



**Measuring the 2s Lamb Shift in Hydrogenlike Gold and Uranium
With an NTD Germanium Microcalorimeter on Cooled, Decelerated Ion
Beams**

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- BRIEFLY DESCRIBE WHY A PRECISE MEASUREMENT OF THE LAMB SHIFT IS AN IMPORTANT TEST OF QED
- REVIEW STATUS OF MEASUREMENTS & HOW THEY HAVE BEEN MADE TO DATE
- DESCRIBE HOW THE μ CAL CAN MAKE SIGNIFICANT IMPROVEMENTS TO EXPERIMENTAL ACCURACY
- DESCRIBE OUR FIRST CAMPAIGN AT GSI-DARMSTADT TO LEARN HOW TO MAKE THIS MEASUREMENT



QED : BASIS + CORNERSTONE OF ALL
PRESENT FIELD THEORIES

- ENORMOUS SUCCESS IN PREDICTING
PROPERTIES OF ELECTRONS IN
WEAK FIELDS

→ HOWEVER

A PRECISE TEST IS STILL PENDING
FOR STRONG FIELD LIMIT
WHERE NEW PHENOMENA MAY APPEAR

GOAL: EXPLORE BEHAVIOR OF ELECTRONS
IN STRONGEST EM FIELDS
ACCESSIBLE EXPERIMENTALLY

PRECISE MEASUREMENTS OF ELECTRON BINDING
ENERGIES ARE WELL-SUITED TO
DEDUCE QED PHENOMENA IN
INTENSE FIELDS

→ COMPARISON OF PREDICTIONS AND
EXPERIMENTALLY DETERMINED
ENERGY LEVELS OF STRONGLY
BOUND ELECTRONS PROVIDES
A CRITICAL TEST OF QED

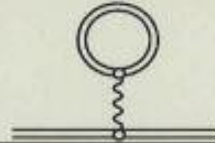
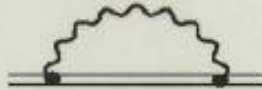
Bound-State QED: 1s Lamb Shift



Sum of all corrections, leading to deviations from the Dirac theory for a point like nucleus

Self energy

Vacuum polarization



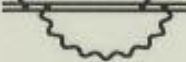
U ⁹²⁺	SE	VP	NS	
	355.0 eV	-88.6 eV	198.7 eV	465.1

2.5 65.4 -15.6 37.8 87.6

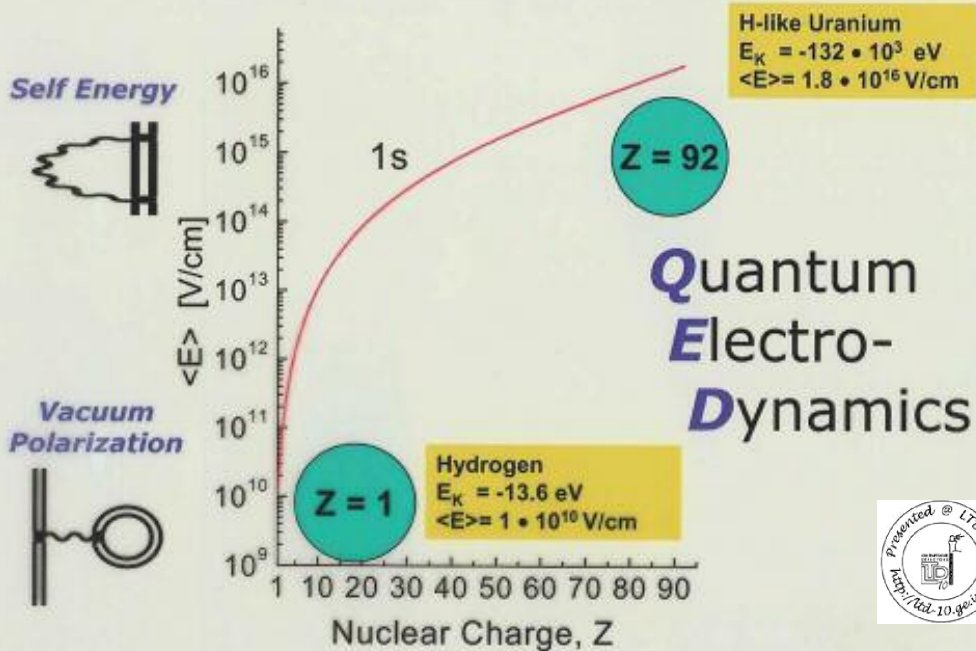
$$\Delta E = \alpha/\pi (\alpha Z)^4 F(\alpha Z) m_e c^2$$

Low Z-Regime: $\alpha Z \ll 1$
 $F(\alpha Z)$: series expansion in αZ

High Z-Regime: $\alpha Z \approx 1$
 $F(\alpha Z)$: series expansion in αZ
 not appropriate

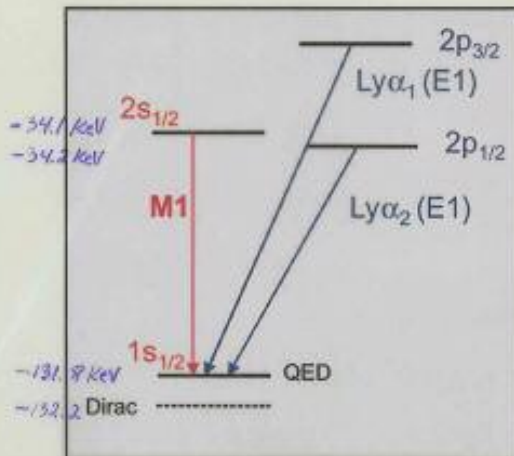
Goal:  $\pm 1 \text{ eV}$

Atomic Physics in Extremely Strong Coulomb Fields



1s-ground state: increase of the electric field strength by six orders of magnitude

The Structure of One-Electron Systems



QED corrections

$$\Delta E \sim Z^4/n^3$$

Z: nuclear charge number
n: principal quantum number

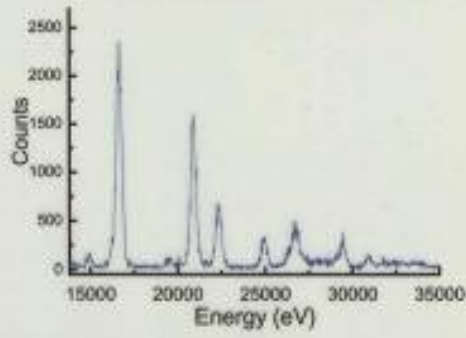
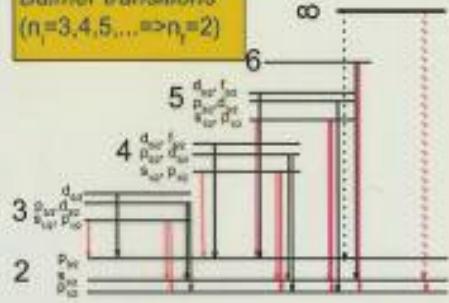


Atomic systems at high-Z

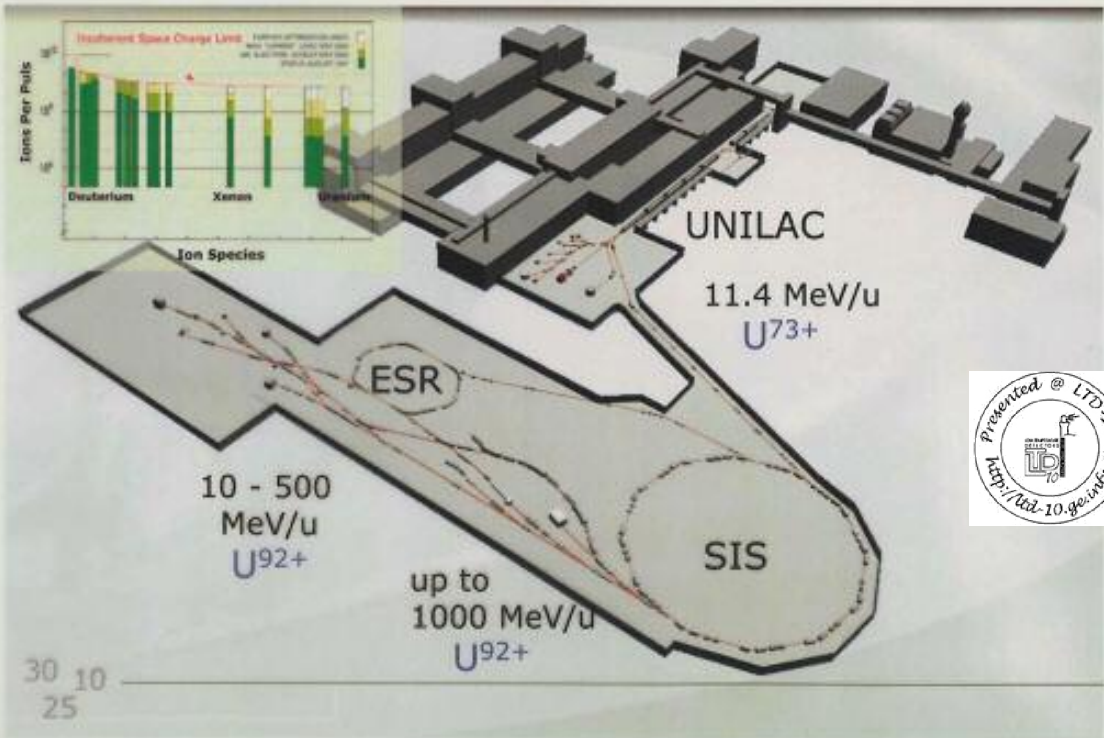
- Large relativistic effects on energy levels and transition rates (e.g. shell and subshell splitting)
- Large QED corrections
- Transition energies close to 100 keV

Balmer transitions
 $(n_i=3,4,5,\dots \Rightarrow n_f=2)$

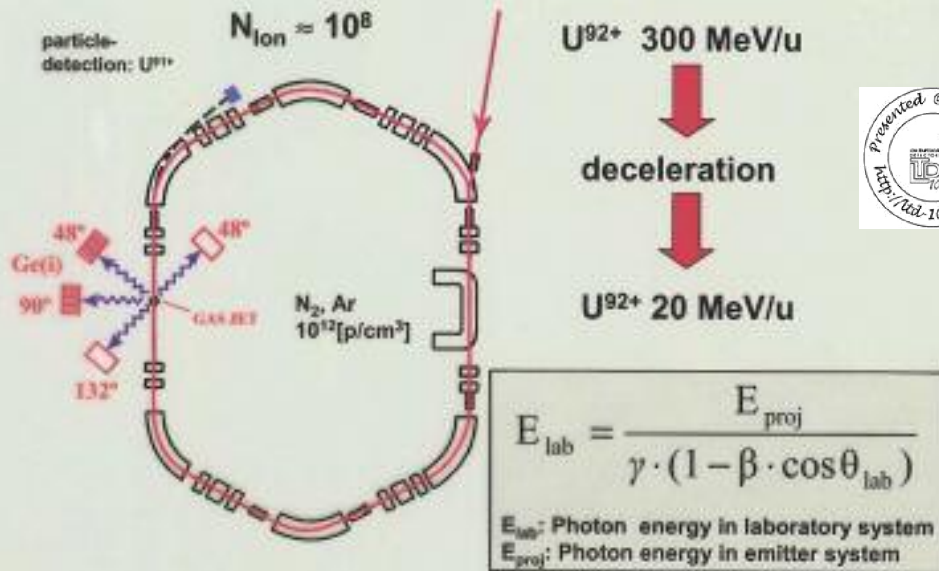
$U^{92+} \Rightarrow N_2$
 49 MeV/u



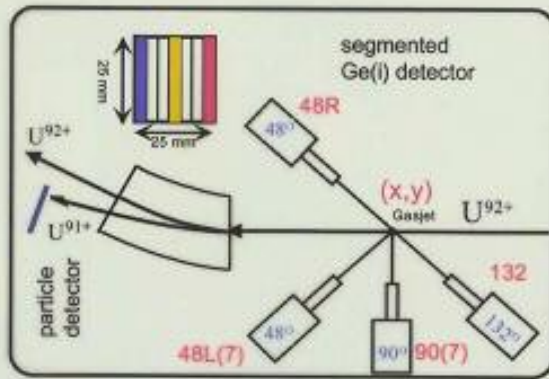
GSI-Accelerator Facility



X-Ray Spectroscopy at the Jet-Target

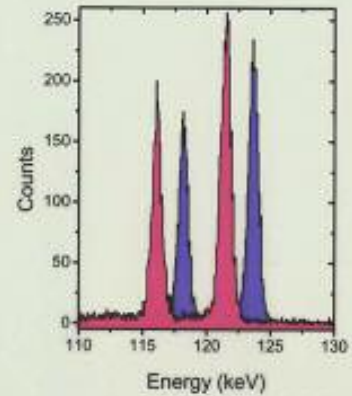


Lamb Shift-Experiment at the Jet-Target



- Simultaneous observation at various angles
- Forward/Backward symmetry
- Left/Right symmetry

$Ly\alpha_1 (2p_{3/2} \rightarrow 1s_{1/2})$
 $102\ 171 \pm 13.2\ eV$



$\Delta\theta \approx 3.0\ deg$

1s-Lamb Shift

Experiment: $468\ eV \pm 13\ eV$
Theory: $466\ eV^*$



The Experimental Challenge

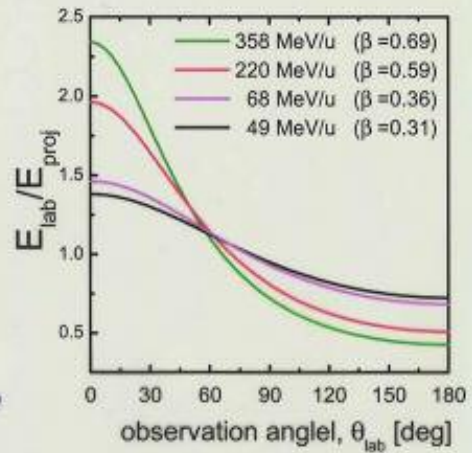


Relativistic Doppler-Transformation

$$E_{\text{lab}} = \frac{E_{\text{proj}}}{\gamma \cdot (1 - \beta \cdot \cos \theta_{\text{lab}})}$$

E_{lab} : Photon energy in the laboratory system
 E_{proj} : Photon energy in the emitter system

Doppler-Correction: Strong dependence on velocity and the observation angle θ_{LAB}



CURRENT STATUS



ΔE (β)	ΔE (fit)	ΔE (geometry)	$Ly-\alpha_1$
$\pm 2.6 \text{ eV}$	$\pm 9.7 \text{ eV}$	$\pm 8.5 \text{ eV}$	102170.7 ± 13.2

STÖHLKER et al. PHYS. REV, 85, 15, 2000

SCALE TO BALMER LINES $\sim 20 \text{ keV}$

ΔE (β)	ΔE (fit)	ΔE (geometry)	
0.52 eV	1 eV	1.5 eV	$\Rightarrow 1.885 \text{ eV}$

BUT: REQUIRES MANY DETECTORS AT SEVERAL LOCATIONS TO RELIEVE ΔE (GEOMETRY).

OR

A SELF-CALIBRATING MEASUREMENT

$$E_{\text{pro}} = \gamma (1 - \beta \cos \theta_{\text{LAB}}) E_{\text{LAB}}$$

DETERMINE FROM BALMER SPECTROSCOPY OF LINES NOT SUBJECT TO QED CORRECTIONS.

$$E_{2s1/2} = a E_{LAB2s1/2}$$



$$\left[\frac{\Delta E_{2s1/2}}{E_{2s1/2}} \right]^2 = \left(\frac{\Delta a}{a} \right)^2 + \left[\frac{\Delta E_{LAB2s1/2}}{E_{LAB2s1/2}} \right]^2$$

$$\left[\frac{\Delta a}{a} \right]^2 = \left[\frac{\Delta E_{CAL}}{E_{CAL}} \right]^2 + \left[\frac{\Delta E_{CALLAB}}{E_{CALLAB}} \right]^2$$

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$$\left[\frac{\Delta a}{a} \right]^2 = \left[\frac{\Delta E_{CALLAB}}{E_{CALLAB}} \right]^2$$

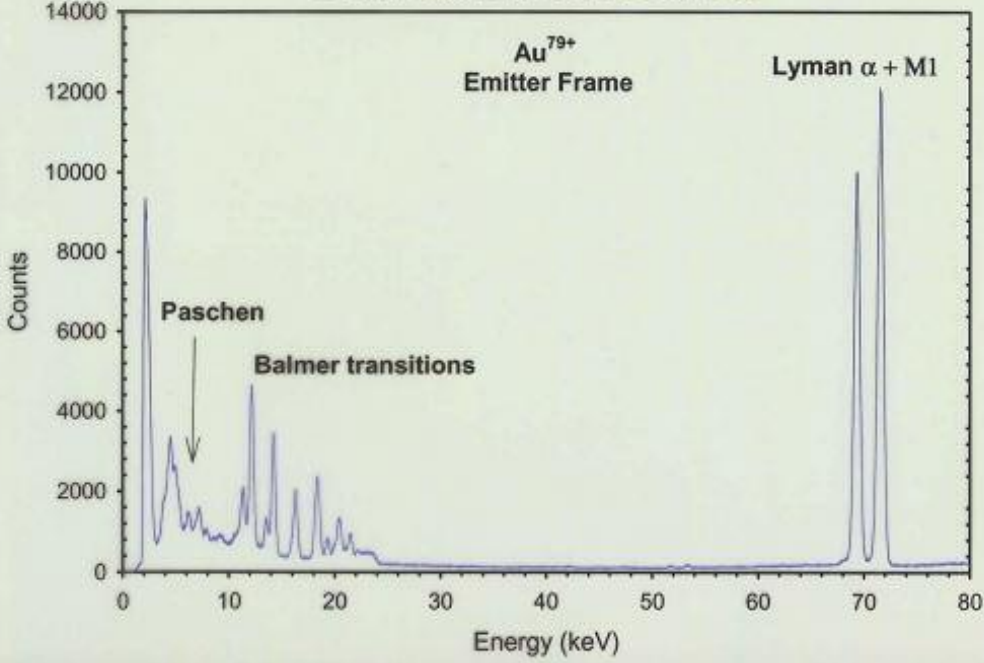
$$\left[\frac{\Delta E_{2s1/2}}{E_{2s1/2}} \right]^2 = \left[\frac{\Delta E_{CALLAB}}{E_{CALLAB}} \right]^2 + \left[\frac{\Delta E_{LAB2s1/2}}{E_{LAB2s1/2}} \right]^2$$

$$\approx \sqrt{2} \frac{1 \text{ eV}}{20 \times 10^3 \text{ eV}} = 7 \times 10^{-5}$$

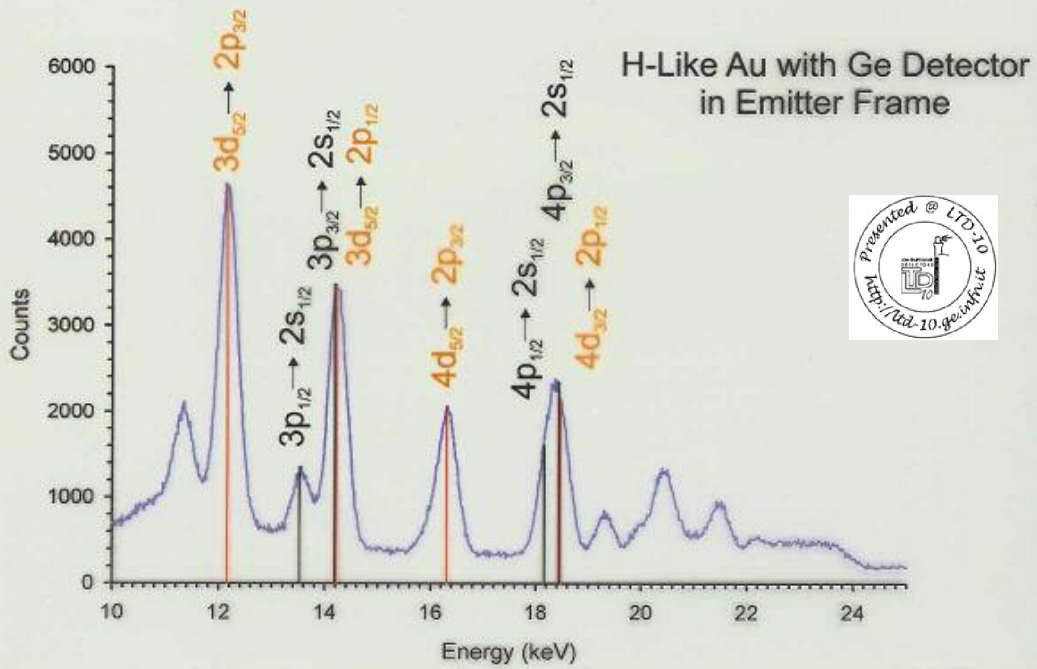
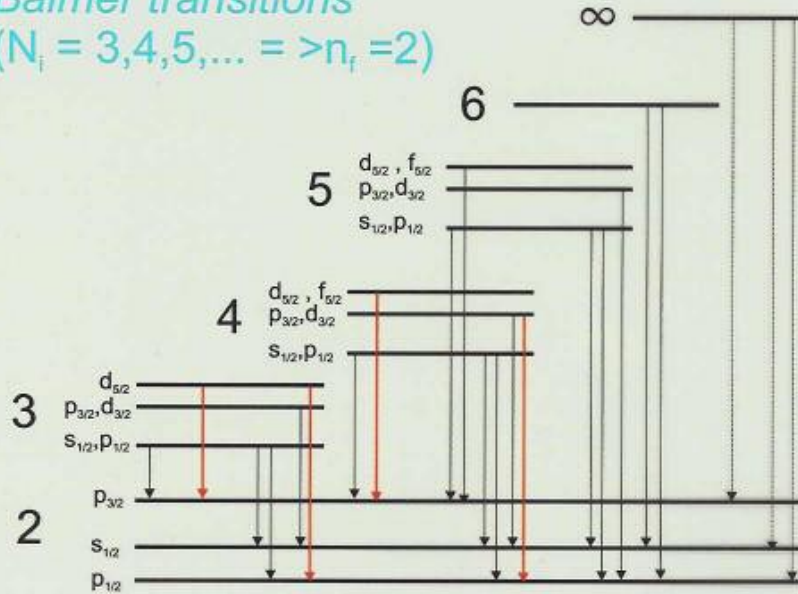
$$\Delta E_{2s1/2} \approx 1.4 \text{ eV!}$$

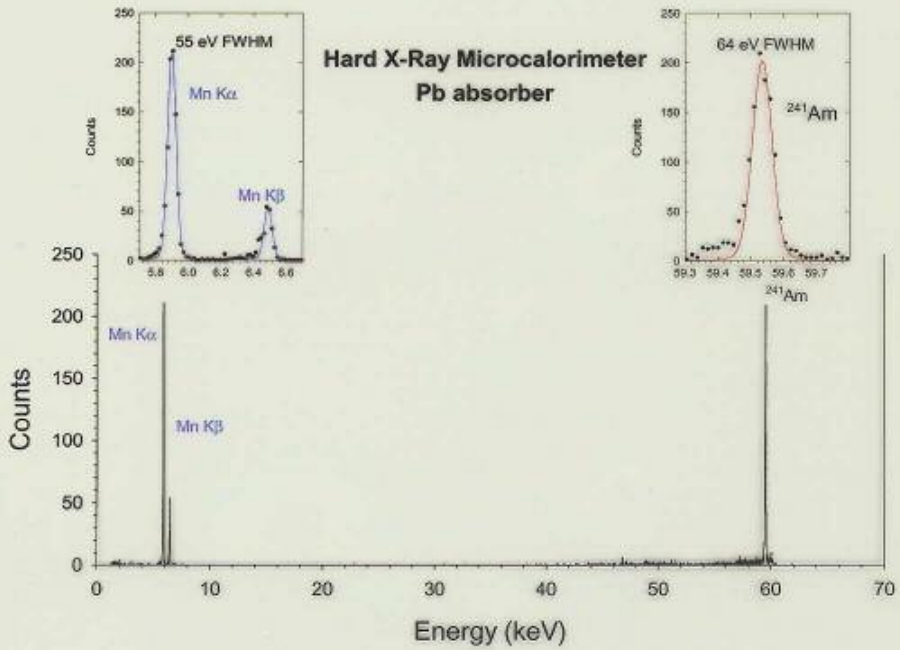
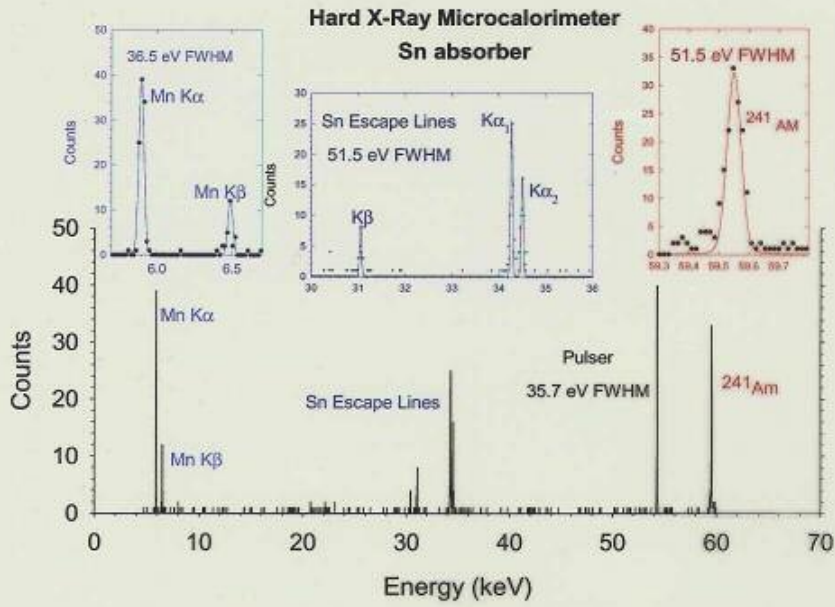


Hydrogenic Gold Measured With A Germanium Detector At GSI ESR

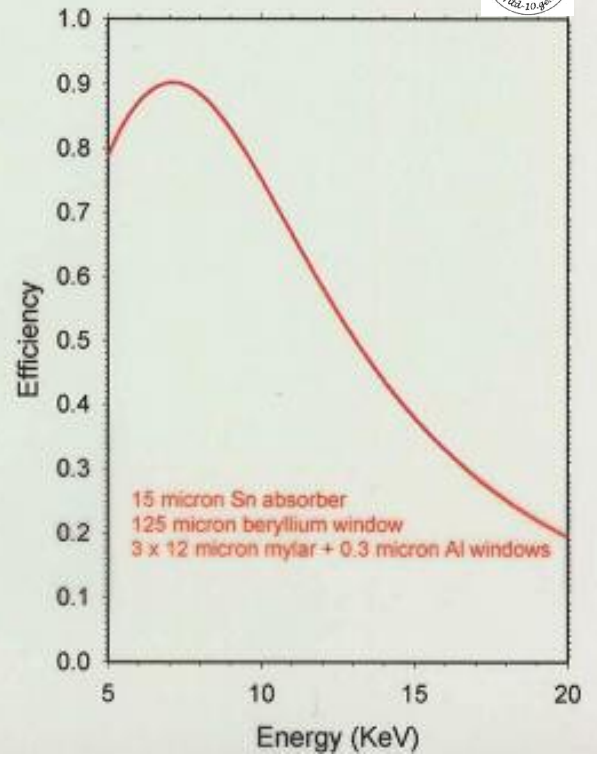
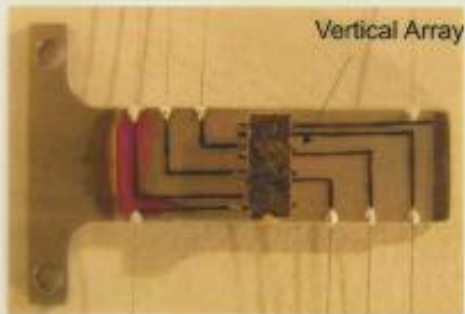
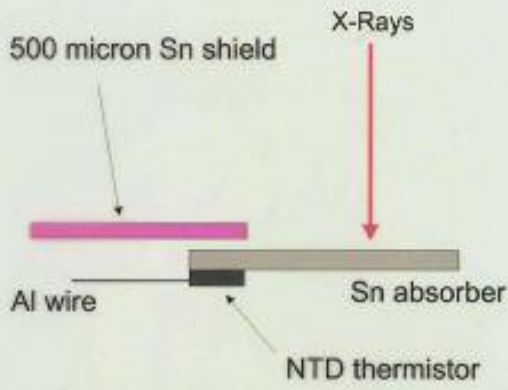


Balmer transitions
 $(N_i = 3, 4, 5, \dots \Rightarrow n_f = 2)$



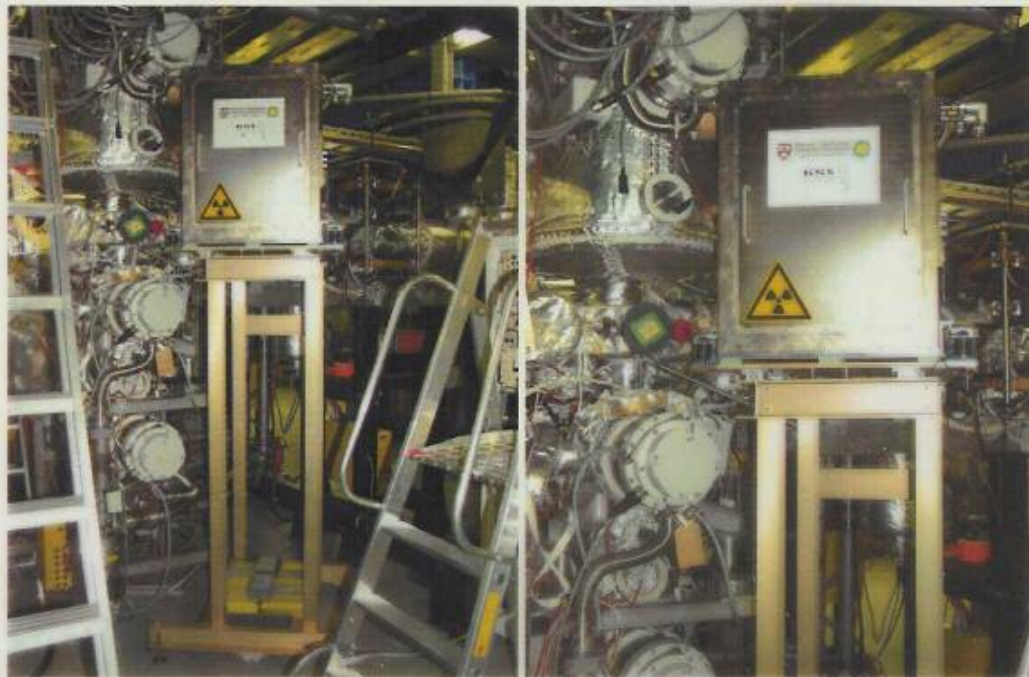
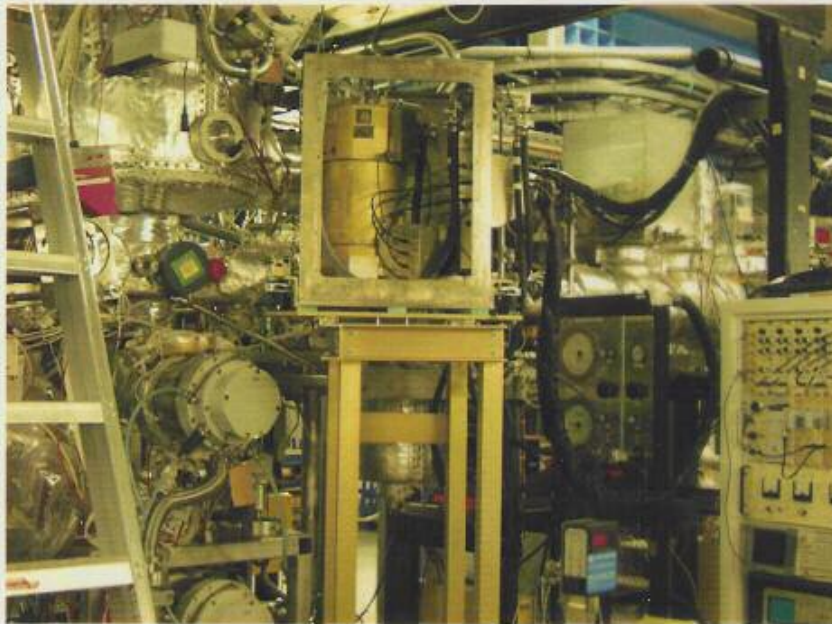


NTD Microcalorimeter Used At GSI ESR



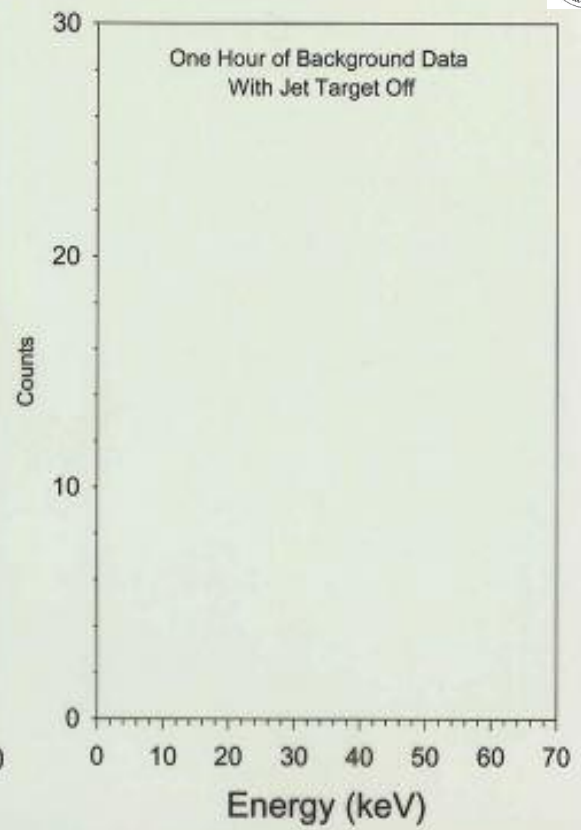
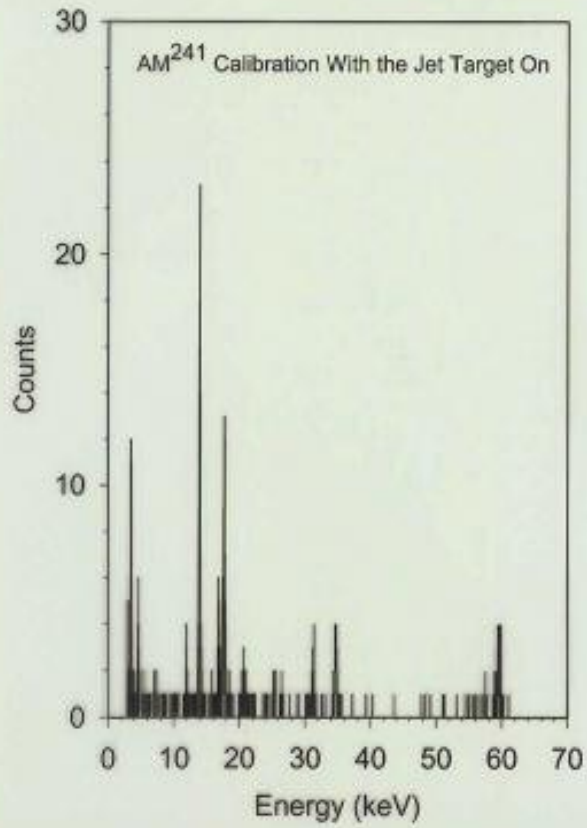


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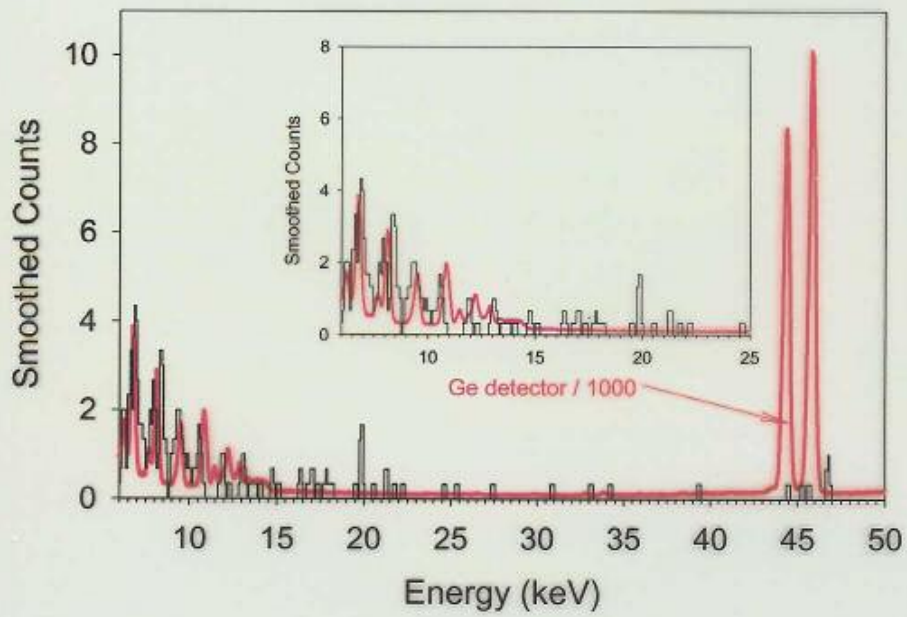
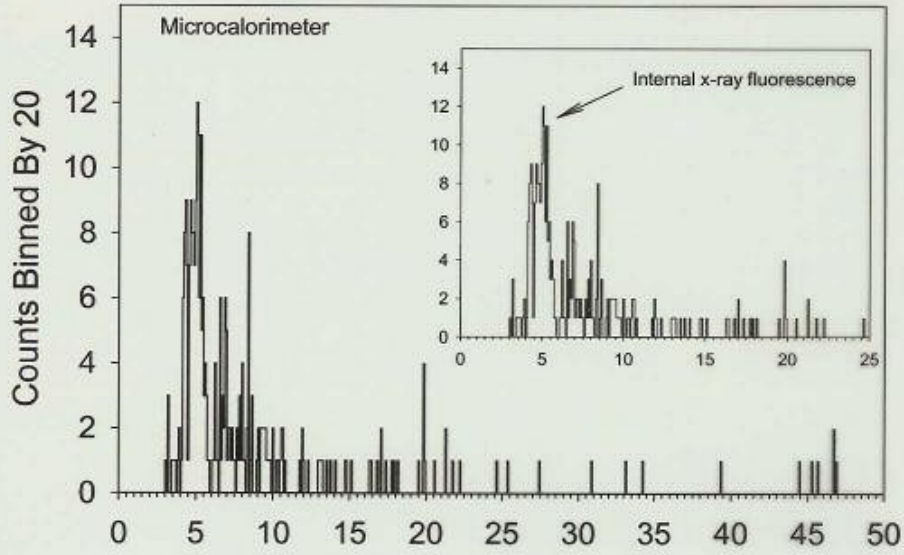




First Operation of SAO Microcalorimeter at the GSI ESR



H-Like Gold at 109 MeV/u ($\beta = 0.44$)



NEXT CAMPAIGN



3 DETECTORS \rightarrow 16 DETECTORS 5.3 x

520 mm \rightarrow 220 mm 5.6 x

145° \rightarrow 90° ; SA CORRECTION:

$$(0.65)^2 \rightarrow (0.896)^2 \quad 1.9x$$

TOTAL INCREASE IN RATE \Rightarrow 56.3 x

$$SA \Rightarrow 5 \times 10^{-8} \text{ sr} \Rightarrow \underline{\underline{2.6 \times 10^{-6} \text{ sr}}}$$