# *Zero-degree Auger Projectile Spectrometry in the New Experimental Storage Ring: Challenges and Prospects*

sparc
Stored Particles Atomic Physics Research Collaboration

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**SPARC-Paris, February 12-15, 2007**

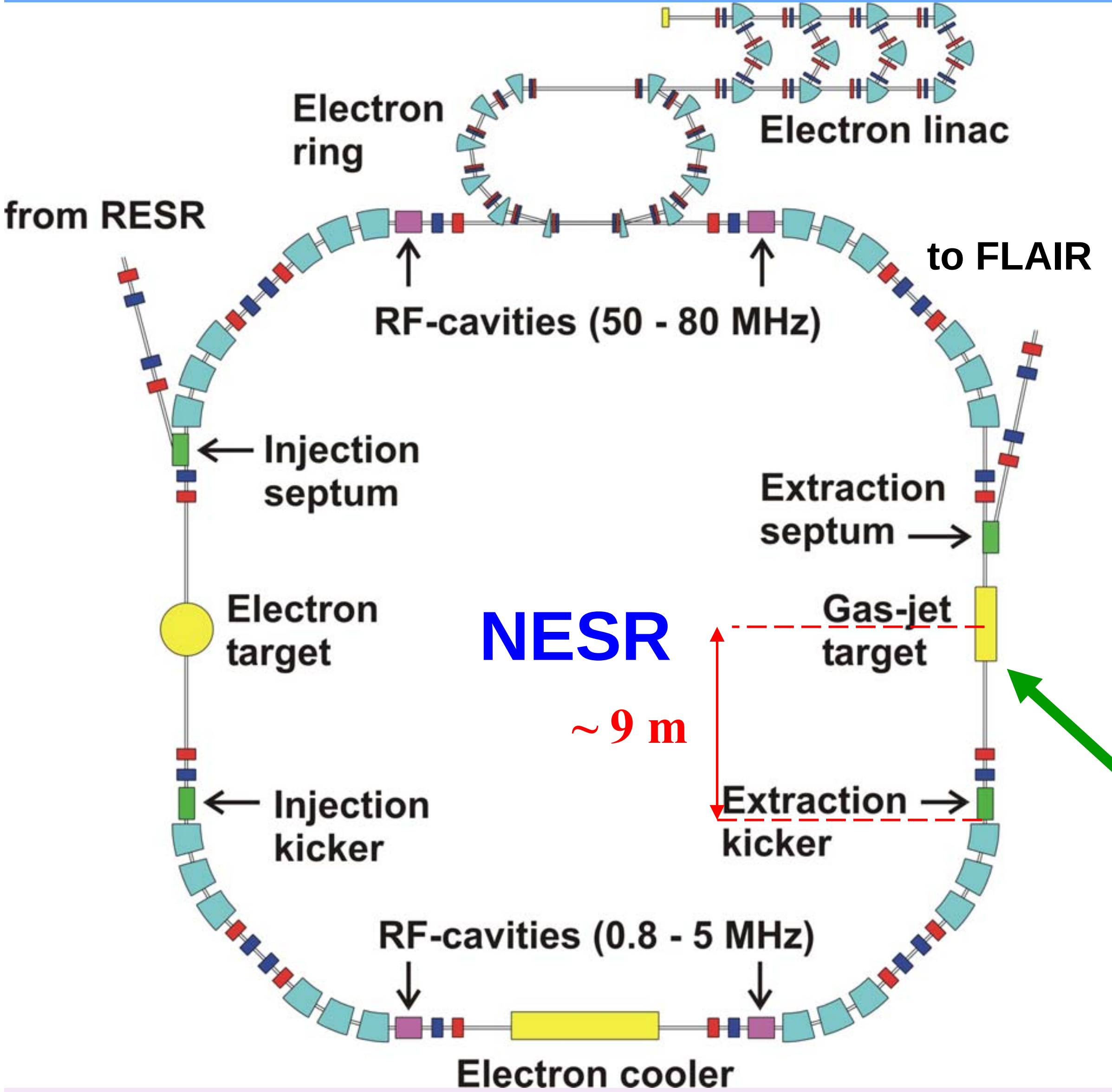
# *Motivation: High resolution electron spectrometry in the NESR*

- **Auger and conversion lines of high-Z few-electron ions produced in collisions with atoms**
  - **No measurements for ions!!! (only neutral targets to date)**
  - **Charge state q-dependence**
  - **high precision Binding Energy determination of atomic levels**

- **Physics of strong fields:**
  - **Collision dynamics, state-selective cross section determination**
  - **Atomic Structure of high-Z few-electron ions (relativistic effects)**

This will require **electron observation in the beam direction**
known as **Zero-degree Auger Projectile Spectroscopy (ZAPS)**
**Of relativistic electrons with lab energies up to about 0.5 MeV**
**Combined with a spectrometer resolution of $\Delta p/p \leq 10^{-4}$**
**access to the natural line widths $\Gamma$ should also be possible**

# *The NESR: the ultimate fantasy for atomic collisions physics?*



## *NESR*

- Circumference: **221.11 m**
- Vacuum: **$\leq 10^{-11}$ mbar**
- Ion energies: **4 -740 MeV/u**
- Ion beam species: **H – U**
- Radioactive beams: **yes**
- Ion charge states: **$A/q \leq 2.7$**
- Number of ions: **$\sim 10^{8}$**
- Beam particle current: **$\sim 10^{13}$ #/s**
- Emittance: **0.1 – 1 mm-mrad**
- Momentum $\Delta p/p$ (cooled): **$\leq 10^{-4}$**

**Gas-jet target** **(extrapolation from ESR)**

- Areal Density: **$10^{12}$-$10^{13}$ #/cm$^2$**
- Length: **1.4 - 4 mm**
- Background pressure: **$10^{-9}$ mbar**

## *Two different electron spectroscopies*

### Zero-degree Auger Projectile e- Spectroscopy (ZAPS)

- used successfully since the 1980's primarily at Tandems to measure Auger electrons from projectiles excited via capture, excitation or ionization and combinations
- emitter: low-Z HCI ions in the 0.1- 3 MeV/u collision regime
- electrostatic spectrometers:

  lab electron energies $\varepsilon$ = 0-6 keV and $R_\varepsilon = \Delta\varepsilon/\varepsilon \sim 0.1\%$

$$\frac{\Delta p}{p} = \frac{\gamma}{\gamma+1}\frac{\Delta\varepsilon}{\varepsilon}$$

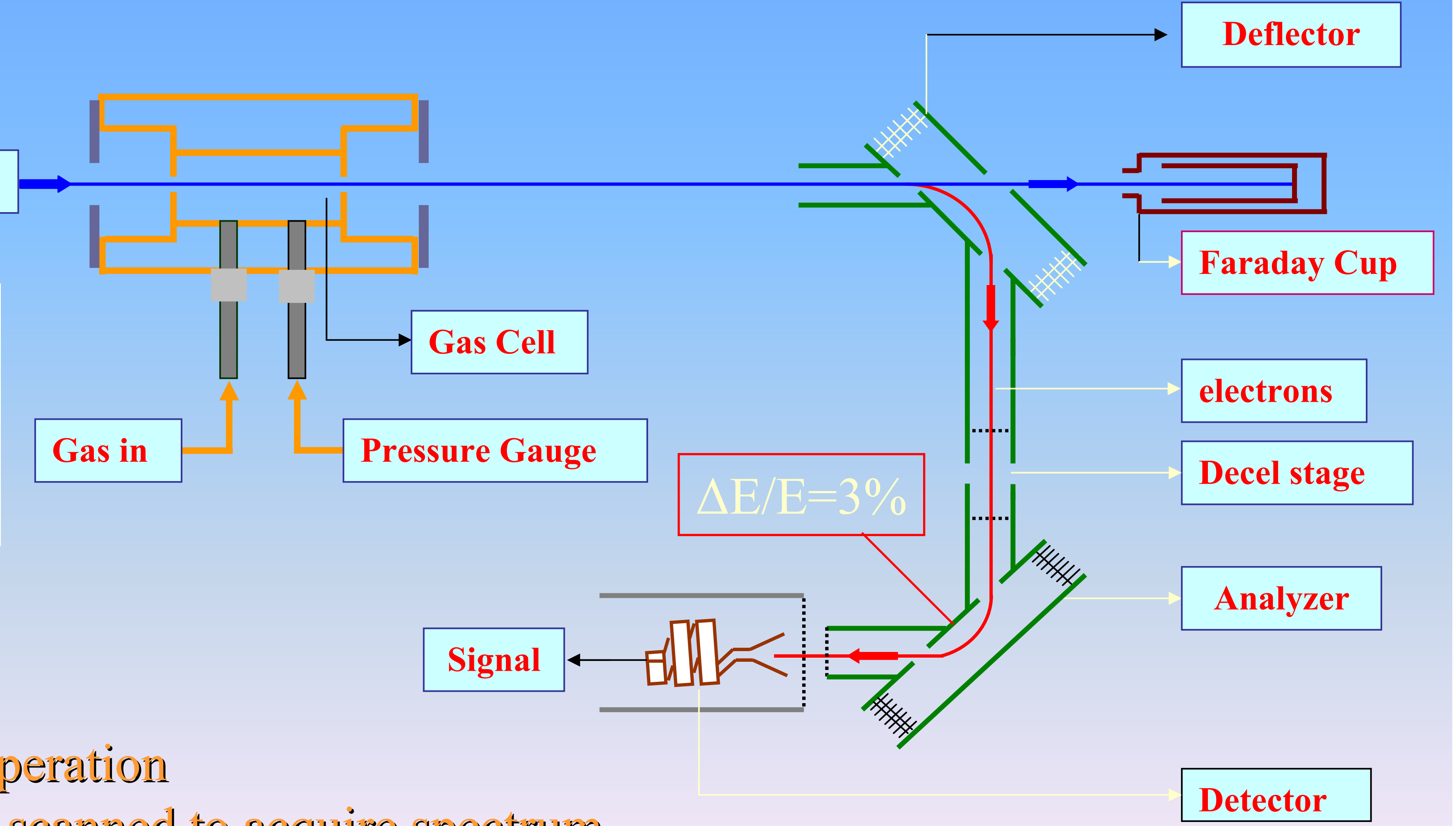
### β-ray spectroscopy

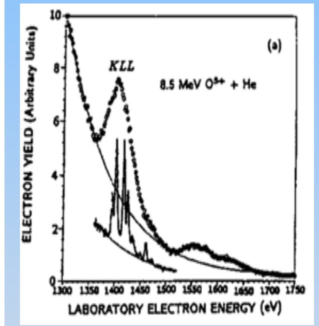
- used successfully in the 1950-1970's at high flux reactors or with radioactive sources to measure conversion and Auger electrons
- emitter: stationary high-Z neutral activated target atoms
- large radius (e.g. 50cm Uppsala, 100cm Chalk River, 50cm BILL) double focusing magnetic spectrometers:

  lab electron energies $\varepsilon \leq 3$ MeV and $R_p = \Delta p/p \sim 0.01\text{- }0.05\%$

The SPARC electron spectroscopy initiative
is expected to combine both expertise

# *Traditional $0^0$ $e^-$ spectrometer*
# *two-stage $45^0$ parallel plate with intermediate deceleration stage*



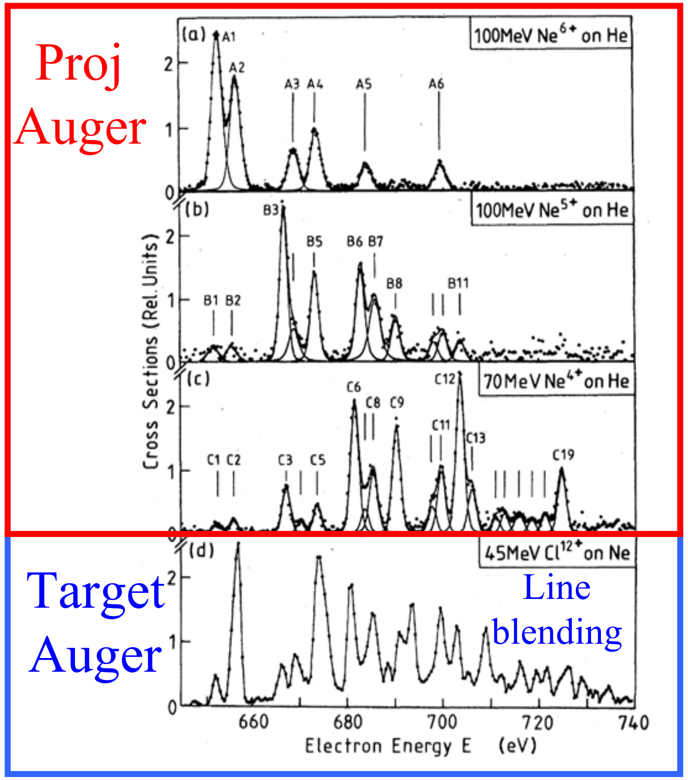


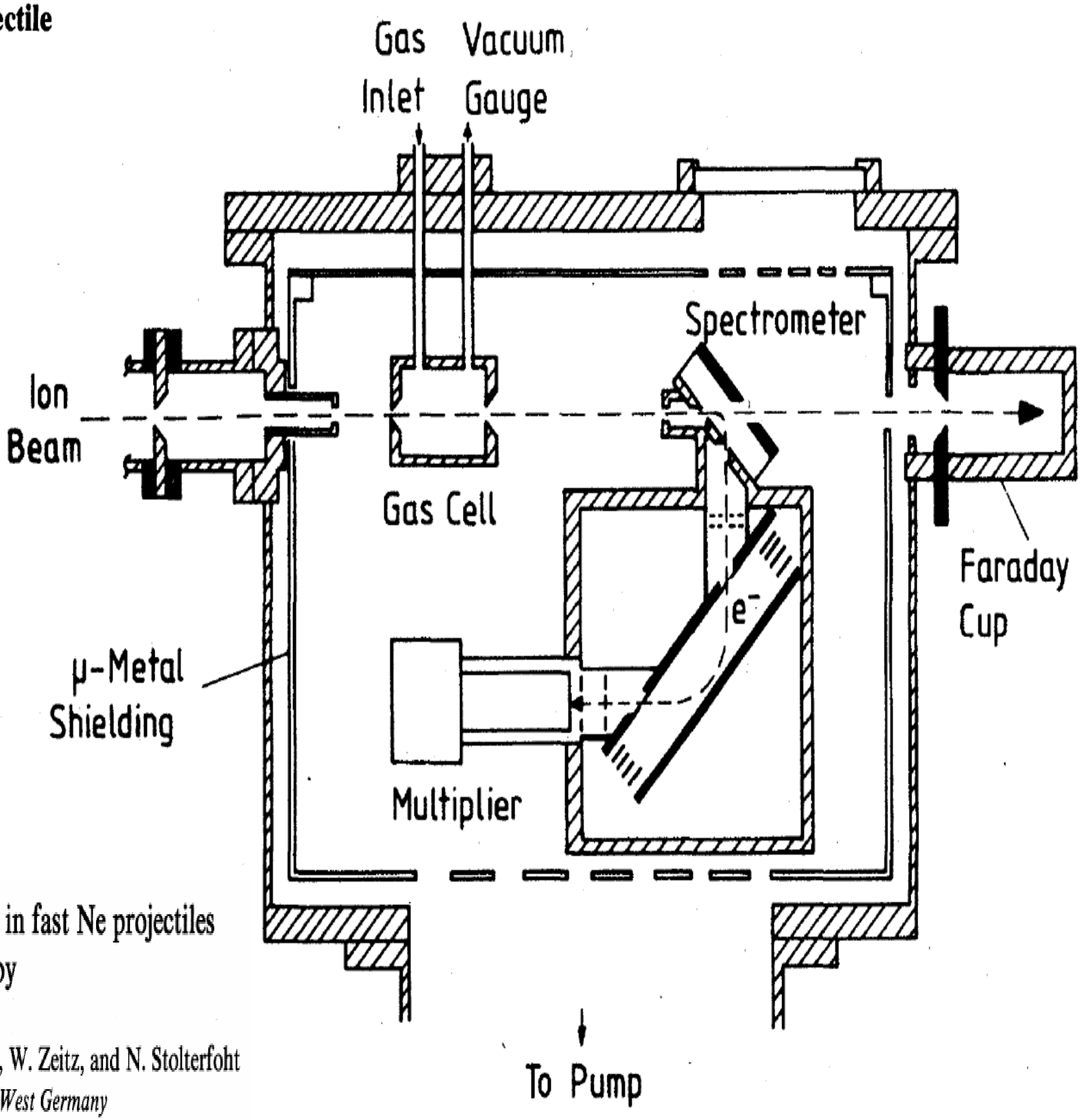
- Robust operation
- Voltages scanned to acquire spectrum
- High resolution ~0.1% uses deceleration stage with fixed pass energy

## Selective production of Auger electrons from fast projectile ions studied by zero-degree Auger spectroscopy

JPB**16** (1983) 3965

A Itoh, T Schneider, G Schiwietz, Z Roller, H Platten, G Nolte,
D Schneider and N Stolterfoht





## Selective production of Li-, Be-, and B-like *K* vacancy states in fast Ne projectiles studied by zero-degree Auger spectroscopy

PRA**31** (1985) 684

A. Itoh,* D. Schneider, T. Schneider, T. J. M. Zouros, G. Nolte, G. Schiwietz, W. Zeitz, and N. Stolterfoht
*Hahn-Meitner-Institut für Kernforschung Berlin, D-1000 Berlin 39, West Germany*

# *Advantages of $0^0$ Auger projectile spectrometry (ZAPS)*

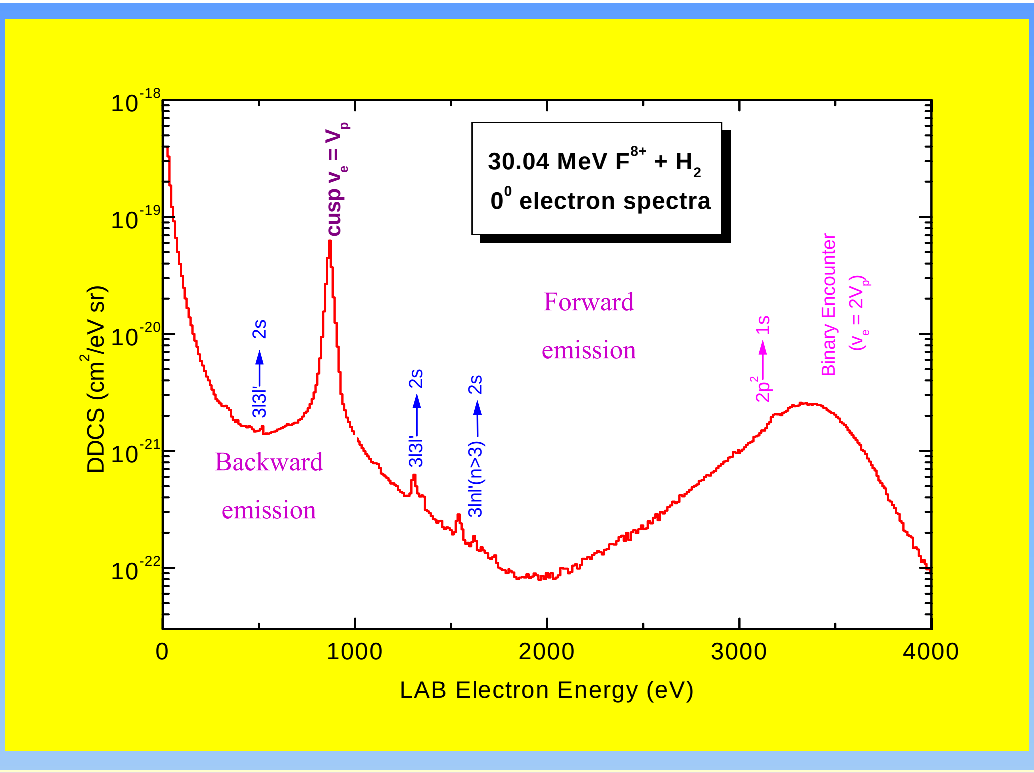
- Only a **single** pre-selected Projectile charge state involved
  - considerable simplification of lines in spectrum
  - no line blending (mixture of different charge states)
  - "ion surgery" collisions with low-Z few-electron targets (He, $H_2$)
  - very successful in isoelectronic studies

- **High resolution** technique with relatively high overall efficiency
  - $\Delta E/E \sim 0.1\%$, $\Delta\theta \sim 1^0$, $\Delta\Omega \sim 10^{-4}$ sr
  - Resolution good enough to resolve most K-Auger lines
  - Much more efficient than comparable resolution crystal X-ray spectrometers (for low-Z ions high Auger yield, no window absorption, large $\Delta\Omega$)

- Determination of **absolute** double differential cross sections
  - collisional energy dependence of well defined transition

- Deceleration stage provides useful variable resolution
  - low resolution or high resolution can be used as needed

Question: How can ZAPS be done effectively in the NESR?

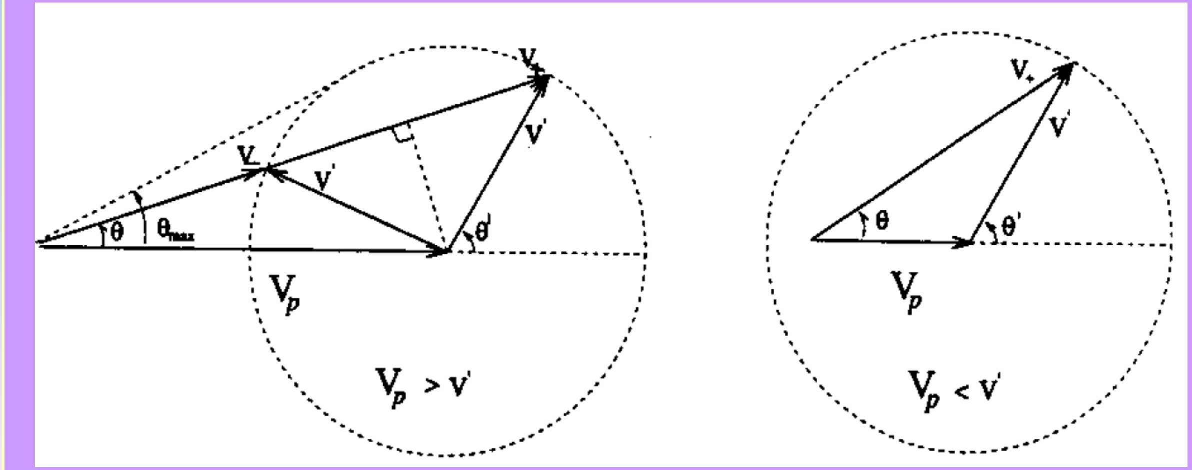


# Important features of
# $0^0$ Electron emission spectrum

1. Low energy Target e- continuum
2. Cusp e- at $v = V_p$
3. High energy Projectile e- continuum
4. Broad Binary Encounter e- Peak
5. Kinematically shifted
   Auger Projectile e- lines

## Emission from moving source

## Kinematics: Laboratory energy Shifting and Doubling



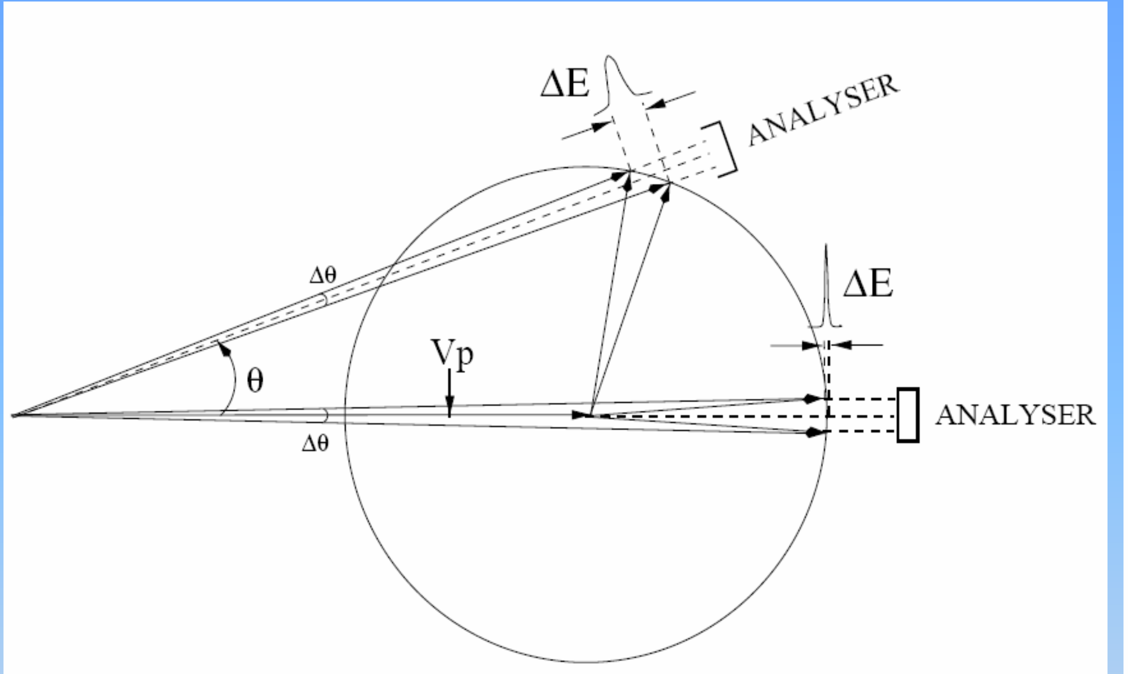
Projectile electrons are shifted energetically to higher and lower laboratory energies depending on whether they are emitted in the forward (+) or backward (-) direction.

$$\text{For } \theta = 0^0 :$$

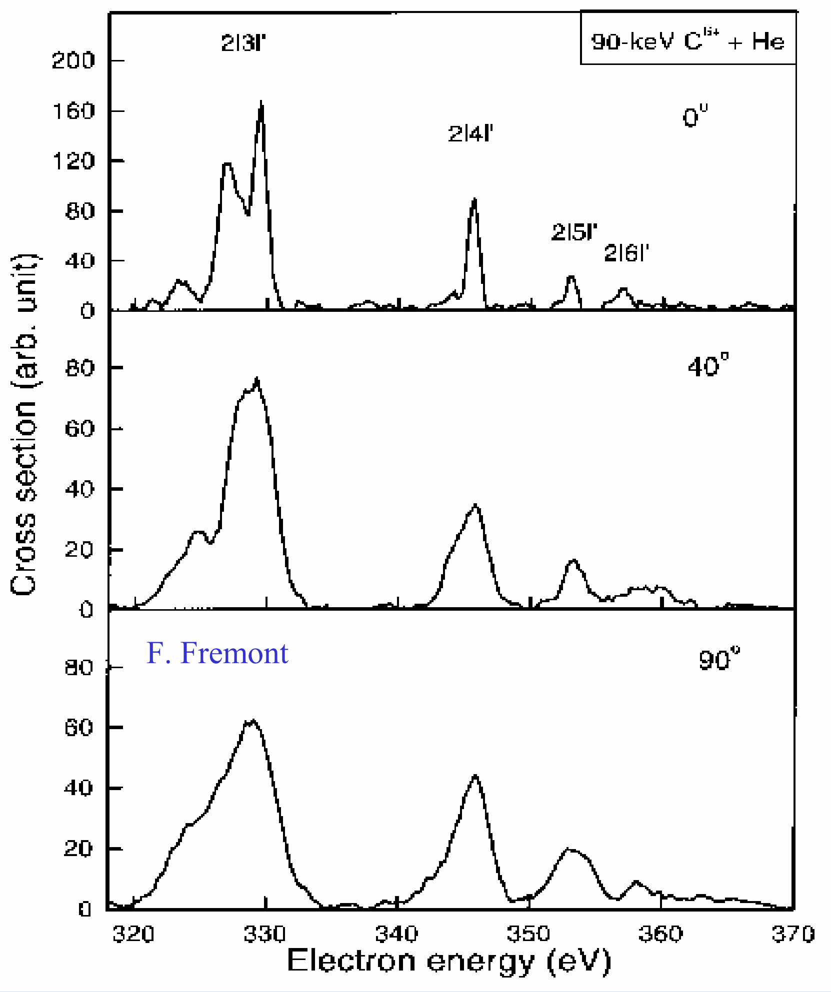
$$v_\pm = V_p \pm v' \quad \text{(classical)}$$

$$\beta_\pm = \frac{\beta_p \pm \beta'}{1 + \beta_p \beta'} \quad \text{(relativistic)}$$

# *Kinematics:*
# *Instrumental Line Broadening I*



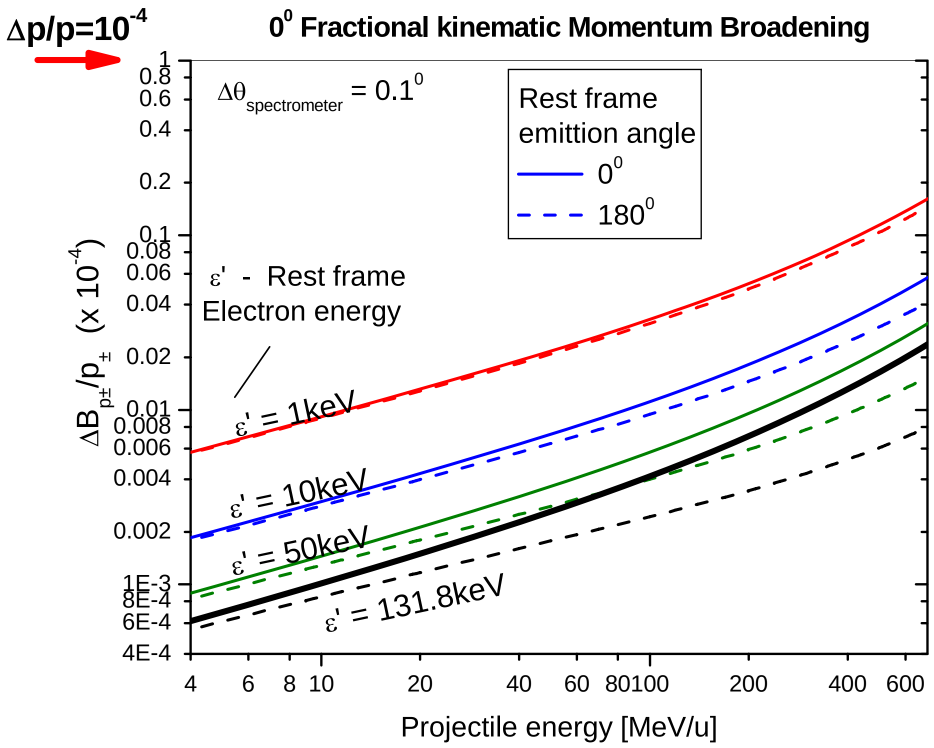
$$\Delta E_\theta = \begin{cases} |\,\varepsilon(\theta+\Delta\theta/2)-\varepsilon(\theta-\Delta\theta/2)\,| & \text{for } \theta > 0^0 \\ |\,\varepsilon(\Delta\theta/2)-\varepsilon(0^0)\,| & \text{for } \theta = 0^0 \end{cases}$$



F. Fremont

For $\theta>0^0$ $\Delta E_\theta \sim \Delta\theta$, while for $\theta=0^0$ $\Delta E_\theta \sim \Delta\theta^2$ thus substantial gains in resolution can be attained by going to $\theta=0^0$ observation angle

# *Kinematics:*
# *Instrumental Line Broadening II*



At $0^0$ the kinematic broadening
- grows with projectile velocity $V_p$
- grows approximately as $\Delta\theta^2$
- diminishes with Auger energy ε′

2nd order fractional momentum broadening :

$$\frac{\Delta B_{p\pm}}{p_{\pm}} = \frac{\Delta\theta^2}{8}\frac{V_p}{v'} \quad \text{(classical)}$$

$$\frac{\Delta B_{p\pm}}{p_{\pm}} = \frac{\Delta\theta^2}{8}\frac{\beta_p}{\beta'}\frac{|1\pm\beta_p\beta'|}{(1-\beta_p^2)} \quad \text{(relativistic)}$$

| | Range in spectrometer acceptance angle Δθ | | | |
|---|---|---|---|---|
| $\Delta B_{p\pm}/p_{\pm} = 10^{-4}$ | ε′=1keV | | ε′=131keV | |
| | 4 MeV/u | 740 MeV/u | 4 MeV/u | 740 MeV/u |
| Δθ (dgrs)<br>ΔΩ ($10^{-4}$ sr) | **1.35**<br>5.55 | **0.25**<br>0.19 | **4.15**<br>52.5 | **0.65**<br>1.29 |

# *Comparison of Tandem - NESR*
# *Typical Beam and Target operational parameters*

| | Target density n ($10^{13}$ #/cm$^2$) | Target Length L (cm) | n L ($10^{13}$#/cm$^2$) | Charge State q | Beam Current $I_p=I_q/qe$ ($10^{10}$#/s) | $I_p$ n L ($10^{25}$ #/cm$^2$s) |
|---|---|---|---|---|---|---|
| **Tandem** | **160**<br>**(50mTorr)** | **5** | **800** | **1-10** | **0.6-60** | **4.8-480** |
| **NESR** | **16***<br>**(5mTorr)** | **0.1-0.4** | **1.6 - 6.4** | **$A/q \leq 2.7$**<br>**$^{238}U^{89-92+}$** | **1250 - 11000**** | **20 -700** |

*projected from experience with ESR jet target

** Assuming a constant $10^8$ particles in the NESR over the 4-740 MeV/u energy range and for q=92

**NESR advantages (+) vs disadvantages (-)**

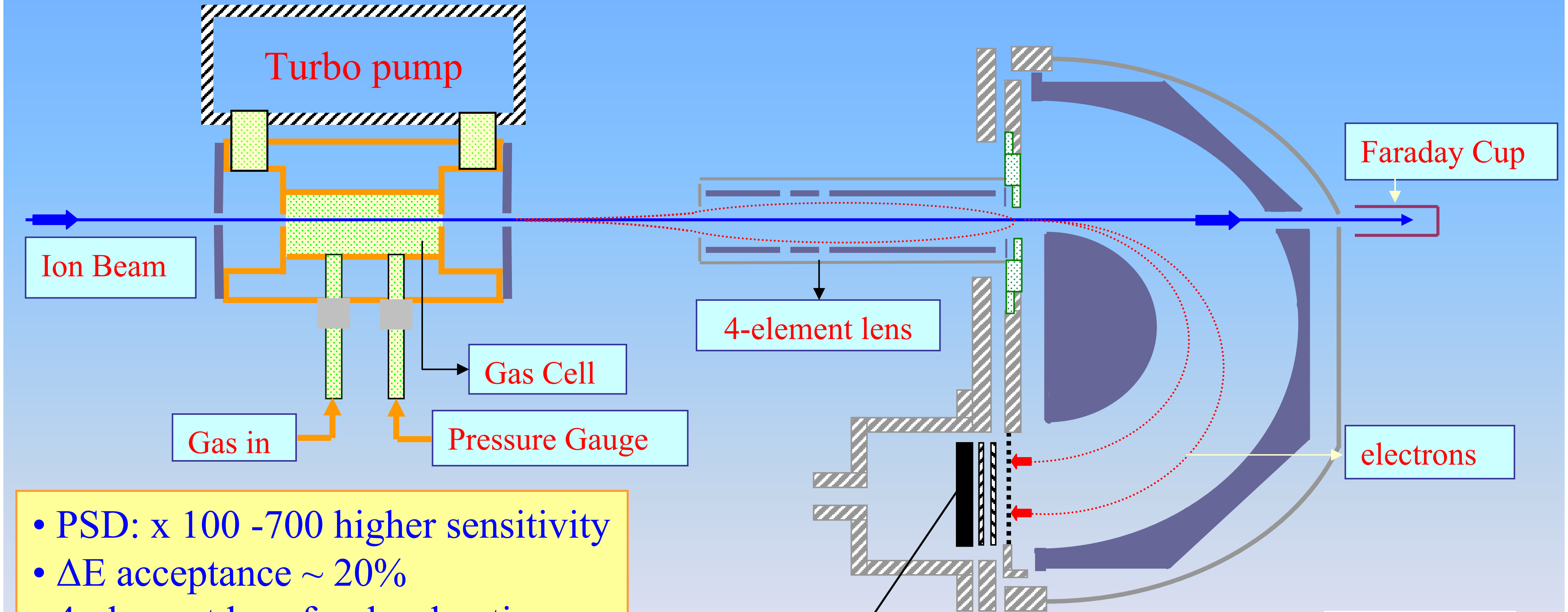
(+) High particle current, increases with collision energy

(-) jet target: smaller density and effective length (but note Grisenti talk on liquid targets)

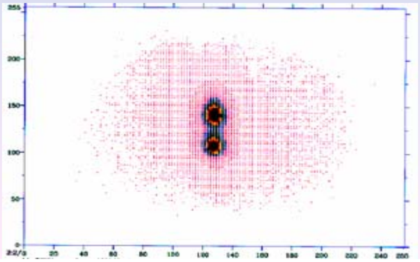
Question: Possibility of cell target? Would increase rate by at least x500!

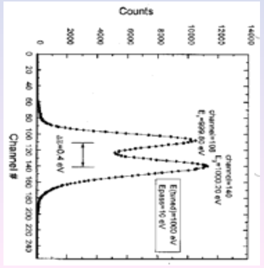
*The Univ. of Crete*
*ZAPS spectrometer*
*At Kansas State U.*

# Technical developments:
# 2-D PSD with 4-element lens + doubly differentially pumped gas cell



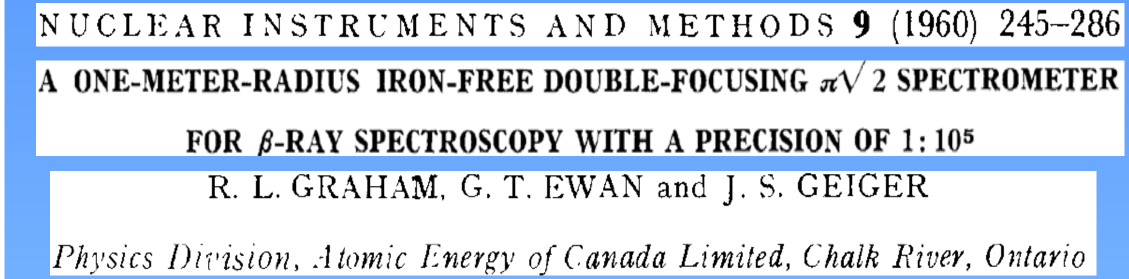
PSD-RAE
X-Position
Y- Position
Timing





- PSD: x 100 -700 higher sensitivity
- ΔE acceptance ~ 20%
- 4-element lens for deceleration and focusing
- Resolution ~ 0.05-0.1%
- $\Delta\Omega = 1.8 \times 10^{-4}$ sr ($\Delta\theta = 0.868^0$)

# *β – ray spectroscopy*

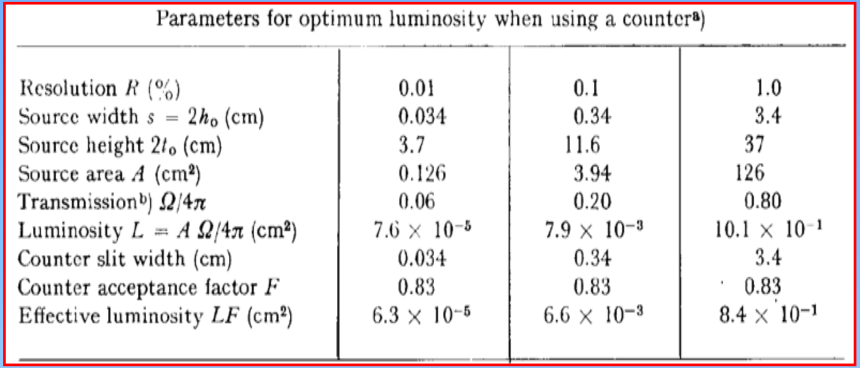


NUCLEAR INSTRUMENTS AND METHODS **9** (1960) 245–286

**A ONE-METER-RADIUS IRON-FREE DOUBLE-FOCUSING $\pi\sqrt{2}$ SPECTROMETER FOR β-RAY SPECTROSCOPY WITH A PRECISION OF 1 : $10^5$**

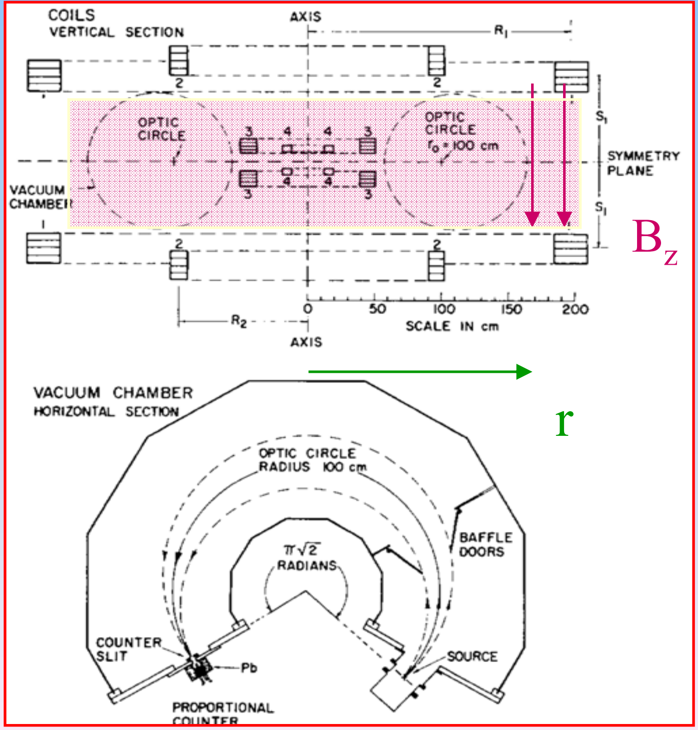
R. L. GRAHAM, G. T. EWAN and J. S. GEIGER

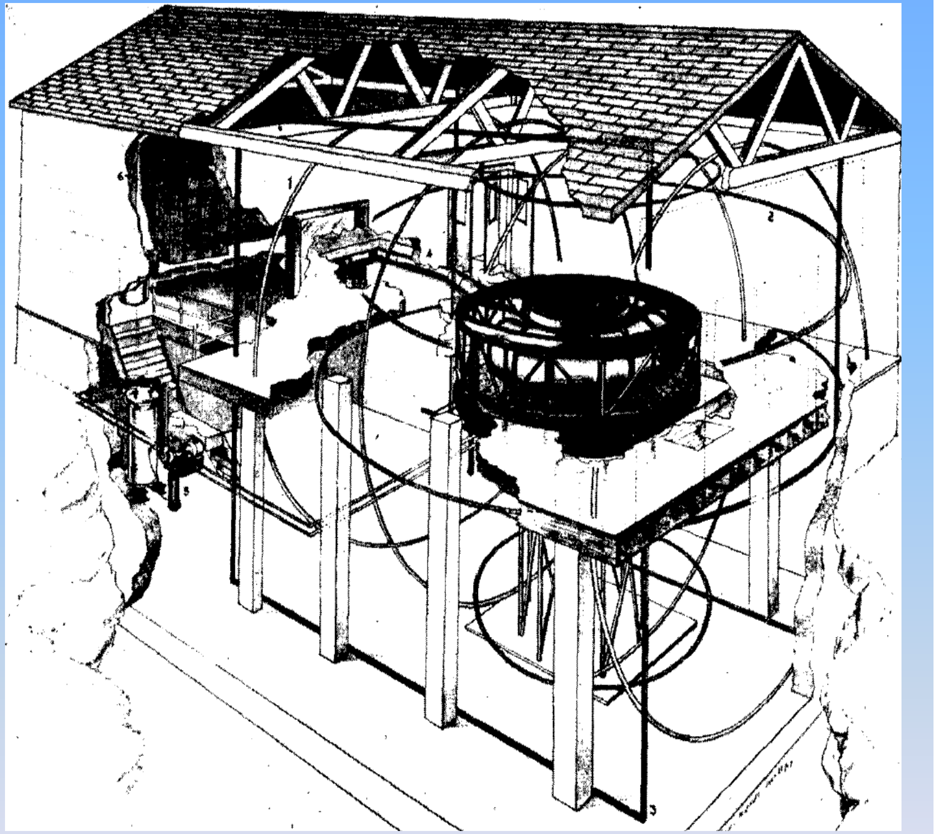
*Physics Division, Atomic Energy of Canada Limited, Chalk River, Ontario*



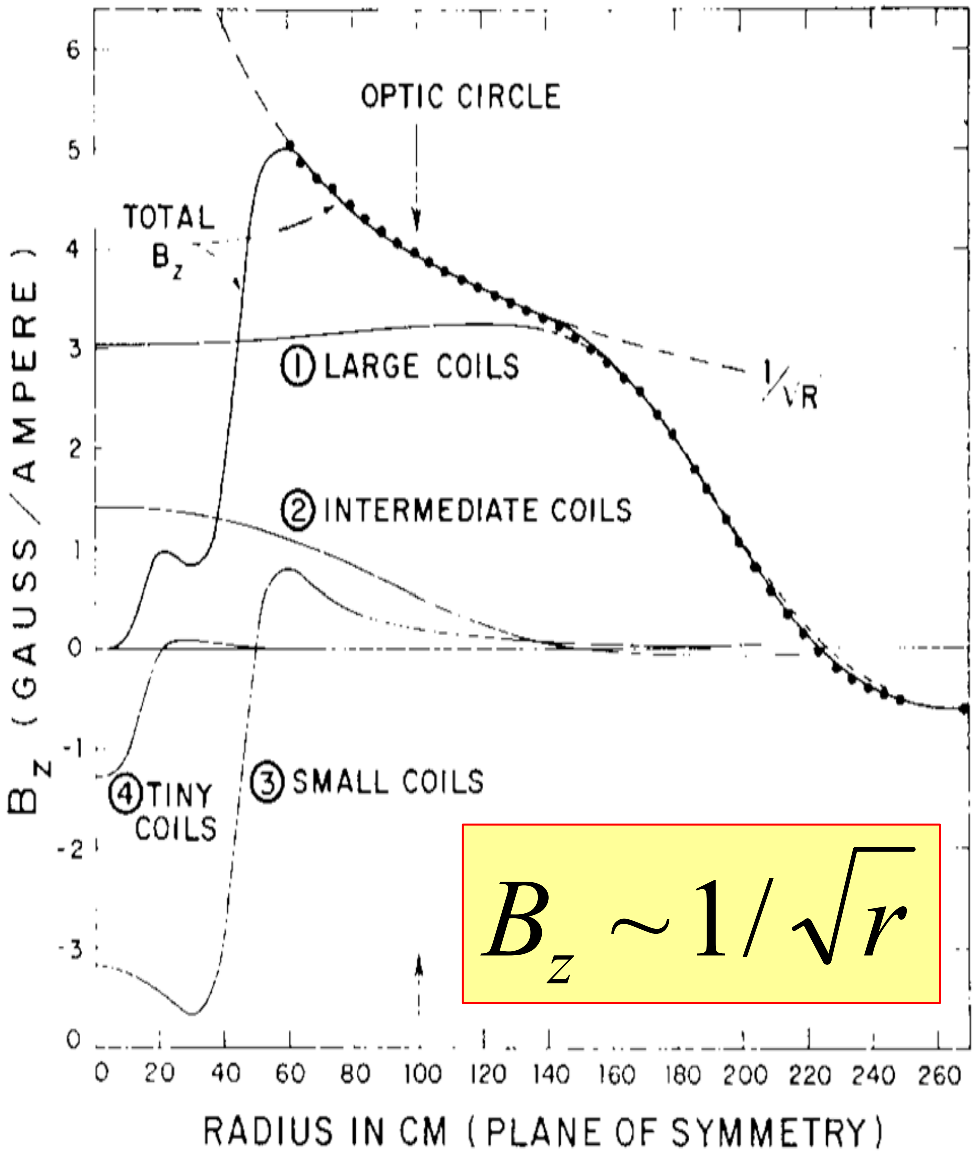
Parameters for optimum luminosity when using a counter[a])

| | | | |
|---|---|---|---|
| Resolution $R$ (%) | 0.01 | 0.1 | 1.0 |
| Source width $s = 2h_0$ (cm) | 0.034 | 0.34 | 3.4 |
| Source height $2t_0$ (cm) | 3.7 | 11.6 | 37 |
| Source area $A$ (cm²) | 0.126 | 3.94 | 126 |
| Transmission[b]) $\Omega/4\pi$ | 0.06 | 0.20 | 0.80 |
| Luminosity $L = A\,\Omega/4\pi$ (cm²) | $7.6 \times 10^{-5}$ | $7.9 \times 10^{-3}$ | $10.1 \times 10^{-1}$ |
| Counter slit width (cm) | 0.034 | 0.34 | 3.4 |
| Counter acceptance factor $F$ | 0.83 | 0.83 | 0.83 |
| Effective luminosity $LF$ (cm²) | $6.3 \times 10^{-5}$ | $6.6 \times 10^{-3}$ | $8.4 \times 10^{-1}$ |

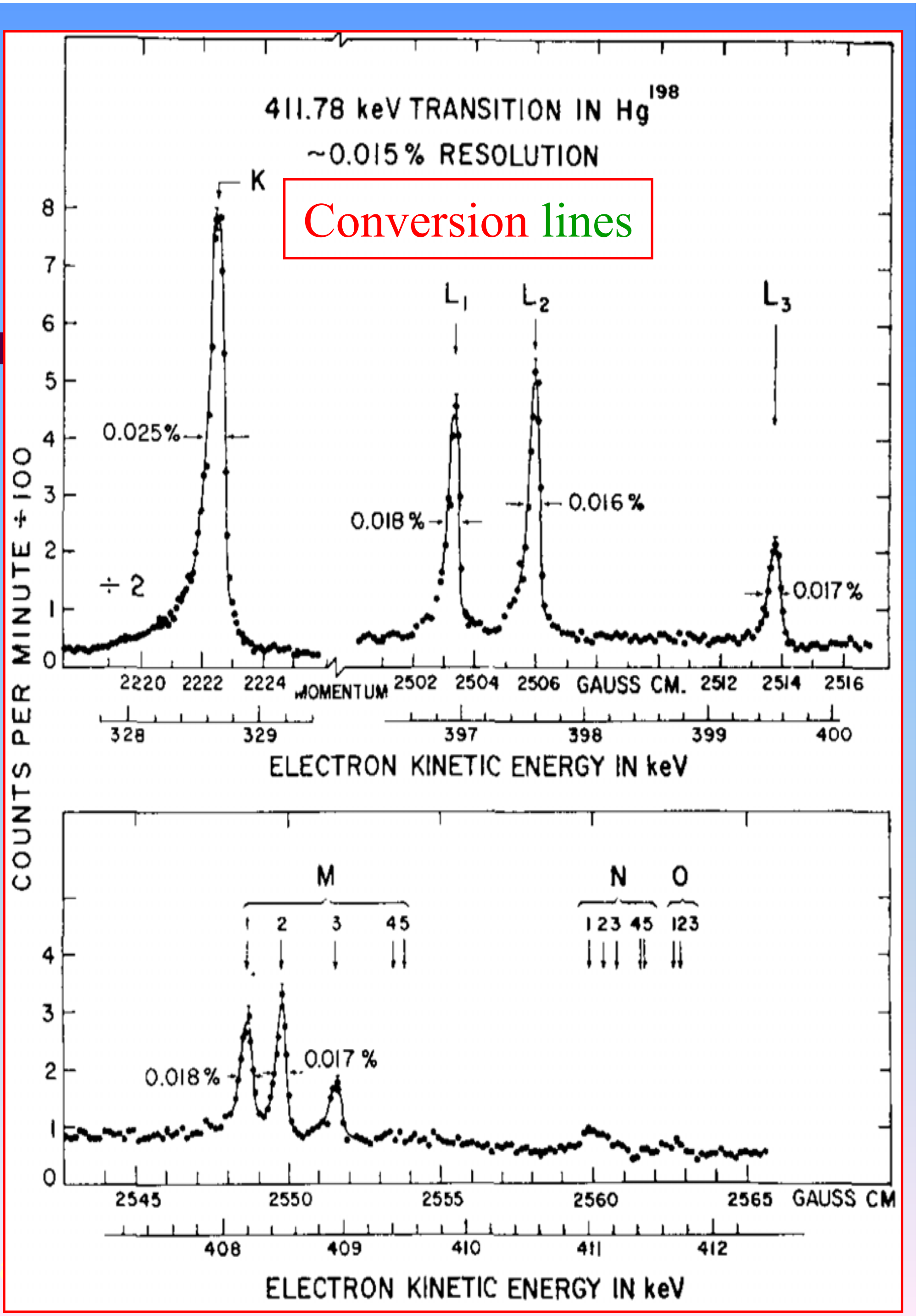




Dedicated machines requiring huge housing
To ensure field uniformity and easy access

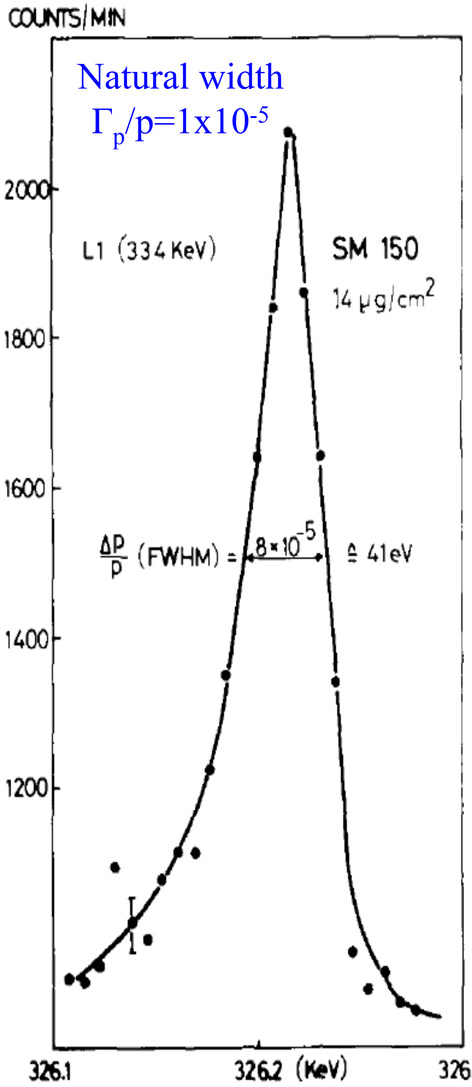


$$B_z \sim 1/\sqrt{r}$$



Conversion lines

# 50cm 1/r BILL electron iron-core spectrometer



Natural width

$\Gamma_p/p=1\mathrm{x}10^{-5}$

Fig. 18. Best resolution of BILL measured with the $L_1$ line of the 334 keV transition in $^{150}$Sm.

Slit widths:

Entry = $s_1$

Exit = $s_2$

$s_1=s_2$ = 0.2 mm

**$\rho$ =50 cm**

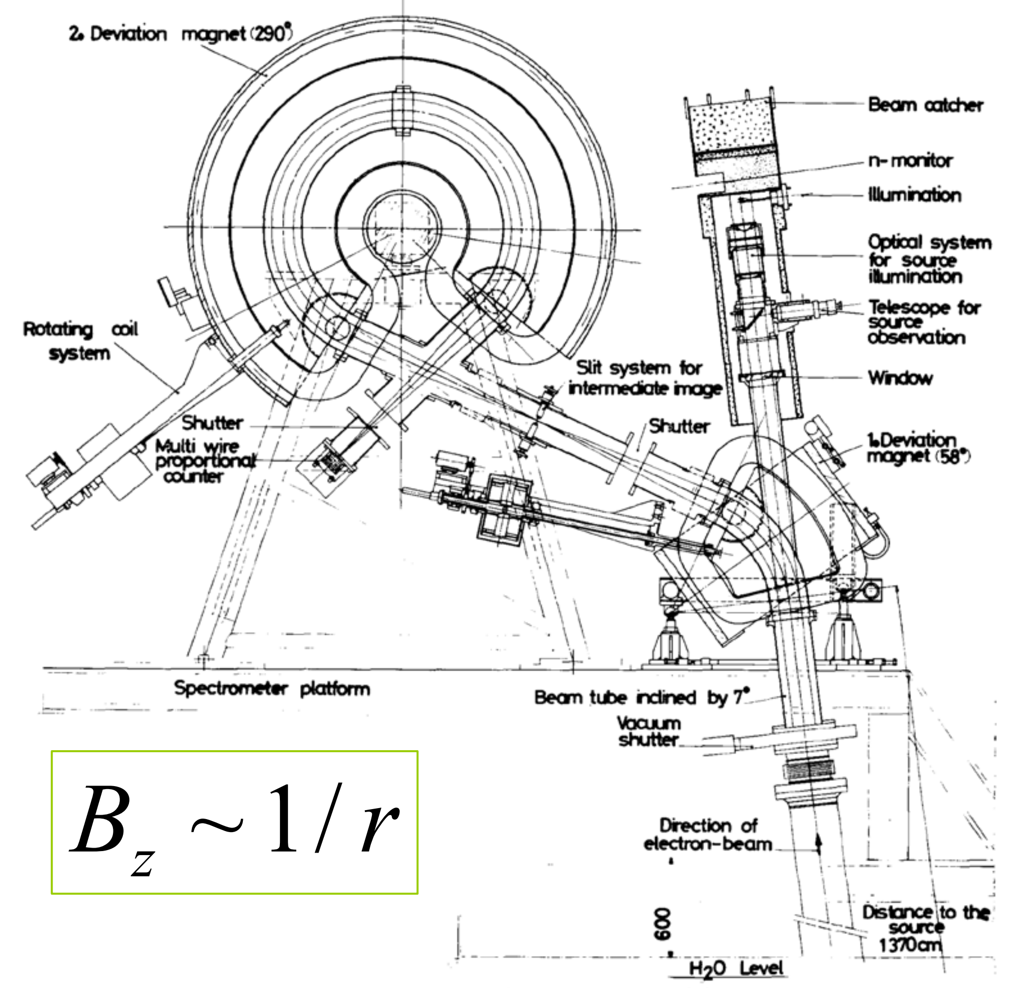
Best resolution

$\Delta p/p$ = 7.6 x $10^{-5}$

NUCLEAR INSTRUMENTS AND METHODS 154 (1978) 127-149

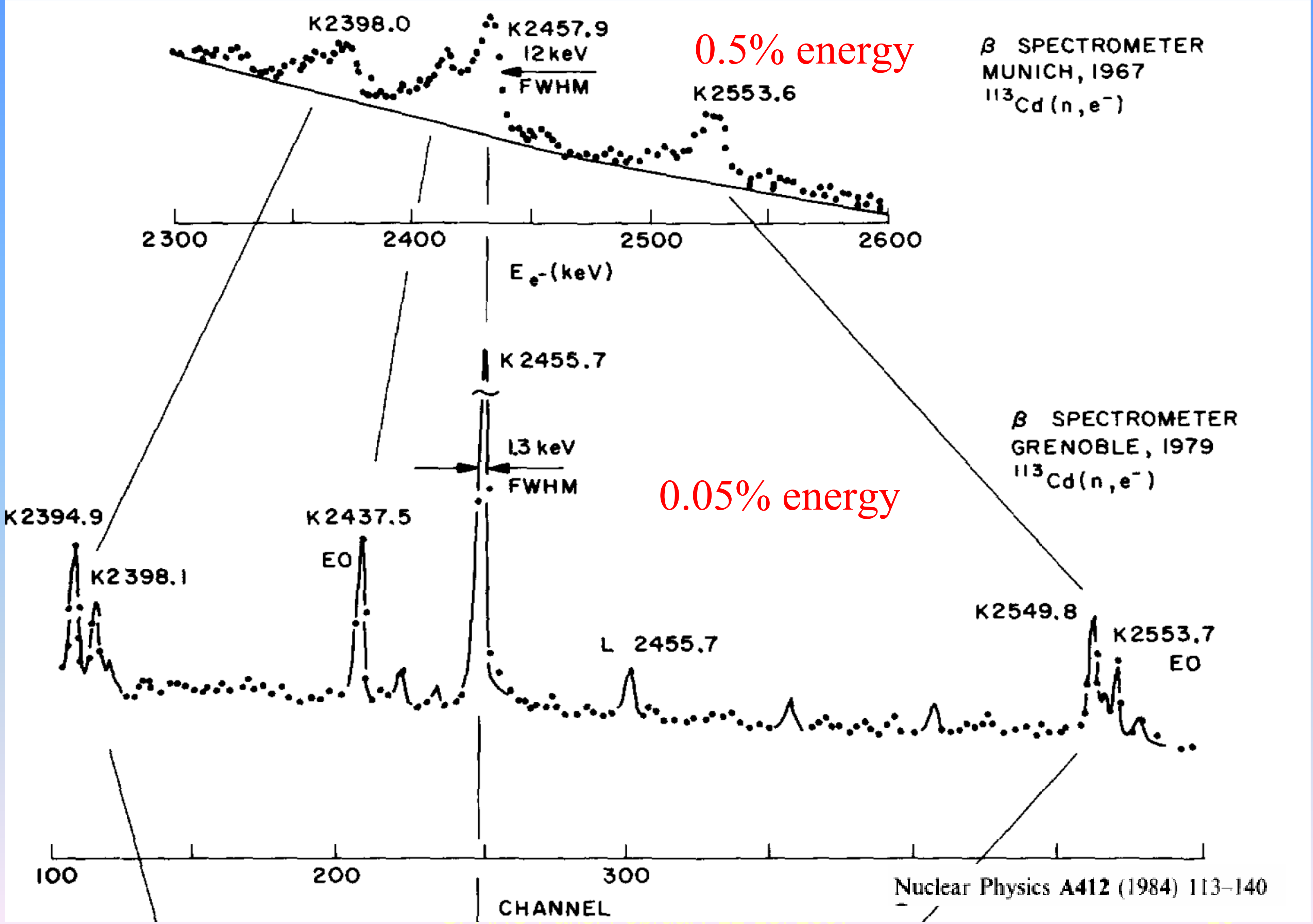
THE DOUBLE FOCUSING IRON-CORE ELECTRON-SPECTROMETER "BILL" FOR HIGH RESOLUTION (n, e⁻) MEASUREMENTS AT THE HIGH FLUX REACTOR IN GRENOBLE

W. MAMPE, K. SCHRECKENBACH, P. JEUCH, B. P. K. MAIER, F. BRAUMANDL, J. LARYSZ and T. von EGIDY*
*Institut Laue-Langevin, 38042 Grenoble Cèdex, France*



$$B_z \sim 1/r$$

Fig. 2. Schematic view of the spectrometer BILL demonstrating the arrangement of the magnets.



0.5% energy

0.05% energy

Nuclear Physics **A412** (1984) 113–140

# Envisioned two-stage magnetic spectrometer

(original ESR proposal Rido Mann et al 1988 – GSI)

## *Use in storage rings: The ultimate ZAPS?*

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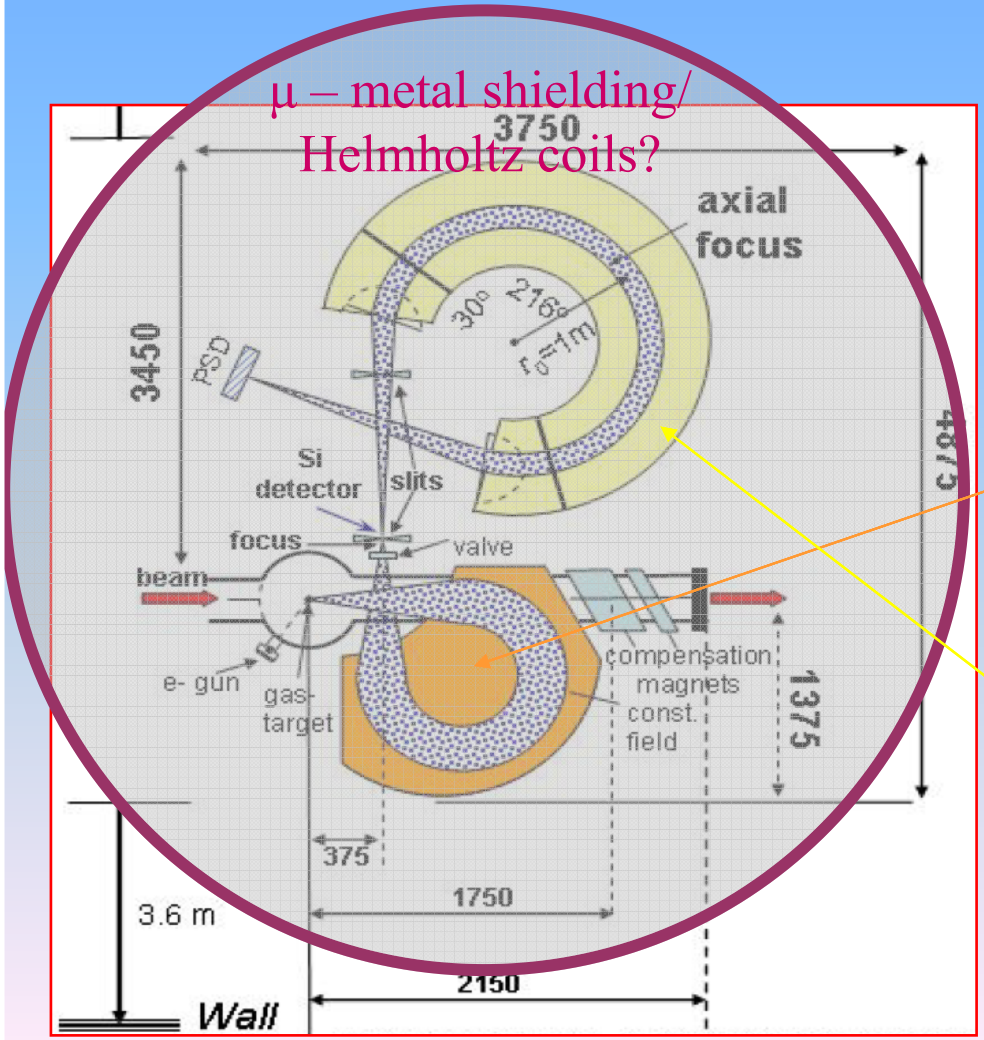
Stored Particles Atomic Physics Research Collaboration

- Ultimate resolution: $\delta p/p < 10^{-4}$
- Lab $e^-$ energy: 3-500 keV



μ – metal shielding/ Helmholtz coils?

1st stage (deflector)

- low dispersion, low resolution
- uniform field dipole
- target spot size 1mm x 1mm
- large angular acceptance 5-$10^0$

2nd stage

- high dispersion, high resolution
- $r^{-n}$ $B_z$-field (n=1 BILL, n=2 Chalk River)
- entry slit widths ~0.1-1 mm
  small angular acceptance 0.1-$0.5^0$
- 2-D PSD

*Resolution contributions*

$\Gamma' = 100$eV, $\varepsilon' = 80$keV, $\Delta\theta = 0.2^0$ (full-acceptance)

Projectile $\Delta p/p = 5 \times 10^{-5}$, Spectrometer $\Delta p/p = 1 \times 10^{-4}$

| | 4 MeV/u | 200 MeV/u | 740 MeV/u |
|---|---|---|---|
| Lab width $\Gamma$ (eV) | **118.895** | **258.73** | **476.01** |
| Kinematic Broadening (eV) | **0.0593** | **2.0875** | **15.267** |
| Projectile-energy Spread (eV) | **1.6310** | **21.805** | **58.677** |
| Spectrometer $\Delta E$ (eV) | **20.066** | **63.963** | **132.92** |

# *Conclusions*

Important technical issues to take into consideration/resolve:

- Iron or Air -core magnet design?
  - Air-core seems better but needs more space!
  - Iron -core: problem of magnetic field uniformity over 1 m radius?

    problem of Remanent magnetization?
- Solid angle considerations - small $\Delta\theta \sim 0.1^0$ (to limit kinematic broadening for line width measurements) will severely limit count rate – PSD necessary
- Good design, optical alignment and slit/baffle controls will be critical
- High quality non-magnetic materials to be used in the entire target area
- Need for highest areal density target (liquid $H_2$/He)?
- At the $10^{-5}$ precision level
  - Earth magnetic field annulment (μ-metal shielding/large Helmholtz coils?)
  - Temperature stability to $\sim 0.1^0$ C

Anybody up to the challenge?

Come join the SPARC electron spectroscopy group!

http://www.gsi.de/fair/experiments/sparc/electron-spectrometers_e.html

# *Bibliography*

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- T.J.M. Zouros and D.H. Lee, in *Accelerator -Based Atomic Physics Techniques and Applications*, ed. S. Shafroth and J.C. Austin, AIP, Chapter 13 (1997) p. 427-479.
- E.P. Benis et al. Phys. Rev. A **69** (2004) 052718.
- W. Mampe et al., NIM **154** (1978) 127-149.
- R.L. Graham, G.T. Ewan and J.S. Geiger, NIM **9** (1960) 245-286.

**For more information also check my home page:**
**http://www.physics.uoc.gr/~tzouros**

# XX International Symposium on Ion-Atom collisions* and

## *SPARC topical meeting on Electron spectrometry in the NESR*

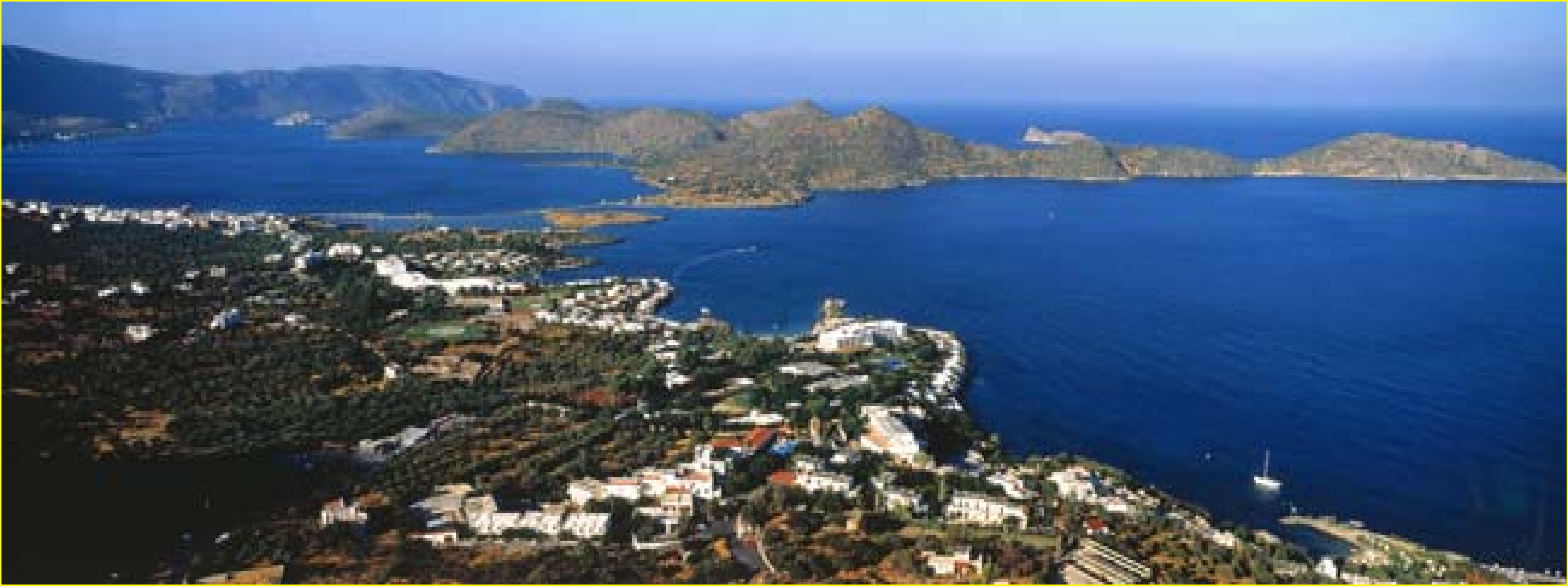
August 1-4, 2007

Agios Nikolaos, Crete, GREECE

2007 Crete

XX ISIAC

*a satellite of XXV ICPEAC - Freiburg



*Resolution contributions*

$\Gamma'$=10eV, $\varepsilon'$=50keV, $\Delta\theta=0.2^0$ (full-acceptance)

Projectile $\Delta p/p = 5 \times 10^{-5}$, Spectrometer $\Delta p/p = 1 \times 10^{-4}$

| | 4 MeV/u | 200 MeV/u | 740 MeV/u |
|---|---|---|---|
| Lab width $\Gamma$ (eV) | **12.291** | **28.857** | **54.048** |
| Kinematic Broadening (eV) | **0.04942** | **2.0248** | **15.347** |
| Projectile-energy Spread (eV) | **1.3143** | **18.963** | **51.949** |
| Spectrometer $\Delta E$ (eV) | **13.844** | **53.065** | **115.84** |

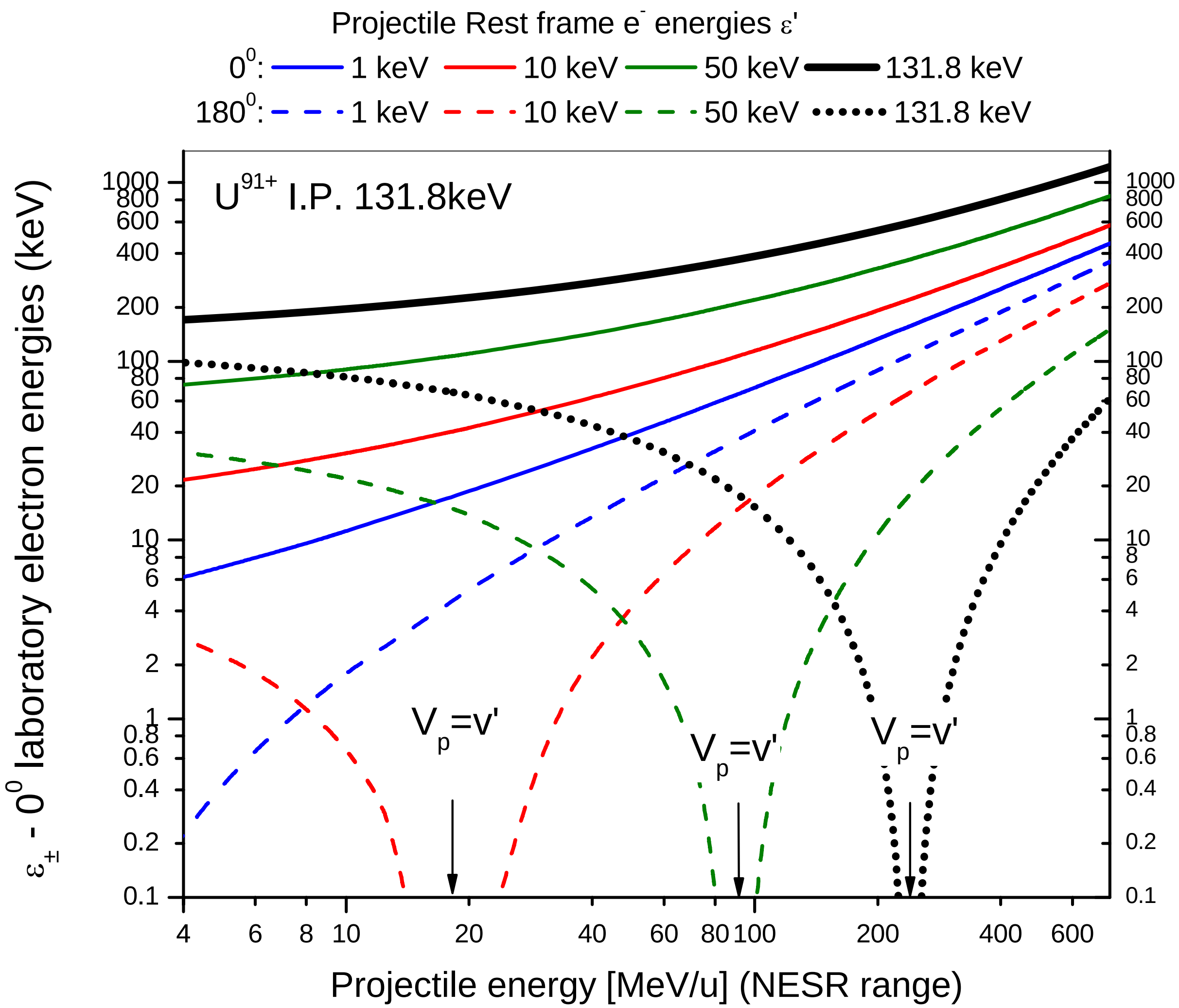
$\Gamma' = 10$eV, $\varepsilon' = 1$keV, $\Delta\theta = 0.2^0$ (full-acceptance)

# *Resolution contributions*

Projectile $\Delta p/p = 5 \times 10^{-5}$, Spectrometer $\Delta p/p = 1 \times 10^{-4}$

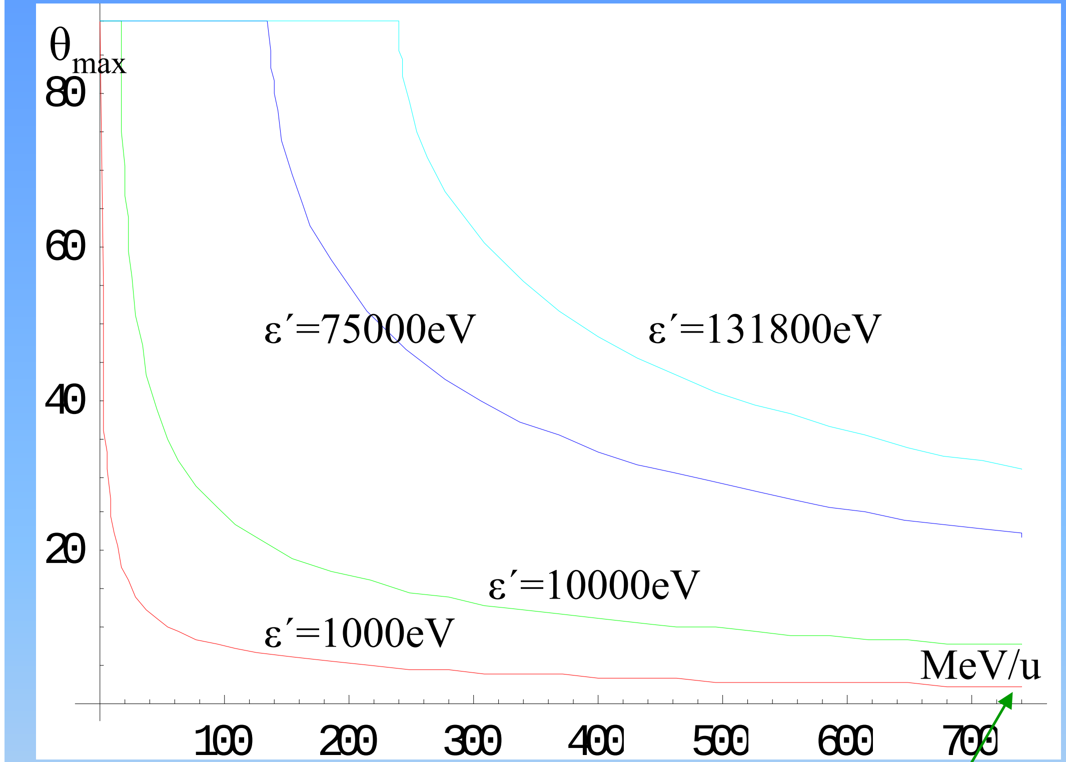
| | 4 MeV/u | 200 MeV/u | 740 MeV/u |
|---|---|---|---|
| Lab width $\Gamma$ (eV) | **24.894** | **122.53** | **256.45** |
| Kinematic Broadening (eV) | **0.0280** | **5.0441** | **47.754** |
| Projectile-energy Spread (eV) | **0.3678** | **11.124** | **34.056** |
| Spectrometer $\Delta E$ (eV) | **1.2258** | **23.851** | **69.620** |

# Kinematics: energy shifting and doubling II



For He-like Uranium
K-Auger series energies
(75 -130 keV rest) frame
Range in Lab from about
100 - 1000 keV (+)
40 - 0 keV (-)
For projectile energies
4 -740 MeV/u

# *Angular compression – "beaming"*



For $V_p\,/\,v' > 1$ ($\beta_p/\beta' > 1$) there is

a maximum lab observation angle $\theta_{max}$ :

$$\theta_{max} = Arc\sin\left[\frac{\beta'\gamma'}{\beta_p\gamma_p}\right]$$

At 740 MeV/u we have:

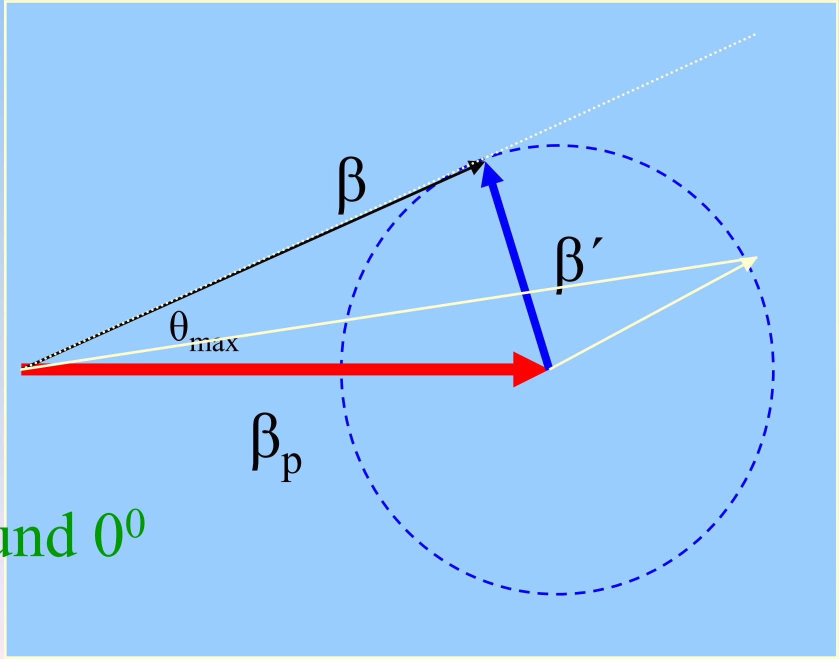
For $\varepsilon'=1000$ eV, $\theta_{max} = 2.407^0$

$\varepsilon' = 10$ eV, $\theta_{max} = 0.24^0$

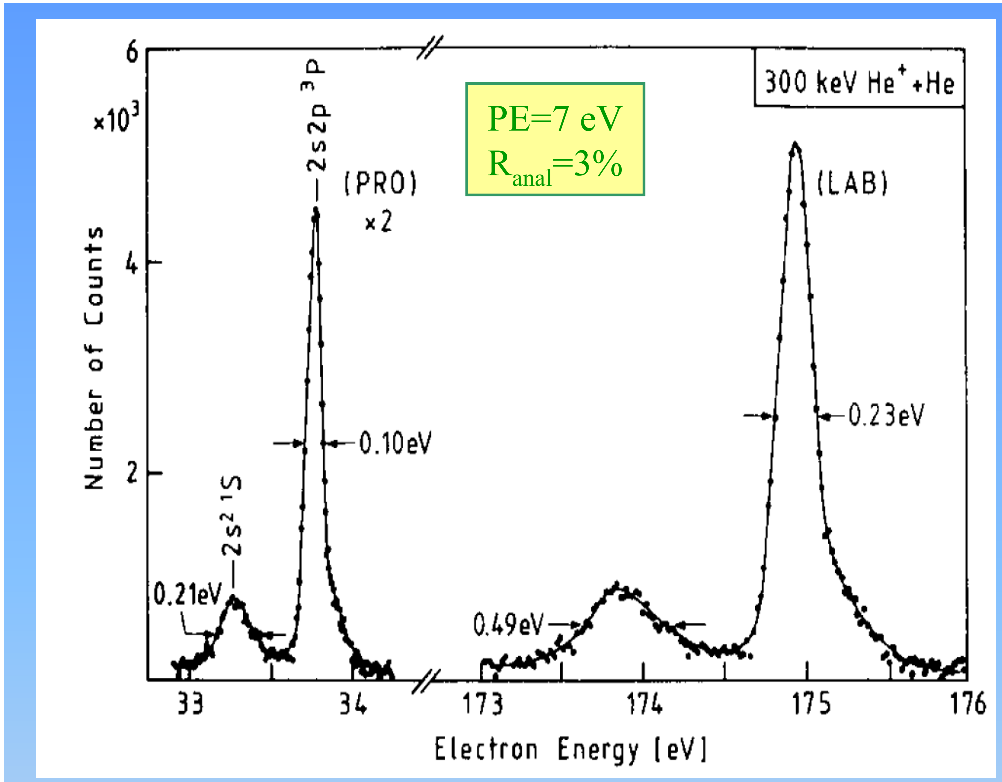
Strong beaming for small electron energies

Practically **total cross section** measured around $0^0$

All differential information averaged out



# *Kinematics:*
# *Line stretching and enhancing*



Natural Line widths Γ’ (rest frame) are
Changed to widths $\Gamma_\pm$ in Lab frame

$0^0$ Kinematic Line Stretching or Compressing:

(- only for $\beta_p > \beta'$)

$\Gamma_{p\pm} = |\Gamma'_{p'}|$ (classical - no stretching)

$\Gamma_{p\pm} = \gamma_p\,|\beta_p\beta' \pm 1|\,\Gamma'_{p'}$ (relativistic - mild stretching)

Momentum Kinematic Line Enhancement

$$\left.\frac{d^2\sigma_\pm}{dp\,d\Omega}\right|_{\theta=0^0} = \frac{d^2\sigma'}{dp'\,d\Omega'} \qquad \text{(classical - No!)}$$

$$\left.\frac{d^2\sigma_\pm}{dp\,d\Omega}\right|_{\theta=0^0} = \frac{\gamma_\pm}{\gamma'}\frac{d^2\sigma'}{dp'\,d\Omega'} = \gamma_p(1+\beta_p\beta')\frac{d^2\sigma'}{dp'\,d\Omega'} \qquad \text{(relativistic)}$$

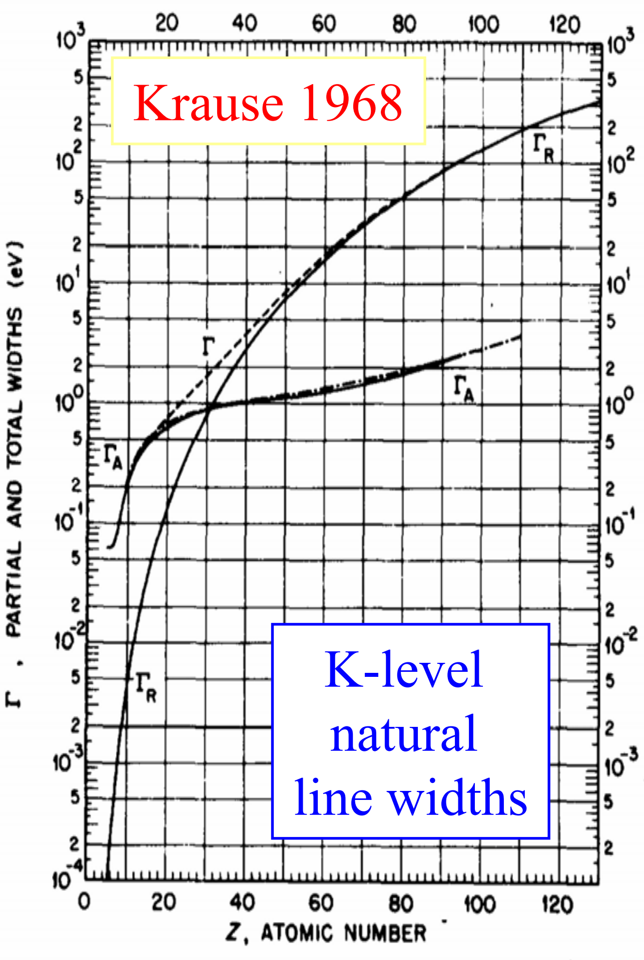
Energy Kinematic Line Enhancement

$$\left.\frac{d^2\sigma_\pm}{d\varepsilon\,d\Omega}\right|_{\theta=0^0} = \frac{V_p \pm v'}{v'}\frac{d^2\sigma'}{d\varepsilon'\,d\Omega'} \qquad \text{(classical - yes!)}$$

$$\left.\frac{d^2\sigma_\pm}{d\varepsilon\,d\Omega}\right|_{\theta=0^0} = \frac{p_\pm}{p'}\frac{d^2\sigma'}{d\varepsilon'\,d\Omega'} = \gamma_p\frac{(\beta_p \pm \beta')}{\beta'}\frac{d^2\sigma'}{d\varepsilon'\,d\Omega'} \qquad \text{(relativistic)}$$

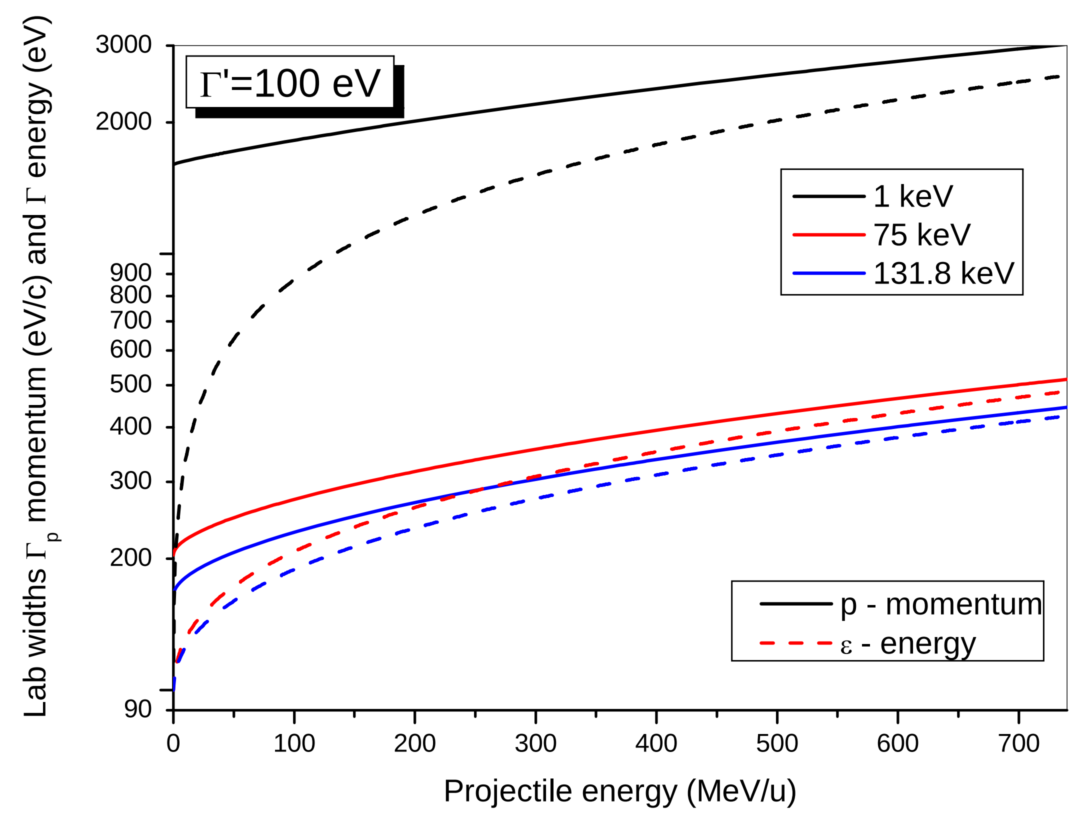
Mild enhancement and stretching
in momentum analysis!!

# *Kinematic Widths and Enhancement factors*


Krause 1968

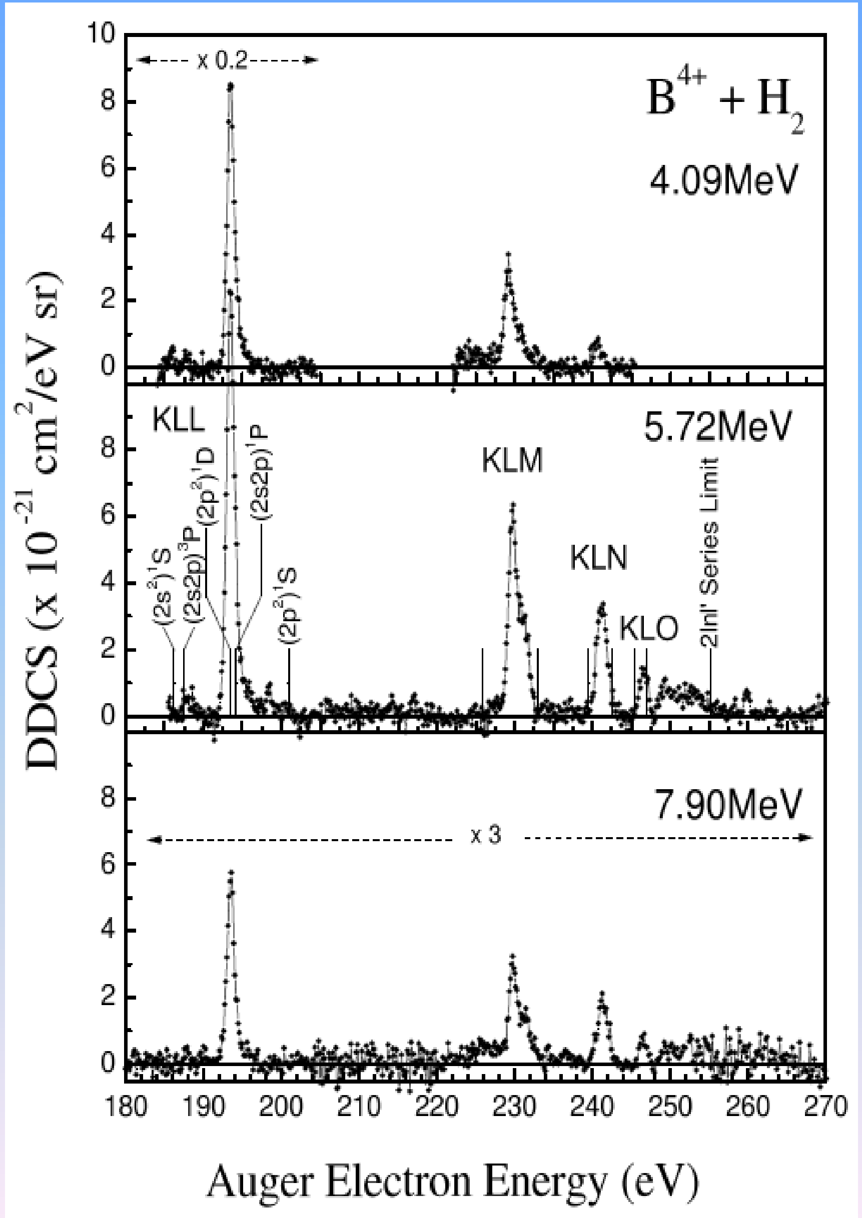
K-level natural line widths

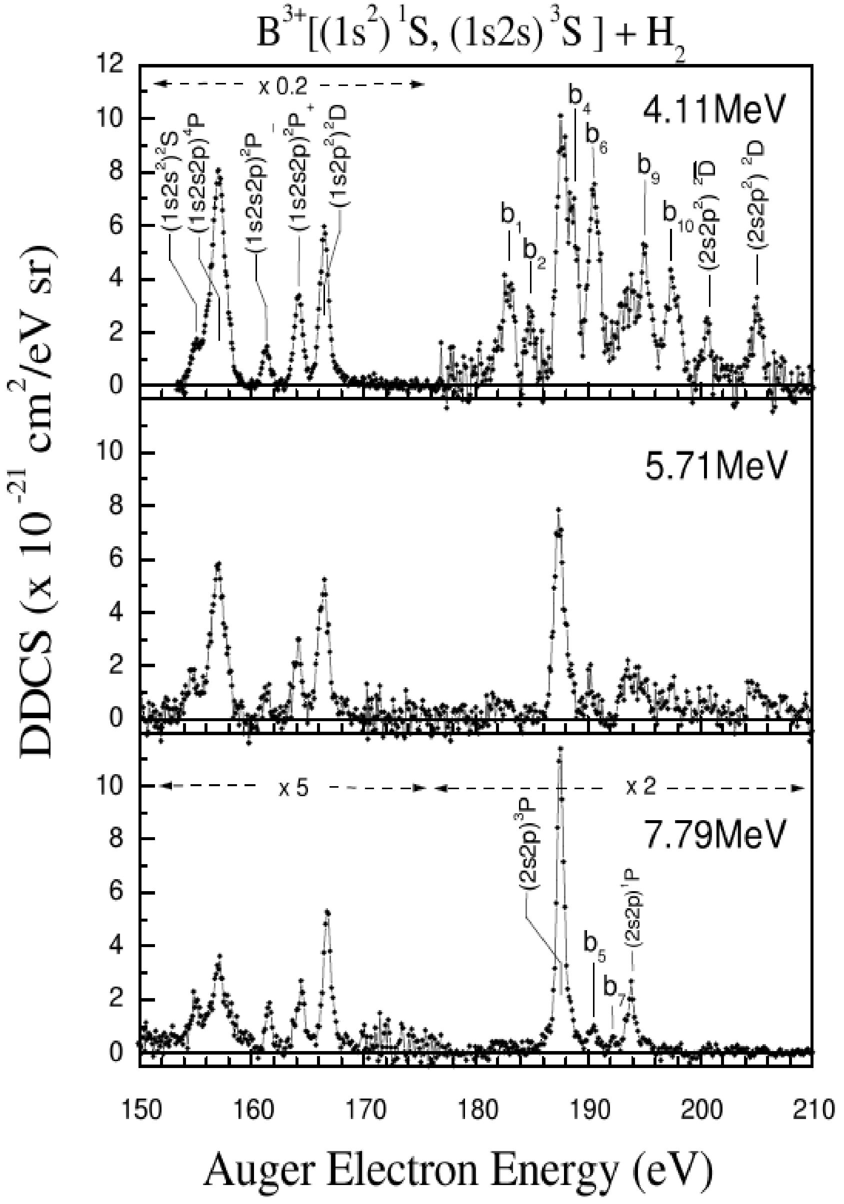
Momentum widths are
stretched only weakly
While energy widths a lot!



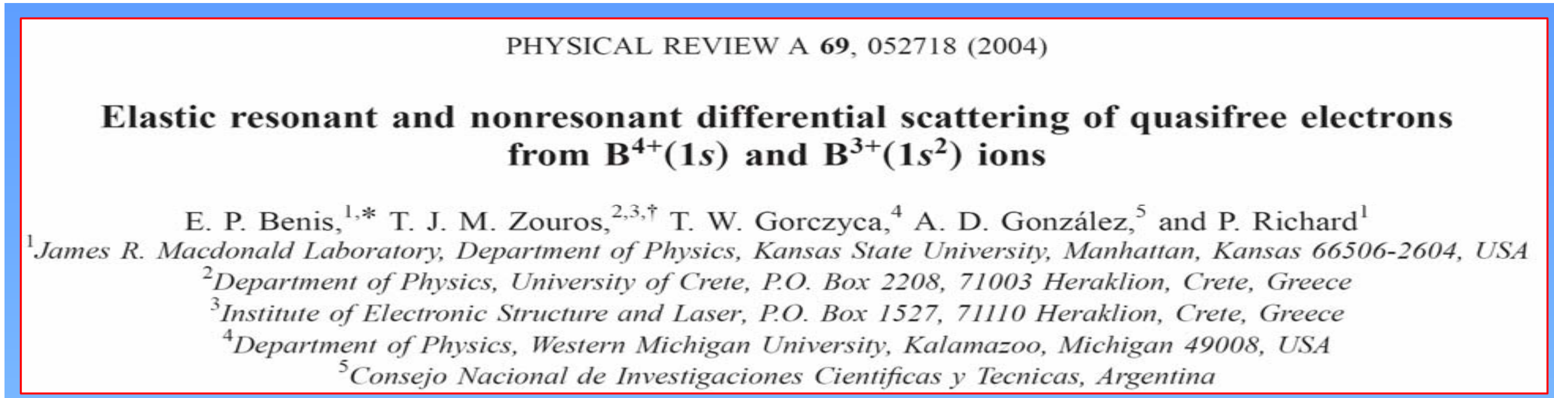
For **atoms**
K line-widths dominated by
Radiative widths at high Z
And Auger widths at low Z
**What about Highly Charged Ions?**

# *Zero-degree Auger Projectile electron spectra*





# *Elastic scattering on $B^{4+}$ and $B^{3+}$*



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## Elastic resonant and nonresonant differential scattering of quasifree electrons from $B^{4+}(1s)$ and $B^{3+}(1s^2)$ ions

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