**Present work**	**activation and in-beam γ spectroscopy**

E_α (keV) E_x (keV)	4497 9215	4510 9227	4523 9239
Present work	**0.92 ± 0.20**	**6.2 ± 0.5**	**1.32 ± 0.24**
Dixon *et al.* 1980	0.5 ± 0.1	5.8 ± 1.2	2.0 ± 0.4

- Phys. Rev. C, submitted last month

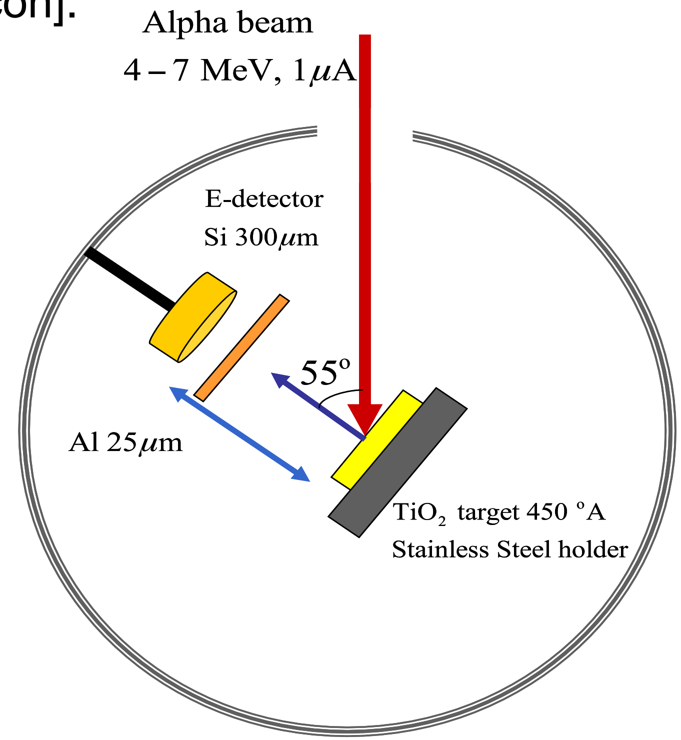


Outlook, ^{40}Ca(α,γ)^{44}Ti

- 4.5 MeV resonances to be studied also by a third technique: AMS measurement in preparation.
- 3.5 MeV resonances: Offline counting still going on
- 2.8 MeV resonance: Second irradiation planned for late 2013.

Feasibility study on ^{44}Ti(α,p)^{47}V reaction with a radioactive ^{44}Ti target (1)

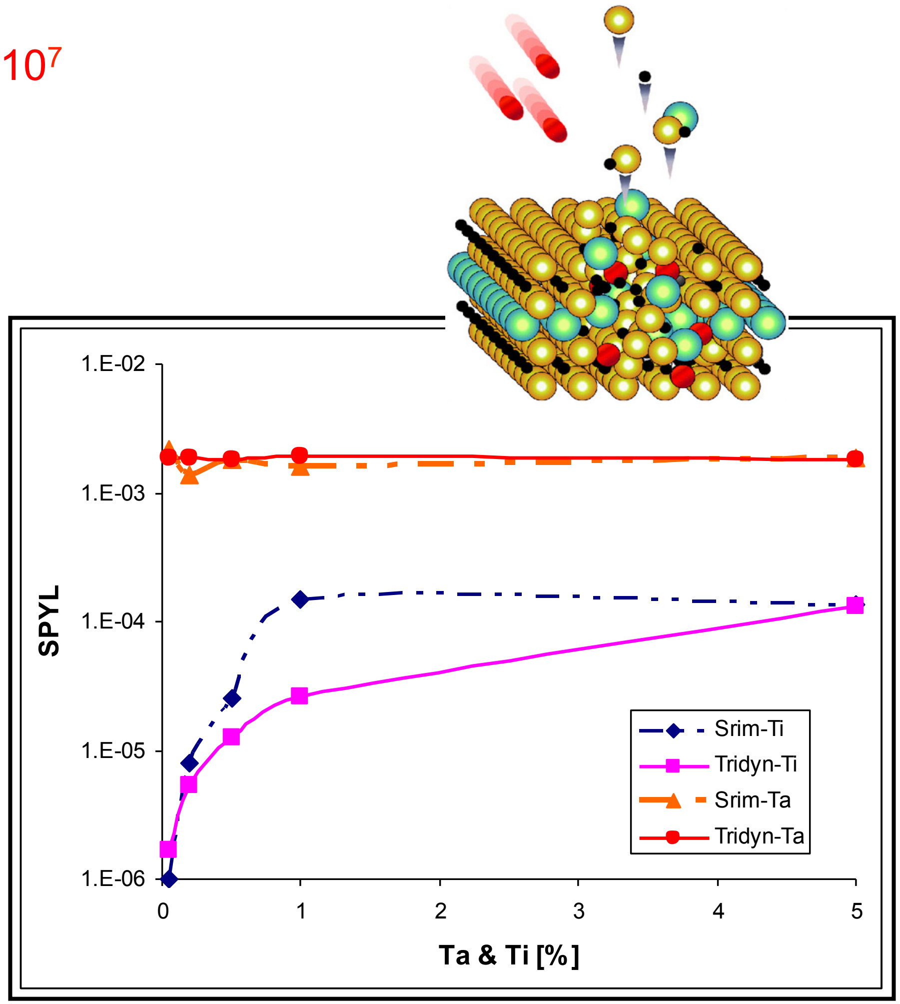
- HZDR Ion Beam Center.
- α-beam at 4 – 7 MeV, Angle = 55°. Current = 1 μA for 1 – 2 weeks.
- 1 MBq ^{44}Ti implanted into metallic Ta matrix (planned, ISOLDE)
- 25 μm Al-foil is used to stop α-particles before the detector.
- 100 – 300 μm PIPS [Partially Implanted Passivated Silicon].



Feasibility study on ^{44}Ti(α,p)^{47}V reaction with a radioactive ^{44}Ti target (2)

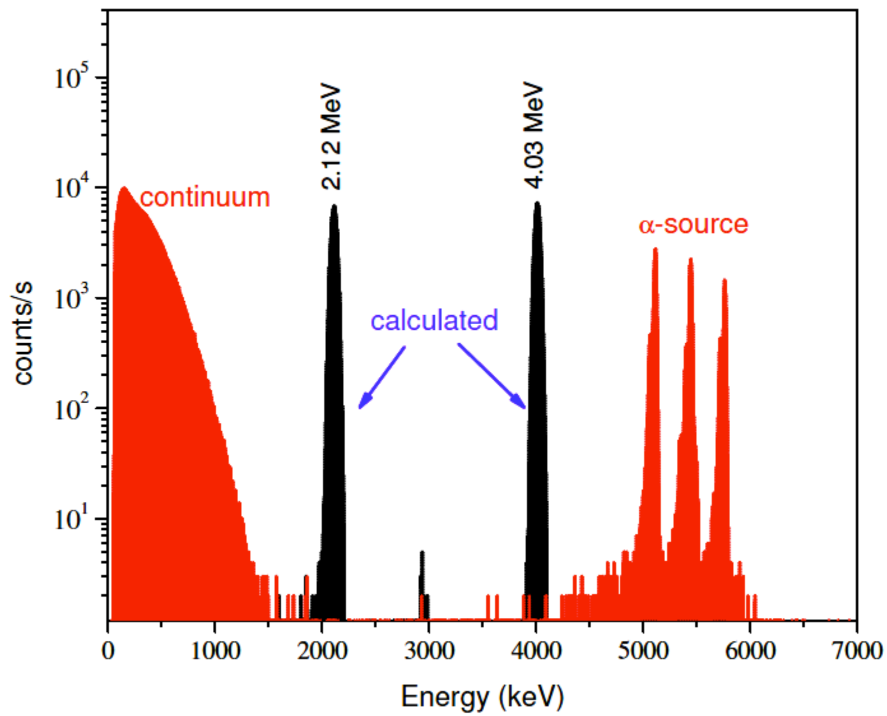
- Safety concern: Sputtering, resulting in contamination
- Target 40 nm, FL = 5.4 x 10^{17} ion/cm^2, NH = 10^7
- Estimating the sputtering yield for 1 day.
- SRIM and TRIDYN
- ^{44}Ti free limit: 100 kBq

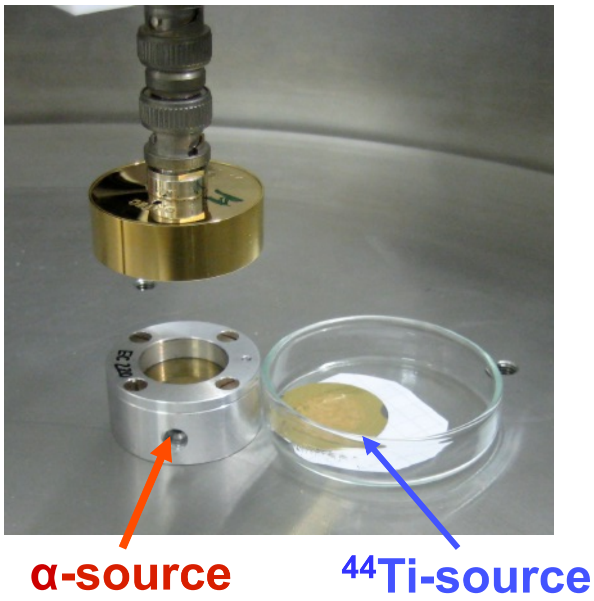
Ti %	Sputter yield	Sputtered ^{44}Ti [kBq]
0.05	1.7 x 10^{-7}	0.3
0.2	6.7 x 10^{-6}	1.4
0.5	1.89 x 10^{-5}	4
1.0	8.80 x 10^{-5}	18
5.0	1.33 x 10^{-4}	27



Feasibility study on $^{44}Ti(\alpha,p)^{47}V$ reaction with a radioactive ^{44}Ti target (3)

- AmCuPu-source and ^{44}Ti (83 kBq) are both observed by the 500 μm Si-detector

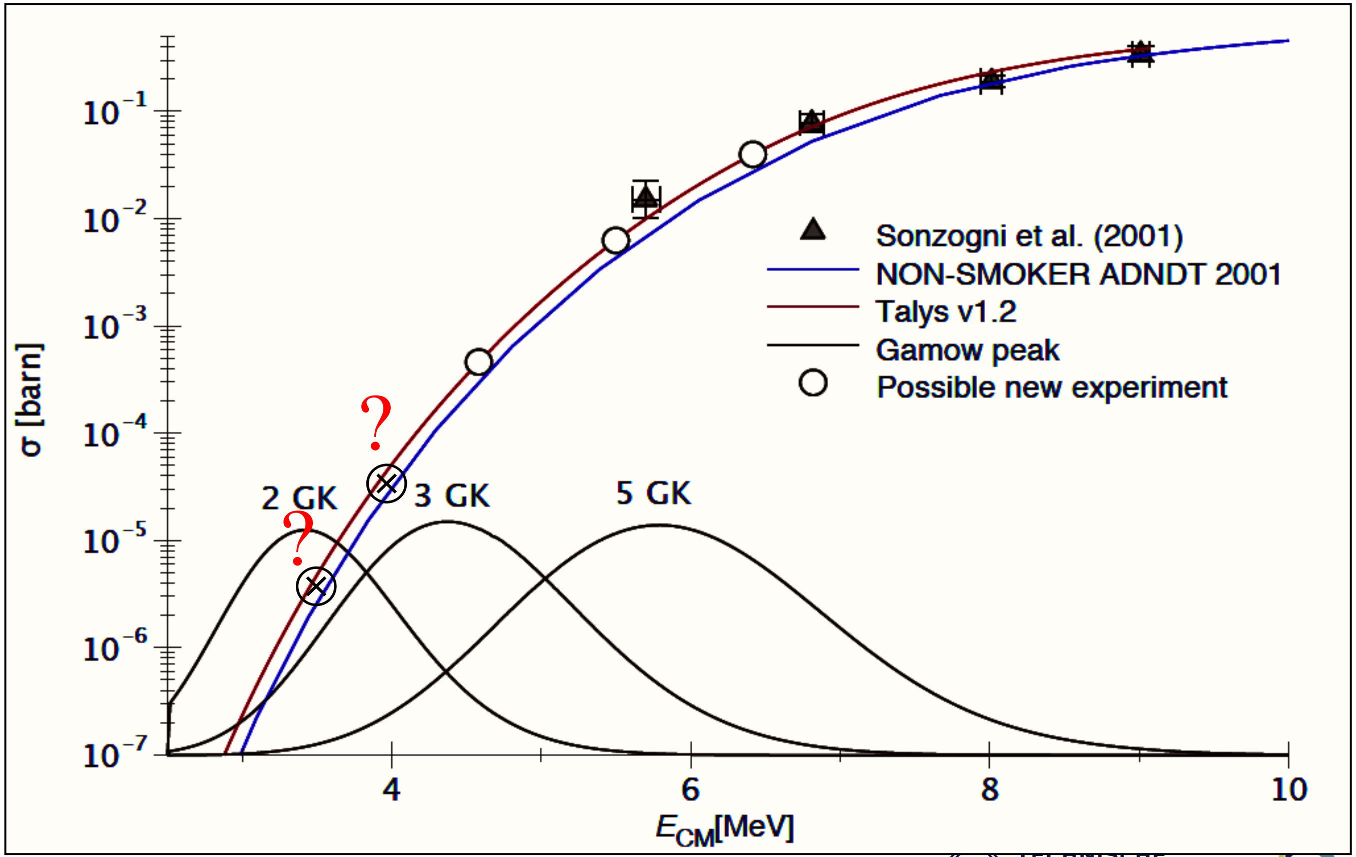




- Continuum ends point is at almost 1.7 MeV.

Feasibility study on ^{44}Ti(α,p)^{47}V reaction with a radioactive ^{44}Ti target (4)

- **Adopting Rauscher calculations, PRC 81, 045807 (2010).**
- **Gamow Windows are re-calculated for T_9 = 2, 3, 5.**
- **Talys code is used. [A. J. Koning, AIP 769, 1154 (2005)]**
- **Three new points are very probable to measure. Two more are question marks.**



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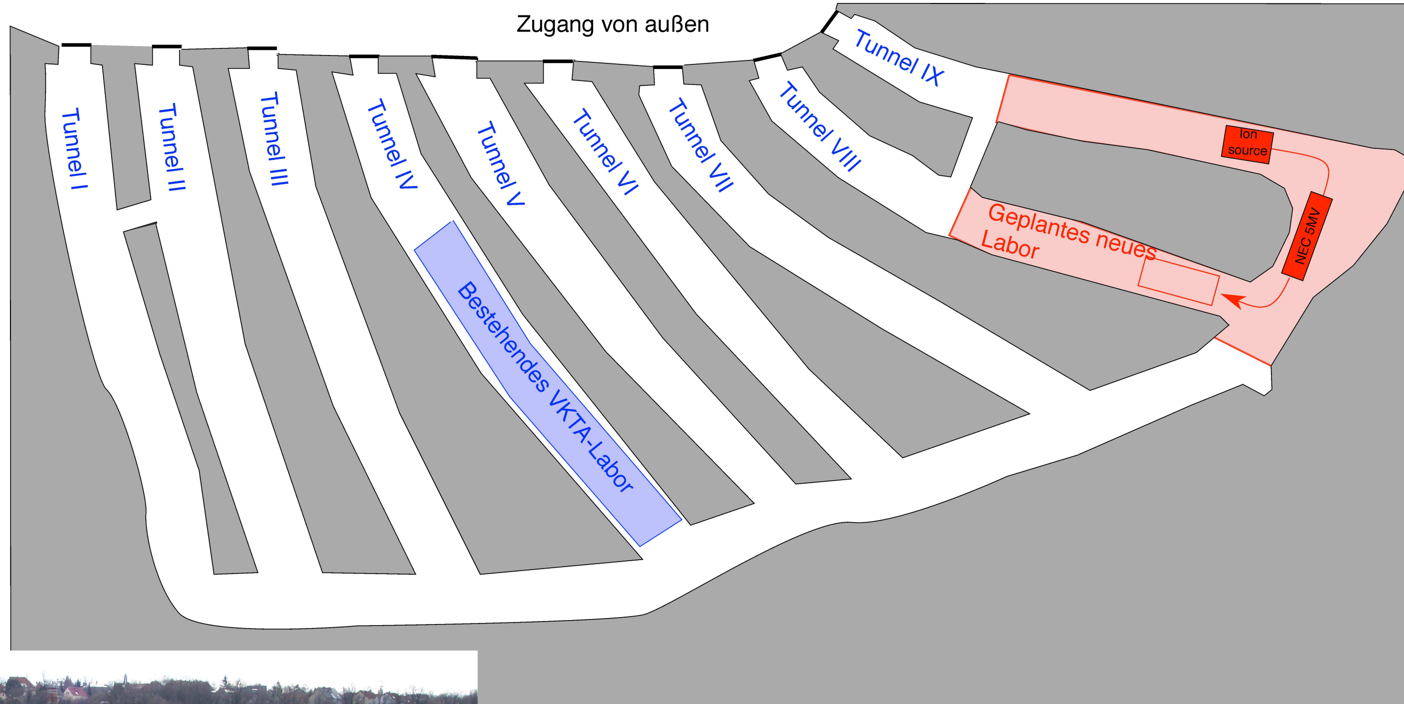
Why not place a used accelerator in Felsenkeller?



- Industrial area (former Felsenkeller brewery)
- Additional space available underground
- Background 3 times worse than LUNA
- Great interest by students, and local citizens
- Synergies with ongoing work at TU Dresden (solar neutrinos) and at HZDR (detector development, nuclear waste transmutation)

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12 year old 5MV Pelletron system from York/UK

- Property of an insolvent spin-off of York University
- Magnets, beamline, pumps, fully digital control

- MC-SNICS sputter ion source (C^- and H^- ions)
- 250 µA upcharge current (double pellet chains)

➔ Well-suited for low-energy nuclear astrophysics

- Purchased by HZDR, brought to Dresden

12 July 2012: Still assembled, in York

24 July 2012: Loading of components in York

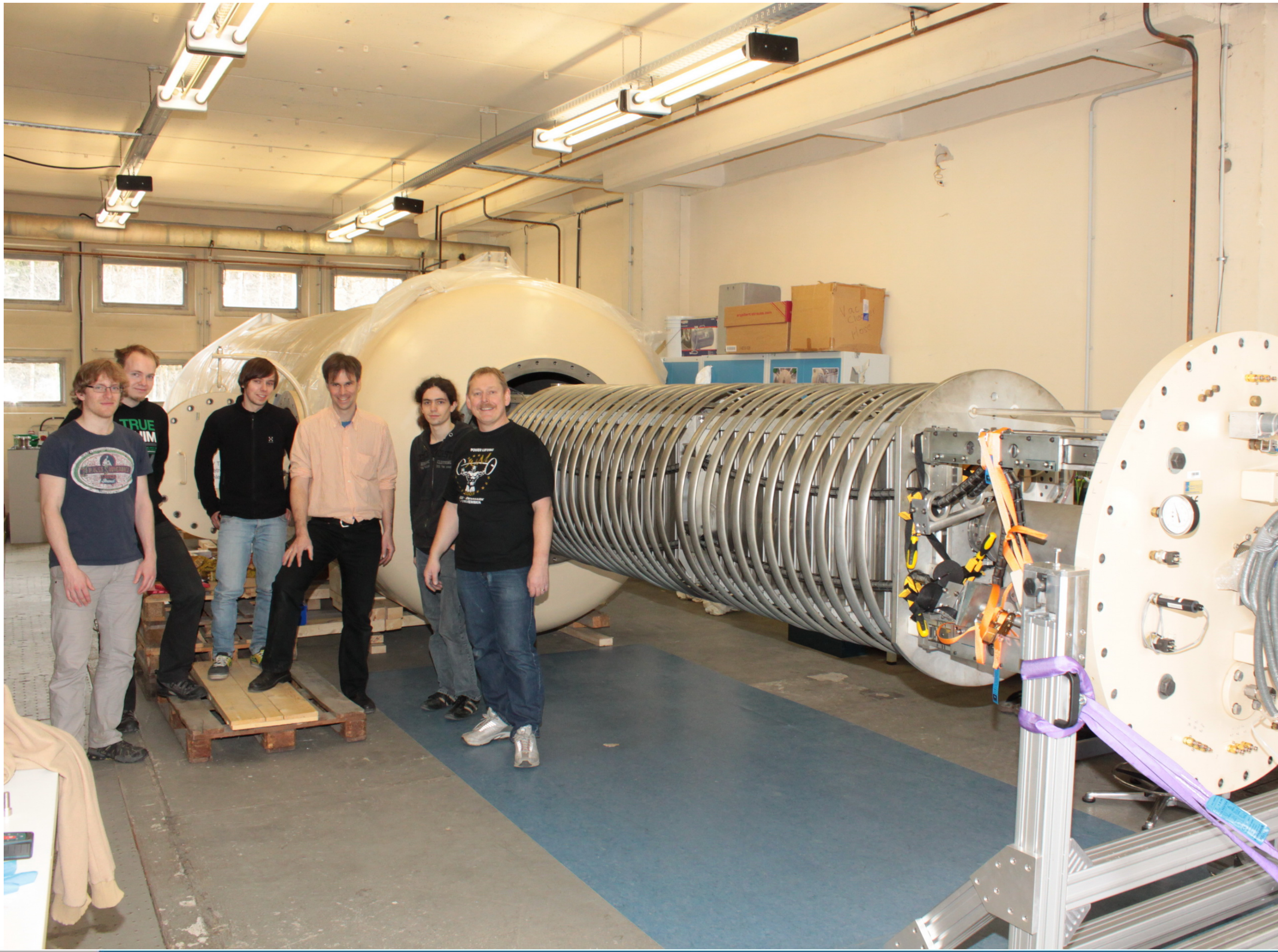
30 July 2012: Unloading of last component in Dresden

Work at HZDR on upgrading 5MV Pelletron

- All accelerator and beam line components stored at HZDR since July 2012
- Two MC-SNICS cesium sputter ion sources came with the purchase
  $^{12}C^-$ beam (designed for ^{14}C): 100 µA
  $^{1}H^-$ beam: 100 µA
  but no good intensity for noble gases (He^-, Ne^-, Ar^-)

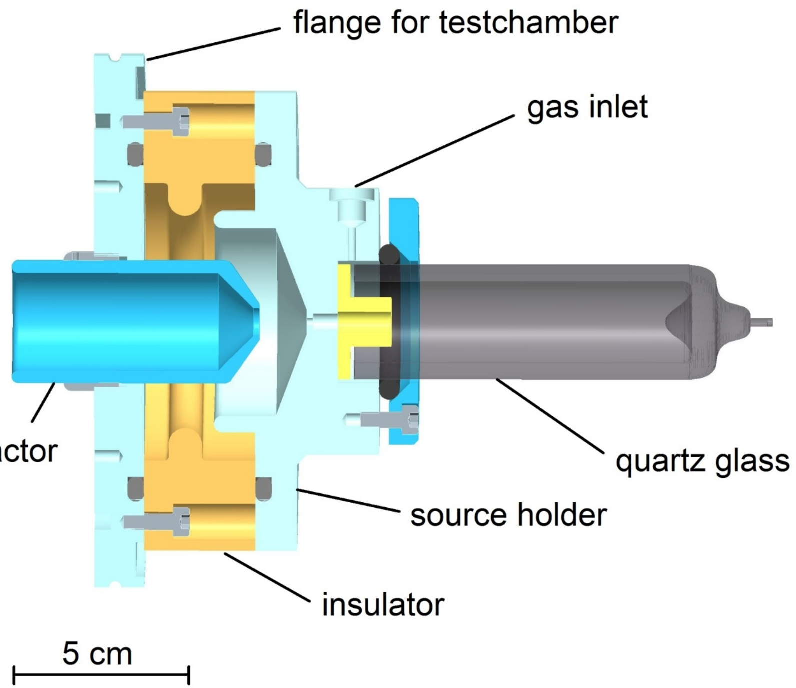
Ongoing projects:

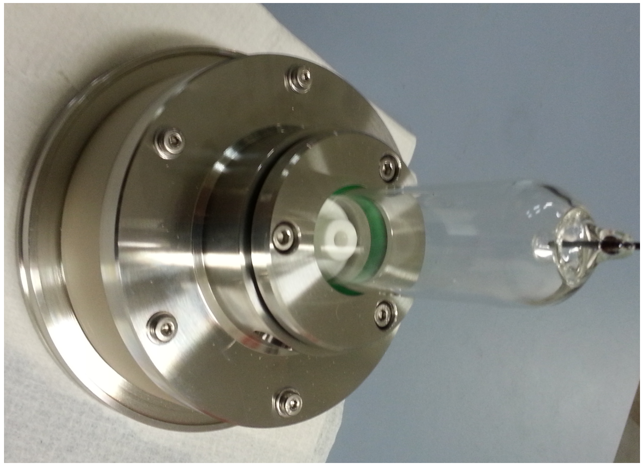
- Terminal ion source
- CAMAC control software
- Windowless gas target



Radio frequency ion source

- In-house development, based on RF ion source on HZDR 2 MV van de Graaf (running since the late 1970's)
- Electrostatic deflector in order to send the beam to the beam line still to be developed
- RF emitter based on Russian high power valves
- Aim: provide 100 μA positive noble gas ions (He^+, Ne^+, Ar^+)
- Diploma thesis work under way (S. Reinicke)





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Civil construction

Permissions needed:

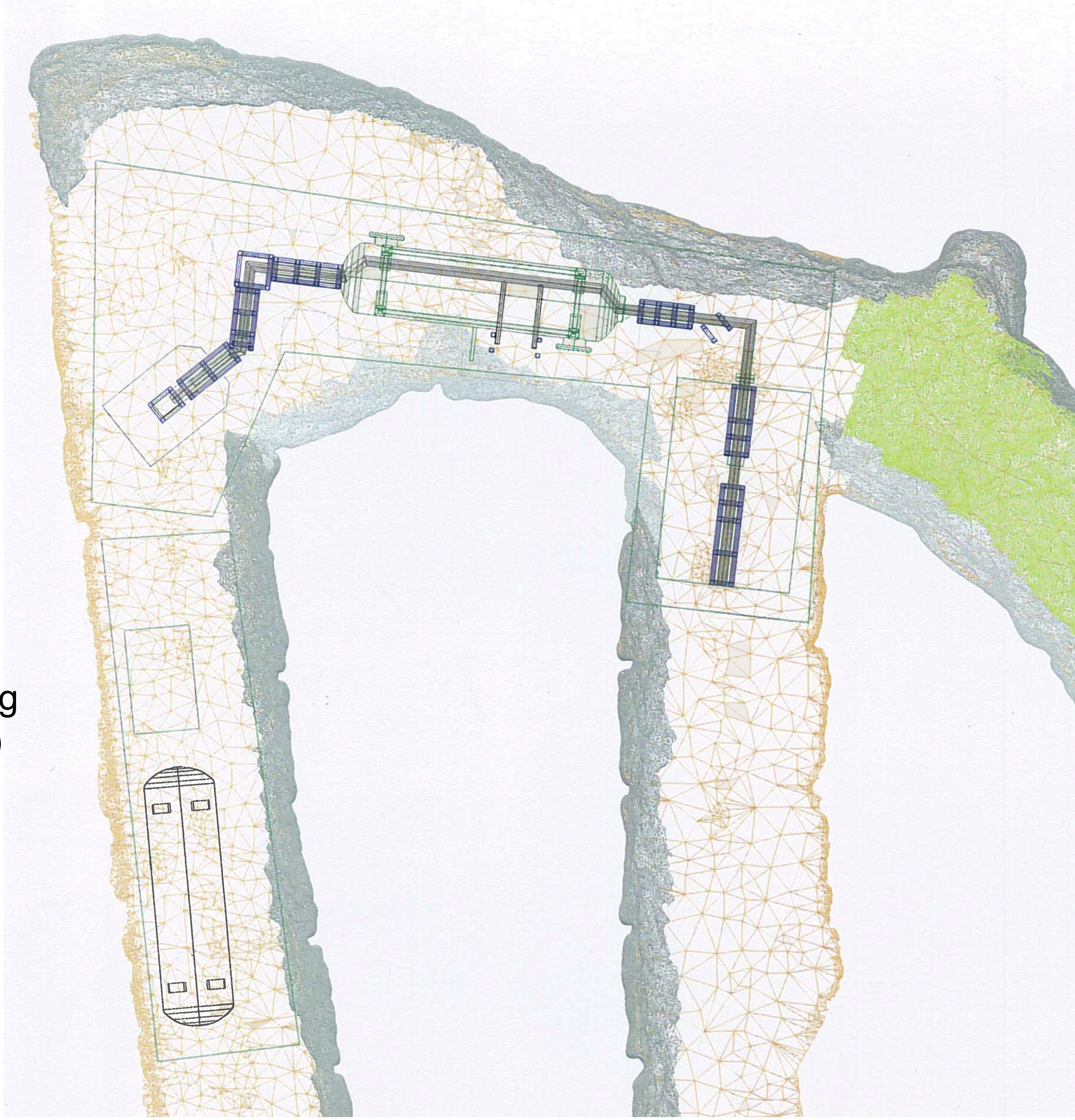
- Construction permit
- Operation of an ion accelerator

Main safety issues:

- Radioprotection and access
- Suffocating gas (SF_6)
- Fire and evacuation

Status

- Draft project by two private engineering firms (civil and laboratory engineering) completed, January 2013
- Construction not yet funded; discussions with HZDR and local university



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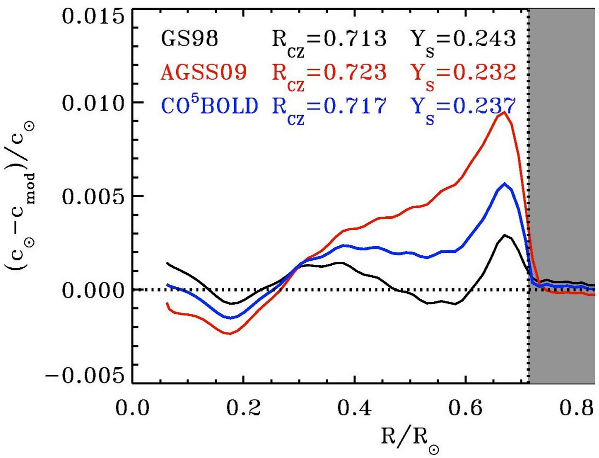
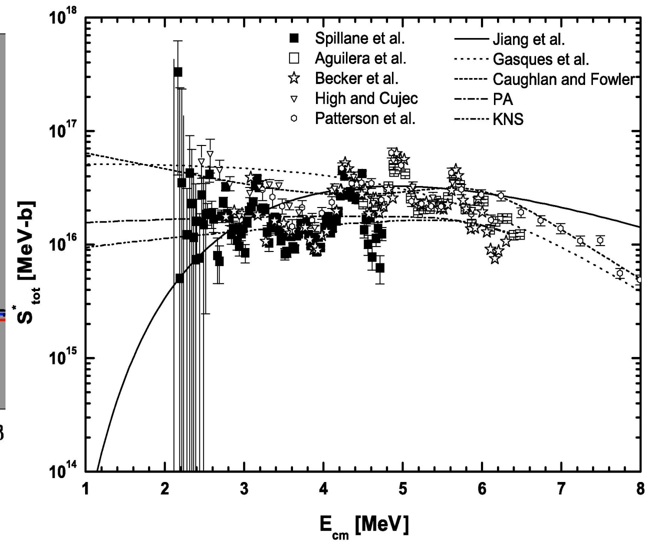
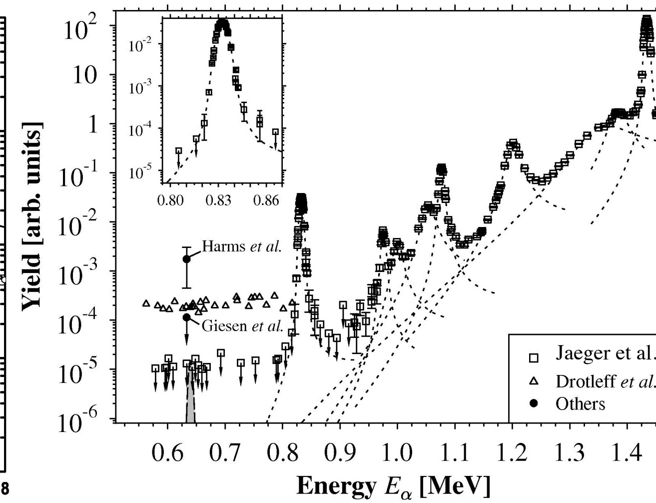
Felsenkeller accelerator, science program

Joint effort HZDR (Daniel Bemmerer et al.) – TU Dresden (Kai Zuber et al.)

- Solar fusion reactions — day one project: $^{14}N(p,\gamma)^{15}O$
- Carbon burning in type Ia supernova precursors — day two project: $^{12}C(^{12}C,p)^{23}Na$
- Neutron sources for the astrophysical s-process — day three project: $^{22}Ne(\alpha,n)^{25}Mg$

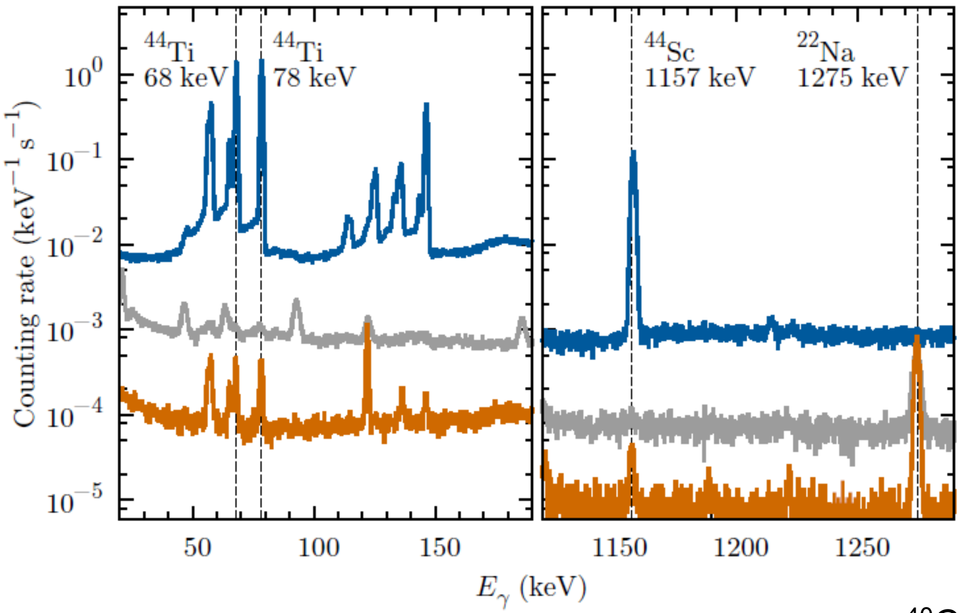


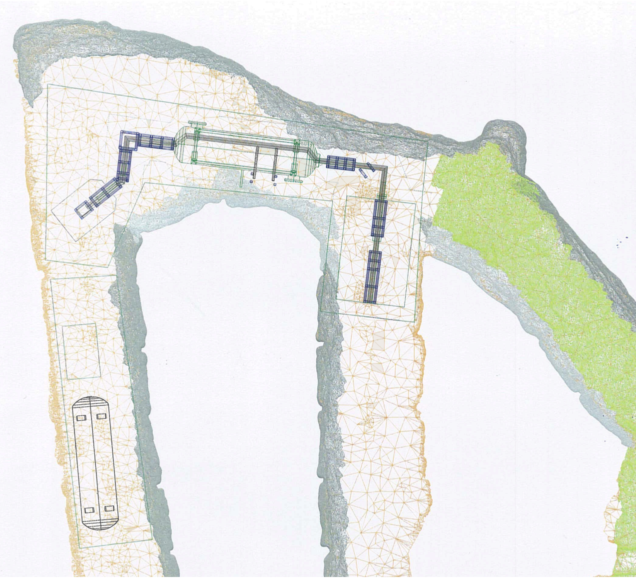




- Educational tool to teach low-background methods and maintain nuclear competence
- High-energy implantations (Ar^{+})
- Beam time will be available for external users

Study of ^{40}Ca(α,γ)^{44}Ti in the Dresden Felsenkeller





- ^{40}Ca(α,γ)^{44}Ti resonances at 4.5 MeV studied by in-beam spectroscopy and activation, AMS planned
- ^{40}Ca(α,γ)^{44}Ti resonances at 2.7-3.7 MeV in progress
- ^{44}Ti(α,p)^{47}V feasibility study underway
- 5 MV high-current Pelletron bought in 2012 and transported to Dresden
- Construction planned but not yet funded
- Machine will be wide open to outside users!

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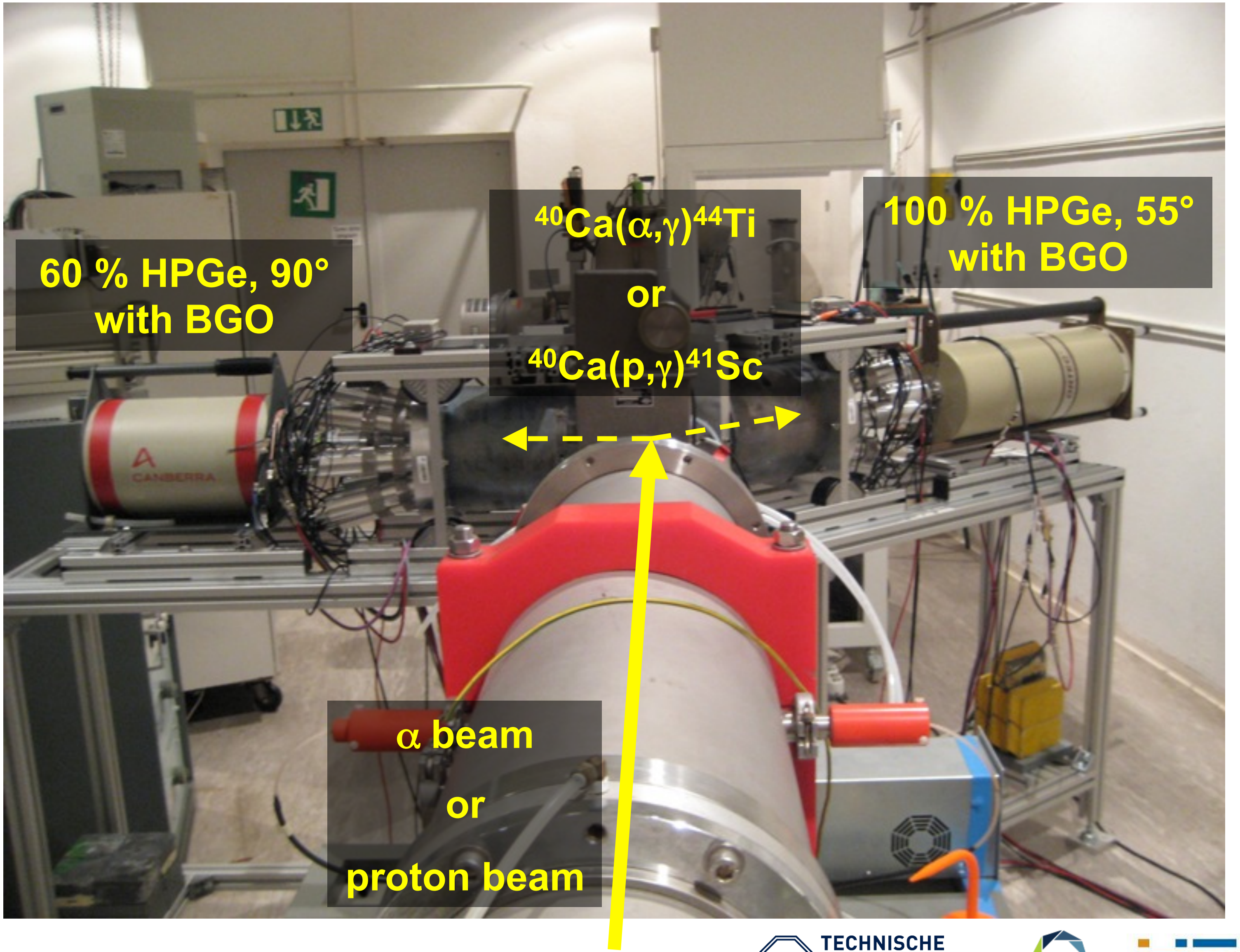
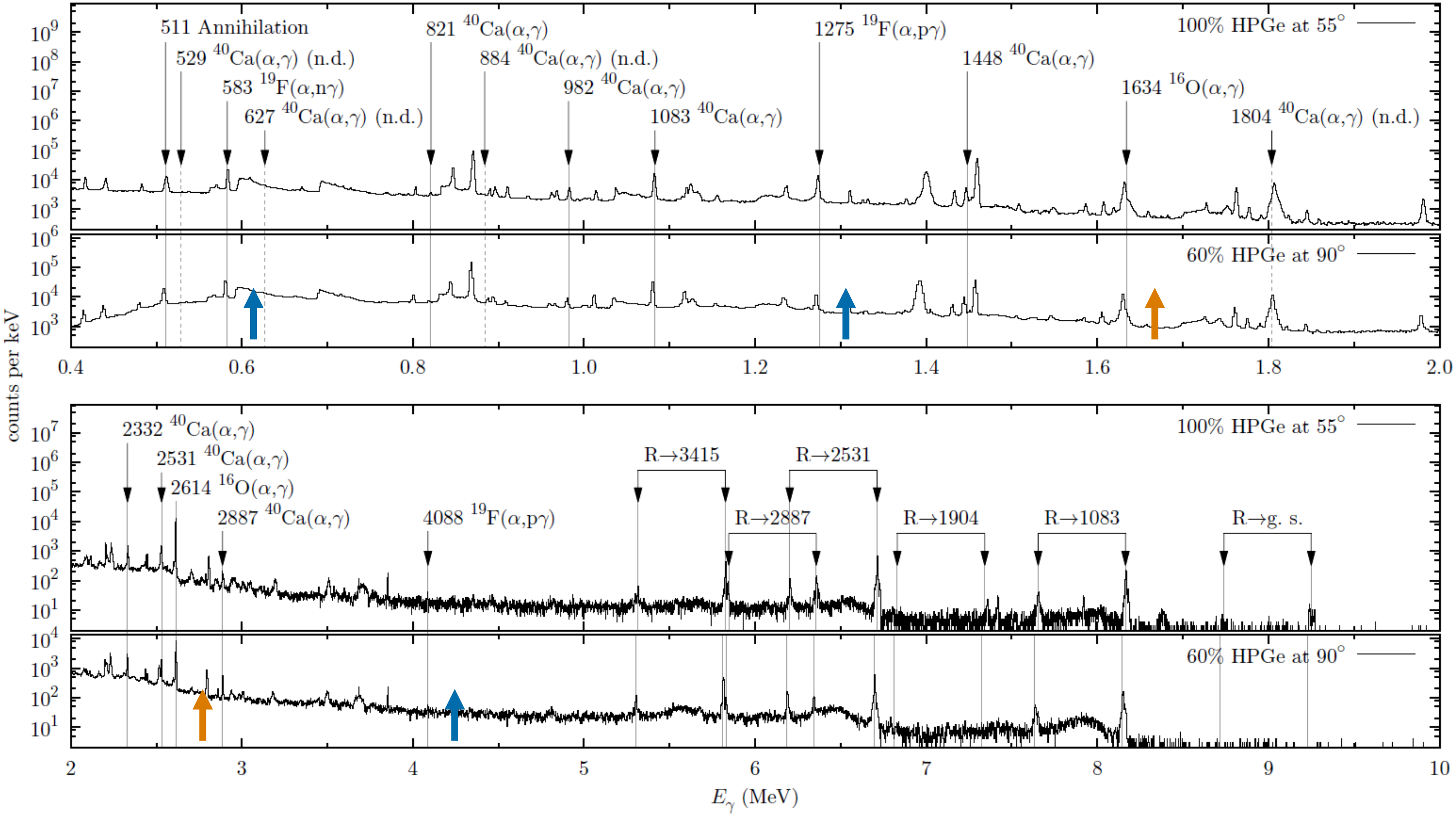
Bonus material

^{40}Ca(α,γ)^{44}Ti experiment at HZDR, setup



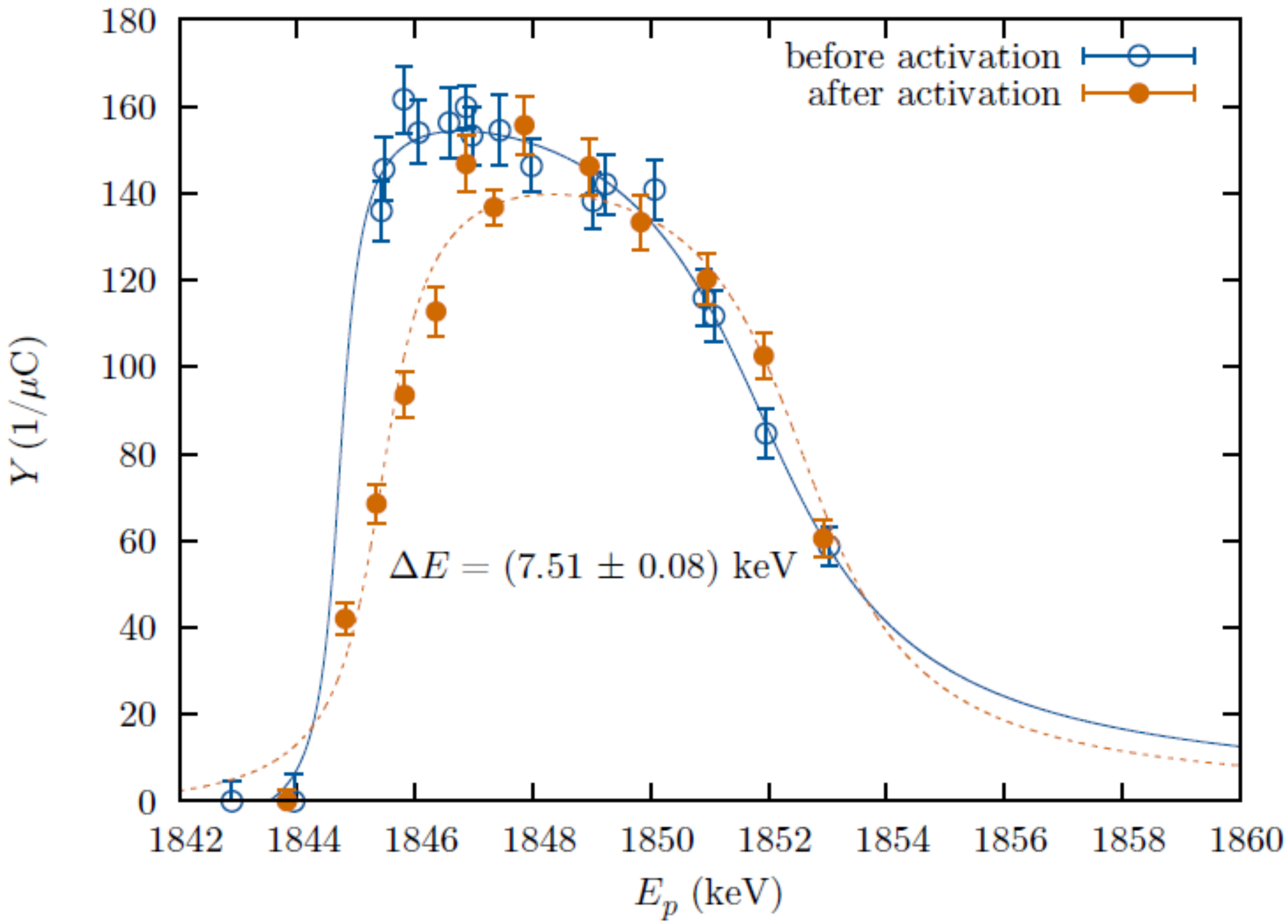
Alpha induced in-beam γ-ray spectra



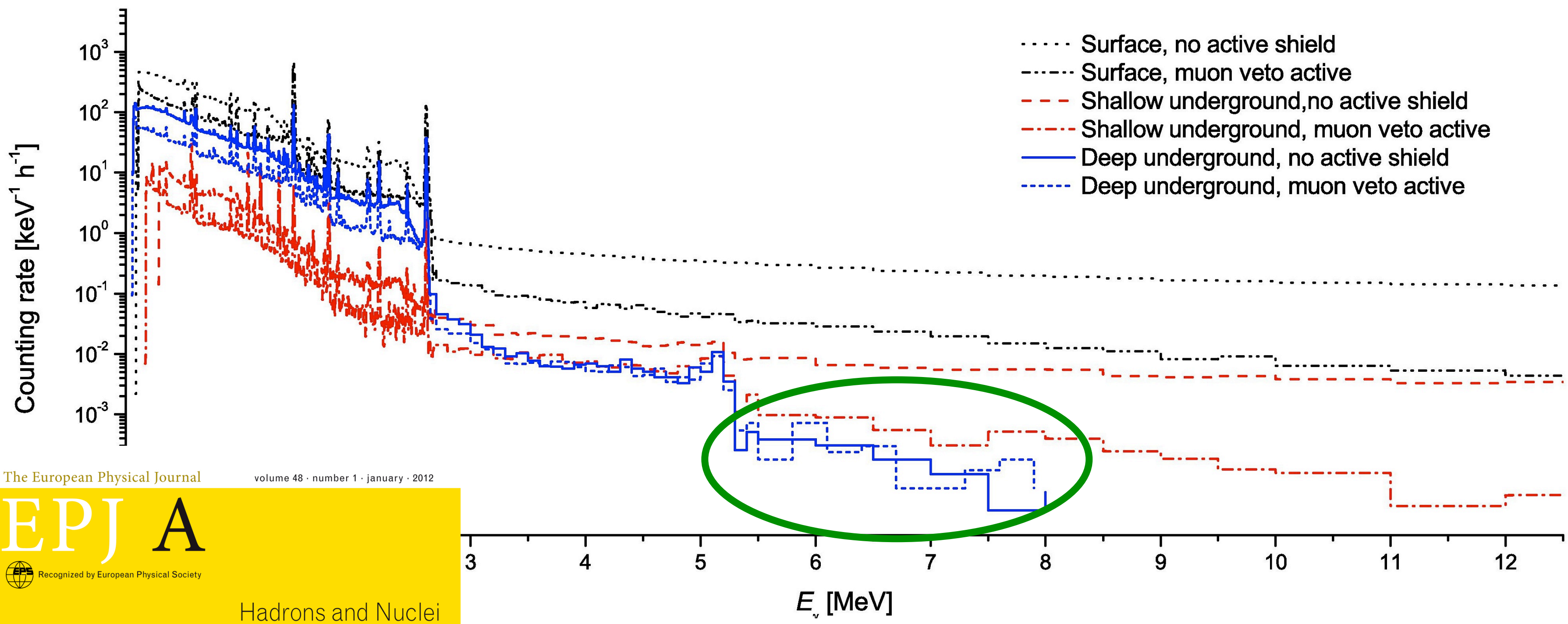
- Primary and secondary γ rays from the resonance triplet.
- Weak contaminant γ rays from ^{19}F and ^{16}O can be seen.

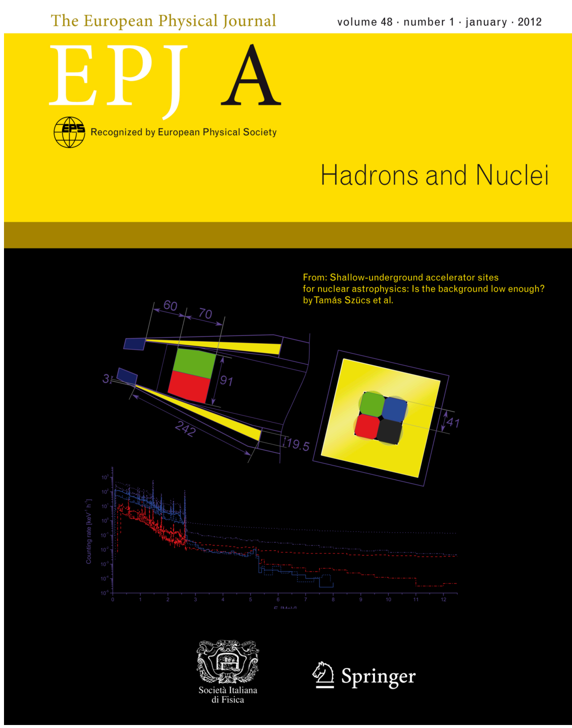
Target scans before and after the activation

- Proton beam does not create parasitic ^{44}Ti.
- Using the E_p = 1842 MeV resonance in the ^{40}Ca(p,γ)^{41}Sc reaction.
- About 48 h activation with a current of 1.5 μA at the water cooled target.



Background study, in a HPGe detector typical for nuclear astrophysics





→ Felsenkeller: Combination of active veto and 47m rock gives a background close to the deep-underground background at 6-8 MeV.

→ Explanation: Environmental (α,n) neutrons dominate the deep-underground background.

T. Szücs et al.,
Eur. Phys. J. A 48, 8 (2012)

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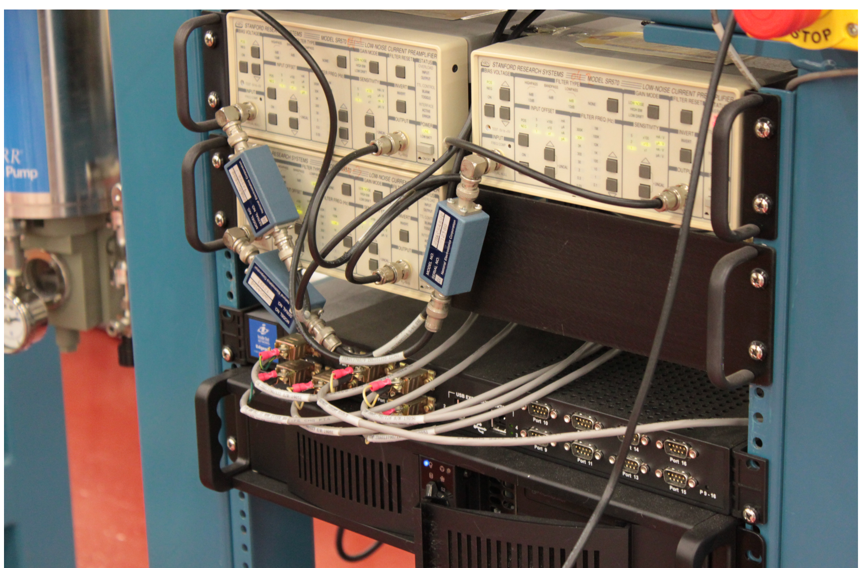
CAMAC and RS232 control

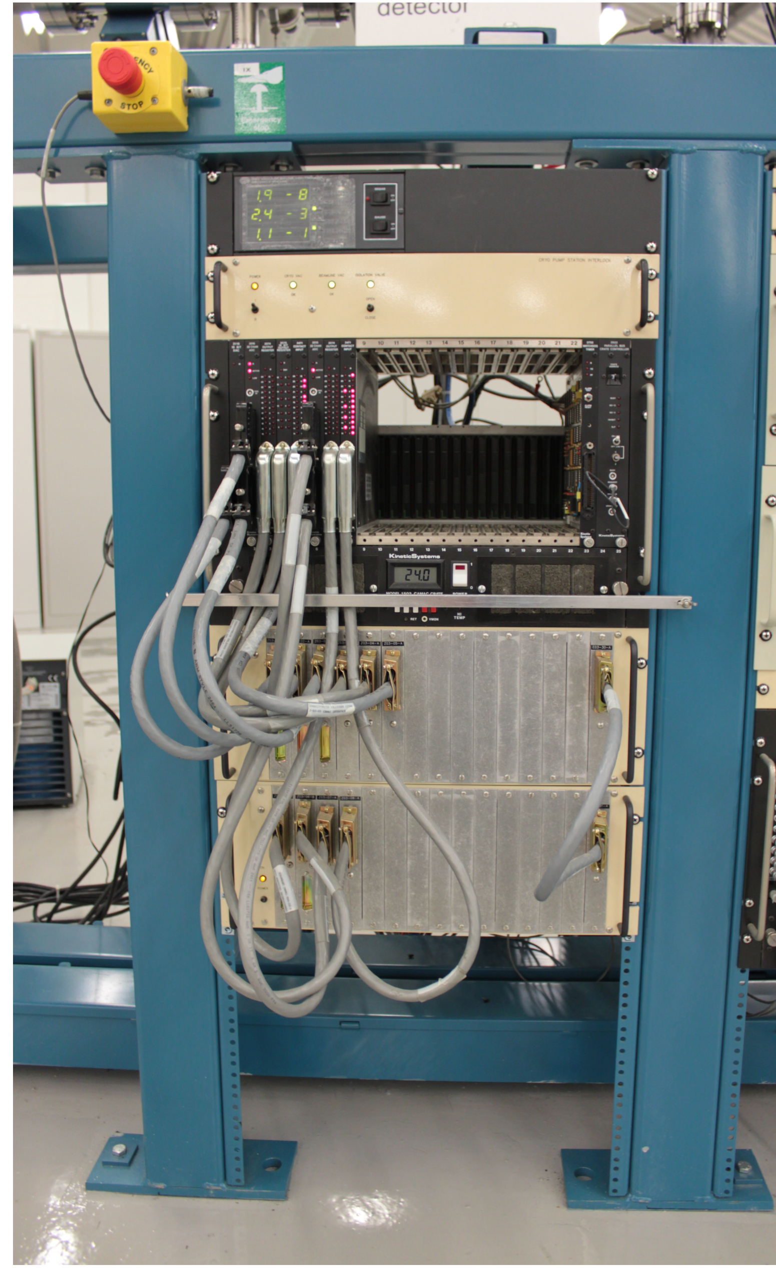
Status quo:

- CAMAC crate controllers with CAMAC DACs+ADCs, accessed via ethernet by NEC proprietary control software
- RS232 controlled devices accessed via industrial PCs and ethernet, also by NEC proprietary control software
- No access to source codes provided

Ongoing work

- B.Sc. thesis ongoing on additional slow control of CAMAC units (J. Wielicki)
- Aim to have an alternative way of controlling beam transmission relevant devices





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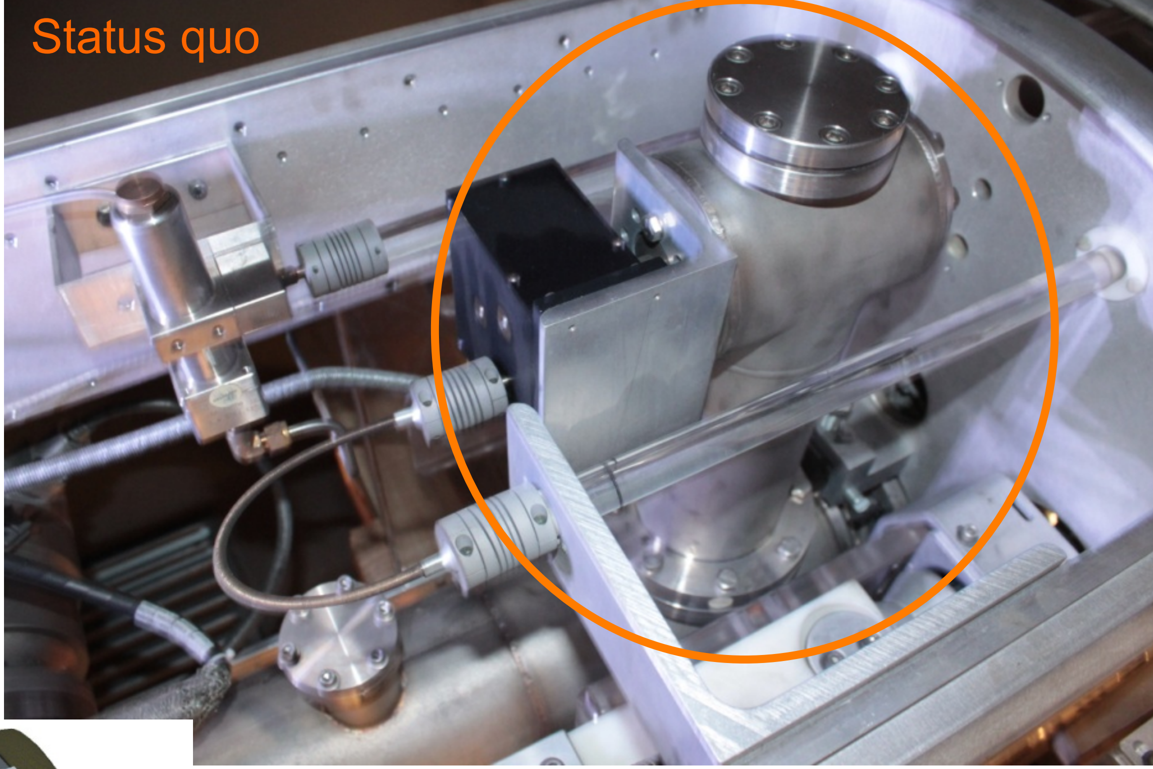
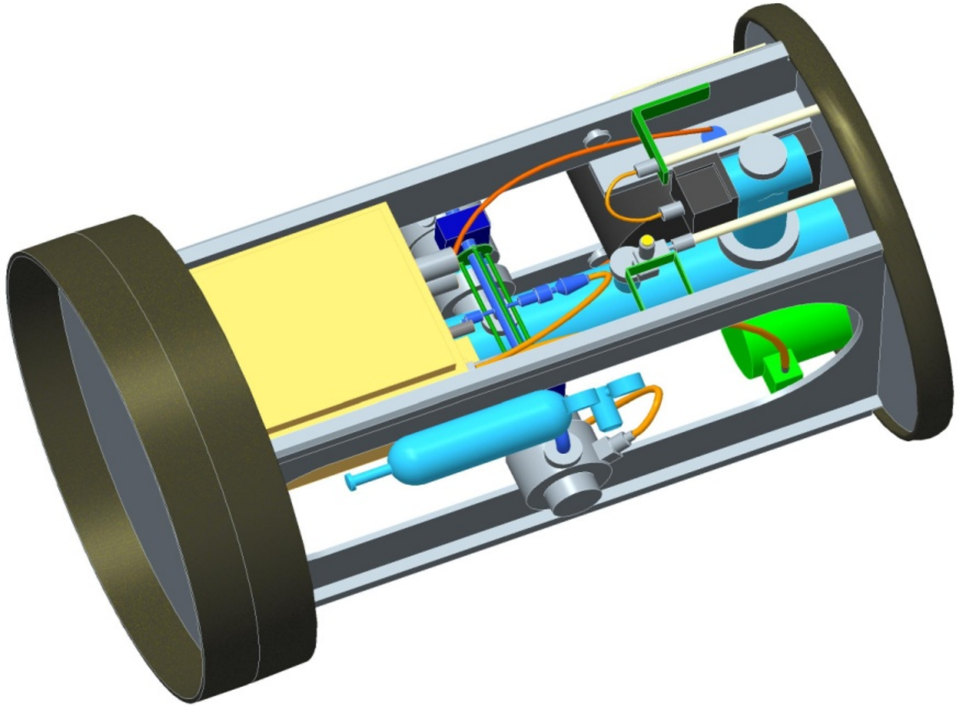
High voltage terminal

- 500 W of electrical power available on high voltage terminal (rotating shaft system)
- Gas stripper system will remain on terminal, including two 360 l/s turbomolecular pumps
- Carbon foil stripper system not necessary any more, has been removed





The European community for underground accelerators

- Workshop on “Underground nuclear-reaction experiments for astrophysics and applications”, Dresden/Germany April 2010: *30 participants from 8 countries*
  `http://www.hzdr.de/felsenkeller`
  ”Due to the extensive science programme, the long running time per experiment, and the number of researchers involved (...), most participants see it necessary to call for at least two European underground facilities to be realized. (...) A consensus emerged that all facilities should be as open as possible to the community (...). The observational and computational astrophysicists should be included at the earliest stage, helping drive and define the science agenda and creating the added value of multidisciplinarity (...)”.

- NuPECC Long Range Plan 2010, released on 8 December 2010:
  `http://www.nupecc.org`
  “An immediate, pressing issue is to select and construct the next generation of underground accelerator facilities. Europe was a pioneer in this field, but risks a loss of leadership to new initiatives in the USA. Providing an underground multi-MV accelerator facility is a high priority. There are a number of proposals being developed in Europe and it is vital that construction of one or more facilities starts as soon as possible.”

- Follow-up workshops in Gran Sasso (2011), Canfranc/Spain (2012), Gran Sasso (2013)