



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

**E. Silver, H. Schnopper, G. Austin, R. Ingram, G. Guth and S. Murray**  
Smithsonian Astrophysical Observatory

**N. Madden, D. Landis, J. Beeman and E. E. Haller**  
Lawrence Berkeley National Laboratory

**Th. Stöhlker**  
Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany

- 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  $\mu$ 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

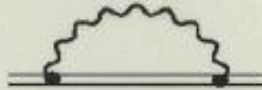
## Bound-State QED: 1s Lamb Shift



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

Self energy

Vacuum polarization



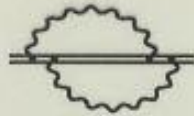
U <sup>92+</sup>	SE	VP	NS	
	355.0 eV	-88.6 eV	198.7 eV	465.1
2.5	65.4	-15.6	37.8	87.6

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

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

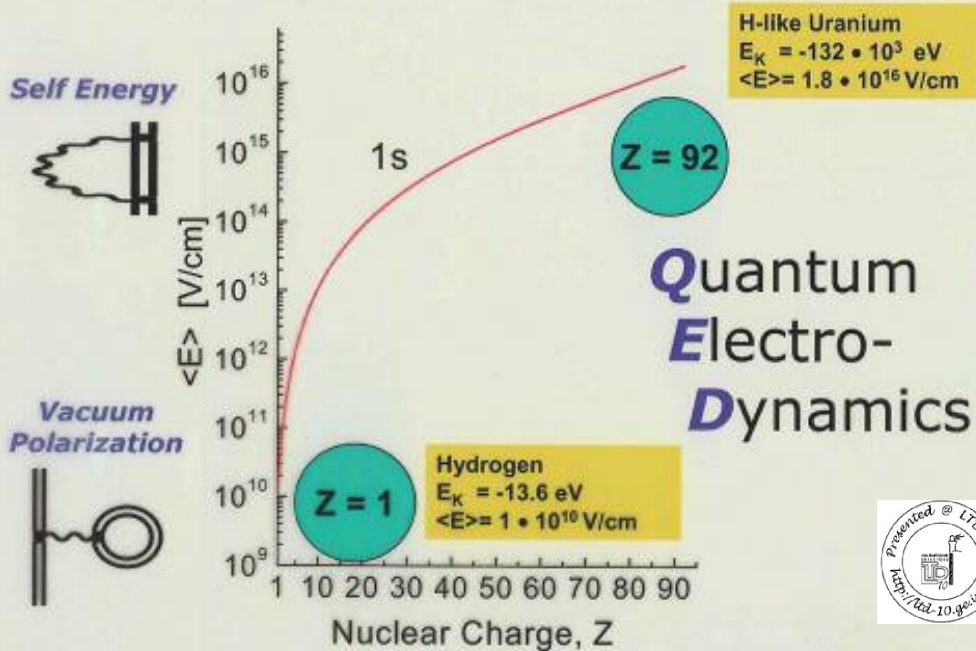
High Z-Regime:  $\alpha Z \approx 1$   
 $F(\alpha Z)$ : series expansion in  $\alpha Z$   
 not appropriate

Goal:



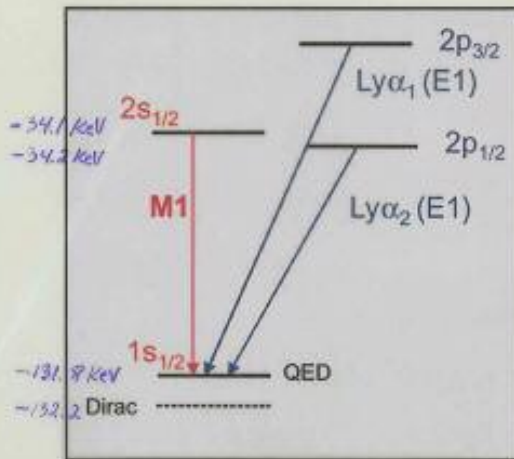
$\pm 1$  eV

## Atomic Physics in Extremely Strong Coulomb Fields



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

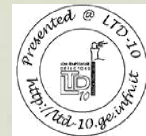
## The Structure of One-Electron Systems



### QED corrections

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

Z: nuclear charge number  
n: principal quantum number

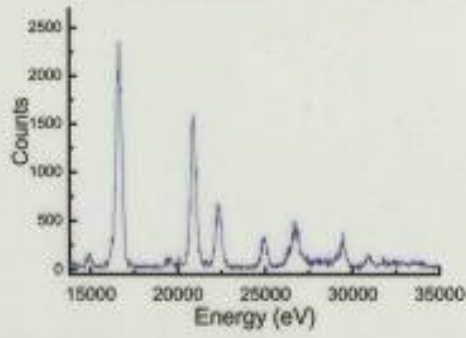
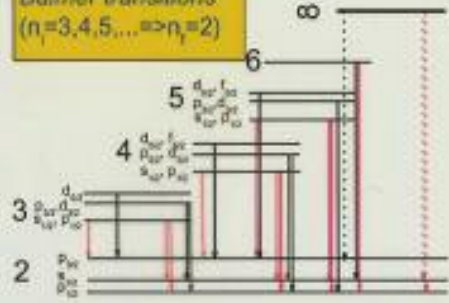


Atomic systems at high-Z

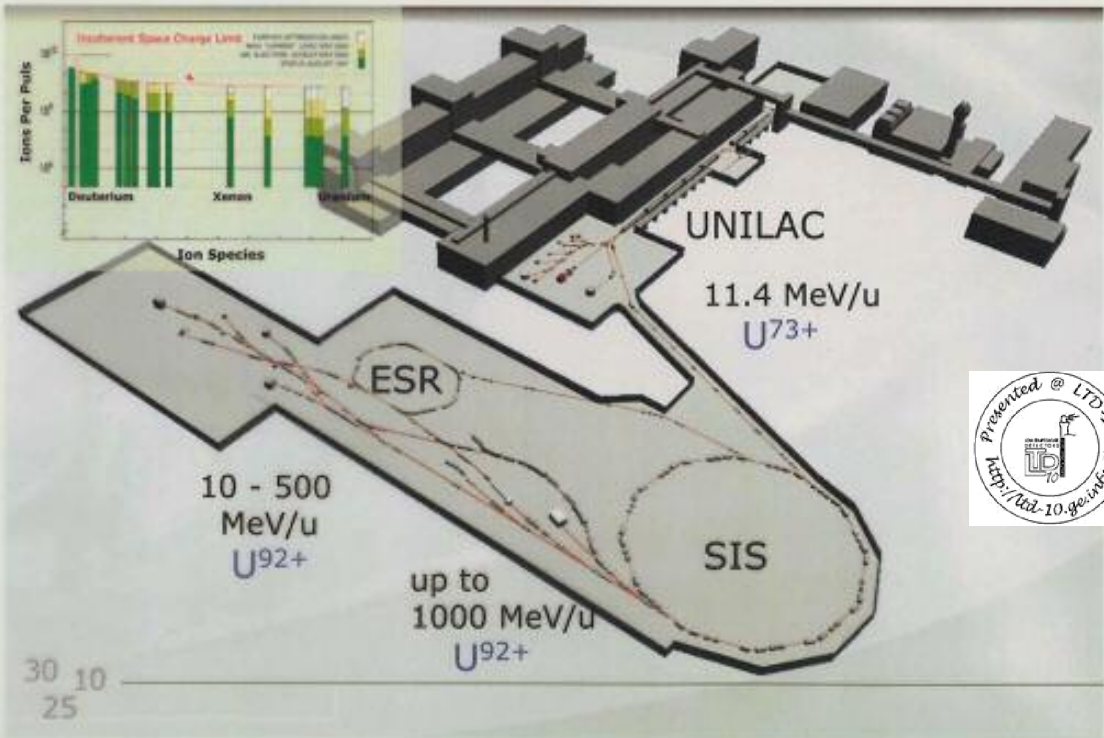
- Large relativistic effects on energy levels and transition rates (e.g. shell and subshell splitting)
- Large QED corrections
- Transition energies close to 100 keV

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

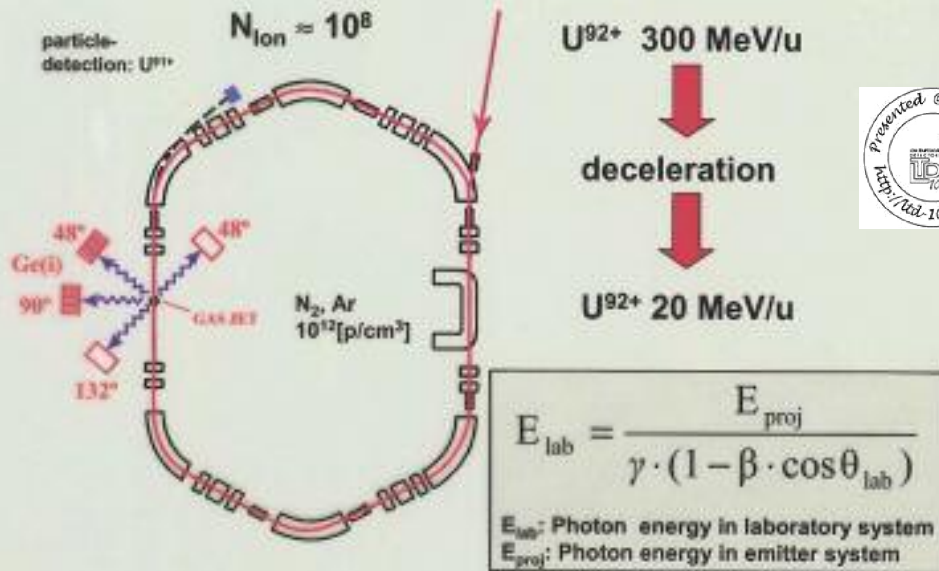
$U^{92+} \Rightarrow N_2$   
 49 MeV/u



# GSI-Accelerator Facility

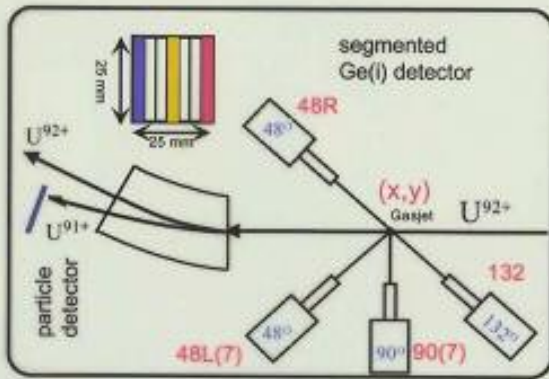


## X-Ray Spectroscopy at the Jet-Target



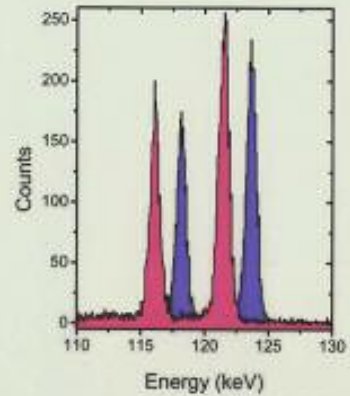


## Lamb Shift-Experiment at the Jet-Target



- 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

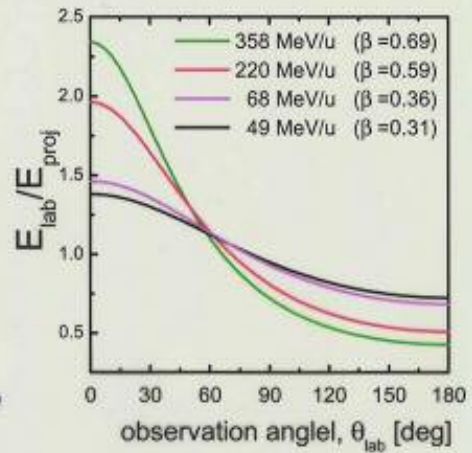


### Relativistic Doppler-Transformation

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

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

**Doppler-Correction:** Strong dependence on velocity and the observation angle  $\theta_{\text{LAB}}$



CURRENT      STATUS



$\Delta E$ ( $\beta$ )	$\Delta E$ (fit)	$\Delta E$ (geometry)	$Ly-\alpha_1$
$\pm 2.6 \text{ eV}$	$\pm 9.7 \text{ eV}$	$\pm 8.5 \text{ eV}$	$102170.7 \pm 13.2$

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

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

$\Delta E$ ( $\beta$ )	$\Delta E$ (fit)	$\Delta E$ (geometry)	
$0.52 \text{ eV}$	$1 \text{ eV}$	$1.5 \text{ eV}$	$\Rightarrow 1.885 \text{ eV}$

BUT: REQUIRES MANY DETECTORS AT SEVERAL LOCATIONS TO RELIEVE  $\Delta E$  (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.

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



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

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

⇓  
≪≪≪

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

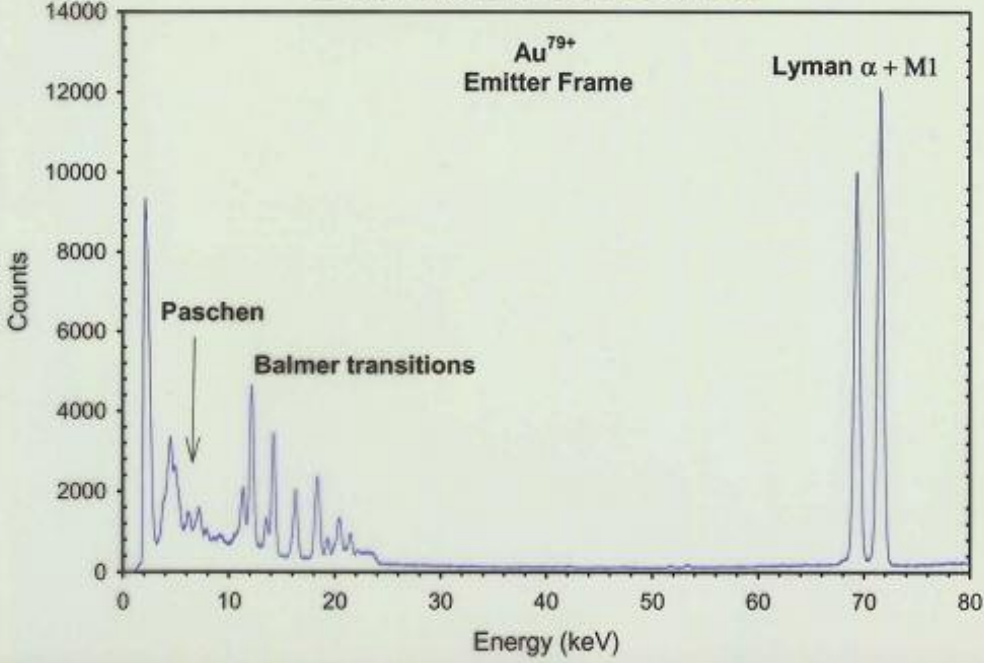
$$\left[ \frac{\Delta E_{2s1/2}}{E_{2s1/2}} \right]^2 = \left[ \frac{\Delta E_{CALLAB}}{E_{CALLAB}} \right]^2 + \left[ \frac{\Delta E_{LAB2s1/2}}{E_{LAB2s1/2}} \right]^2$$

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

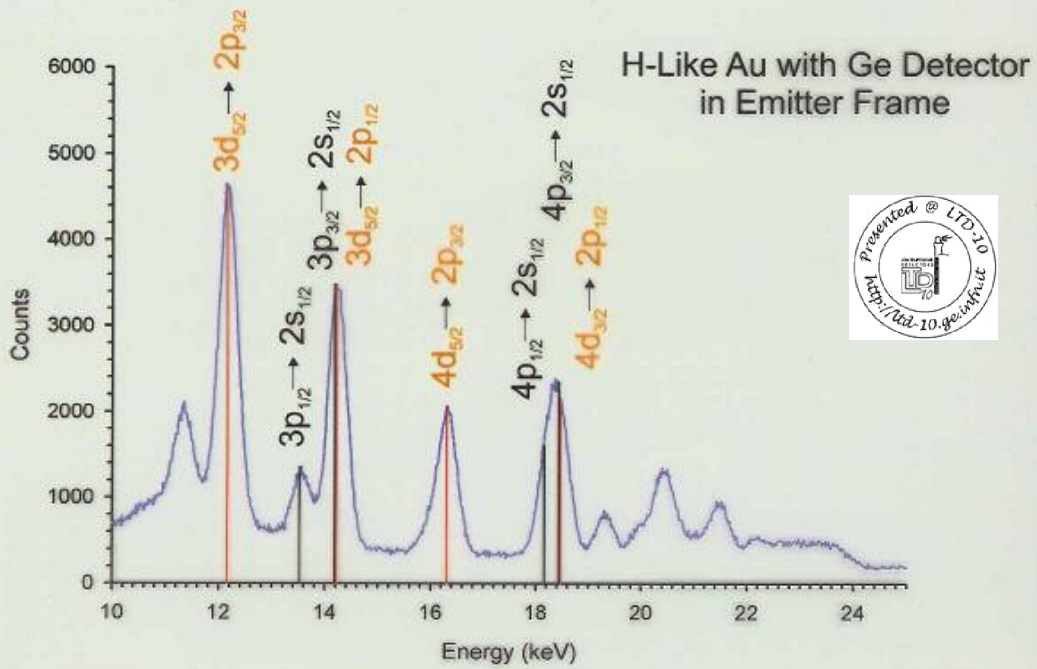
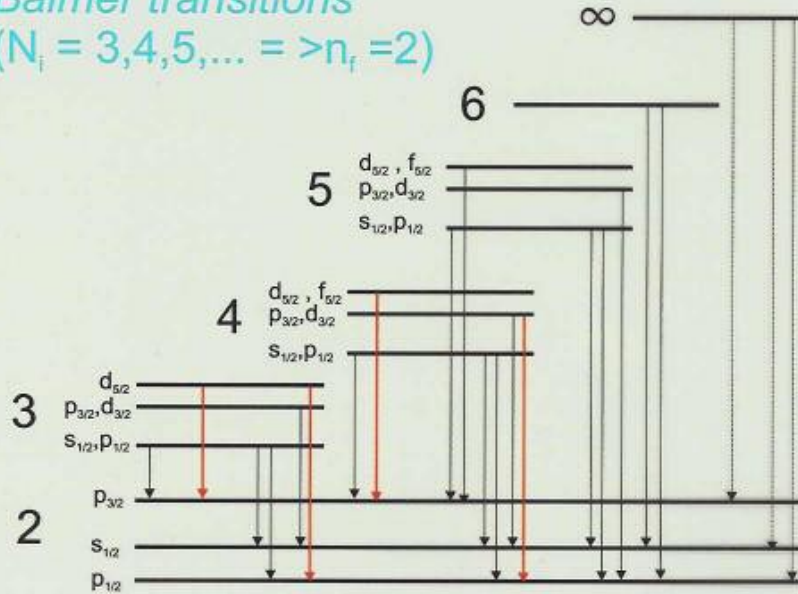
$$\Delta E_{2s1/2} \approx 1.4 \text{ eV!}$$

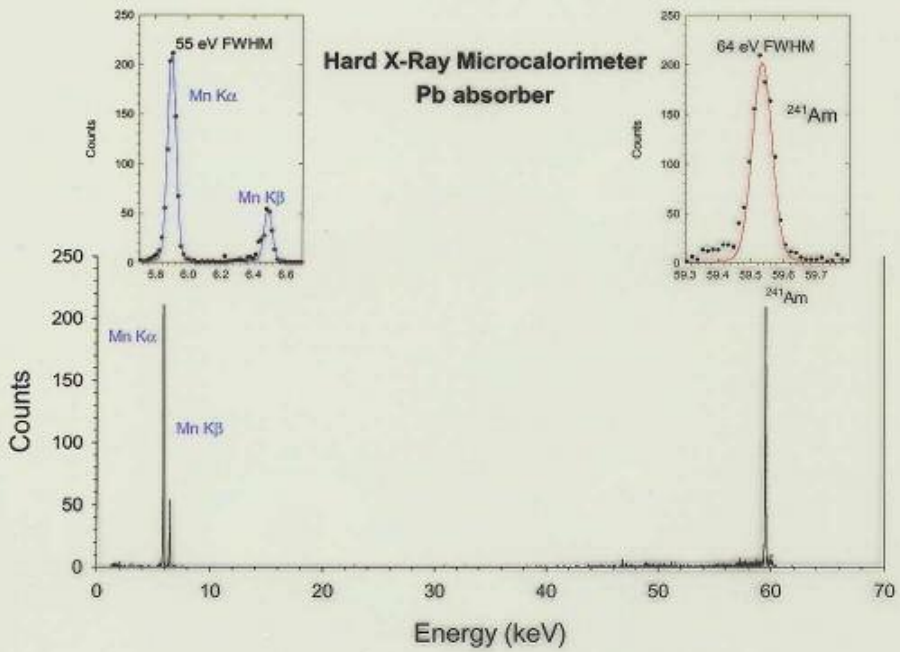
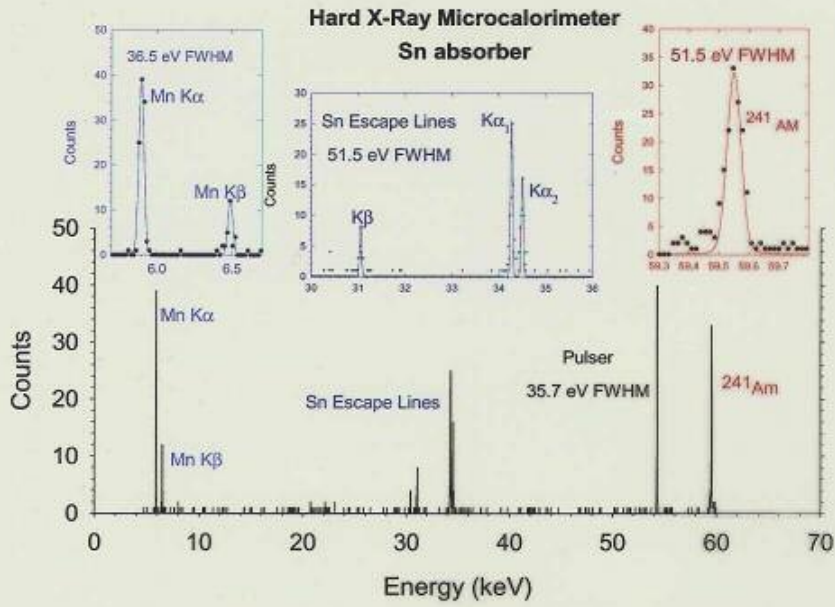


### Hydrogenic Gold Measured With A Germanium Detector At GSI ESR

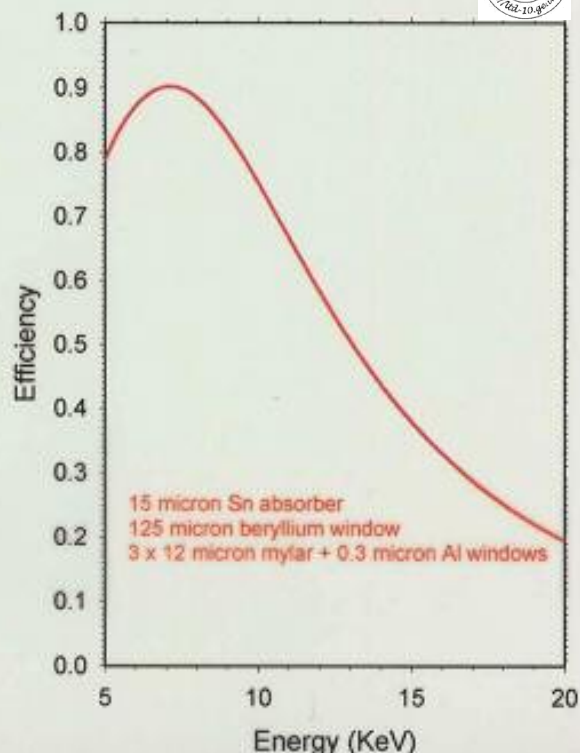
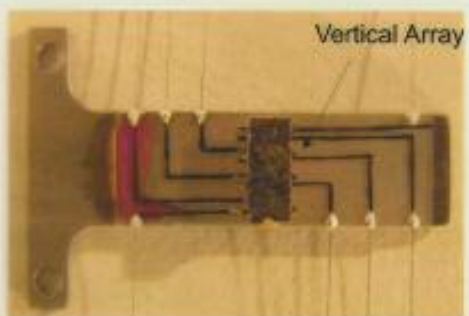
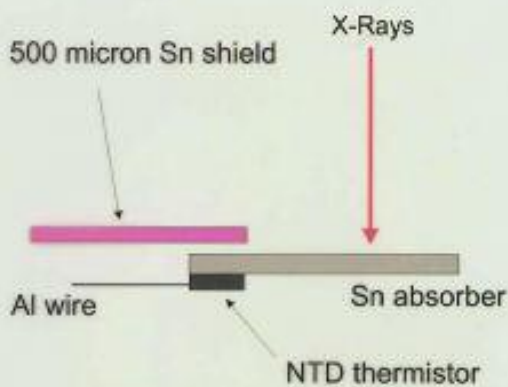


Balmer transitions  
 $(N_i = 3, 4, 5, \dots \Rightarrow n_f = 2)$





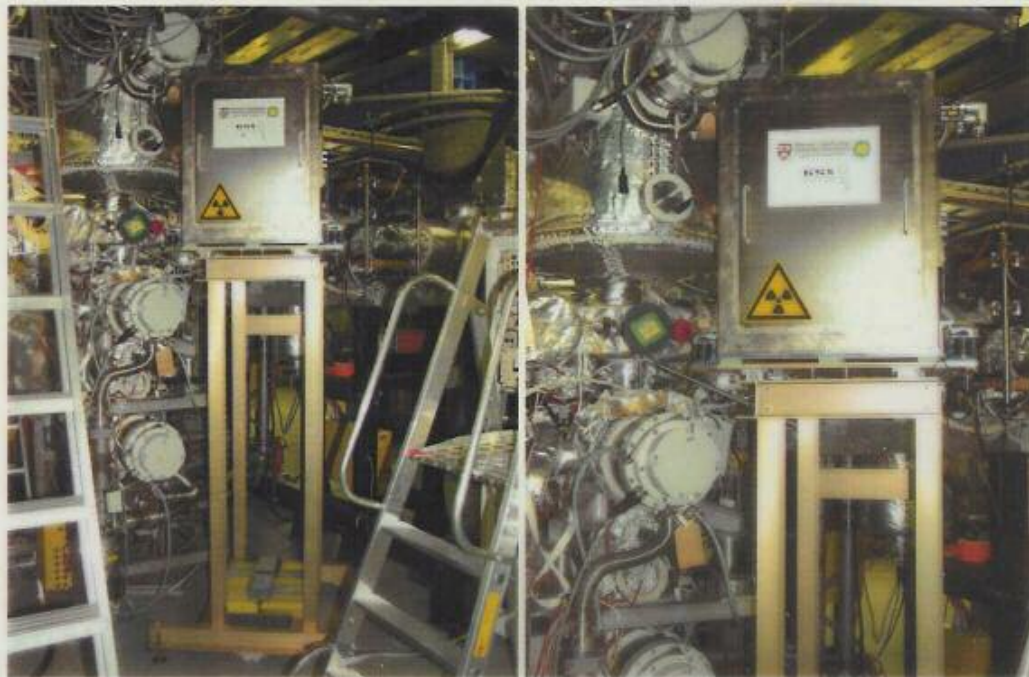
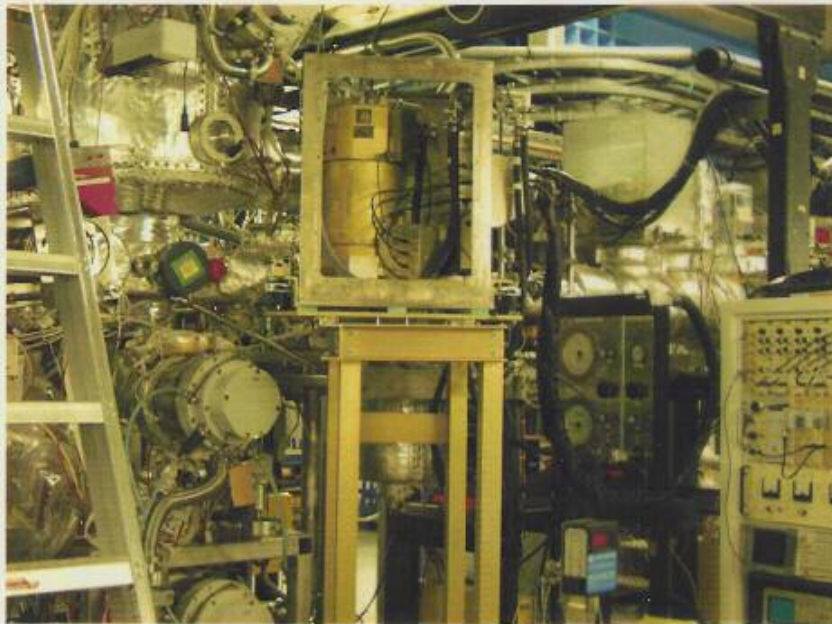
# NTD Microcalorimeter Used At GSI ESR





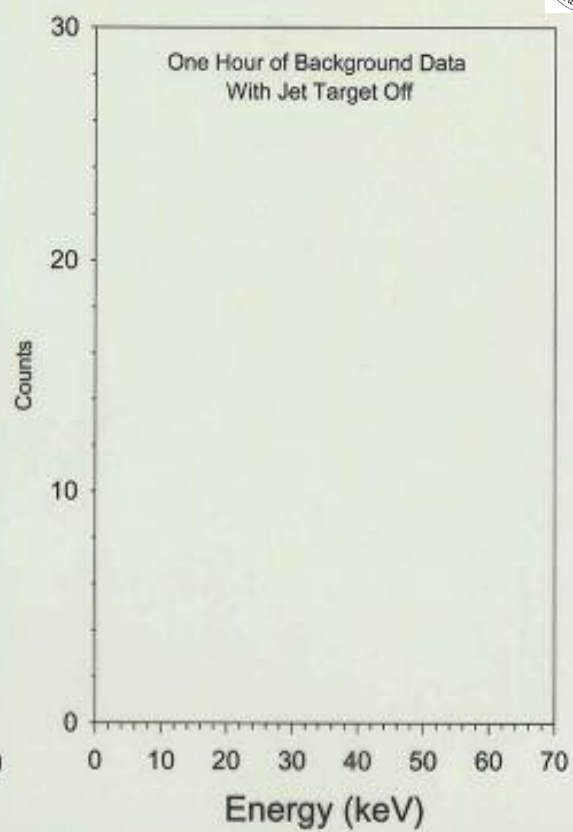
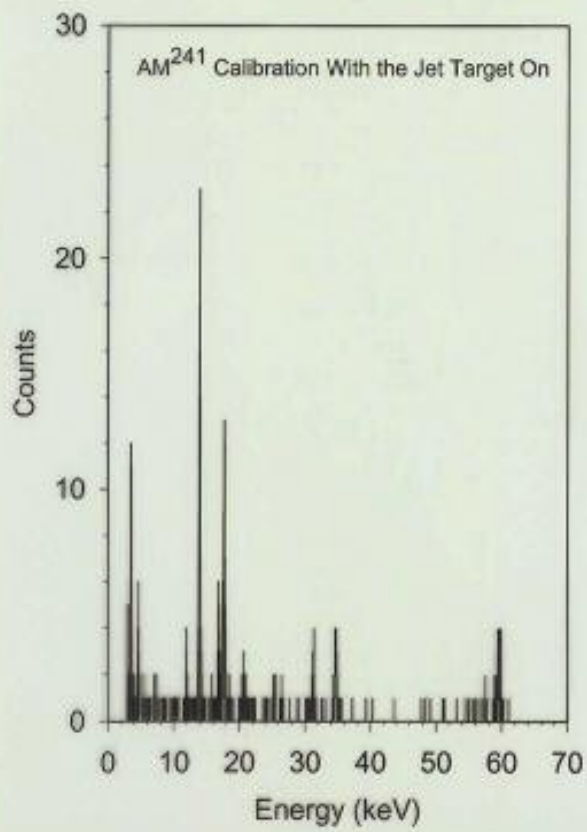


RC 248113  
28.5.97

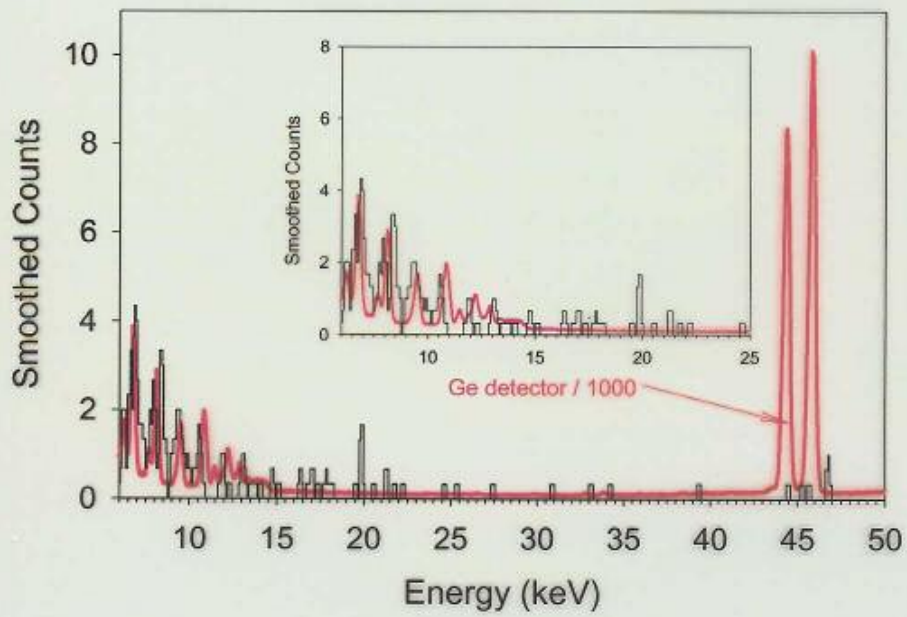
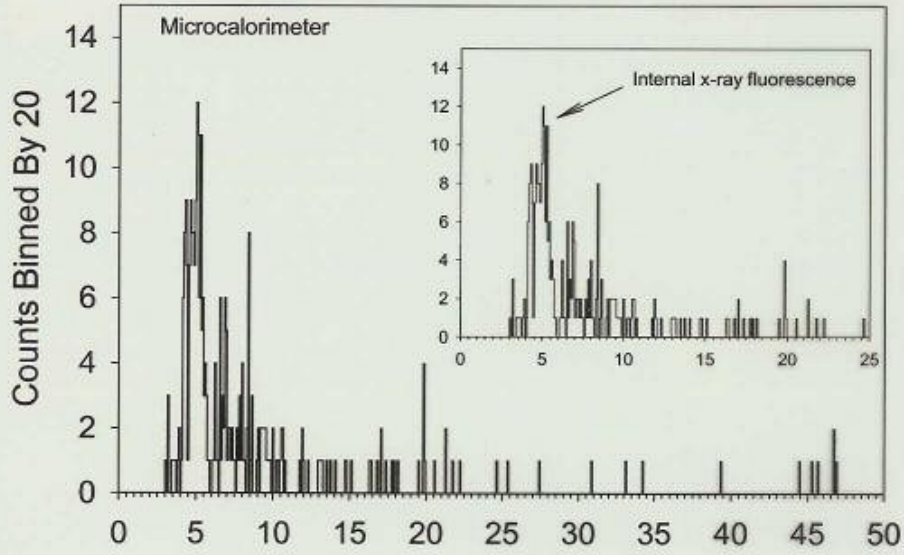




### First Operation of SAO Microcalorimeter at the GSI ESR



### 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

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