2nd workshop on

Exotic **R**adionuclides from **A**ccelerator **Wa**ste for **S**cience and **T**echnology

(ERAWAST II)

The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction

studied by activation

02/09/2011

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Supported by DFG (BE 4100/2-1)

The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Outline

- Introduction
- Weak ^{44}Ti sources by D. Schumann (PSI)
- Setup at HZDR
- State of the art
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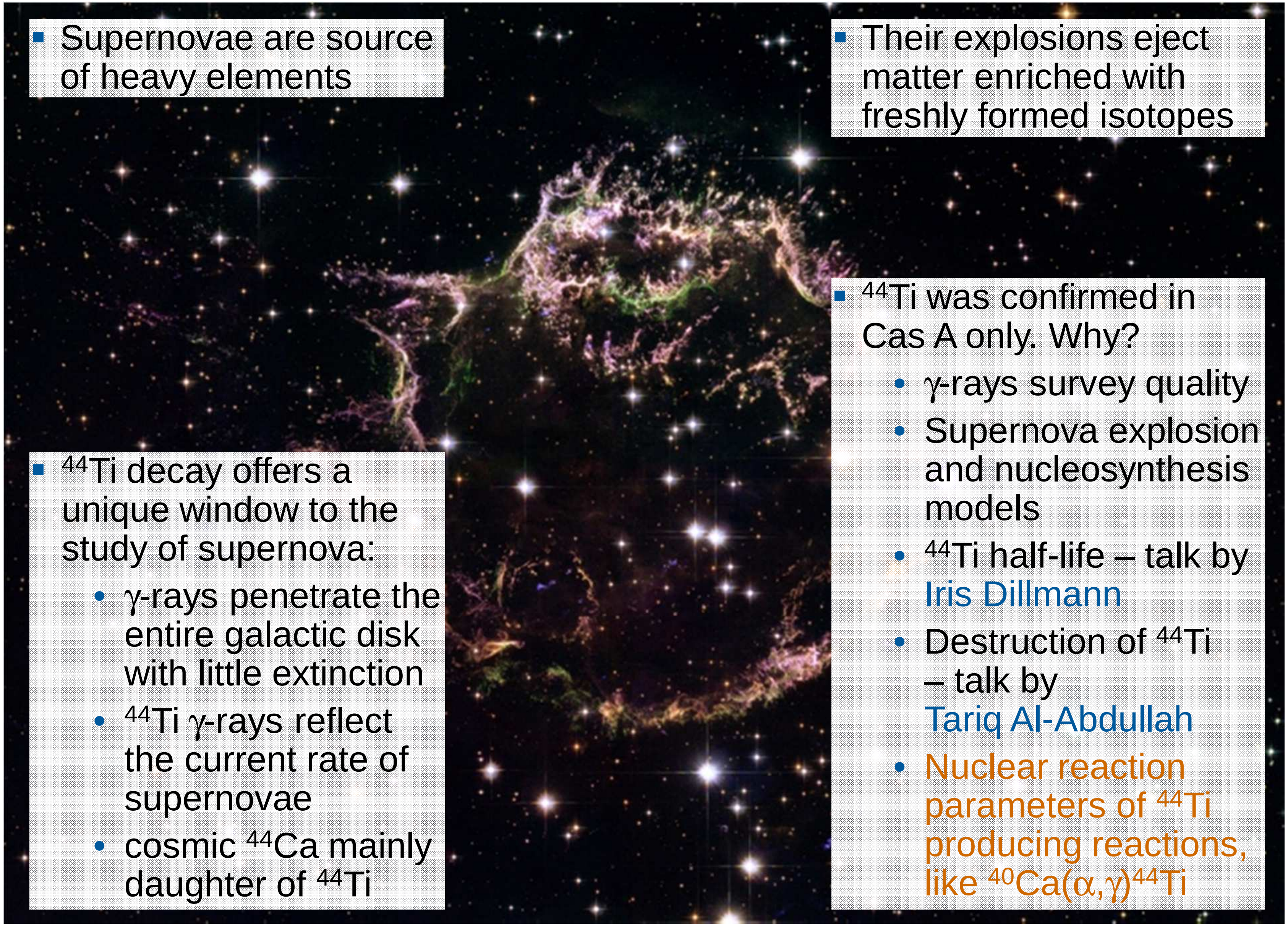
Supernova remnant Cassiopeia A



- Supernovae are source of heavy elements

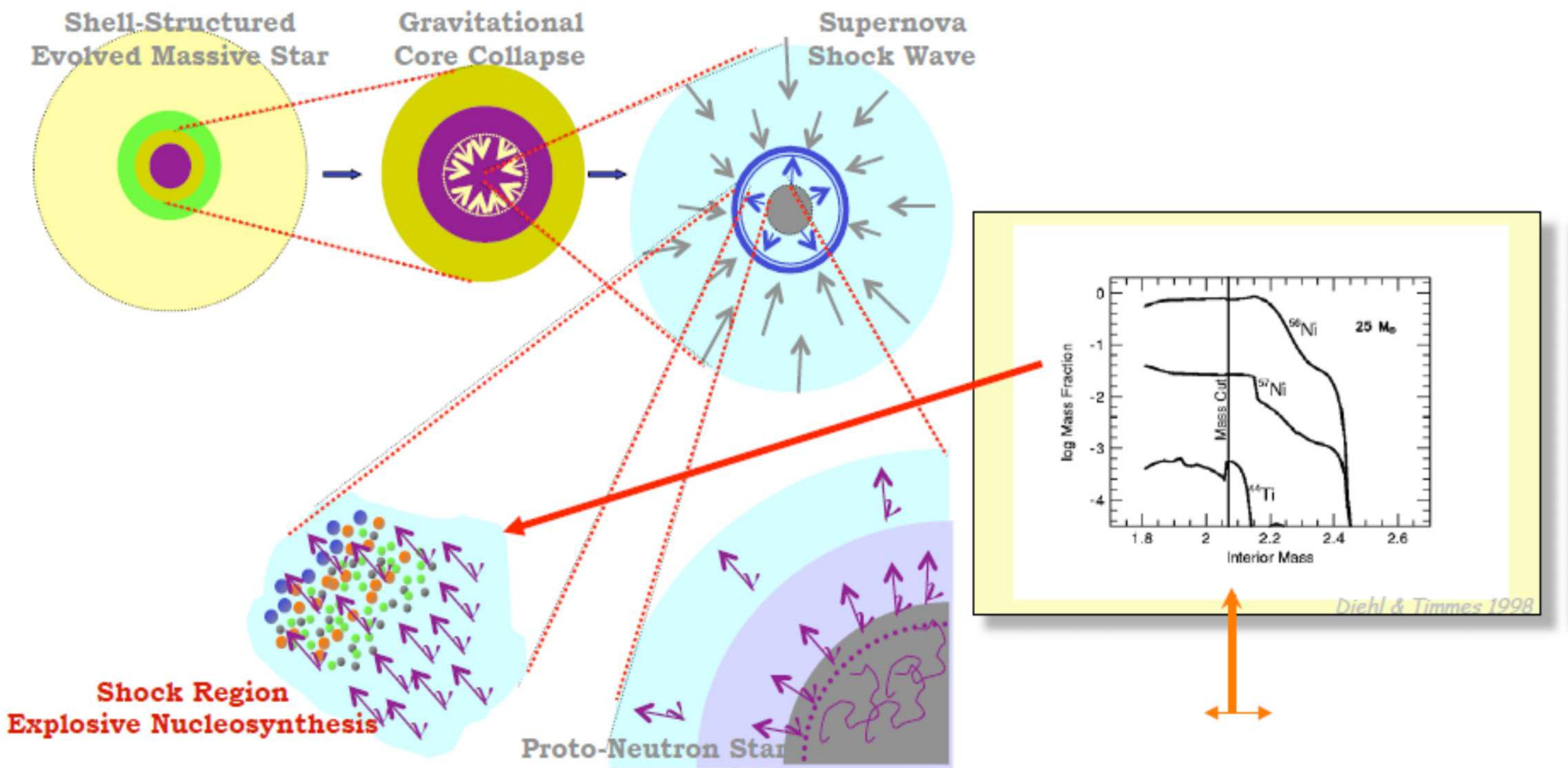
- Their explosions eject matter enriched with freshly formed isotopes

- ^{44}Ti decay offers a unique window to the study of supernova:
  - γ-rays penetrate the entire galactic disk with little extinction
  - ^{44}Ti γ-rays reflect the current rate of supernovae
  - cosmic ^{44}Ca mainly daughter of ^{44}Ti

- ^{44}Ti was confirmed in Cas A only. Why?
  - γ-rays survey quality
  - Supernova explosion and nucleosynthesis models
  - ^{44}Ti half-life – talk by Iris Dillmann
  - Destruction of ^{44}Ti – talk by Tariq Al-Abdullah
  - Nuclear reaction parameters of ^{44}Ti producing reactions, like $^{40}Ca(\alpha,\gamma)^{44}Ti$

Image was taken with the NASA/ESA Hubble Space Telescope and edited by Fesen and Long 2006

Production of ^{44}Ti in supernovae



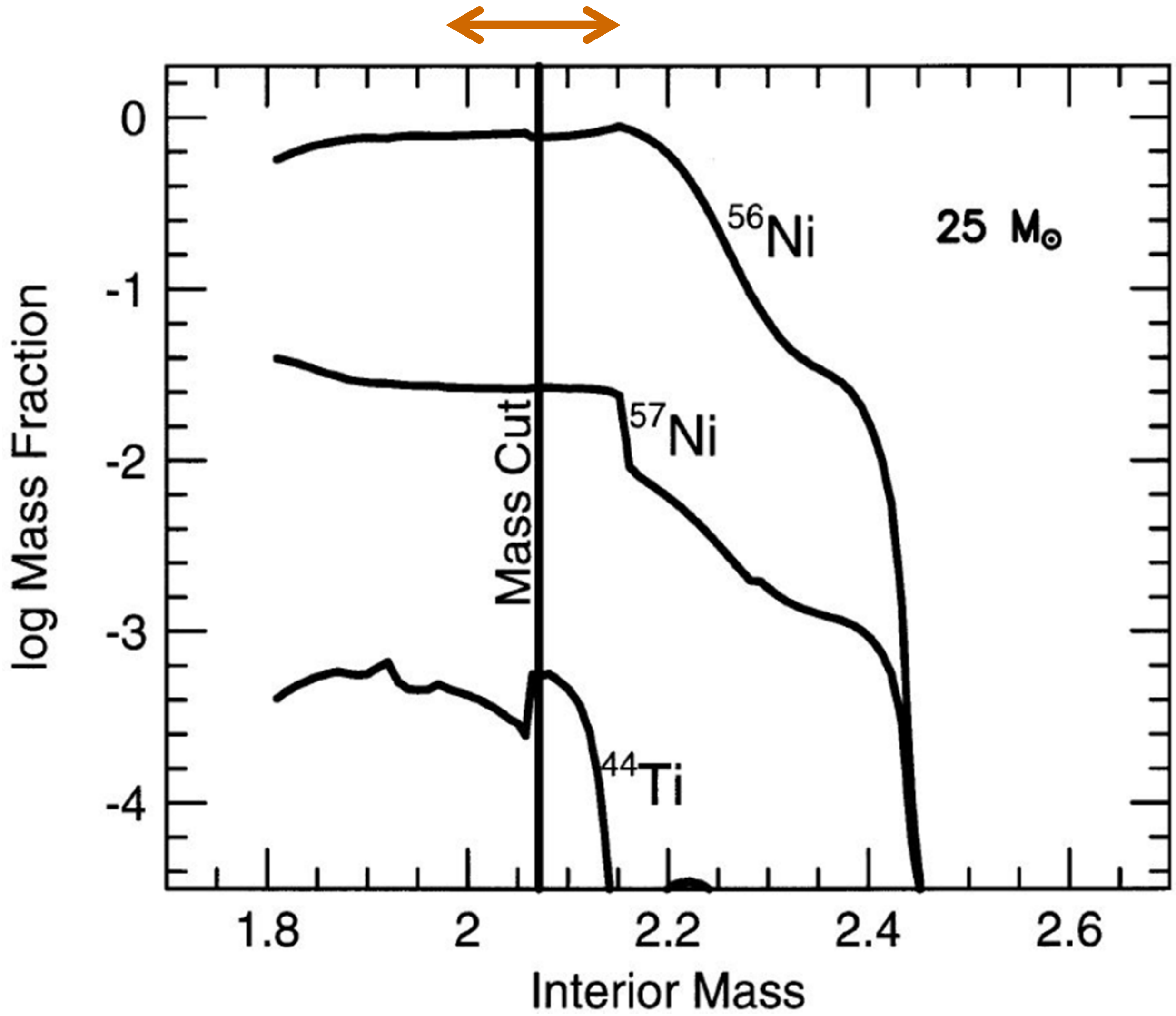
- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out,
  => "see" Inner SN Material

Experimental Nuclear Astrophysics Workshop, Dresden (D), Apr 28-30, 2010

Roland Diehl

The mass cut

- Diehl et al. 1998:
  - The abundance of ^{44}Ti and ^{56}Ni as a function of mass inside a 25M$_\odot$ star is shown
  - The **mass cut** is shown as the solid vertical line
  - Everything interior to the **mass cut** becomes part of the neutron star
  - Everything exterior may be ejected, depending on how much mass falls back onto the neutron star during the explosion
- The position of the **mass cut** determines, if ^{44}Ti is detectable in a Supernova

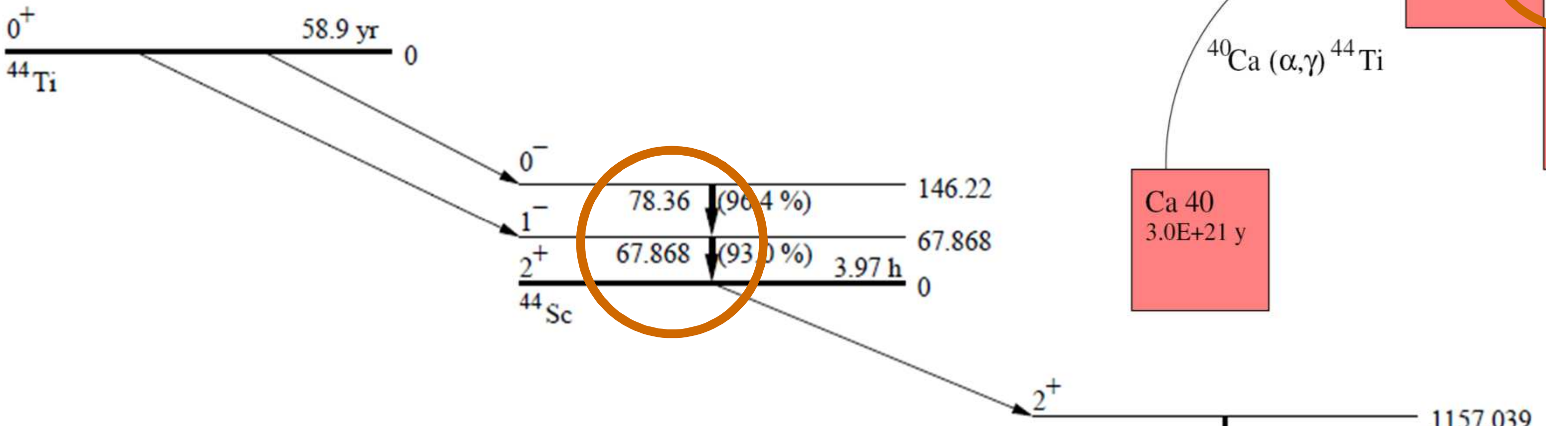


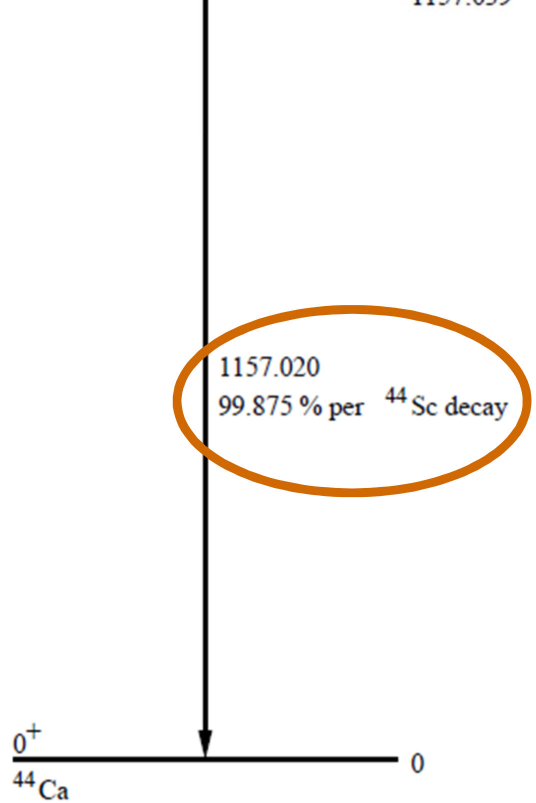
Mass profiles of ^{44}Ti and ^{56}Ni for a 25$M_\odot$ core-collapse supernova model (adapted from Hoffman et al. 1995)

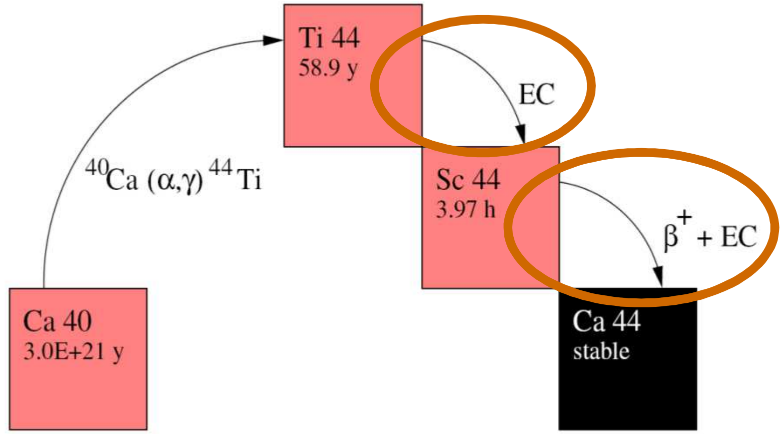
- $T_{1/2}(^{56}Ni)$ = 6.08 d
- $T_{1/2}(^{57}Ni)$ = 35.6 h
- $T_{1/2}(^{44}Ti)$ = 58.9 y

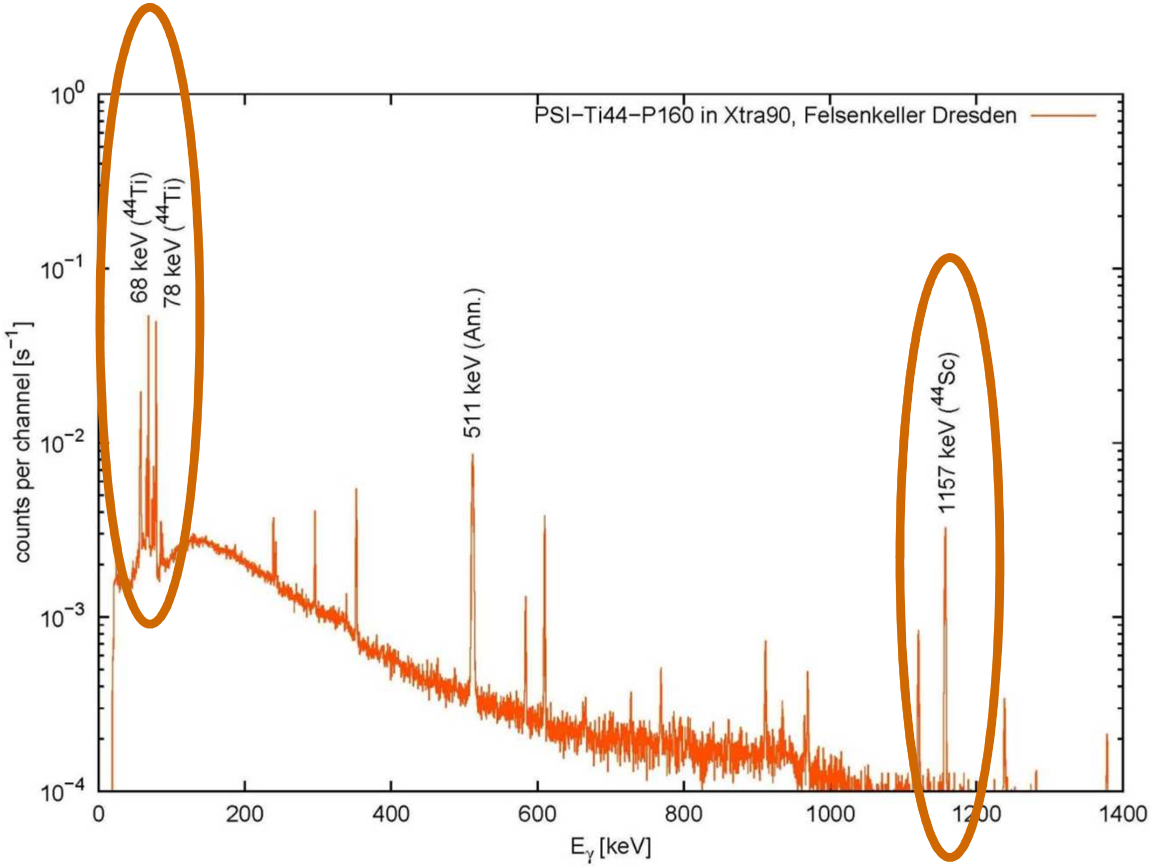
The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Introduction

Decay of ^{44}Ti and ^{44}Sc









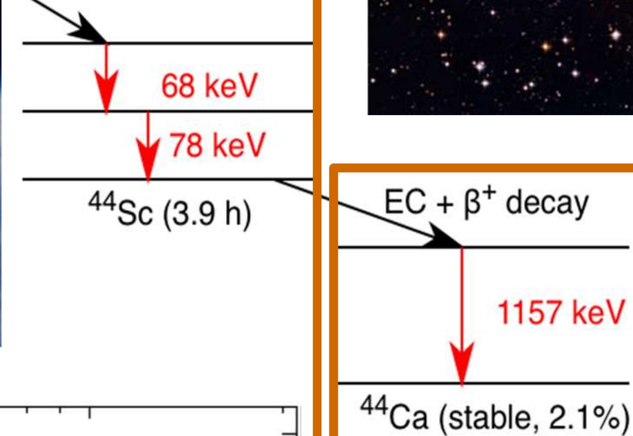
Supernova signal: ^{44}Ti in Cassiopeia A

- ^{44}Ti is produced near the **mass cut** between infalling and ejected material in the α-rich freeze out phase
- Sensitive probe of supernova models

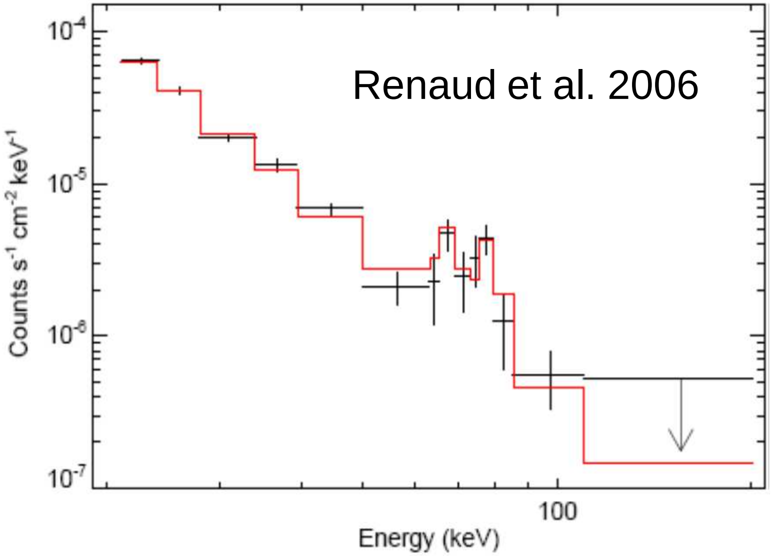
Fesen and Long 2006

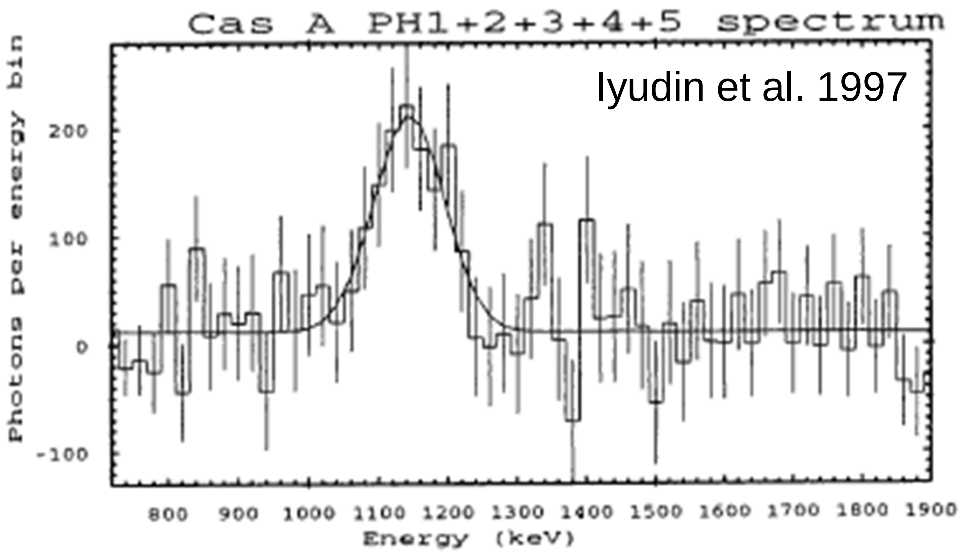
- image was taken with the NASA/ESA Hubble Space Telescope

IBIS on INTEGRAL, ESA



COMPTEL on CGRO, NASA





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The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Outline

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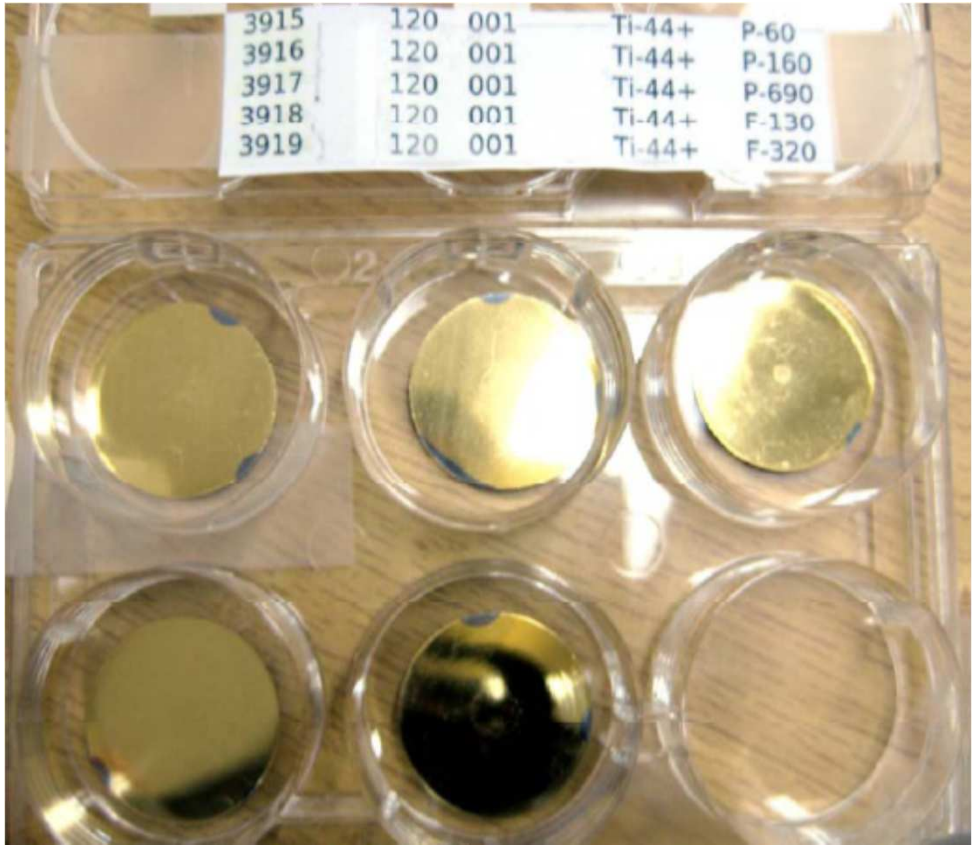
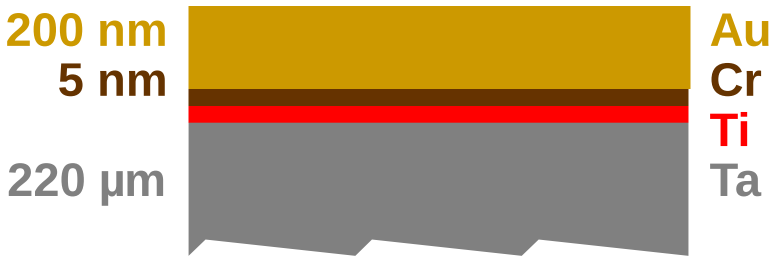
Preparation and structure of weak ^{44}Ti sources



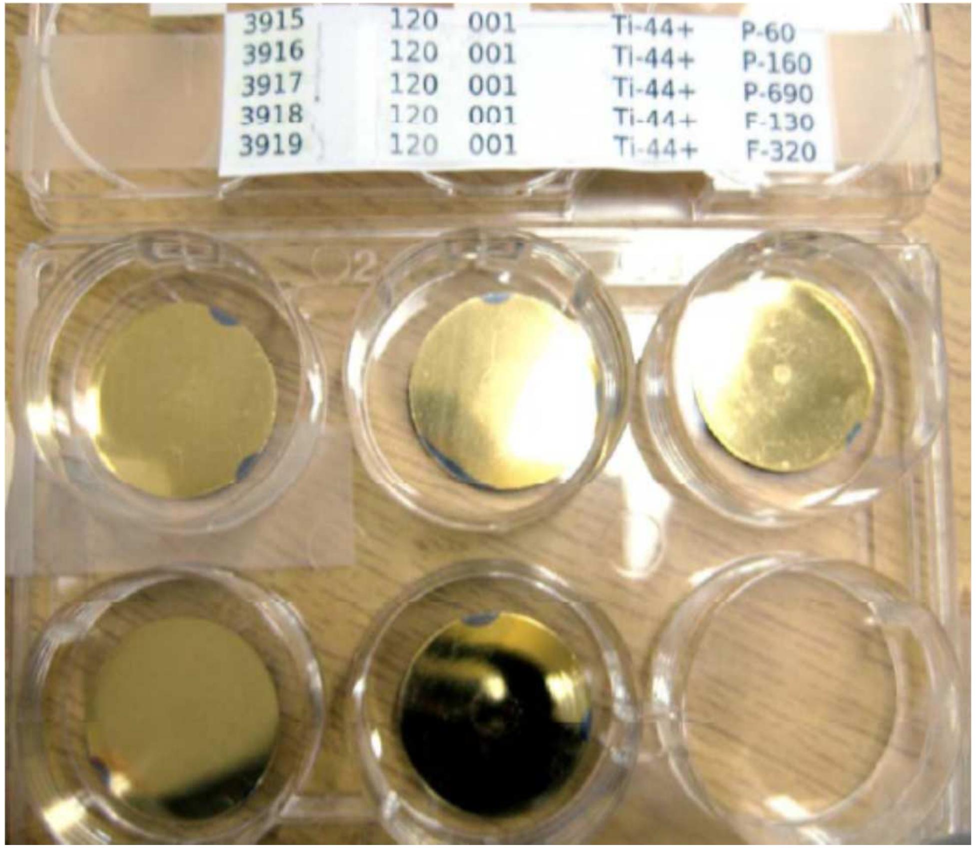
- preparation:
  - by vaporating radionuclide-containing diluted nitric acid on **tantalum** plates
  - 5 nm **chromium** serve as adherent layer for the protective layer
  - covered with 200 nm thick **gold** layer afterwards in order to protect the surface
- structure:



- more details:
  - SCHUMANN, D.; NEUHAUSEN, J.: Accelerator waste as a source for exotic radionuclides. In: *J. Phys. G: Nucl. Part. Phys.* ***35*** *(2008) 014046*
  - SCHUMANN, D.; SCHMIDT, K.; BEMMERER, D.: Characterization and Calibration of weak ^{44}Ti sources for astrophysical applications. In: *PSI Annual Report 2010*

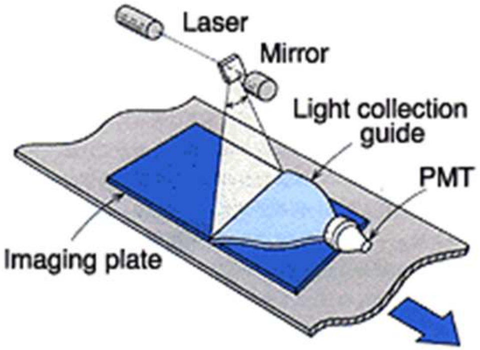
The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Weak ^{44}Ti sources by D. Schumann (PSI)

Characterization of weak ^{44}Ti sources with imaging plates



- Irradiation of the imaging plate

- Scanning the imaging plate

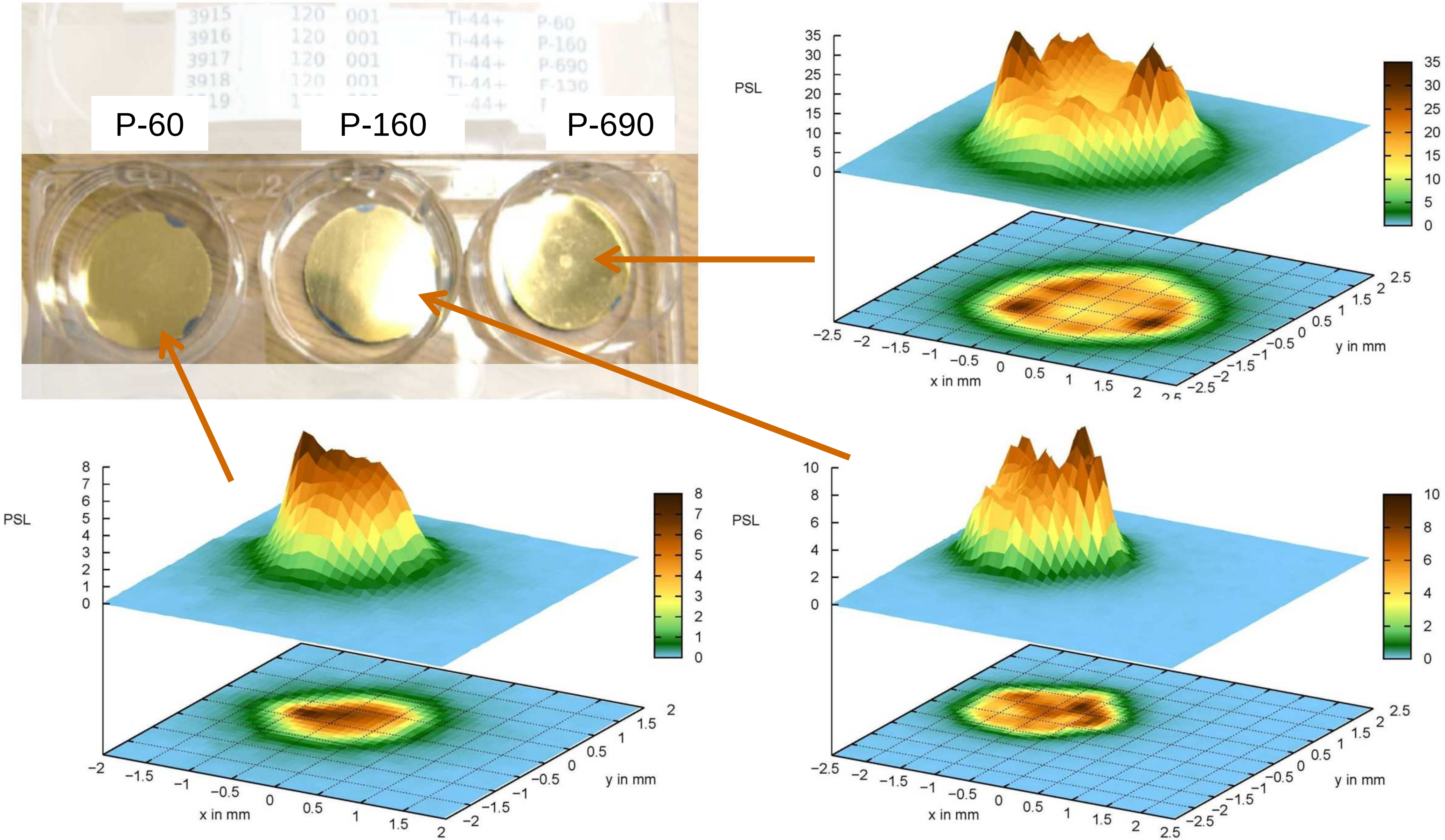


  - Resolution: 5 µm
  - Gradation: 65,536 (16 bit)

- Plot the data

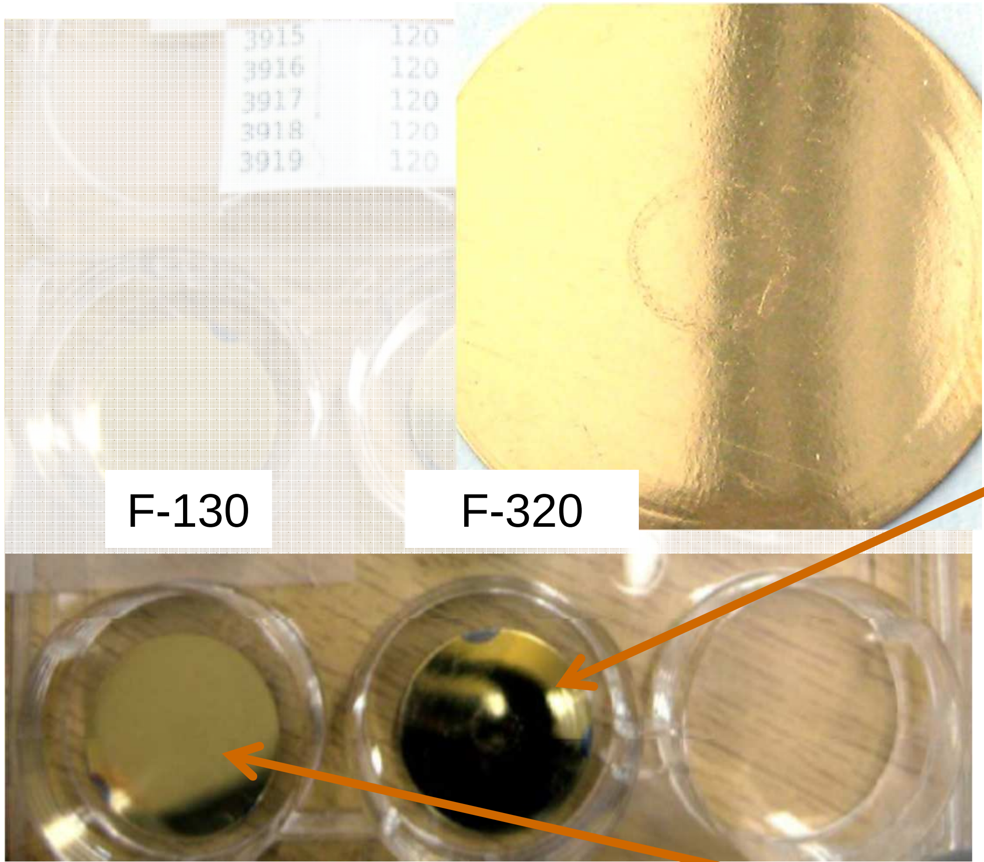
http://home.fujifilm.com/info/products/science/toc.html

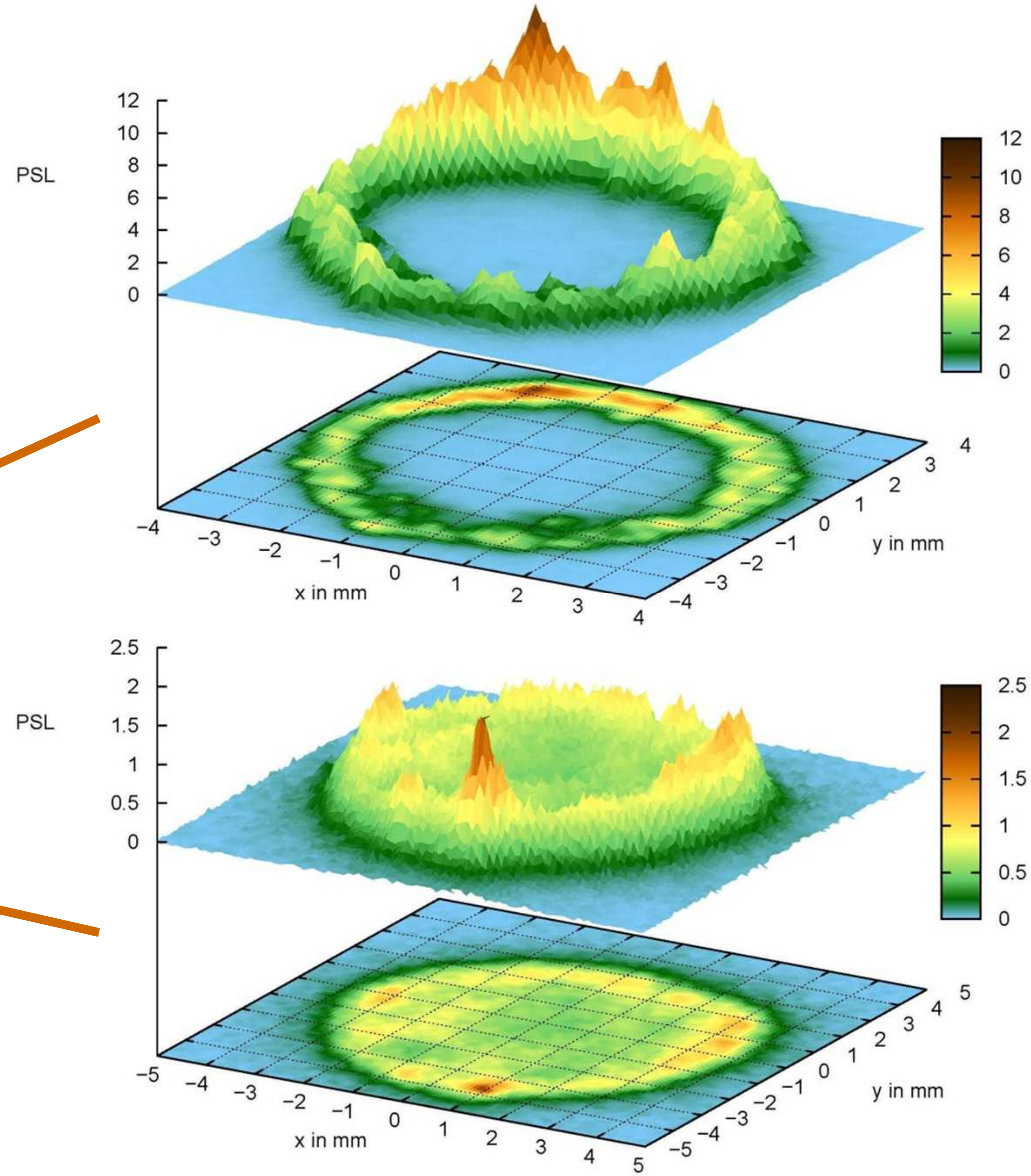
Characterization of weak ^{44}Ti point sources



- PSL corresponds to the γ-ray intensity

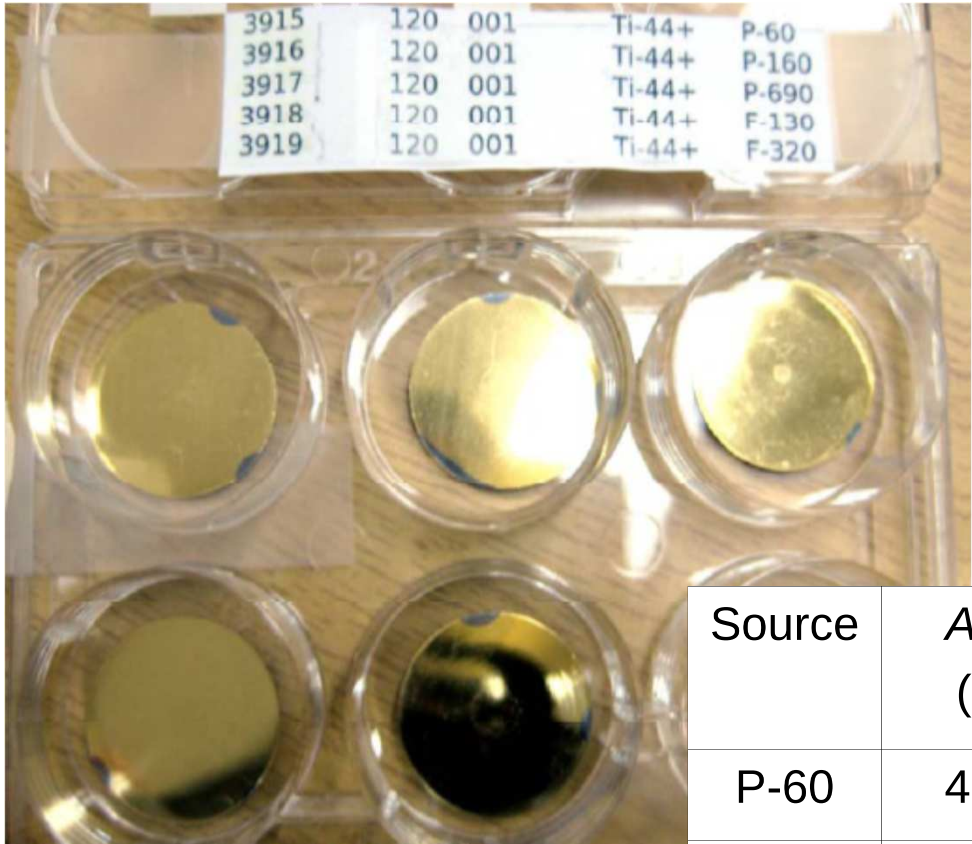
Characterization of weak ^{44}Ti plane sources



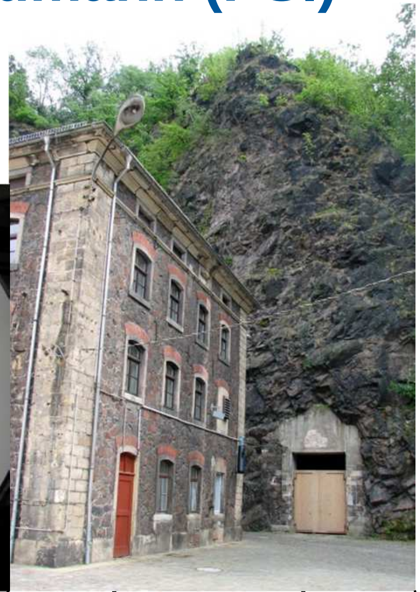


- PSL corresponds to the γ-ray intensity

Calibration of weak ^{44}Ti sources



- used high-precision calibration sources



- underground laboratory – talk by Daniel Bemmerer

Source	*A* [Bq] (PSI)	*A* [Bq] (HZDR)	*A* [Bq] (Felsenkeller Dresden)
P-60	46 ± 9	35.5 ± 0.4	–
P-160	151 ± 15	67.5 ± 0.8	63 ± 4
F-130	146 ± 15	137.1 ± 1.7	–
F-320	310 ± 30	225 ± 3	–
P-690	600 ± 60	498 ± 6	–

- reference date: 01/01/2010

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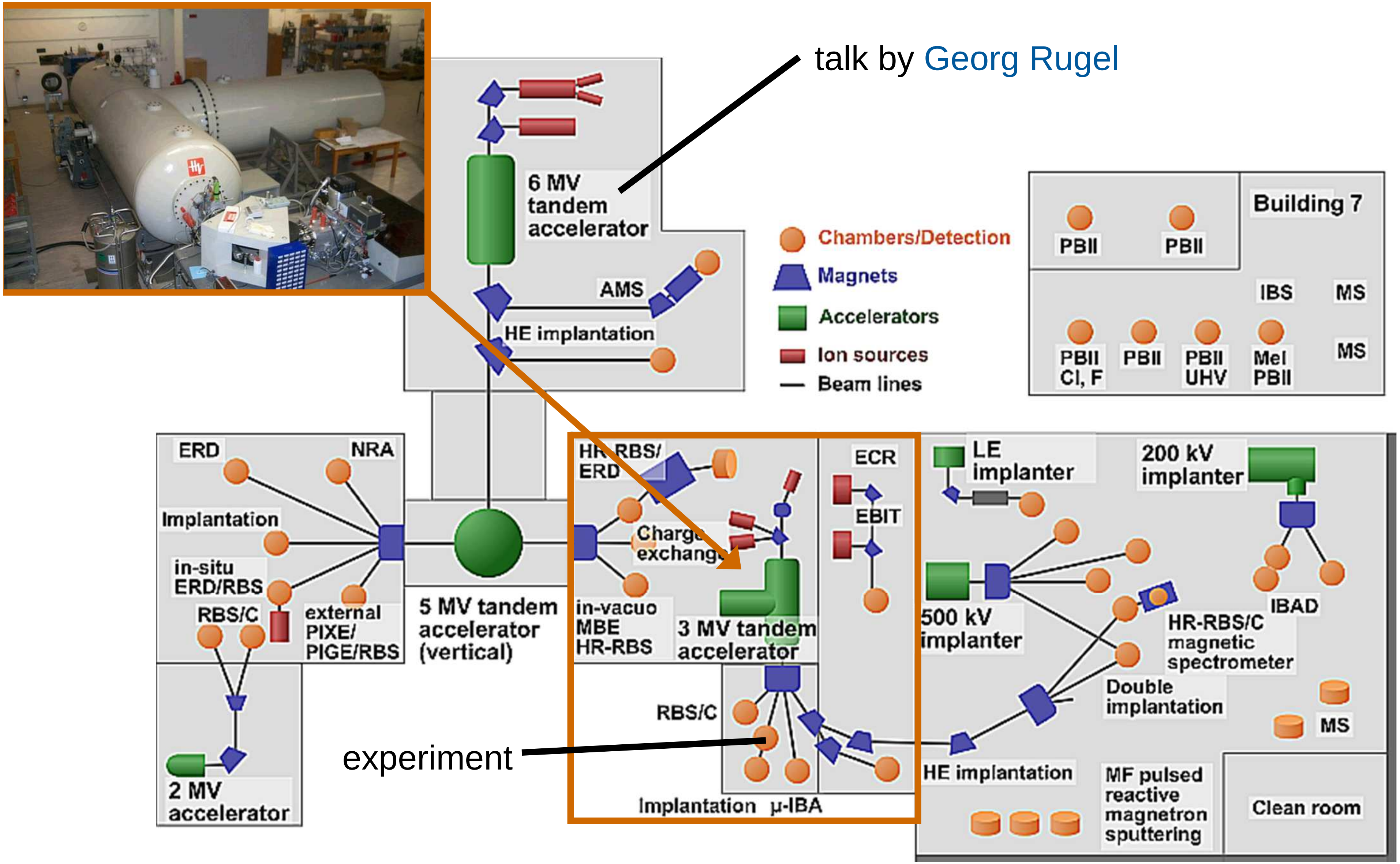
The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Setup at HZDR

Ion Beam Center at HZDR



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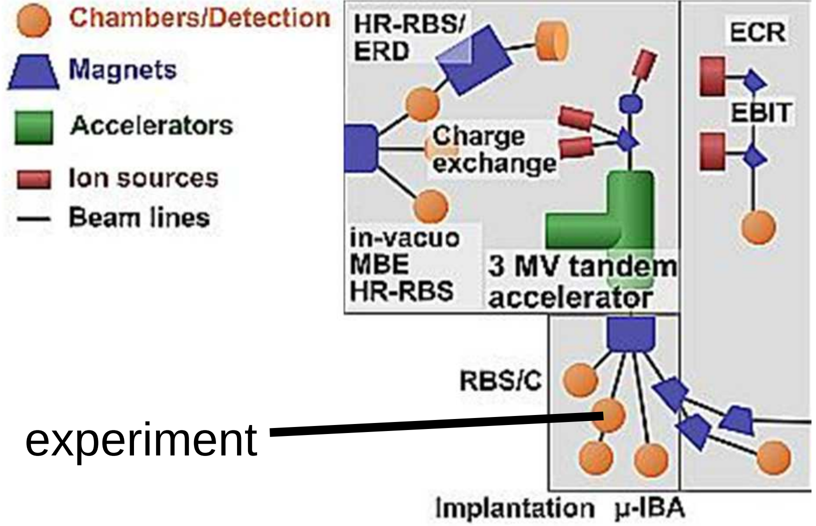
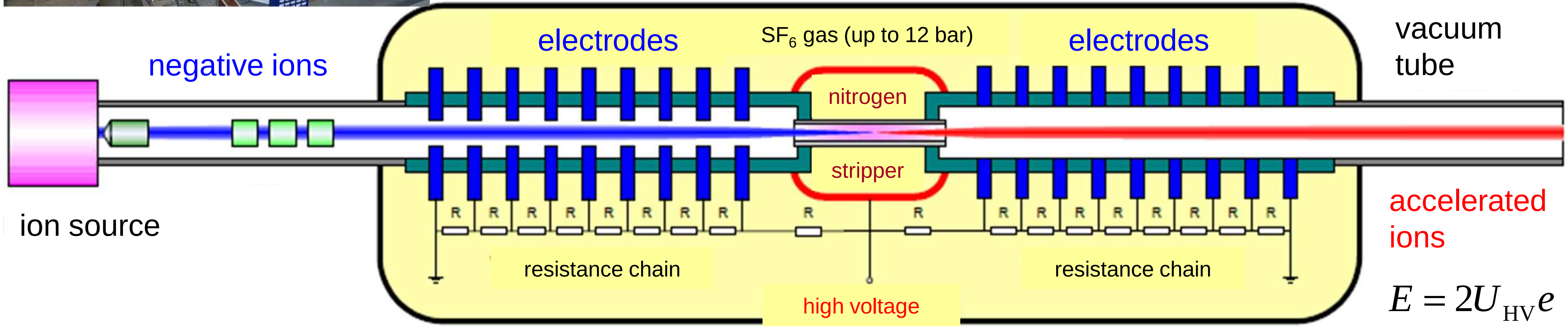
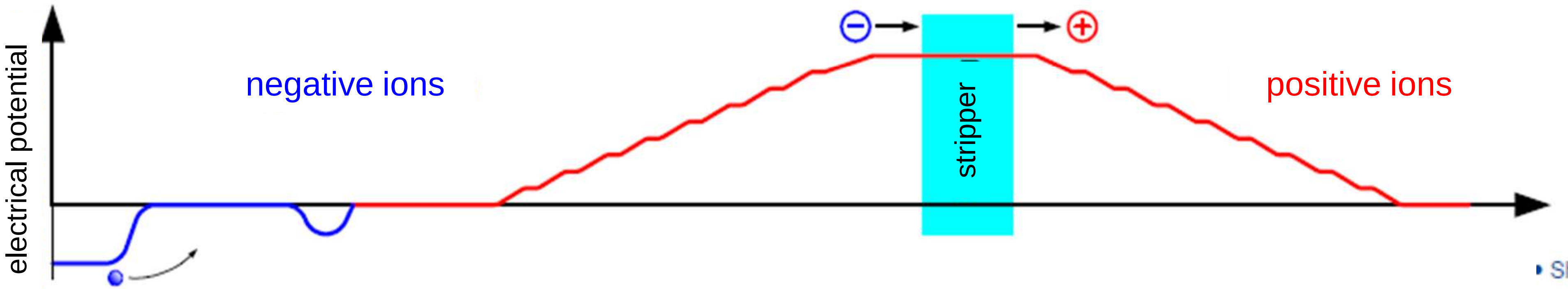
The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Setup at HZDR

3 MV Tandetron at Ion Beam Center







Sh. Akhmadaliev

Beam energy calibration of 3 MV Tandetron

- Nominal ion energies can be read from accelerator E_{nom} = e U_{ion}
- Incident ion energy E_0 at the target **differ** from nominal ion energy E_{nom}
- Calibration by Trompler et al. 2009 (diploma thesis):
  - resonances used: ^{27}Al(p,γ); ^{14}N(p,γ); ^{15}N(p,αγ)
  - energy range: 0.5 to 2.0 MeV
  - fit function: $E_0 = (1.017 \pm 0.002) \cdot E_{nom} - (5.2 \pm 1.0)$ keV
  - statistical error at 4.5 MeV: ΔE_0 = 10 keV (0.2 %)
- New calibration of present work (2010):
  - resonances used: ^{27}Al(p,γ); ^{40}Ca(p,γ); ^{40}Ca(α,γ)
  - energy range: up to 4.5 MeV
  - fit function: $E_0 = (1.0142 \pm 0.0003) \cdot E_{nom}$
  - statistical error at 4.5 MeV: ΔE_0 = 1.3 keV (0.03 %)
- New calibration (without offset) includes α particles

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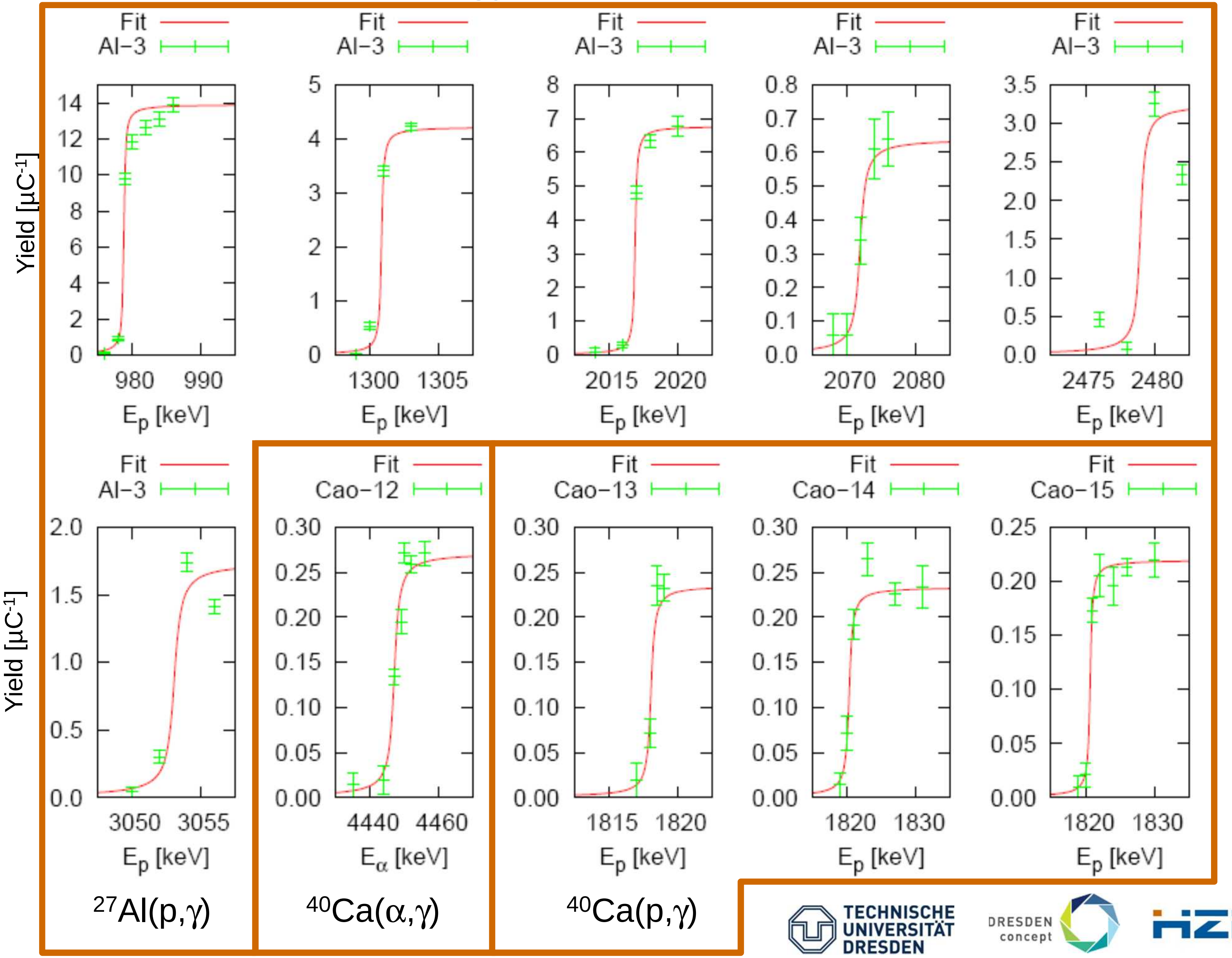
The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Setup at HZDR

Resonances for beam energy calibration of 3 MV Tandetron



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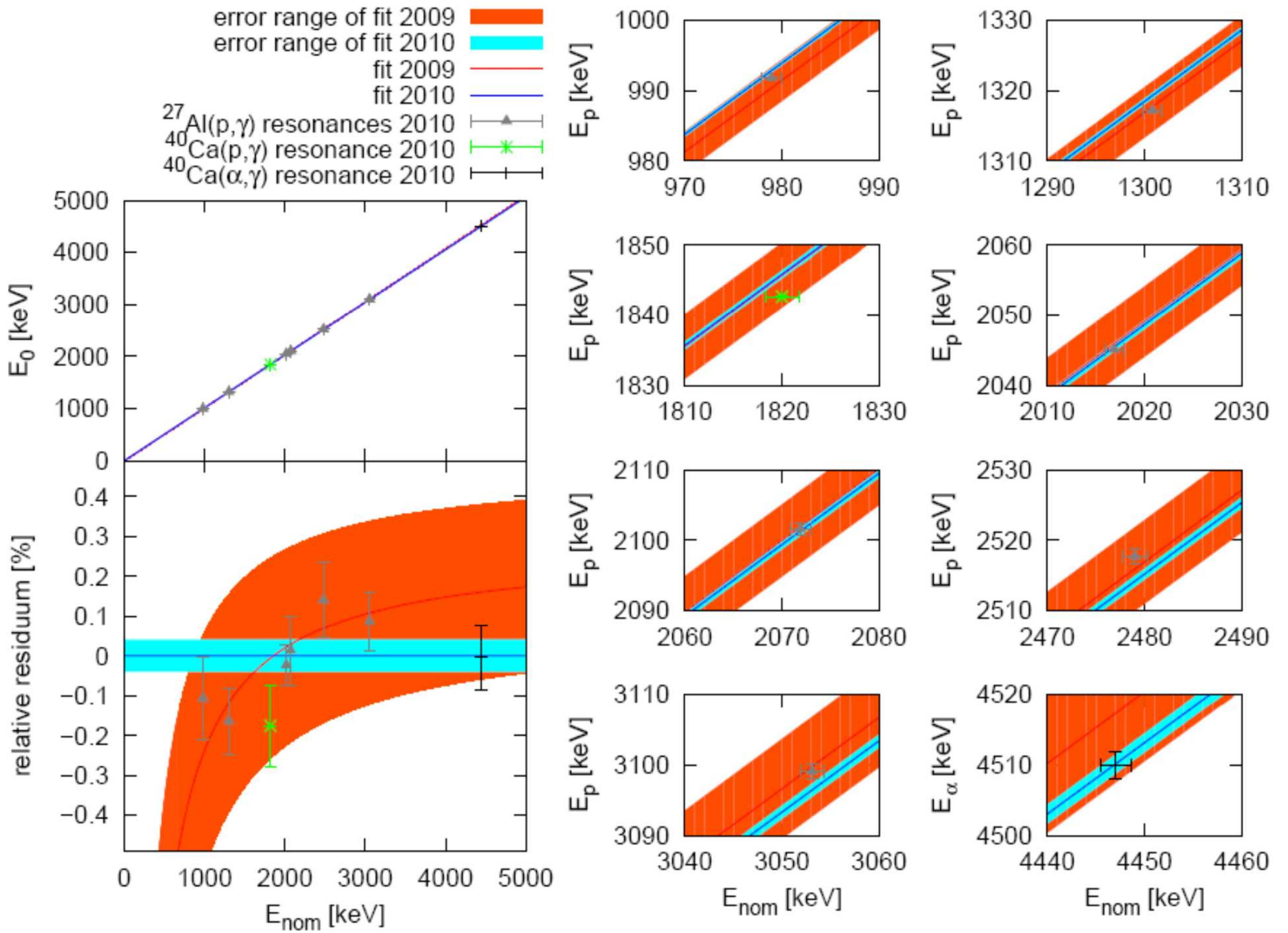
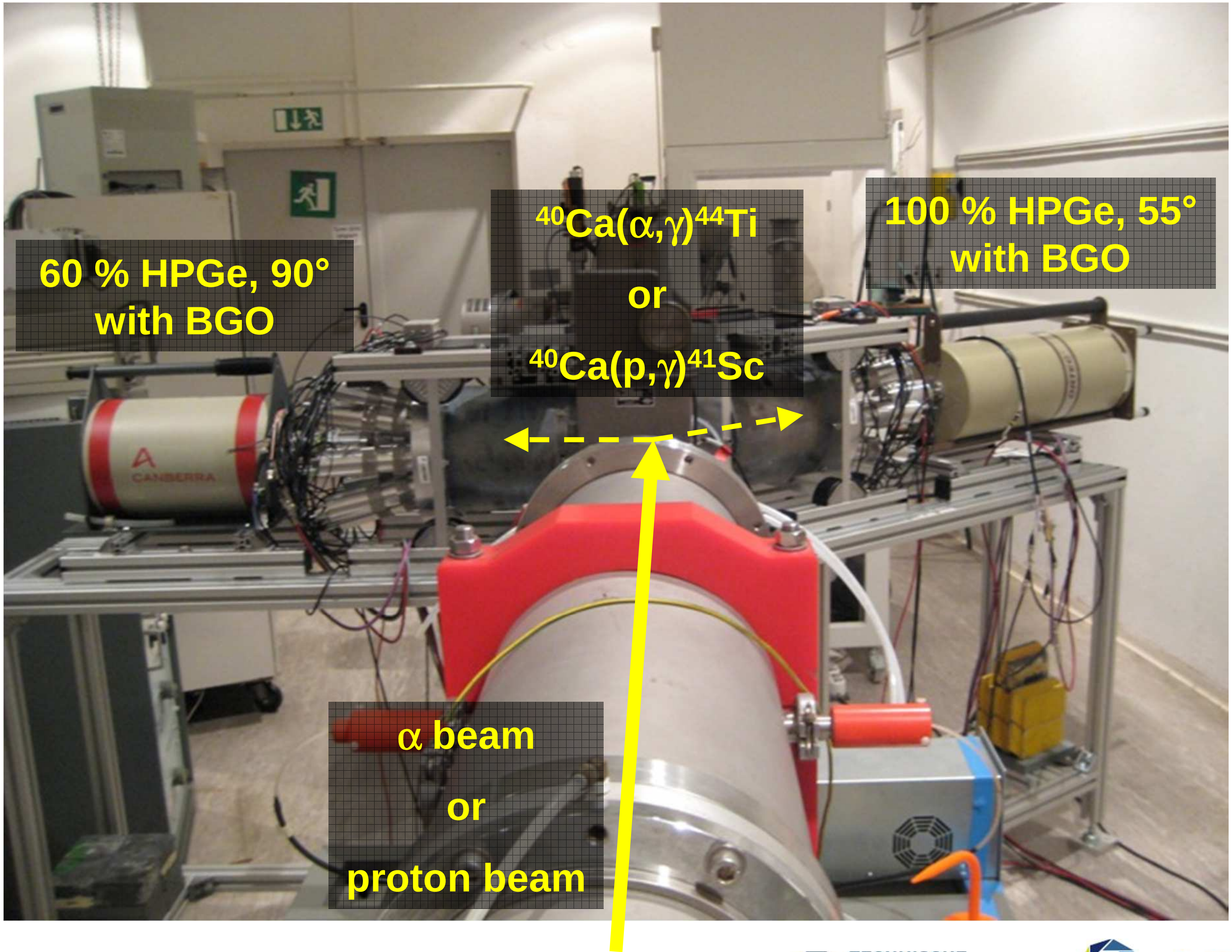
Comparison of old and new calibration of 3 MV Tandetron



The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Setup at HZDR

Beam line and detectors

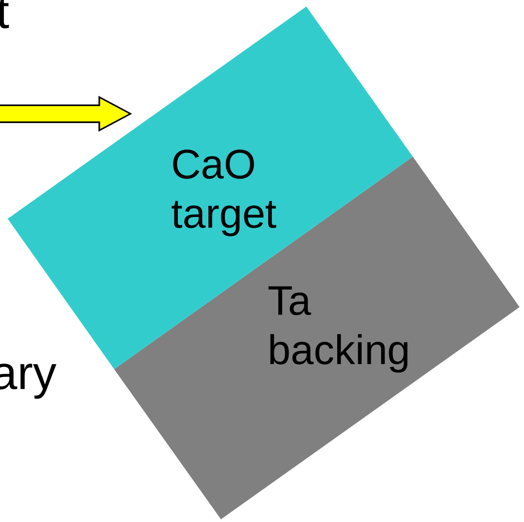


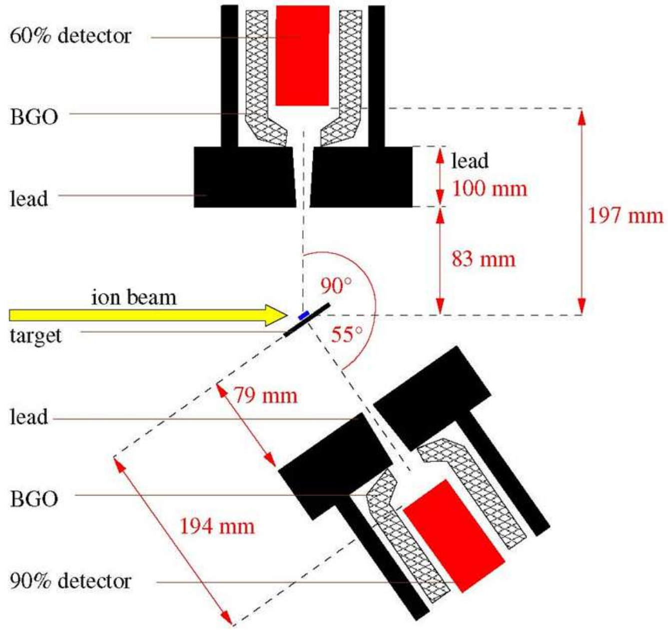
The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Setup at HZDR

Distances and targets

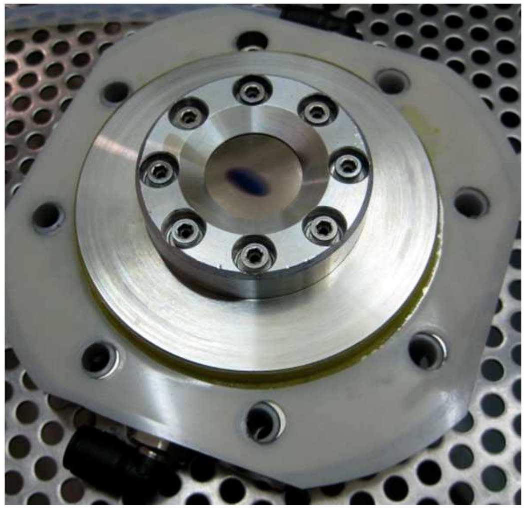
- CaO targets
  - natural composition (96% ^{40}Ca)
  - from GSI target lab, Darmstadt

ion beam

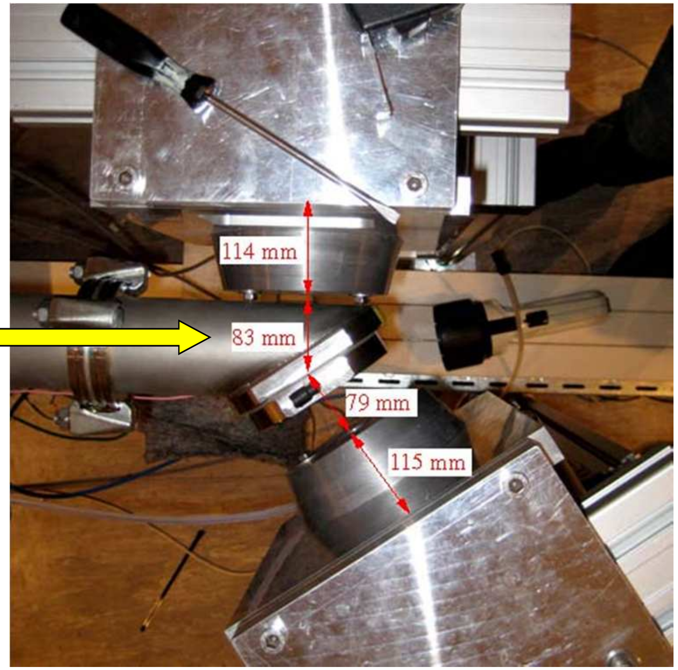




- Al targets
  - for beam energy and efficiency calibration
  - from ATOMKI Debrecen, Hungary
- beam spot after irradiation:



ion beam



- thin gold layer applied **after** irradiation to protect the ^{44}Ti

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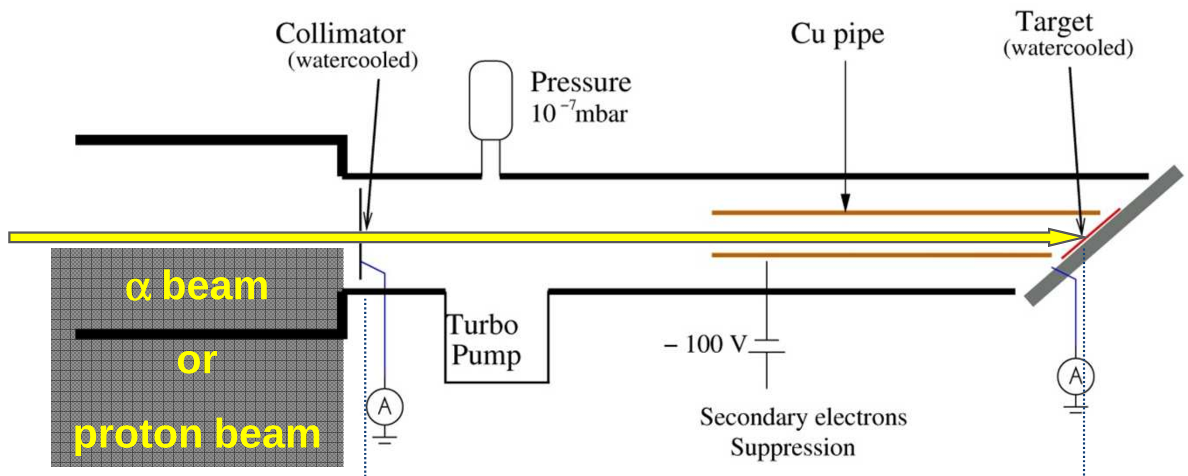
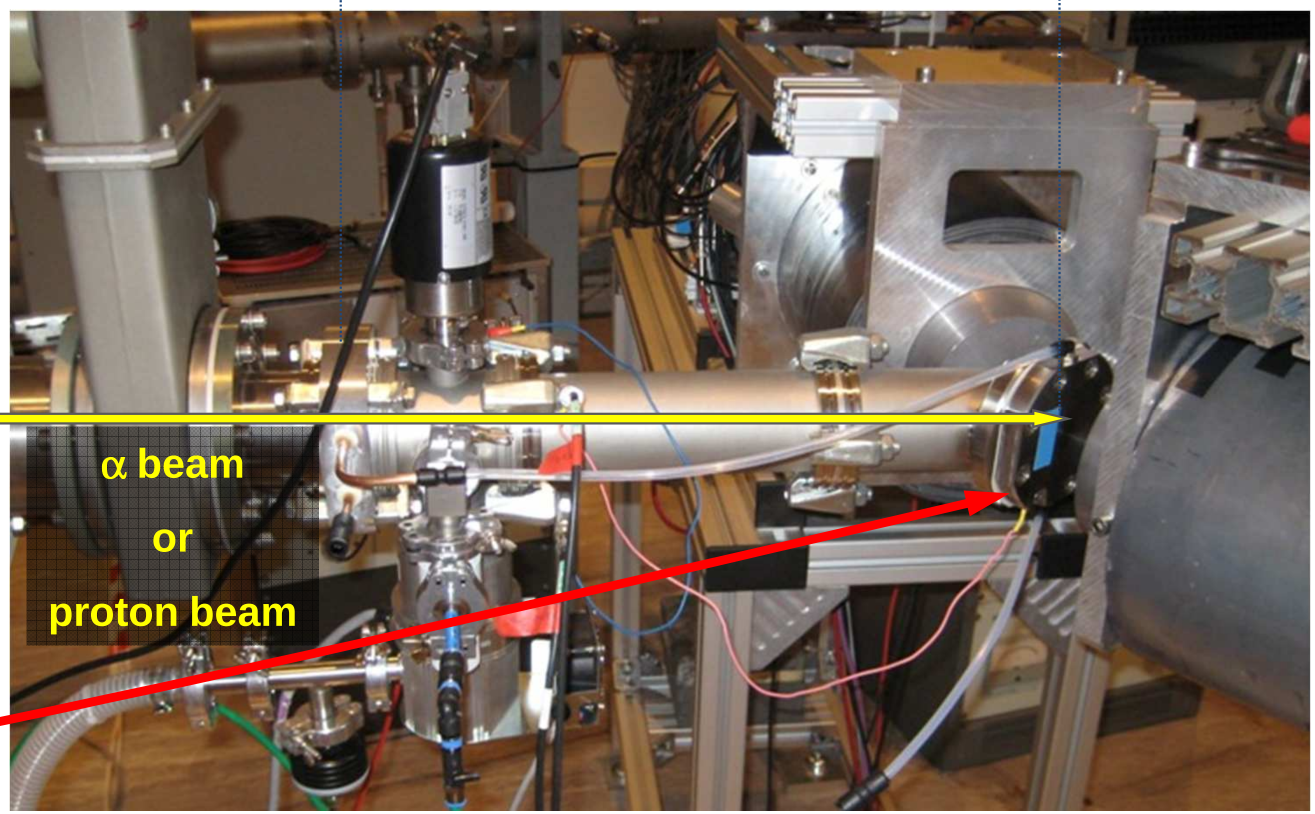
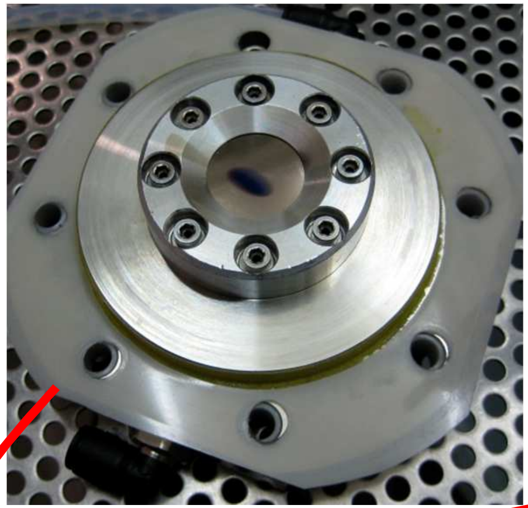
The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Setup at HZDR

Target chamber







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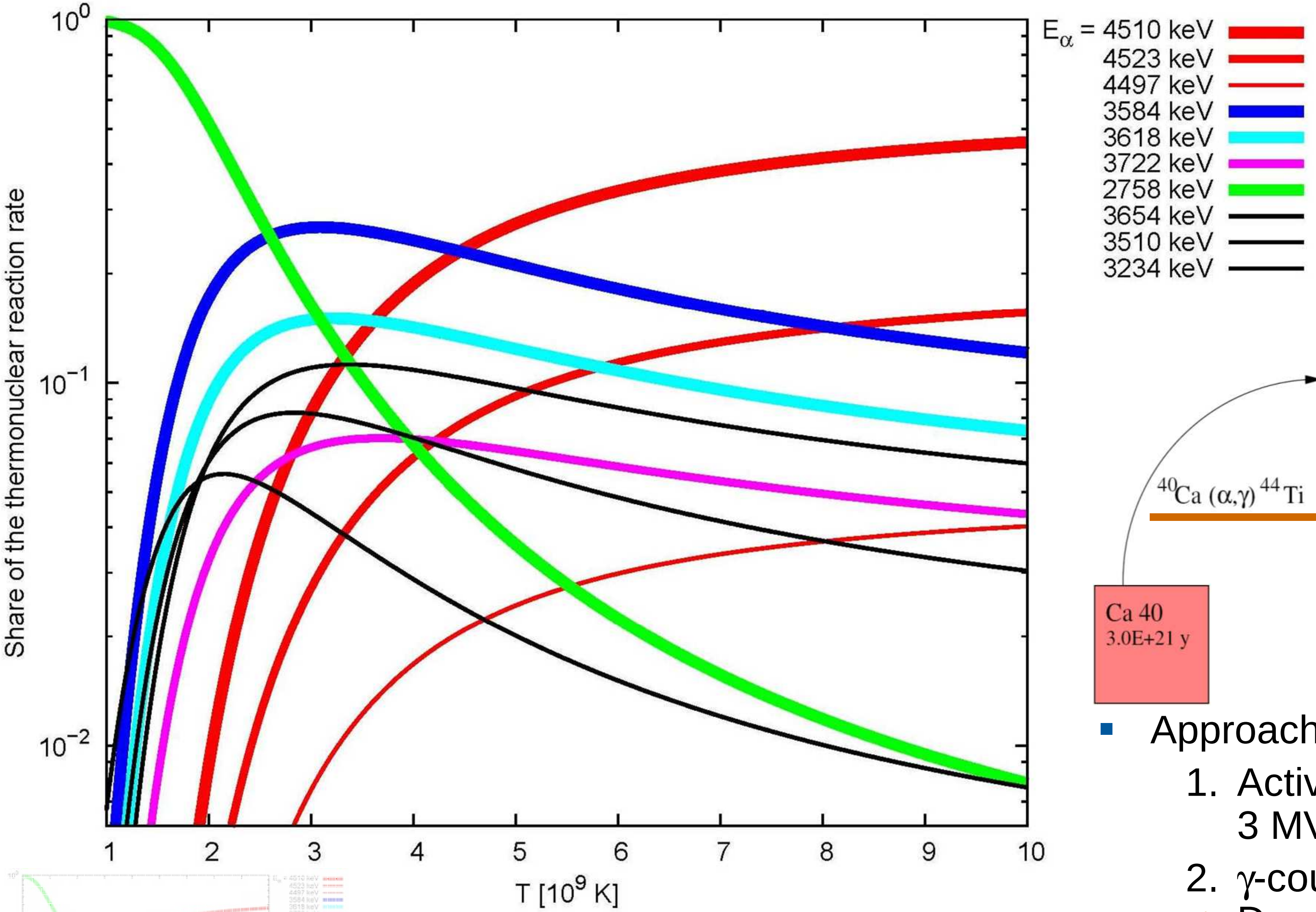
The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - State of the art

Important resonances and approach

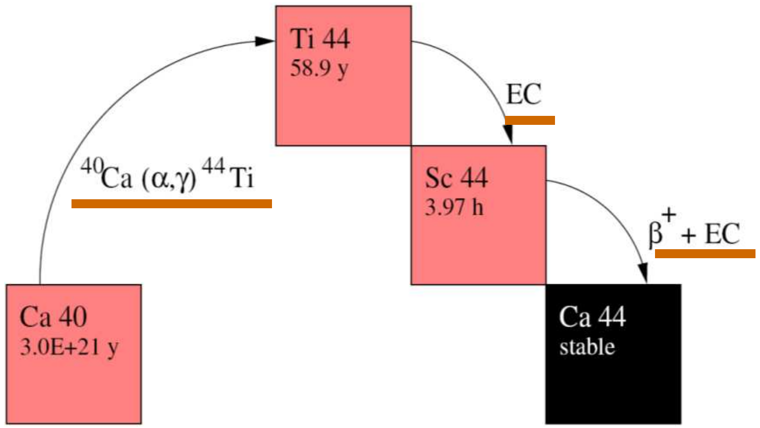


completed

under analysis

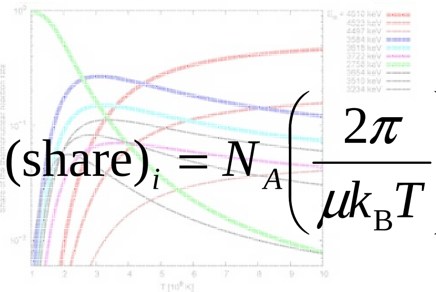
planned 2011

planned 2012



- Approach:
  1. Activation at high-intensity 3 MV Tandetron
  2. γ-counting at Felsenkeller Dresden
  3. Determination of resonance strengths

well-characterized calibration sources are necessary



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

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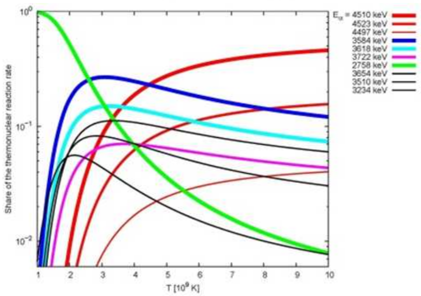
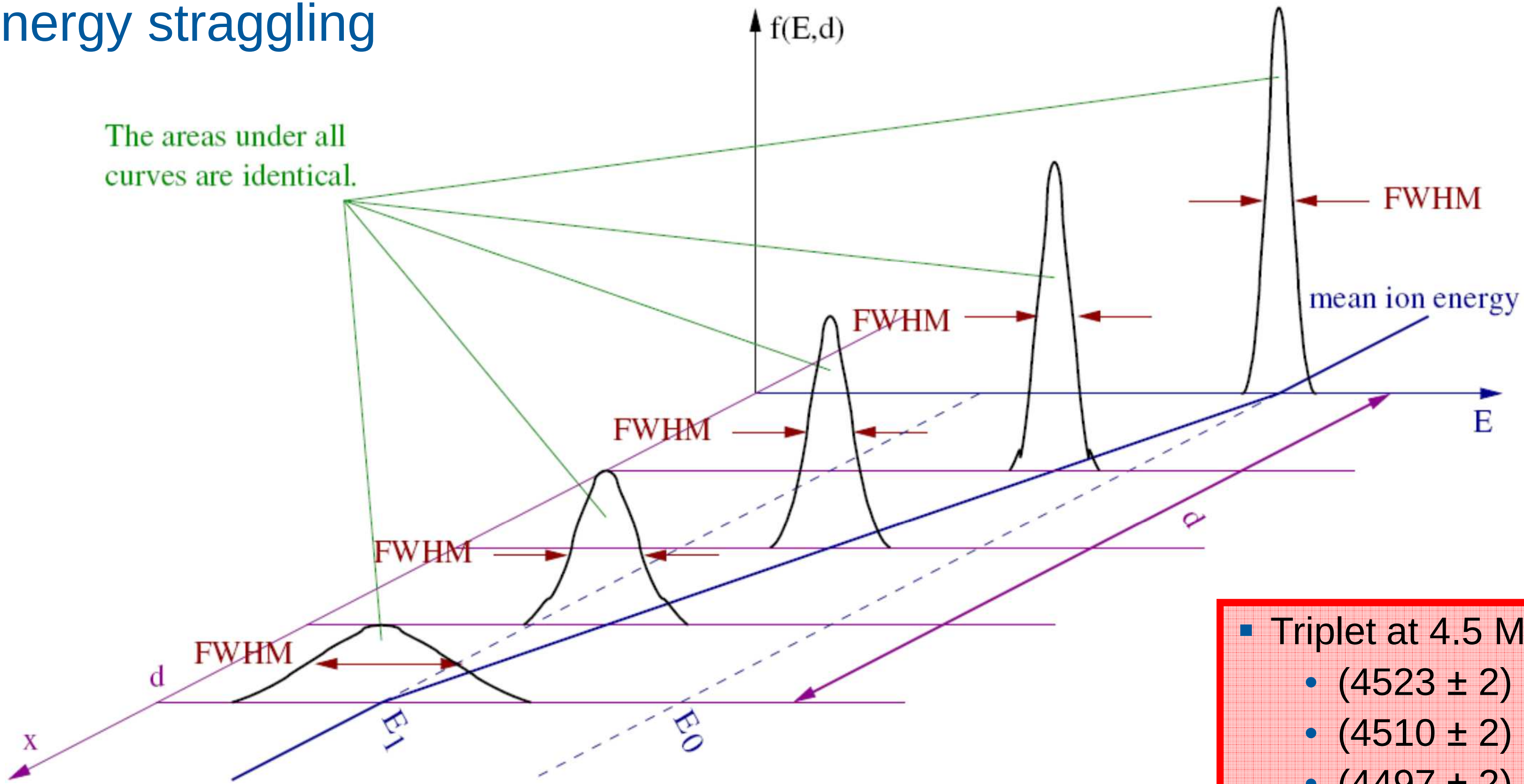
Literature values

Reference	E_α^{lab} [keV]	$\omega\gamma$	
Dixon et al. 1977 (Nat. Res. Council of Canada)	4523, 4510 and 4497	(8.3 ± 1.3) eV	(16 %)
Vockenhuber et al. 2007 (DRAGON at TRIUMF, Canada)	4523, 4510 and 4497	(12.0 ± 1.2) eV	(10 %)
Hoffman et al. 2010 (Lawrence Livermore Nat. Lab.)	4523, 4510, 4497, …	(16 ± 3) eV	(19 %)
Cooperman et al. 1977 (California State Univ., Fullerton)	3618 ± 6	(0.33 ± 0.07) eV	(21 %)
Vockenhuber et al. 2007	3618 ± 6	(0.40 ± 0.08) eV	(20 %)
Cooperman et al. 1977	3584 ± 6	(0.52 ± 0.10) eV	(19 %)
Vockenhuber et al. 2007	3584 ± 6	(0.53 ± 0.12) eV	(23 %)
Cooperman et al. 1977	3722 ± 6	(0.22 ± 0.04) eV	(18 %)
Vockenhuber et al. 2007	3722 ± 6	(0.46 ± 0.11) eV	(24 %)
Cooperman et al. 1977	2758 ± 22	(0.013 ± 0.003) eV	(23 %)
Vockenhuber et al. 2007	2758 ± 22	(0.013 ± 0.007) eV	(44 %)



The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - State of the art

Energy straggling



- Triplet at 4.5 MeV:
  - (4523 ± 2) keV
  - (4510 ± 2) keV
  - (4497 ± 2) keV
- Differences:
  - 13 keV each

- Schematic representation of energy distribution functions *f*(*E*,*d*) for a beam of charged particles as they move through an absorber.
- FWHM of the energy distribution corresponds to energy straggling
- Best approximation by Bohr 1915:

$$\mathrm{FWHM} = 1.20 \times 10^{-12} \sqrt{Z_p^2 Z_t N d}$$

- Measure the sum of all 3 resonance strengths at 4.5 MeV

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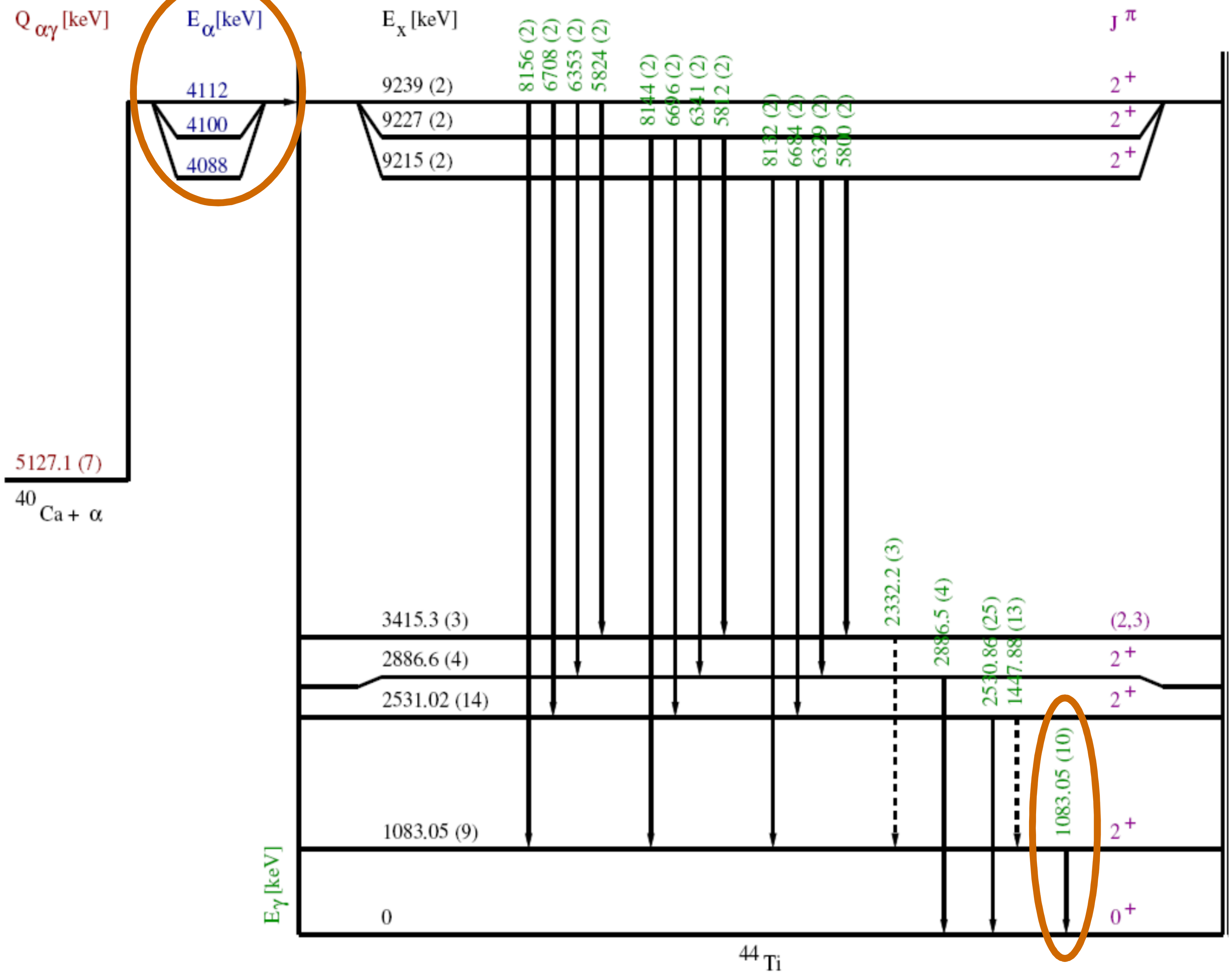
The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - State of the art

Reduced level scheme of ^{44}Ti



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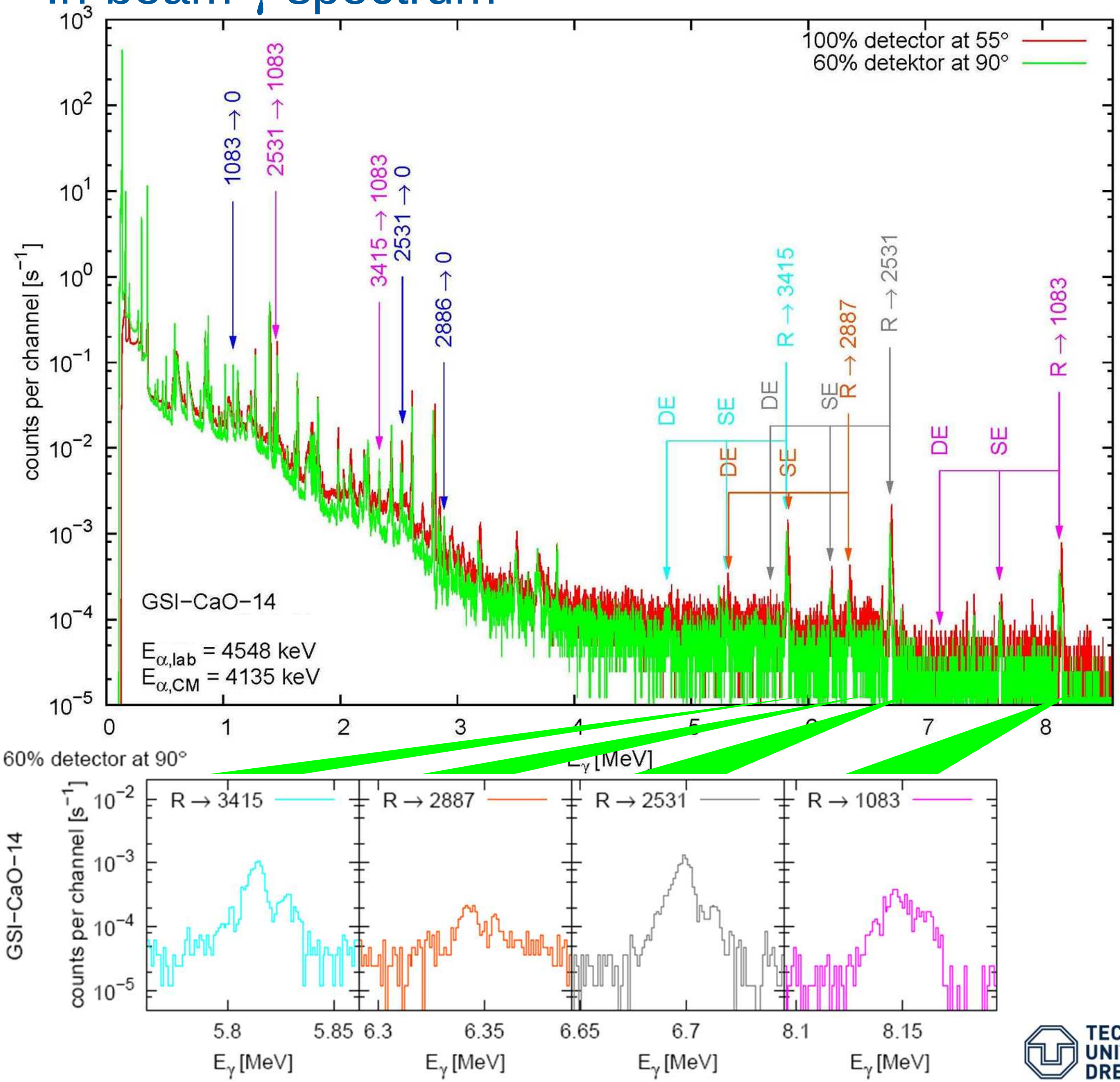
The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Results

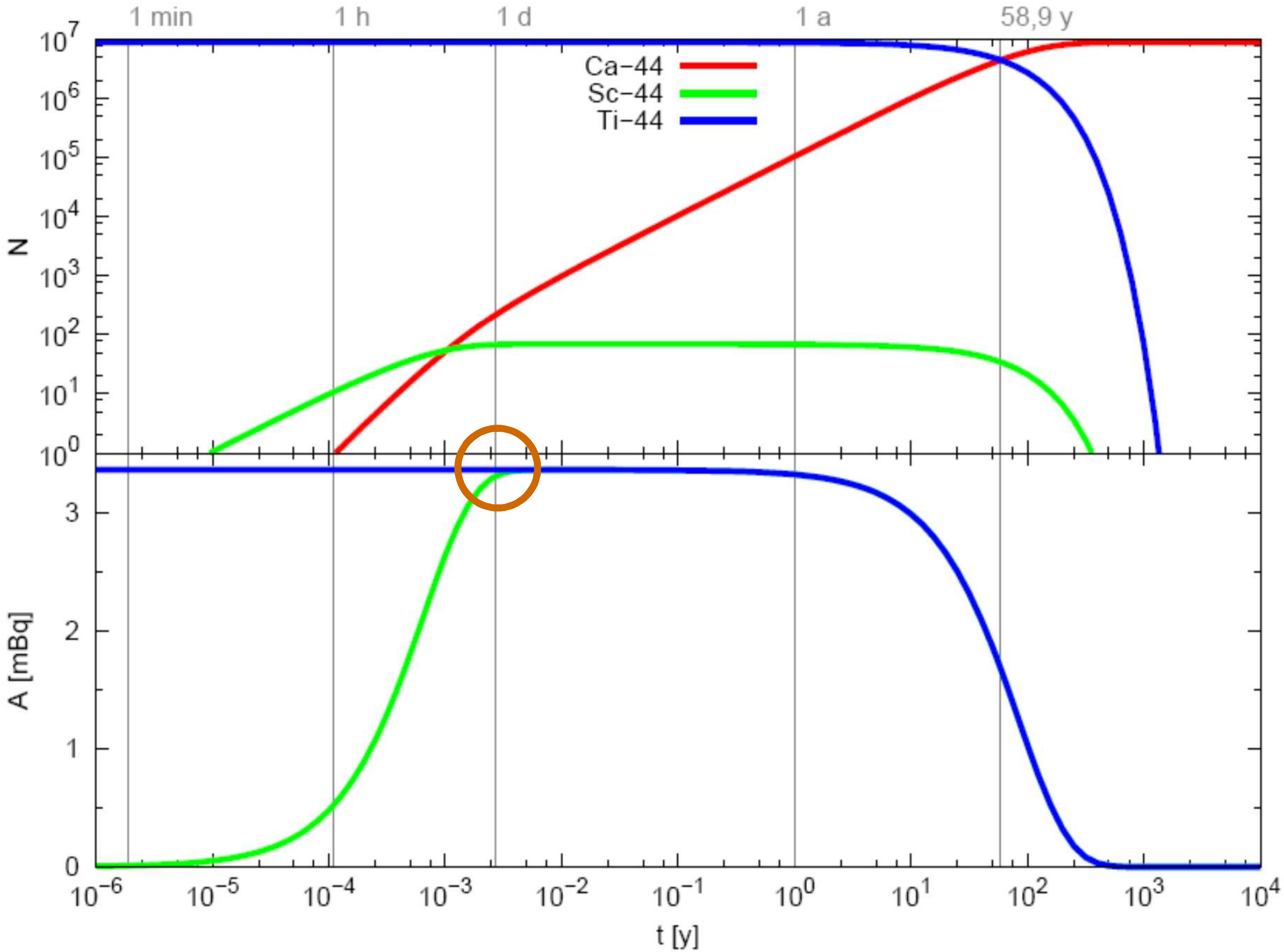
In-beam γ-spectrum



- natural composition (96% ^{40}Ca) in CaO targets
- α reactions on Ca:
  - $^{40}Ca(\alpha,\gamma)$
  - $^{41}Ca(\alpha,p\gamma)^{44}Sc$
  - $^{44}Ca(\alpha,n\gamma)^{47}Ti$
  - $^{44}Ca(\alpha,\gamma)^{48}Ti$
  - etc.
- α reactions on O:
  - $^{16}O(\alpha,\gamma)^{20}Ne$
  - $^{18}O(\alpha,n\gamma)^{21}Ne$
  - etc.
- α reactions on additional contaminations:
  - $^{19}F(\alpha,n\gamma)^{22}Na$
  - $^{19}F(\alpha,p\gamma)^{22}Ne$
  - etc.

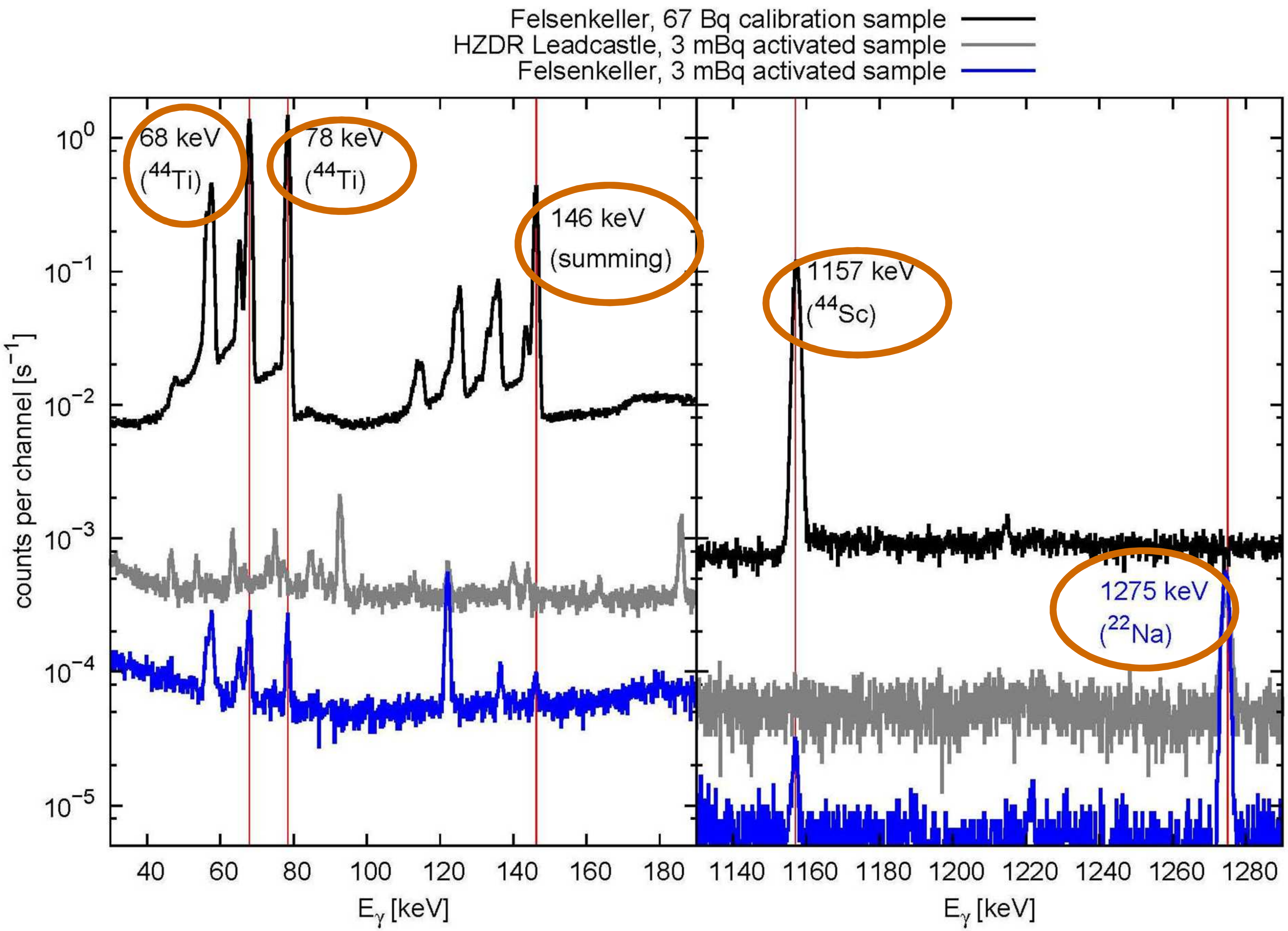
Number of nuclei and activity as a function of time

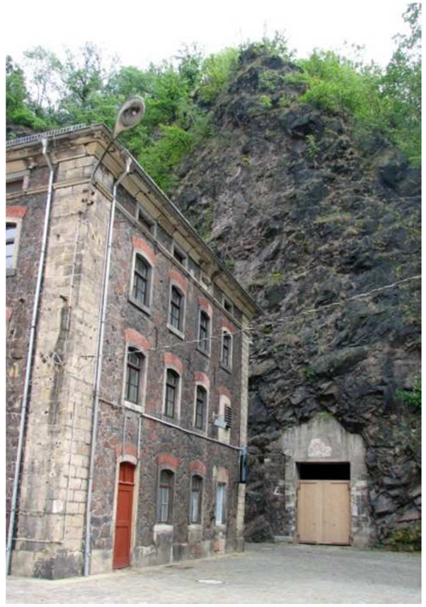
- Example calculation
- Initial number of ^{44}Ti nuclei is 9×10^6
- $T_{1/2}(^{44}Ti)$ = 58,9 y
- $T_{1/2}(^{44}Sc)$ = 3.891 h
- After **1 day** the activity of ^{44}Sc becomes equal to the activity of ^{44}Ti: $A(^{44}Ti)=A(^{44}Sc)$
- Contaminations decayed after a couple of days
- Except for ^{22}Na $T_{1/2}(^{22}Na)$ = 2.6 y
- Then counting in Felsenkeller started



The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Results

Offline spectra from HZDR and Felsenkeller (below 47 m of rock)





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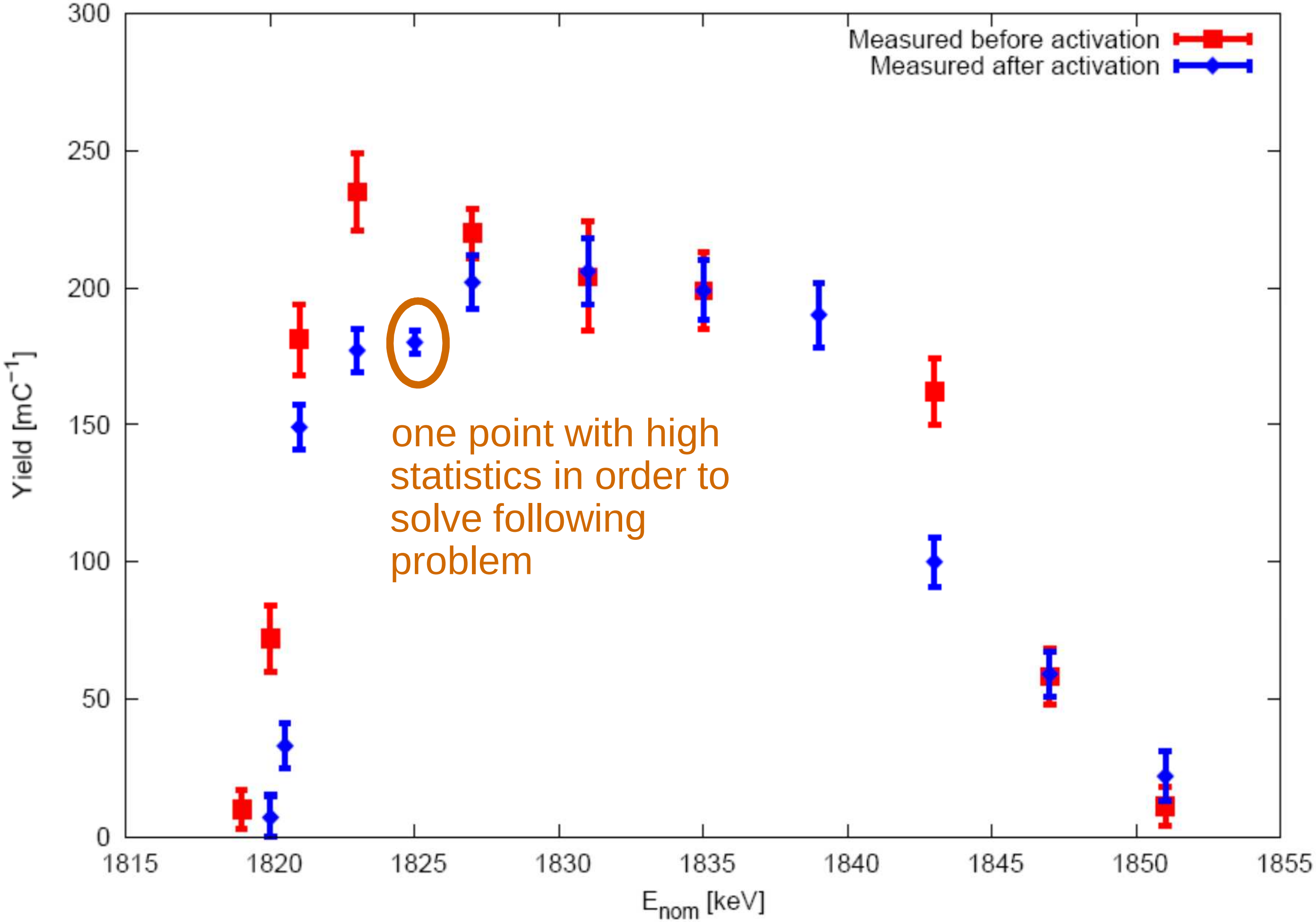
The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Results

Structure scans before and after activation by $^{40}Ca(p,\gamma)^{41}Sc$ reaction



- about 24 hours activation with a current of 1.5 µA at the water cooled target
- Structure scans before and after activation have just negligible distinctions
- Conclusion: Target layer stays stable during the activation

The ^{40}Ca(α,γ)^{44}Ti reaction - Results

Problem: unknown ratio of O to Ca in CaO targets

Solution 1

- Yield Y_p of ^{40}Ca(p,γ)^{41}Sc reaction to determine ratio n of O to Ca in CaO
- Resonance strength $\omega\gamma$ = (140 ± 15) meV (11%) by Zijderhand et al. 1987

$$\varepsilon_{\mathrm{eff,p}} = \frac{\lambda_r^2}{2} \cdot \frac{\omega\gamma}{Y_p} \text{ = effective stopping power}$$

CaO_n

$$\varepsilon_{\mathrm{eff,p}} = \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\mathrm{Ca,p}} + n \cdot \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\mathrm{O,p}}$$

$$n = \frac{n_{\mathrm{O}}}{n_{\mathrm{Ca}}} \quad \Rightarrow \quad \left.\frac{\Delta\varepsilon_{\mathrm{eff}}}{\varepsilon_{\mathrm{eff}}}\right|_{\alpha} = 12\,\%$$

- With this uncertainty (12 %) we find the sum of resonance strengths for the ^{40}Ca(α,γ)^{44}Ti reaction (relative to ^{40}Ca(p,γ)^{41}Sc):

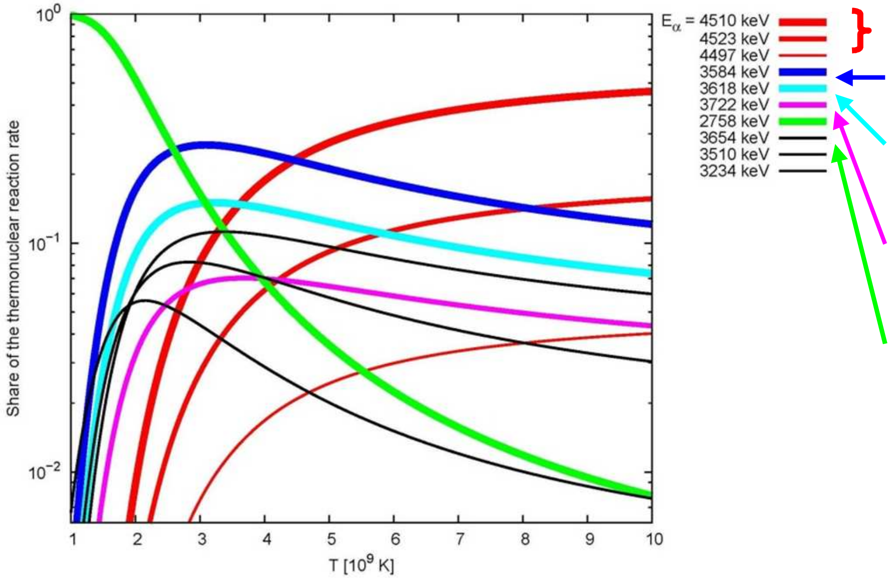
$$\omega\gamma = \frac{Y_\alpha}{\lambda_r^2/2} \cdot \varepsilon_{\mathrm{eff},\alpha} = (12.0 \pm 2.0)\,\mathrm{eV} \qquad (17\,\%)$$

Solution 2

- Effective Stopping power ε can be improved by ERDA (**E**lastic **R**ecoil **D**etection **A**nalysis) measurement of n. – planned in future
- Result of present work assuming O:Ca ratio of 1:1:

$$\omega\gamma = \frac{Y_\alpha}{\lambda_r^2/2} \cdot \varepsilon_{\mathrm{eff},\alpha} = (12.0 \pm 0.8)\,\mathrm{eV} \qquad (7\,\%)$$

Results and Outlook



completed,	ERDA in future
under analysis,	counting at Felsenkeller
under analysis,	counting at Felsenkeller
planned 2011,	18 % uncertainty in literature
planned 2012,	23 % uncertainty in literature

Dixon et al. 1977	**triplet**	$\omega\gamma$ = (8.3 ± 1.3) eV	(16 %)
Vockenhuber et al. 2007		$\omega\gamma$ = (12.0 ± 1.2) eV	(10 %)
result of present work, assuming O:Ca ratio of 1:1		**$\omega\gamma$ = (12.0** ± 0.8) **eV**	(6.7 %)

Cooperman 1977	**3584 keV**	21 % uncertainty
Vockenhuber et al. 2007		20 % uncertainty
present work		under analysis

Cooperman et al. 1977	**3618 keV**	19 % uncertainty
Vockenhuber et al. 2007		23 % uncertainty
present work		under analysis

The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction - Outline

- Introduction
- Weak ^{44}Ti sources by D. Schumann (PSI)
- Setup at HZDR
- State of the art
- Results
- Summary

The ^{40}Ca(α,γ)^{44}Ti reaction - Summary

- Five ^{44}Ti calibration sources supplied by PSI have been studied. First, maps of activity distribution have been created. Furthermore the activities have been determined by γ-ray spectrometry. Hence there are standards which are calibrated to 1.2 %.
- Astrophysically interesting resonance triplet of the ^{40}Ca(α,γ)^{44}Ti reaction at 4.5 MeV has been studied with CaO targets.
- ^{44}Ti activity has been measured in the underground laboratory Felsenkeller Dresden.
- Sum of resonance strengths at laboratory energies of 4497, 4510 and 4523 keV has been determined:

Reference	**Activated E_{lab} [keV]**	$\omega\gamma$	
Dixon et al. 1977	4523, 4510 and 4497	(8,3 ± 1,3) eV	(16 %)
Vockenhuber et al. 2007	4523, 4510 and 4497	(12,0 ± 1,2) eV	(10 %)
Hoffman et al. 2010	4523, 4510, 4497, …	(16 ± 3) eV	(19 %)
present work relative to ^{40}Ca(p,γ)	4523, 4510 and 4497	(12,0 ± 2,0) eV	(17 %)

- Uncertainty will be reduced by ERDA to determine ratio of O to Ca.
- Result of present work assuming O:Ca ratio of 1:1 is (12.0 ± 0.8) eV (7 %).
- Outlook: Study resonances at 3.5 MeV (under analysis) and 2.8 MeV (next year).

Thank you for your attention.

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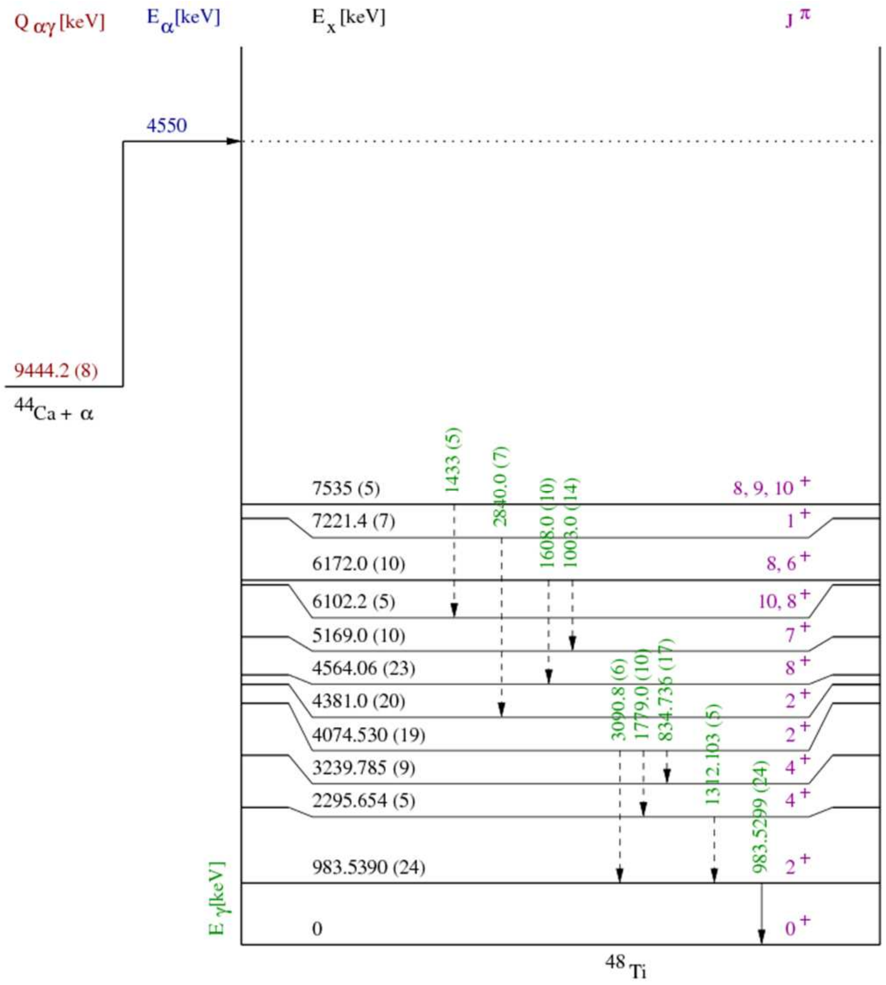
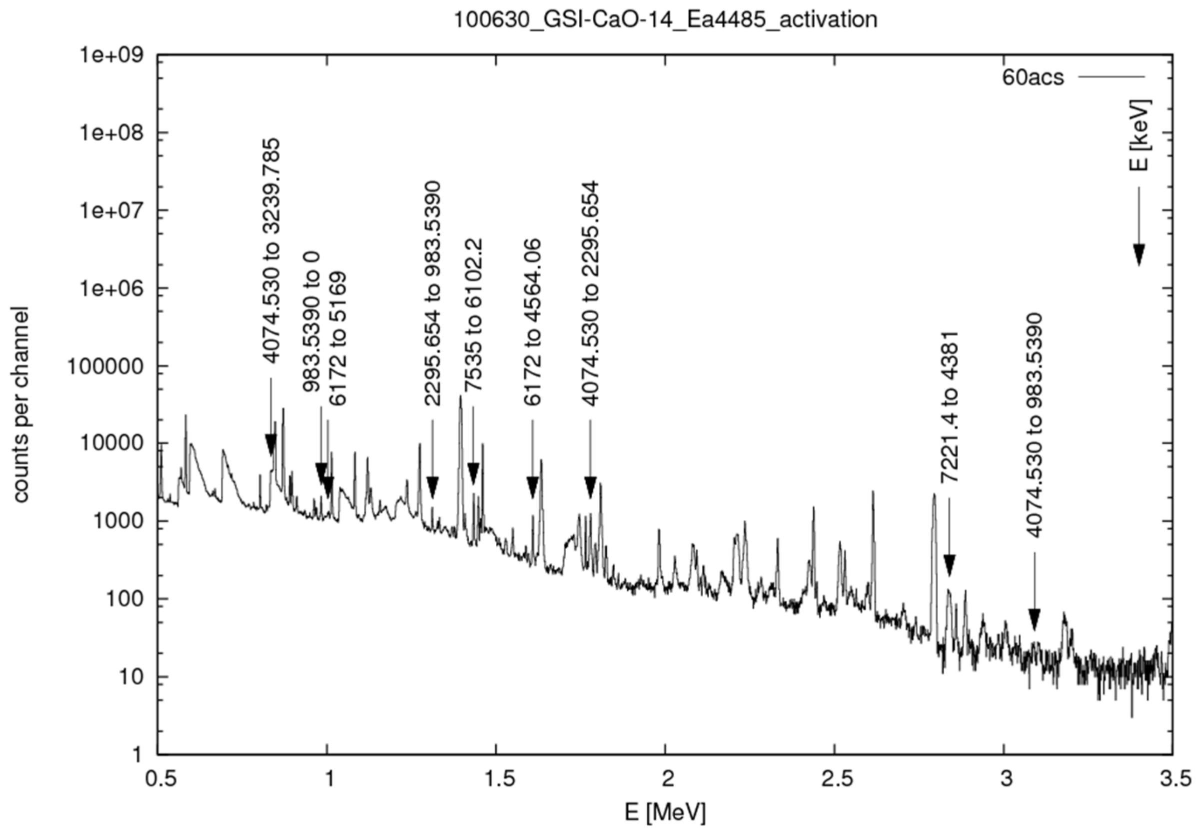
reduced level scheme & measured in beam pulse height spectrum

$^{44}Ca(\alpha,\gamma)^{48}Ti$





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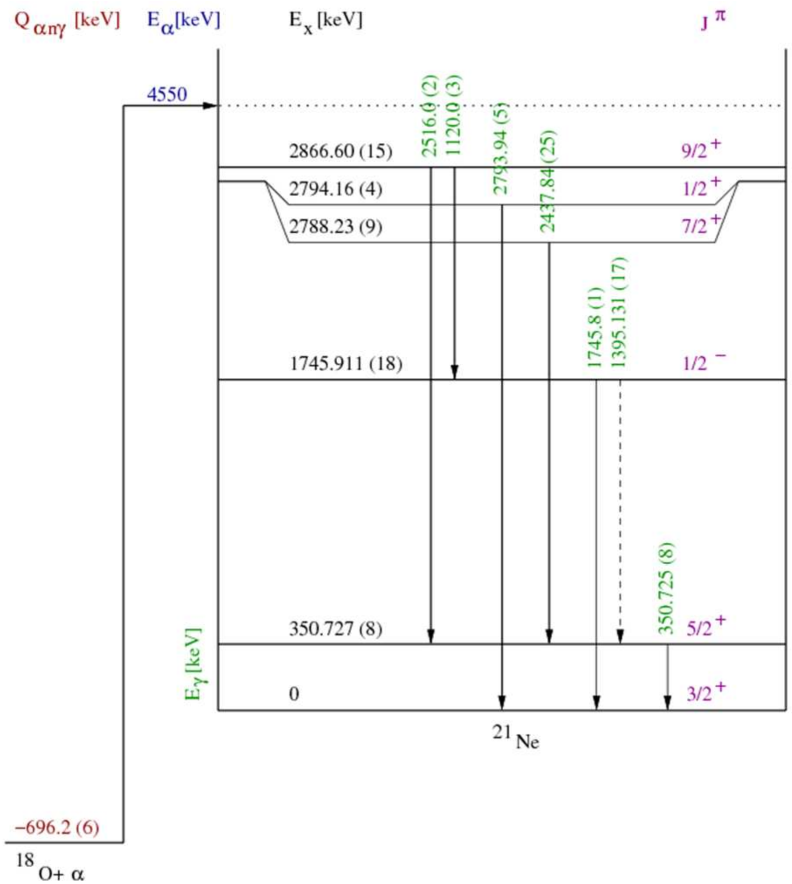
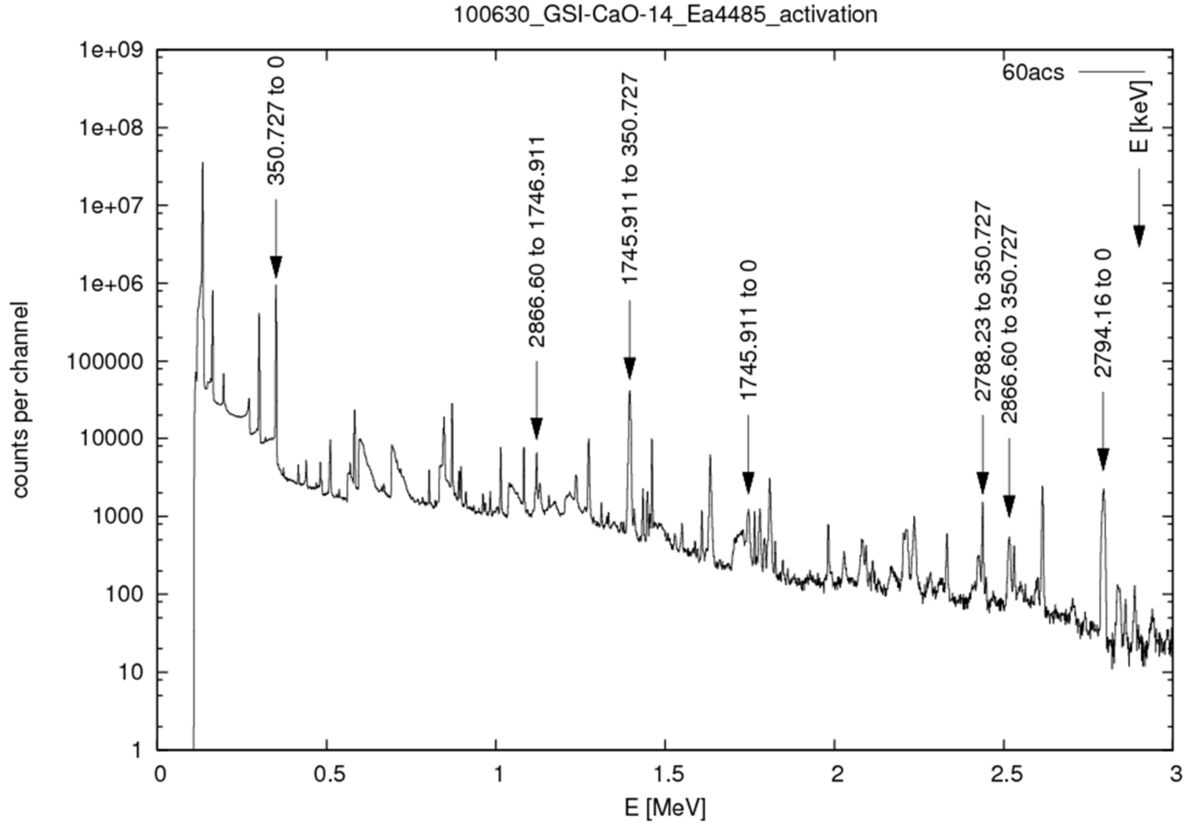
reduced level scheme & measured in beam pulse height spectrum

$^{18}O(\alpha,n\gamma)^{21}Ne$





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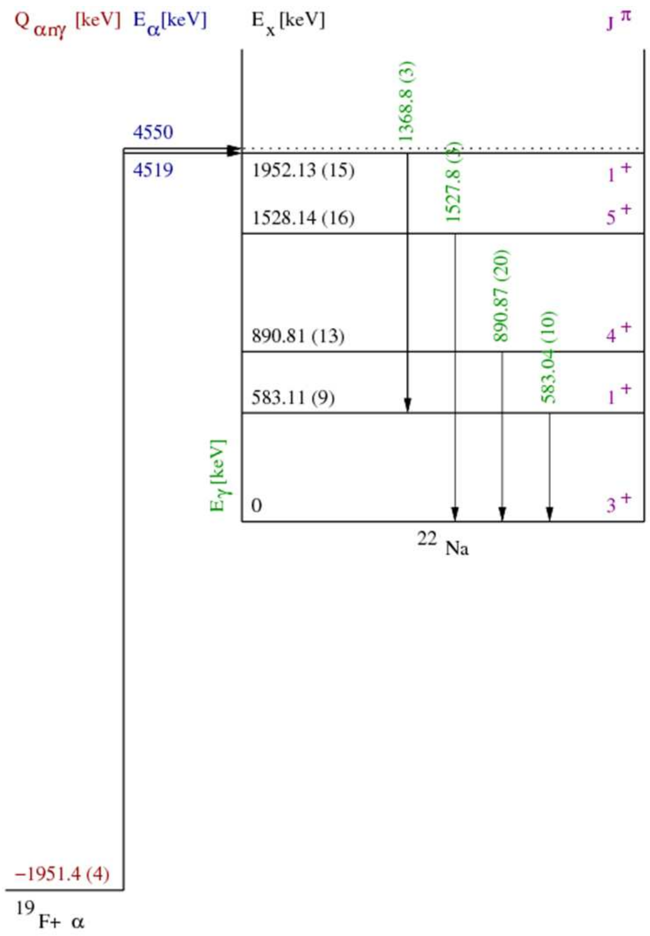
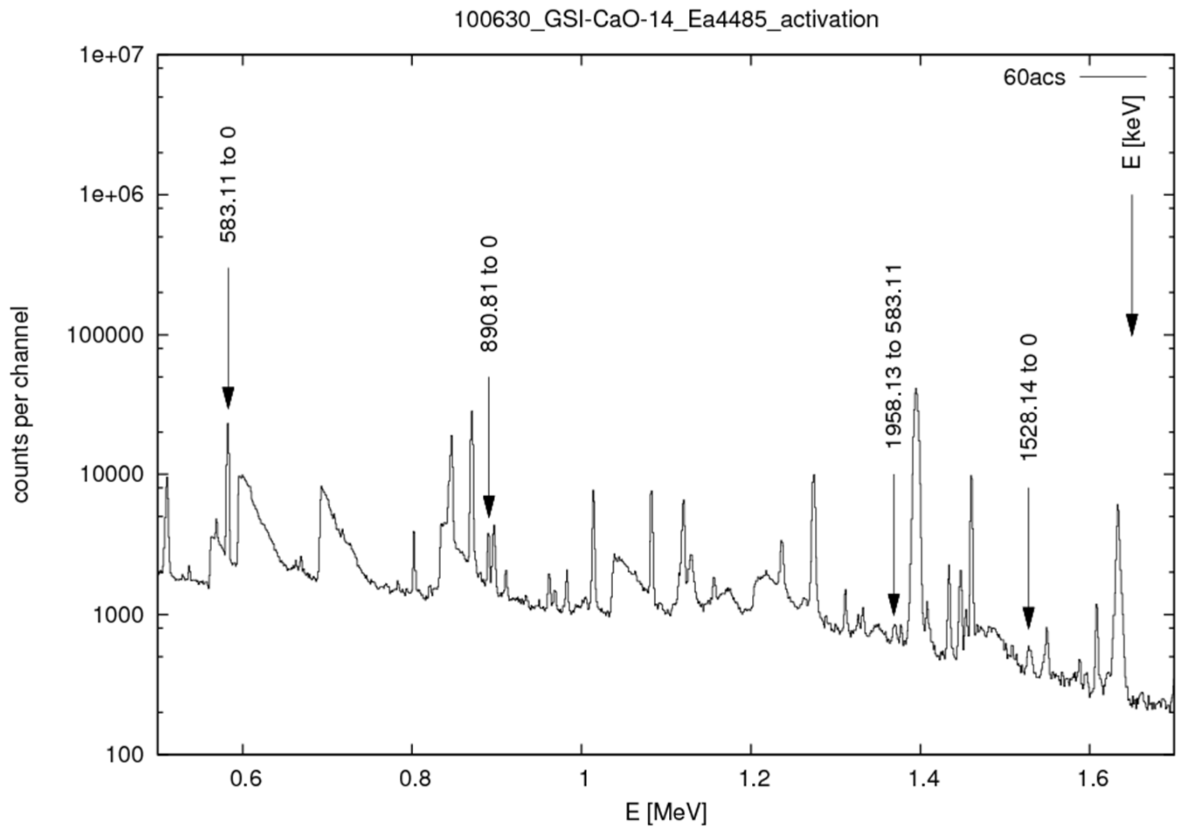
reduced level scheme & measured in beam pulse height spectrum

$^{19}F(\alpha,n\gamma)^{22}Na$





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Impact Analysis

- Yield

$$Y = \frac{N_\gamma}{N_\alpha} = \frac{N_{\mathrm{det}} / \eta_{\mathrm{direkt}}}{\mathrm{I}_\alpha t / e}$$

Y = yield
N_γ = number of emitted photons
N_α = number of incident α-particles
N_{det} = number of detected photons
η_{direkt} = efficiency of the detector
I_α = intensity of the α-beam
t = measuring time
e = elementary charge

- Resonance strenght

$$\omega\gamma = Y \varepsilon_r \left(\frac{\lambda_r^2}{2}\right)^{-1}, \qquad \frac{\lambda_r^2}{2} = \frac{\pi^2 \hbar^2}{E_\alpha^{\mathrm{lab}} m_\alpha} \left(\frac{m_\alpha + m_{\mathrm{Ca}}}{m_{\mathrm{Ca}}}\right)^2$$

$\omega\gamma$ = resonance strength
ε_r = effective stopping power at resonance energy
λ_r = de Broglie wavelength of the resonance
E_α^{lab} = laboratory beam energy
m_α = projectile mass
m_{Ca} = target mass

- Narrow resonance reaction rate

$$N_A \langle \sigma v \rangle = N_A \left(\frac{2\pi}{\mu k_{\mathrm{B}} T}\right)^{3/2} \hbar^2 \exp\left(\frac{-E_\alpha^{\mathrm{lab}}}{k_{\mathrm{B}} T}\right) \omega\gamma$$

$$\mu = \frac{m_\alpha m_{\mathrm{Ca}}}{m_\alpha + m_{\mathrm{Ca}}}$$

N_A = Avogadro constant
$N_A \langle \sigma v \rangle$ = thermonuclear reaction rate
μ = reduced mass of the projectile-target system
k_{B} = Boltzmann constant
T = temperature
$\exp\left(\frac{-E_\alpha^{\mathrm{lab}}}{k_{\mathrm{B}} T}\right)$ = Maxwell-Boltzmann factor

ILIADIS, C.: Nuclear Physics of Stars. Wiley-VCH (2007)