STORAGE RING EXPERIMENTS

at the Interface

of Atomic and Nuclear Physics

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EMMI Workshop

The ^{229m}Th 'Nuclear Isomer Clock'

GSI
Darmstadt, Germany,
September 25 – 27, 2012

Why Storage Rings?

> "New directions in science are launched by new tools much more often than by new concepts.
>
> The effect of a concept-driven revolution is to explain old things in new ways.
>
> The effect of a tool-driven revolution is to discover new things that have to be explained."
>
> **Freeman Dyson, Imagined Worlds**

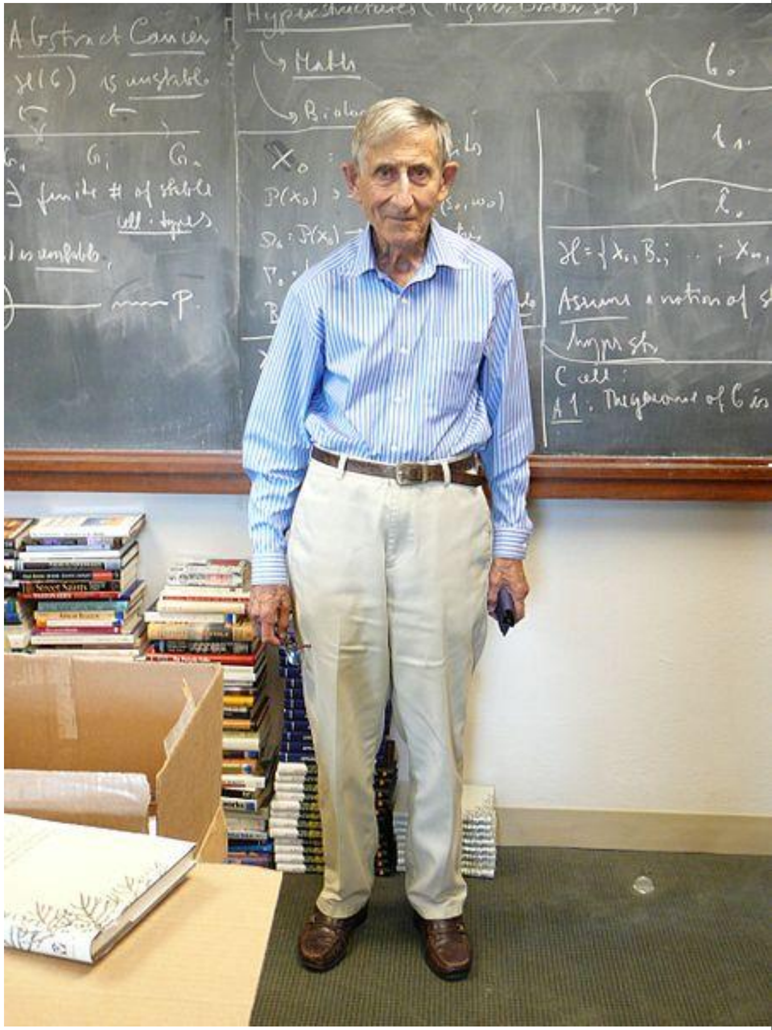
The Role of Failure

You can't possibly get a good technology going without an enormous number of failures. It's a universal rule. If you look at bicycles, there were thousands of weird models built and tried before they found the one that really worked. You could never design a bicycle theoretically. Even now, after we've been building them for 100 years, it's very difficult to understand just why a bicycle works – it's even difficult to formulate it as a mathematical problem. But just by trial and error, we[1] found out how to do it, and the error was essential.

Freeman Dyson

(interview by Stewart Brand)

http://www.wired.com/wired/archive/6.02/dyson.html



Freeman Dyson 2007 (Wikipedia)

Institute for Advanced Studies

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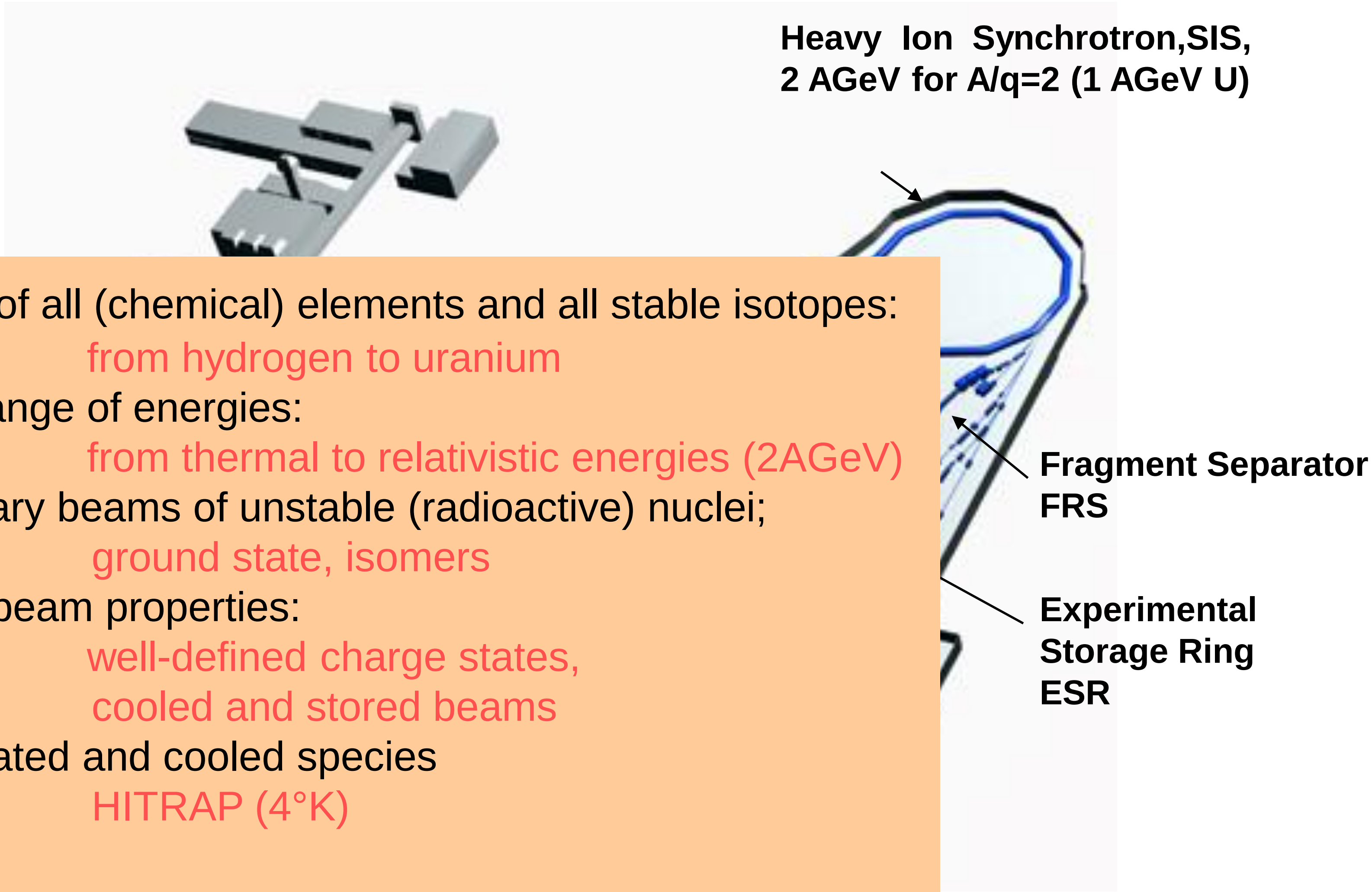
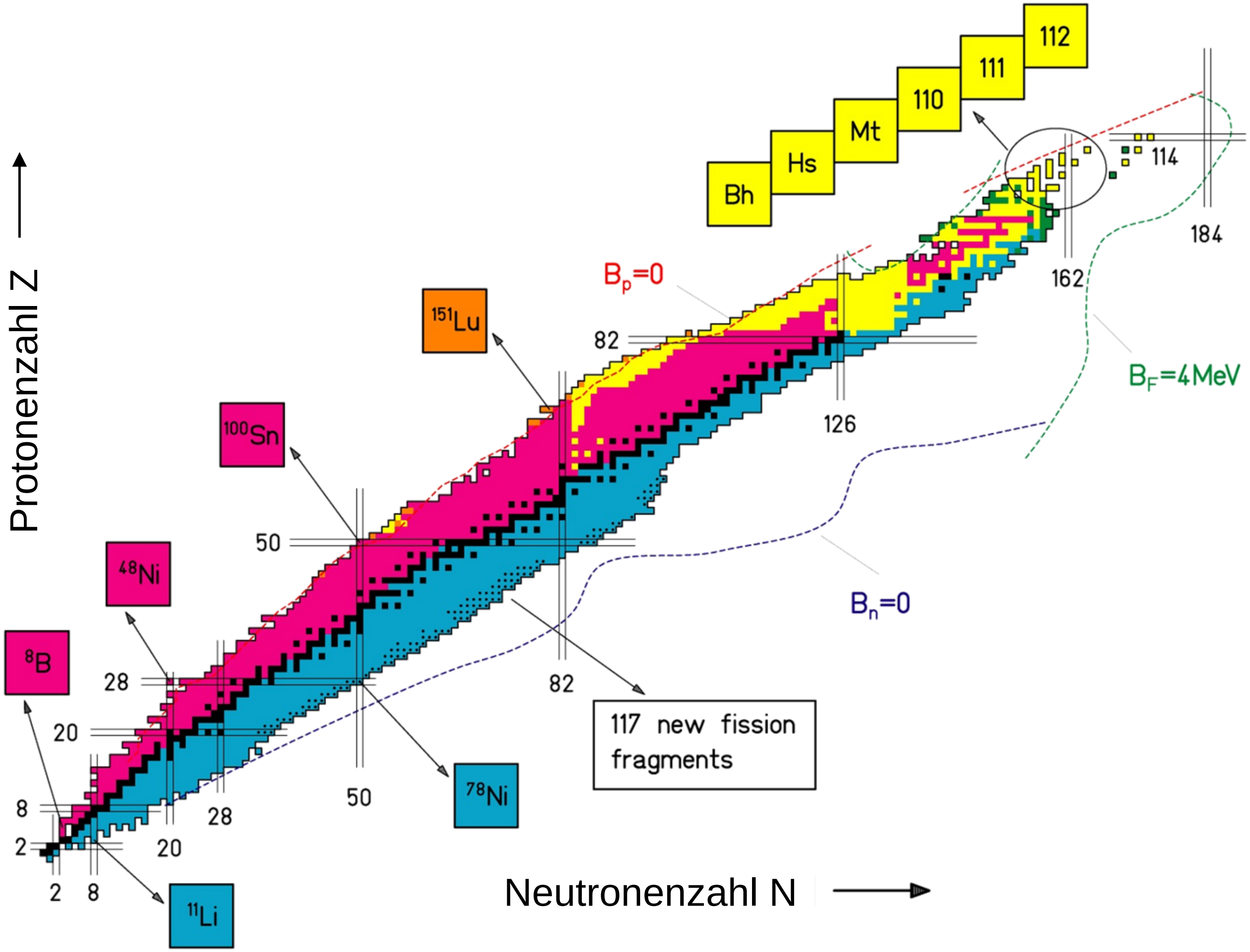
[1] Caveat - cf. also H.M. Enzensberger, *Hammerstein oder Der Eigensinn*, Suhrkamp, Frankfurt/M, 2008 (footnote by C.K.)

Present GSI Accelerators



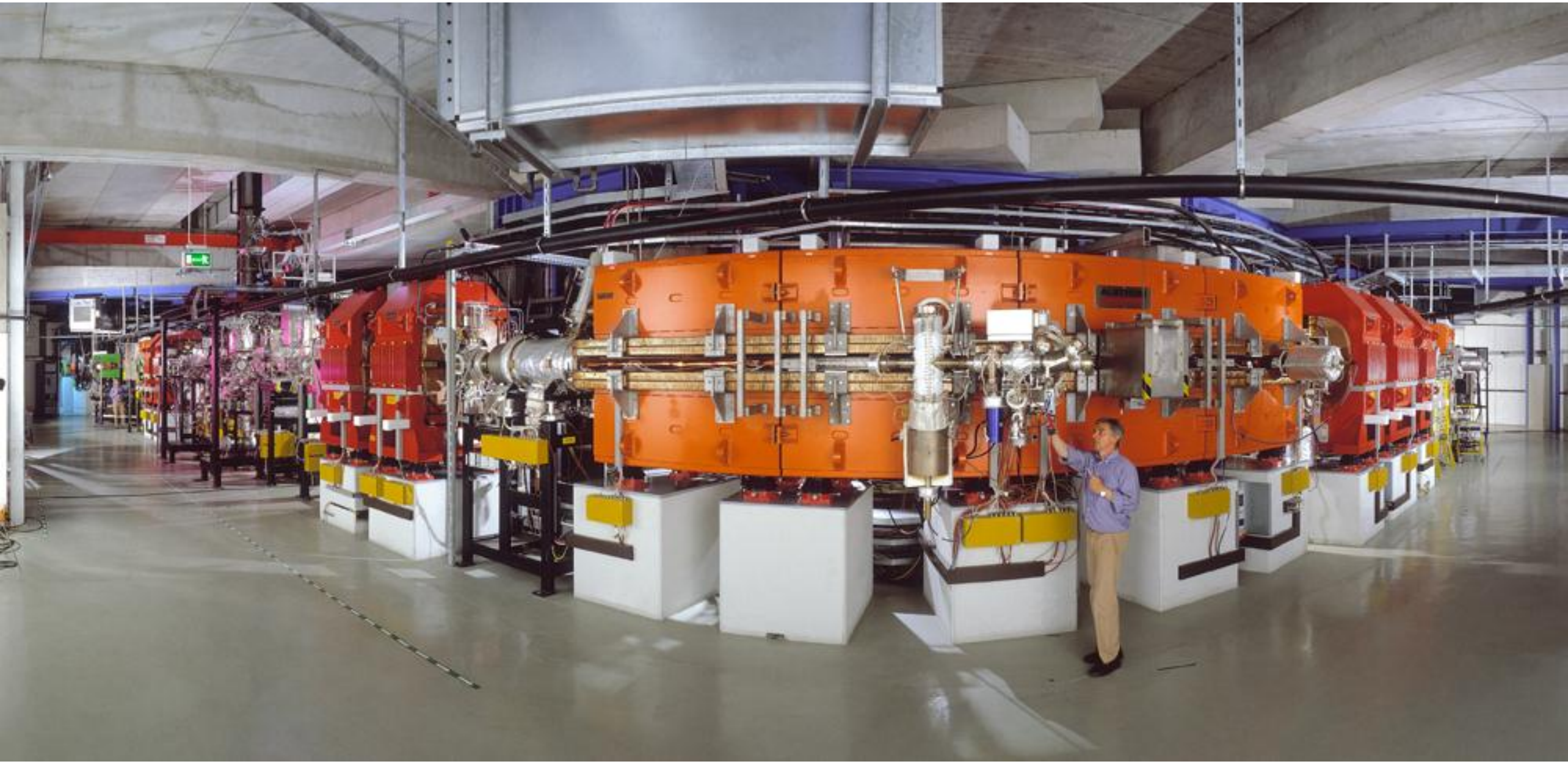
- Beams of all (chemical) elements and all stable isotopes:
  from hydrogen to uranium
- Broad range of energies:
  from thermal to relativistic energies (2AGeV)
- Secondary beams of unstable (radioactive) nuclei;
  ground state, isomers
- Unique beam properties:
  well-defined charge states,
  cooled and stored beams
- Decelerated and cooled species
  HITRAP (4°K)
- (pions)



117 new fission fragments

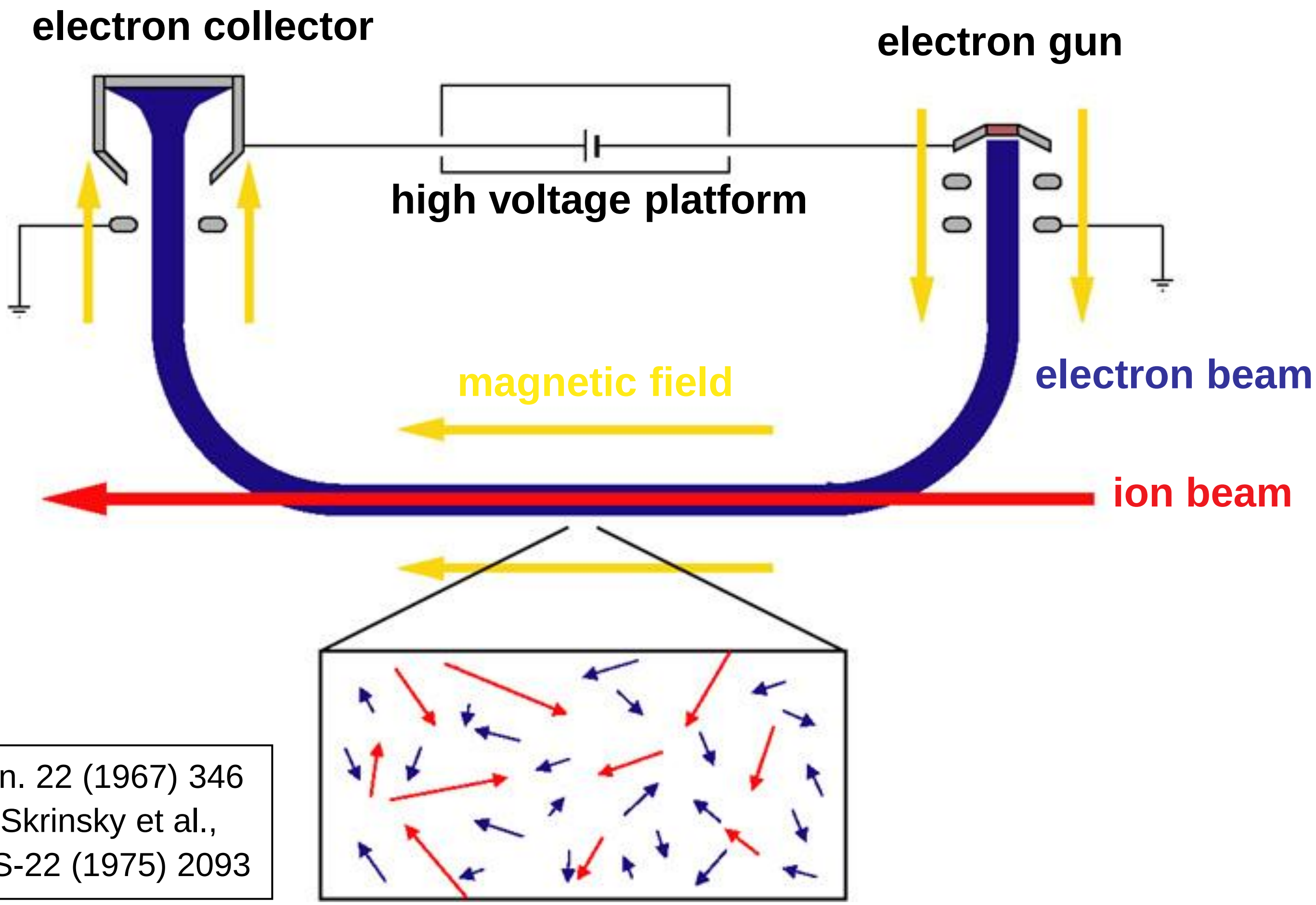
ESR

(Photograph by A. Zschau)



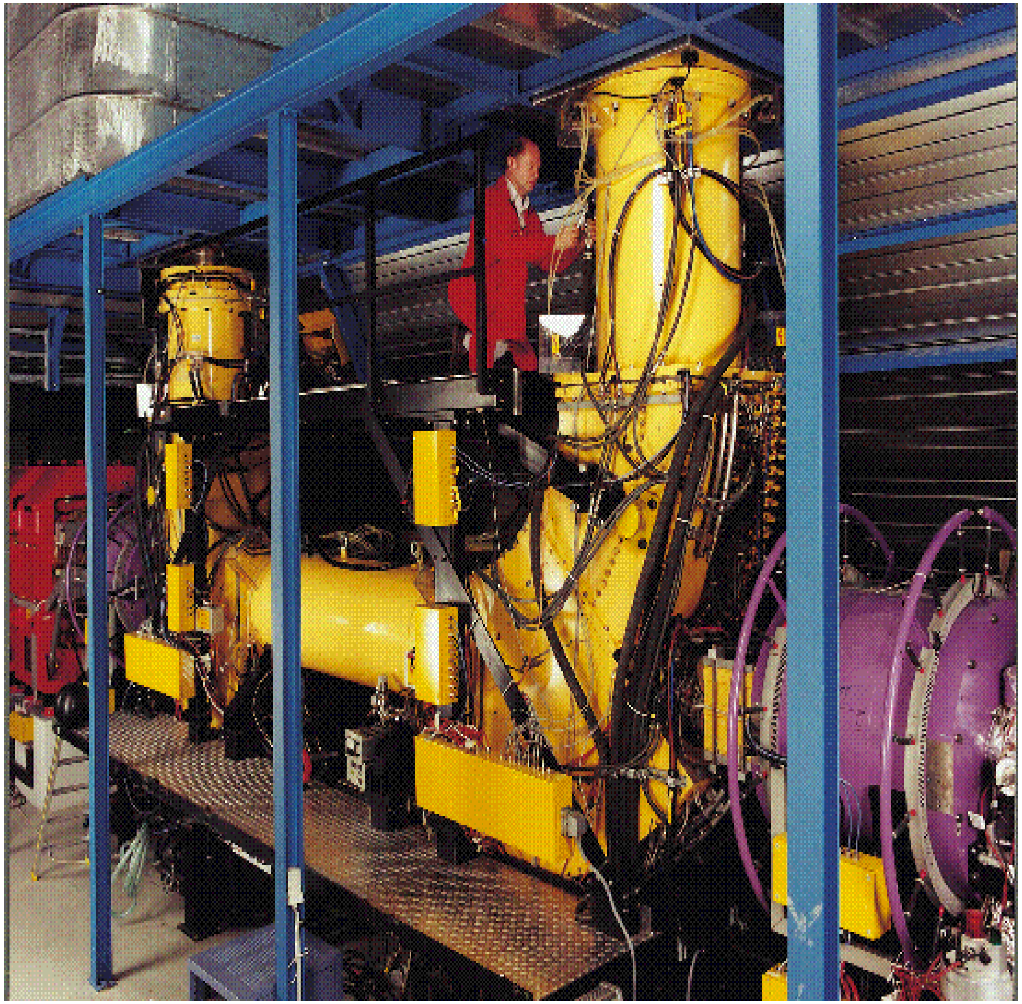
B. Franzke, **NIM B** 24/25 (1987) 18

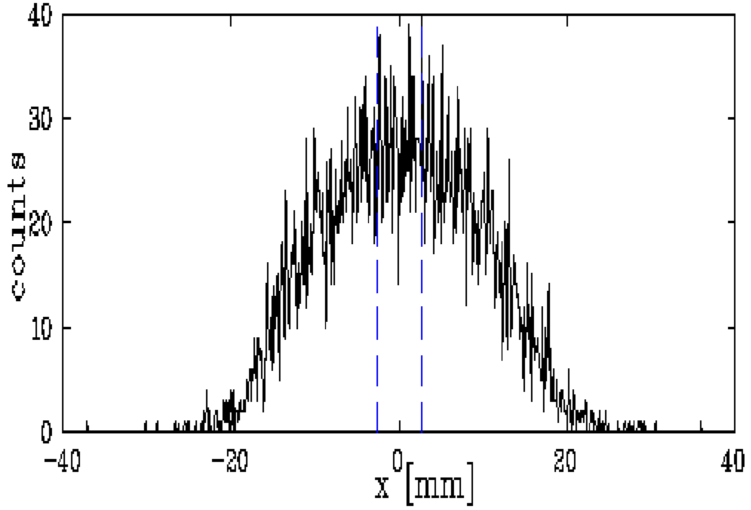
Storage Rings: Electron Cooled Ion Beams

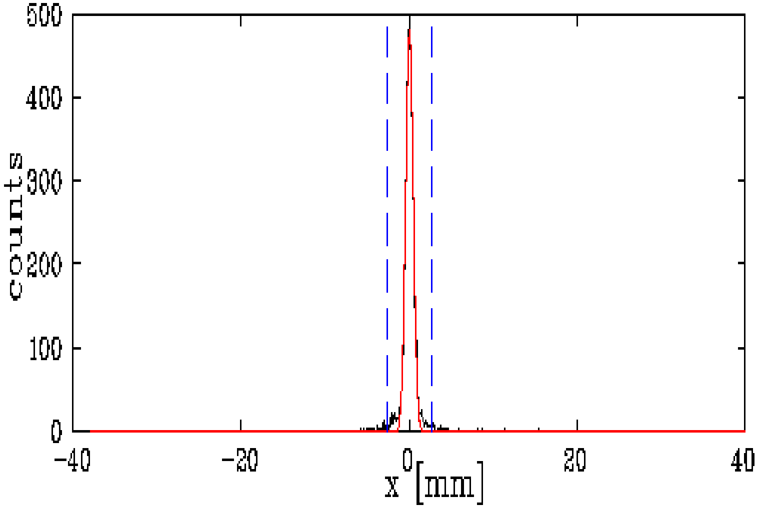


G.I. Budker, At. En. 22 (1967) 346
G.I. Budker, A.N. Skrinsky et al.,
IEEE NS-22 (1975) 2093

Cooling = narrowing velocity, size and divergence of stored ion beams





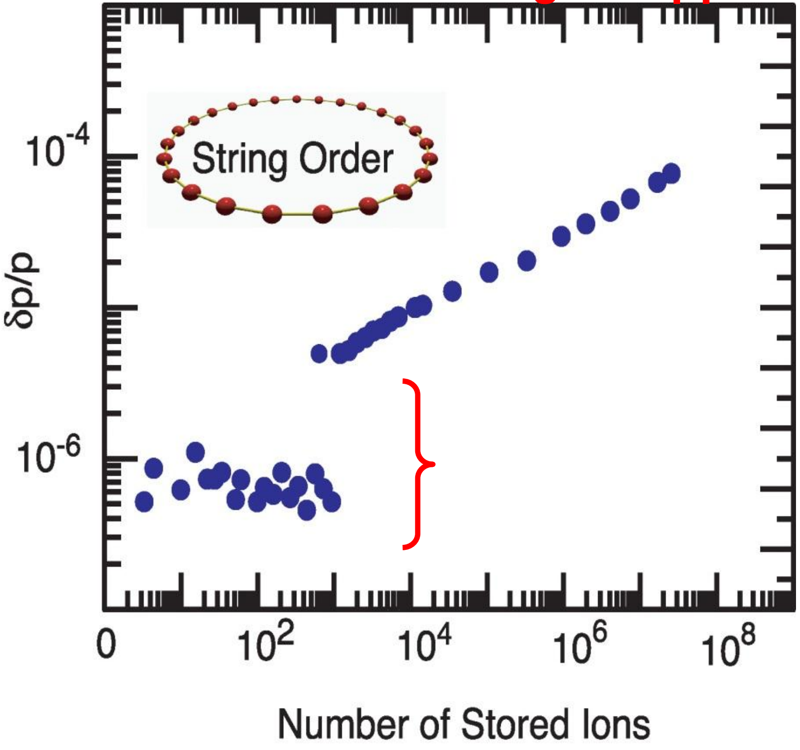


'Phase transition' to a linear ion chain

ESR circumference ≈ 10^4 cm

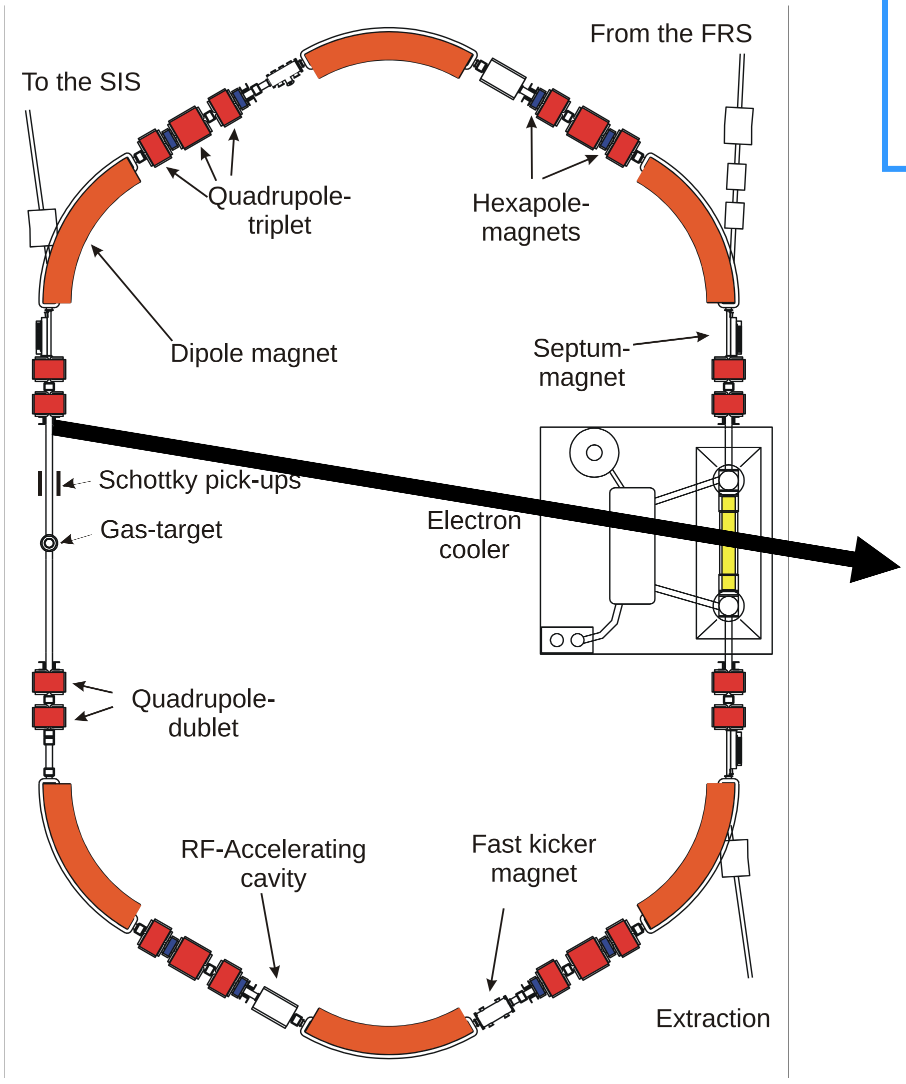
For 1000 stored ions, the mean distance amounts to about 10 cm.

At mean distances of about 10 cm and larger
the intra-beam-scattering disappears.



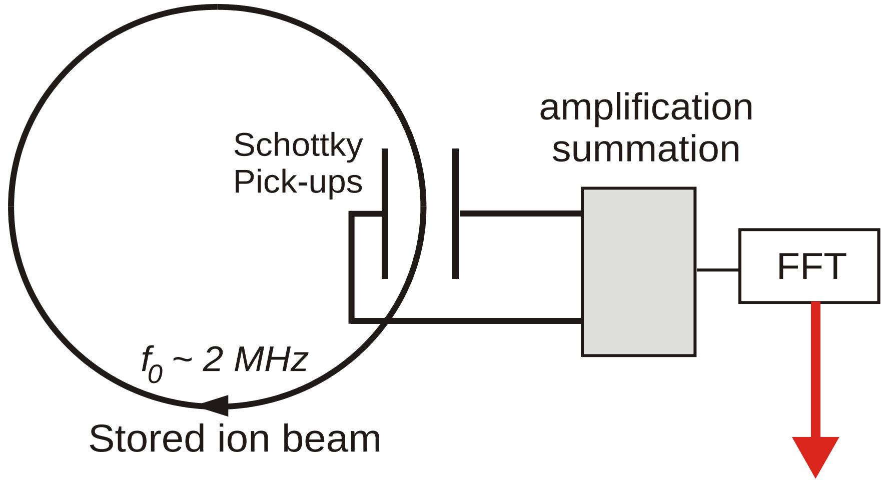
M. Steck et al.,
PRL **77**, 3803 (1996)

Recording the Schottky-noise

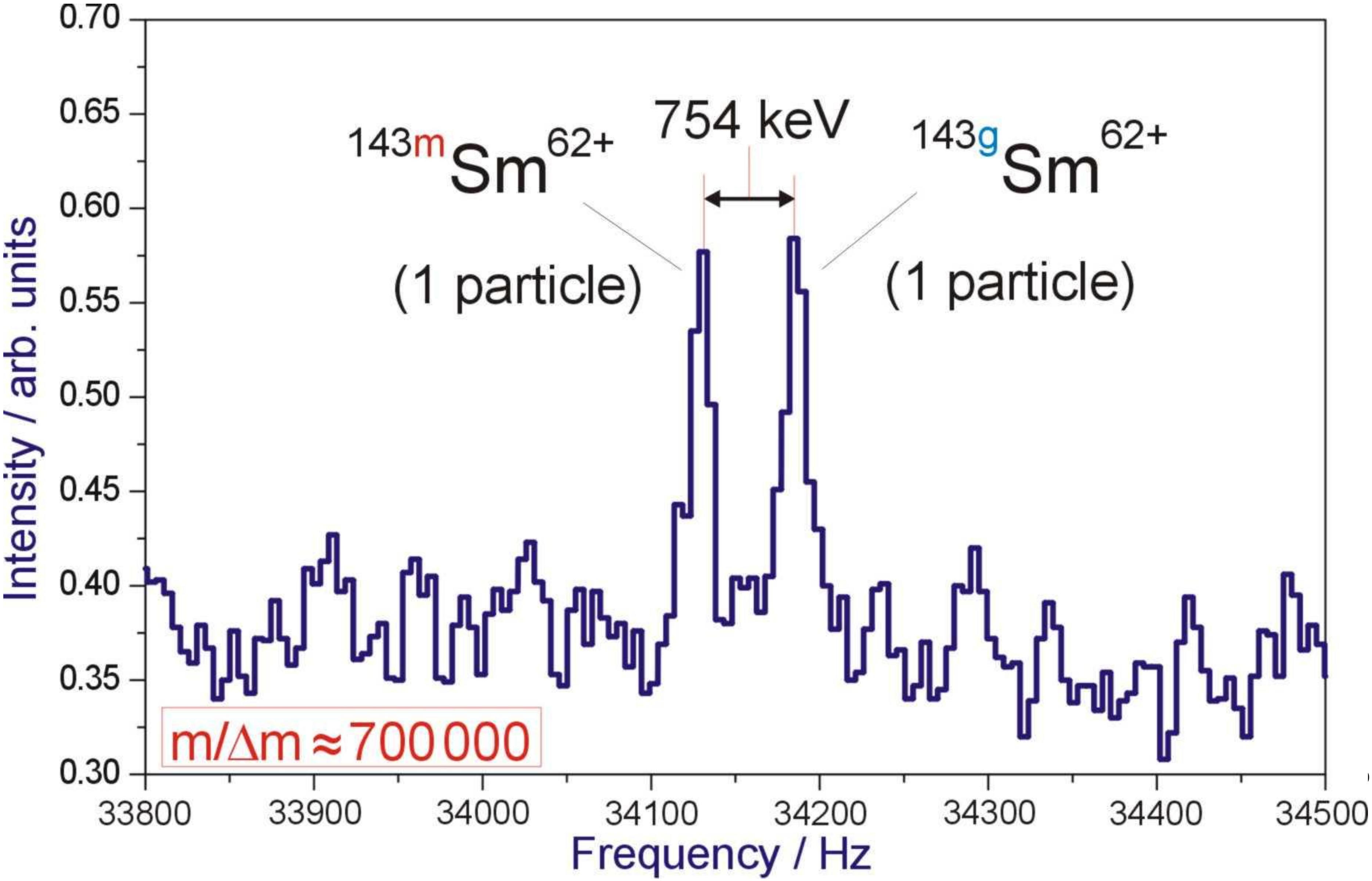


$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \cancel{\frac{\Delta v}{v}}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

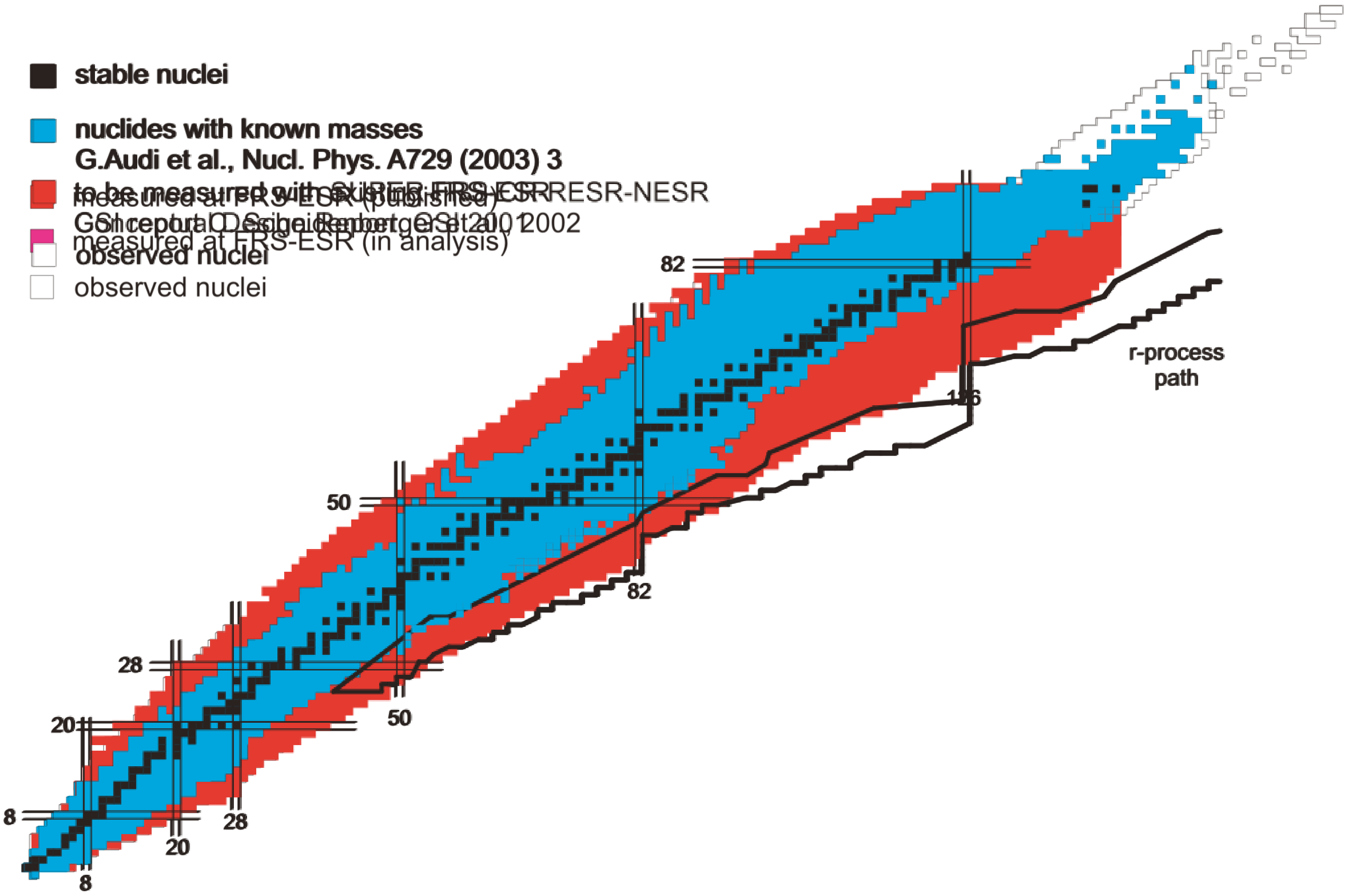
$$\frac{\Delta v}{v} \rightarrow 0$$



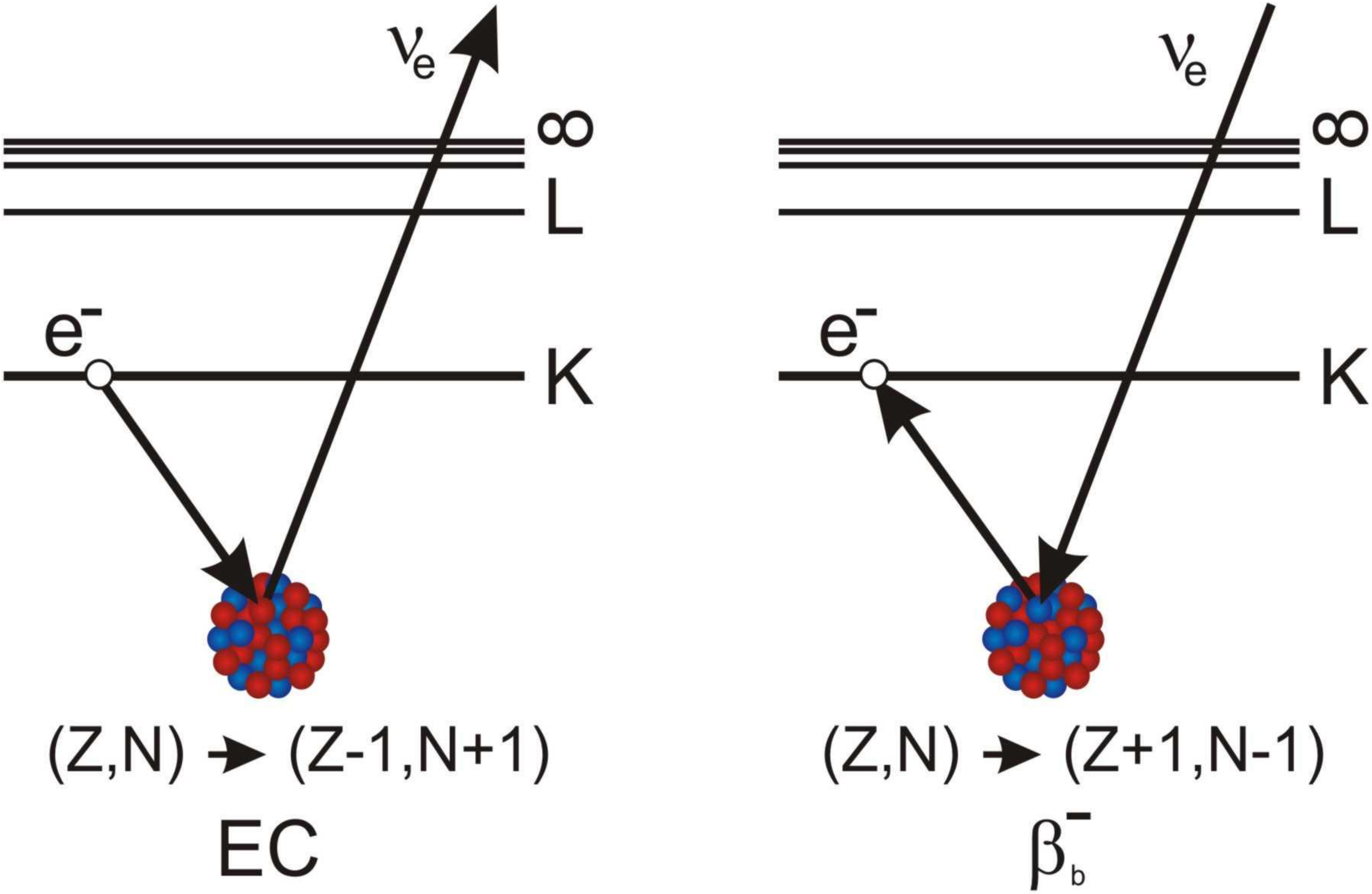
300 kHz / 60 MHz Schottky TCAP



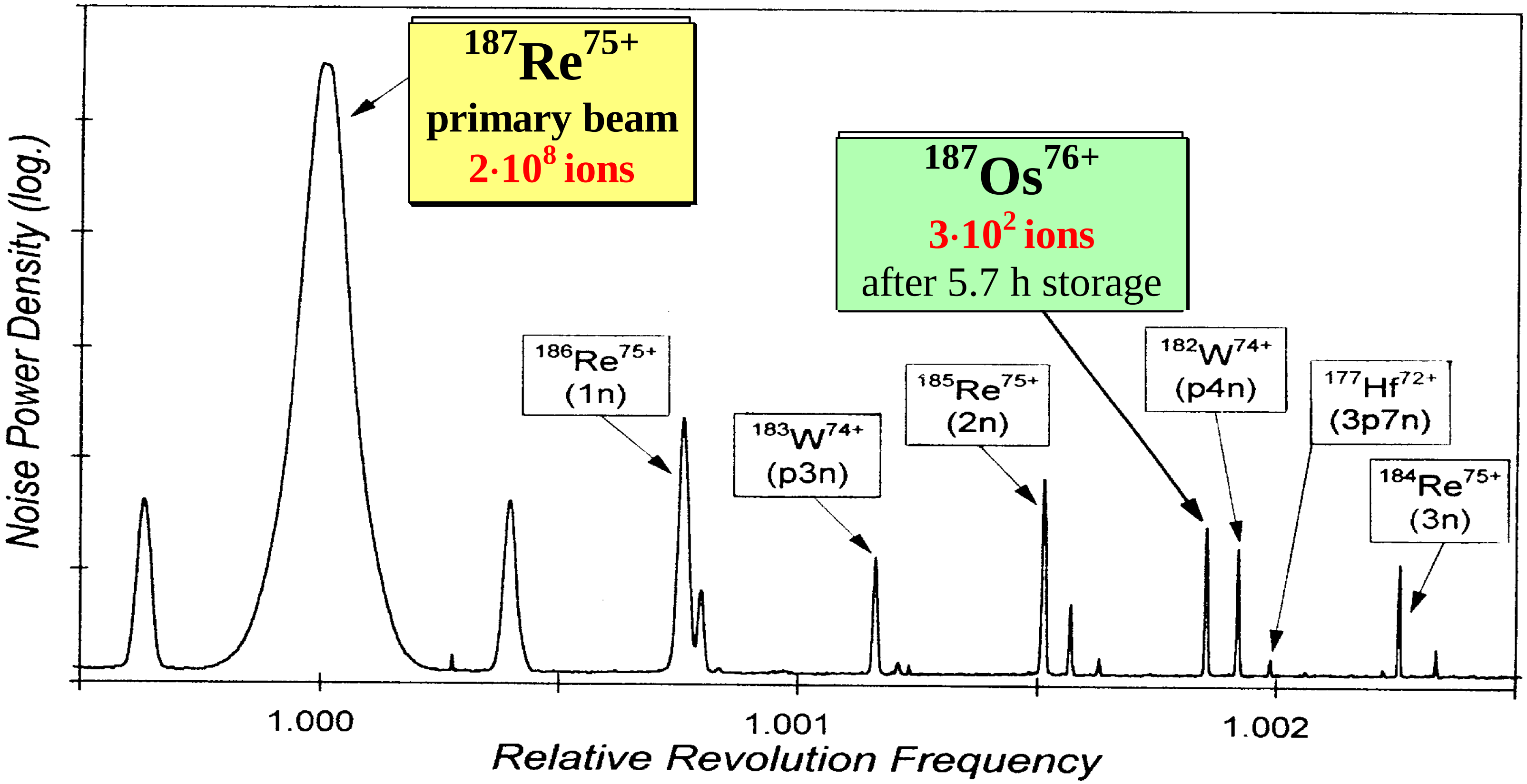
ILIMA: Masses and Halflives



Two-Body Beta Decay



SCHOTTKY SIGNAL OF THE BOUND-STATE β-DECAY $^{187}\mathrm{Re}^{75+} \rightarrow {}^{187}\mathrm{Os}^{75+}$



$^{187}\mathrm{Re}^{75+}$
primary beam
$2 \cdot 10^{8}$ ions

$^{187}\mathrm{Os}^{76+}$
$3 \cdot 10^{2}$ ions
after 5.7 h storage

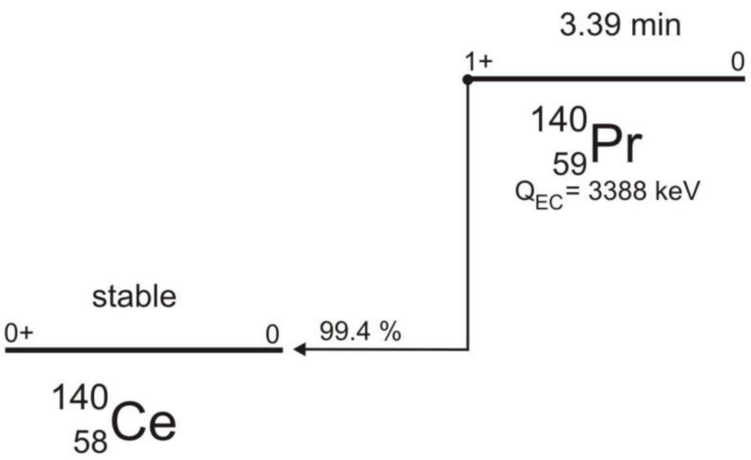
$T_{1/2}$ ($^{187}\mathrm{Re}^{75+}$) = 33(2) y

Orbital Electron Capture

Conventional EC-theory:

W. Bambynek et al., Rev. Mod. Phys. 49, 1977

Gamow-Teller allowed
transition 1^+ □ 0^+



S-electron density at the nucleus:

$|f_S(0)|^2$ □ $1/ n^3$

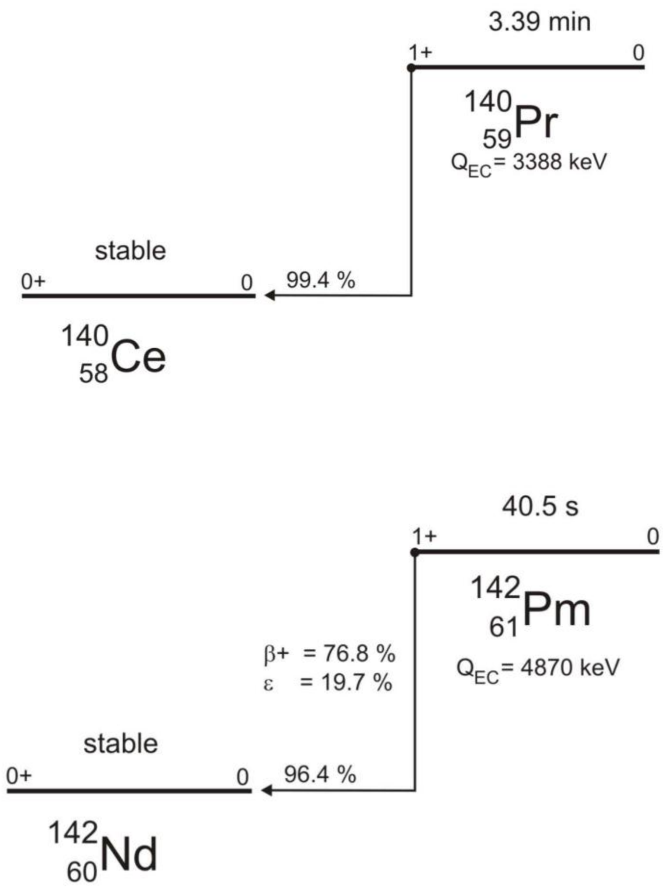
P_{EC} (neutral atom) □ 2 □ $1/ n^3 = 2.4$

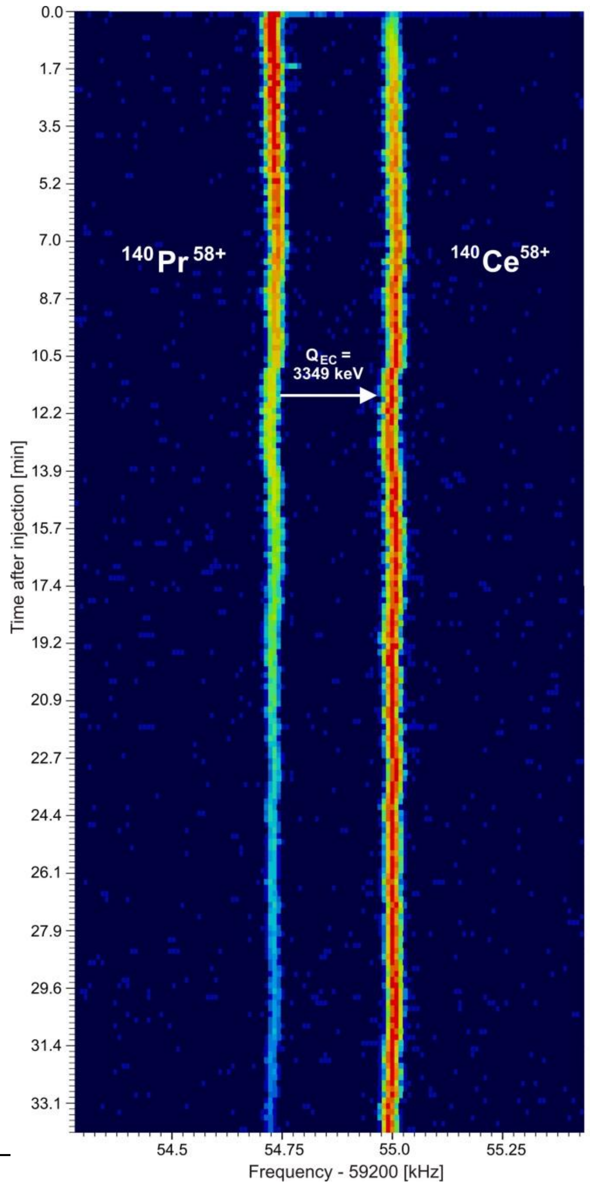
P_K (H-like) □ 1 □ $1/ 1^3 = 1$

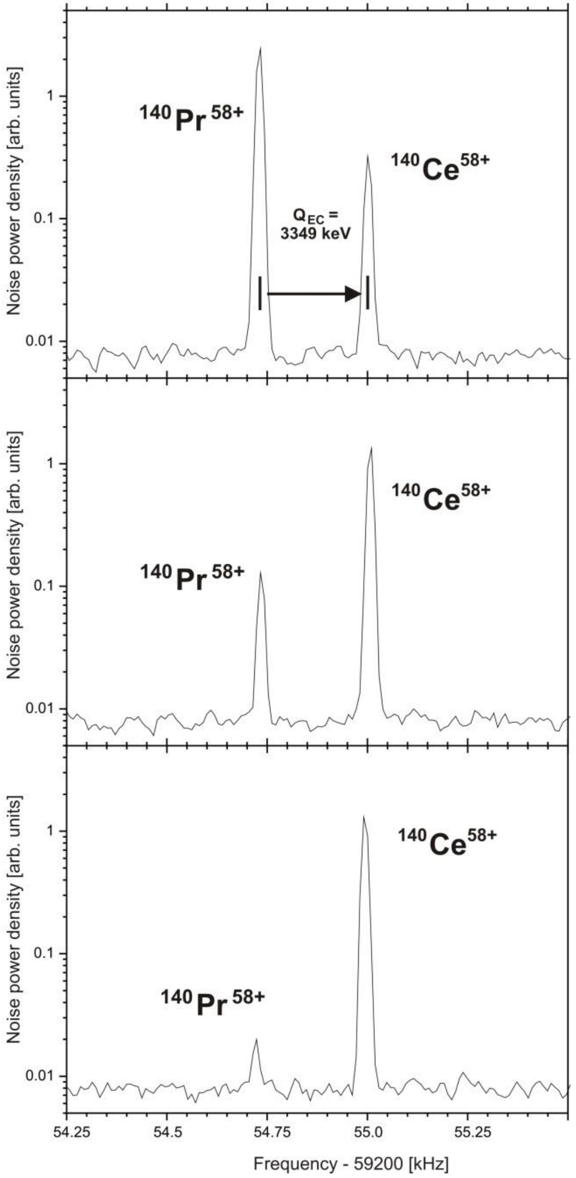
Conclusion:
H-Like ion should have 41%
longer half-life

⎿$_{EC}$(H-like)/⎿$_{EC}$(He-like) ≈ 0.5

Orbital Electron Capture Decay of Few-Electron Ions





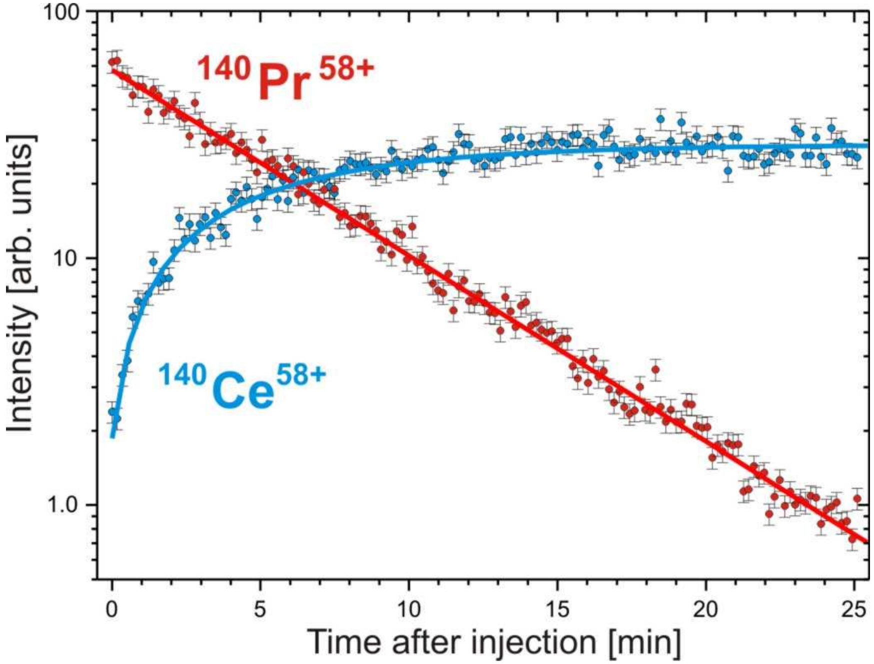


Orbital Electron Capture Decay of Few-Electron Ions

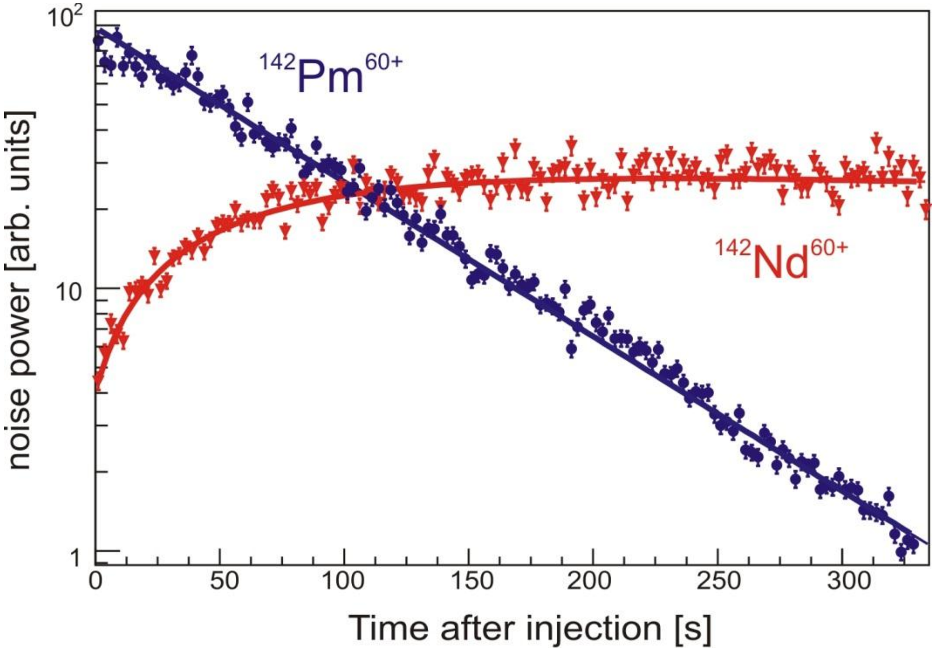
Expectations: $\lambda_{EC}(\text{H-like})/\lambda_{EC}(\text{He-like}) \approx 0.5$

$\lambda_{EC}(\text{H-like})/\lambda_{EC}(\text{He-like}) = 1.49(8)$

$\lambda_{EC}(\text{H-like})/\lambda_{EC}(\text{He-like}) = 1.44(6)$



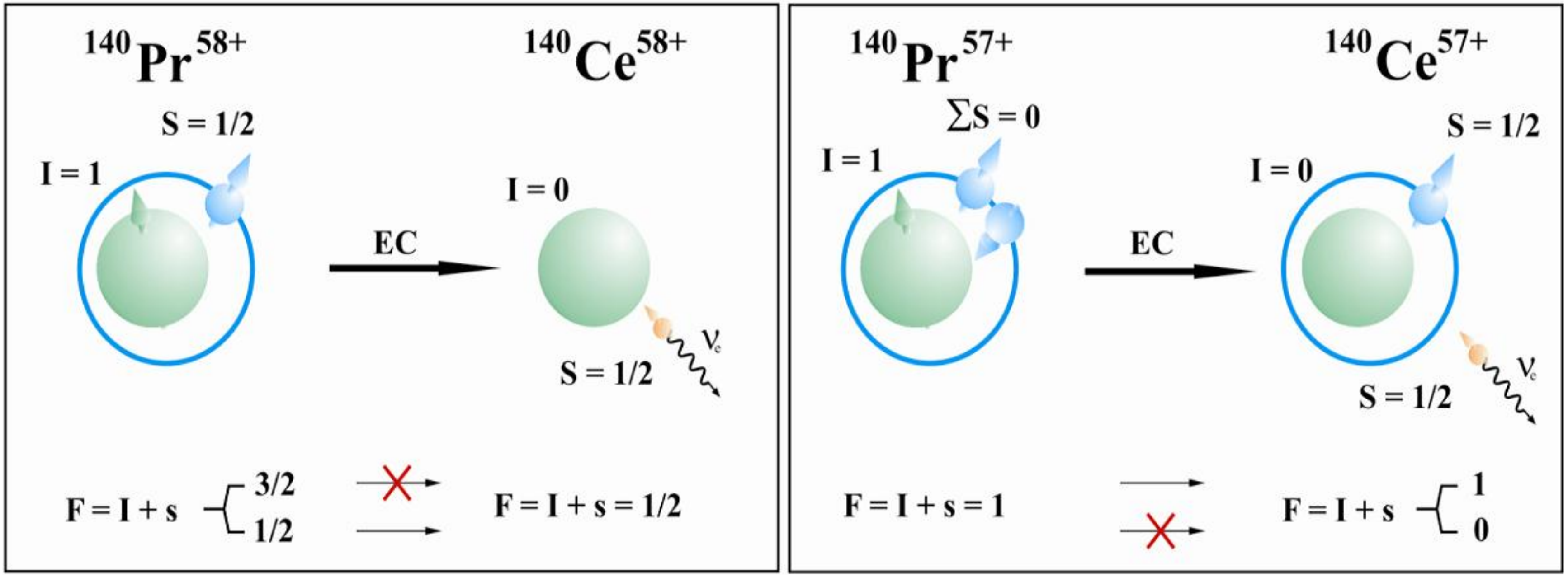
Yu.A. Litvinov et al., Phys. Rev. Lett. 99 (2007) 262501



N. Winckler et al., Phys. Lett. B579 (2009) 36

Orbital Electron Capture Decay of Few-Electron Ions

Gamow-Teller transition $1^+ \rightarrow 0^+$

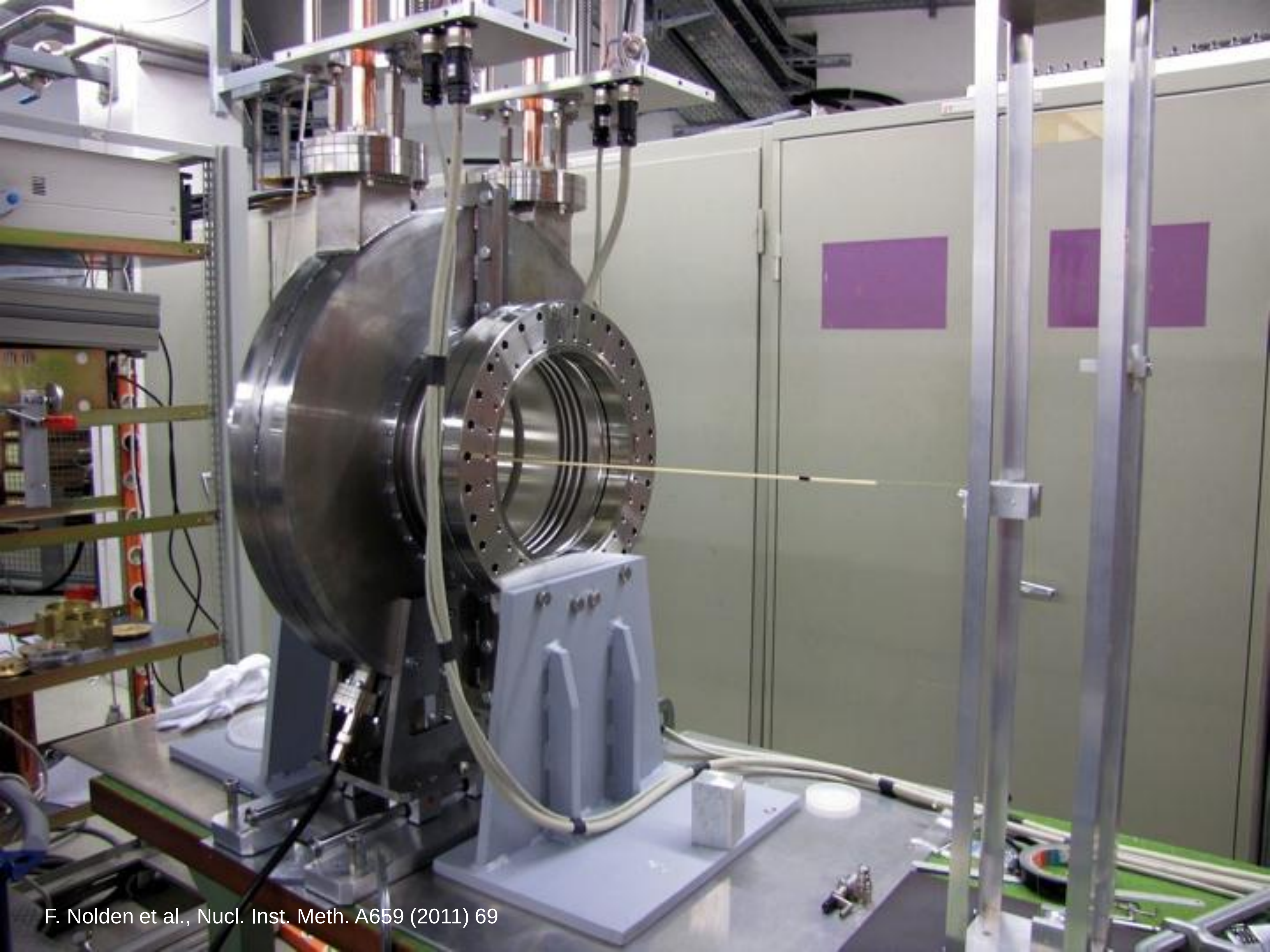


$\mu = +2.7812\mu_N$

I. N. Borzov et al., Phys. At. Nucl. (2009)

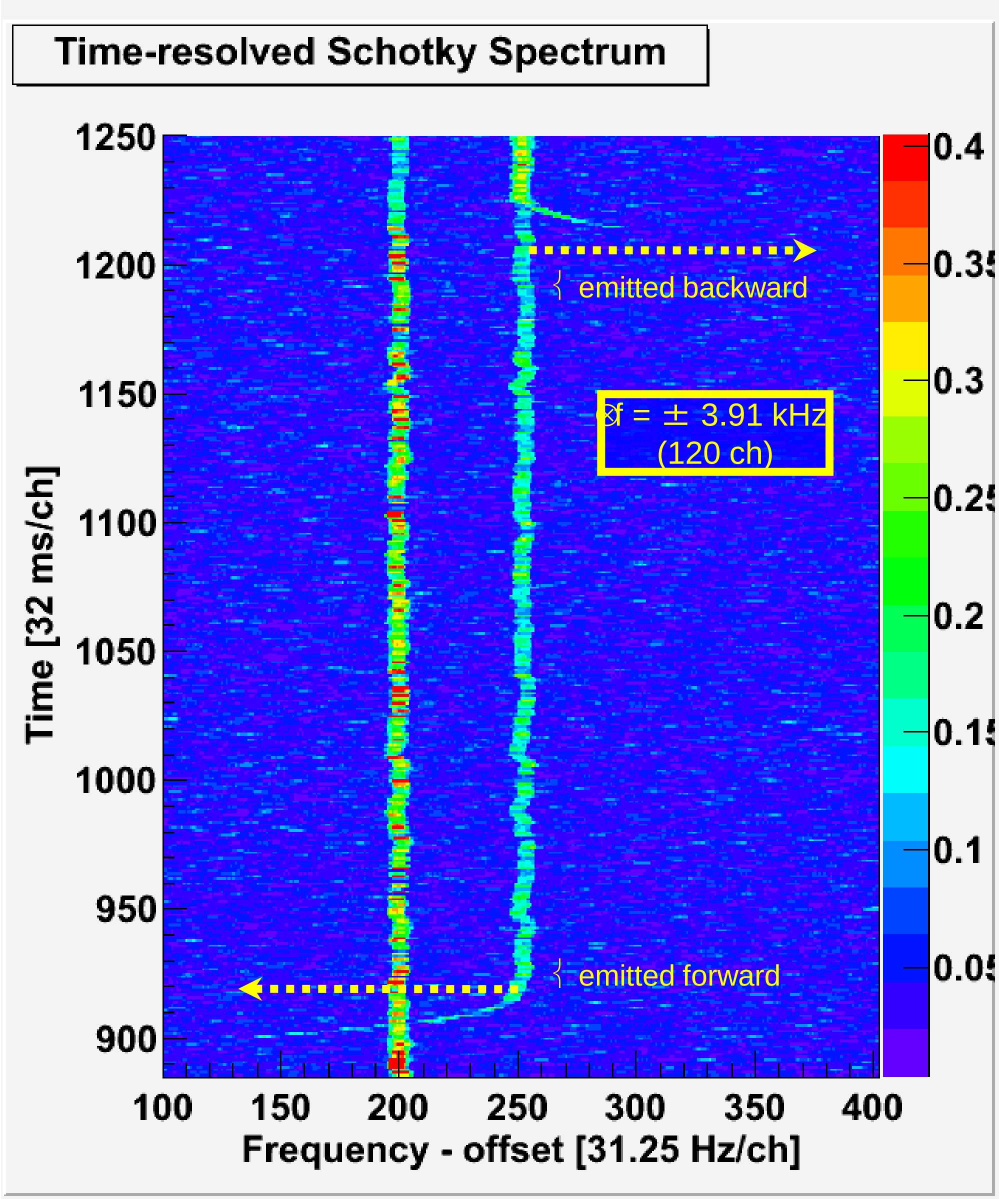
Theory: $\boxed{\lambda(H)/\lambda(He) = (2I+1)/(2F+1)}$

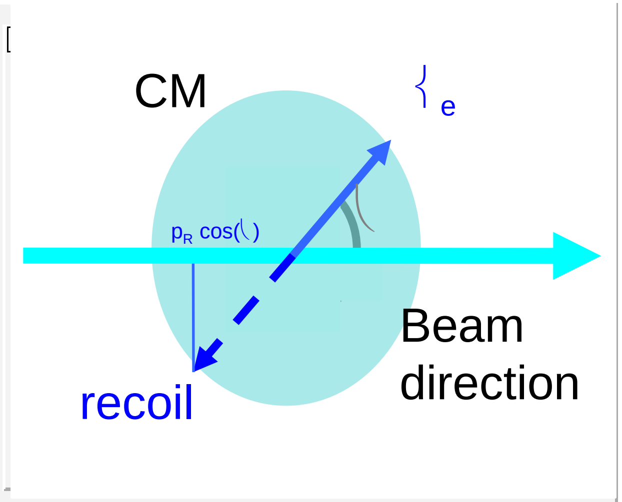
Z. Patyk et al., Phys. Rev. C 77 (2008) 014306

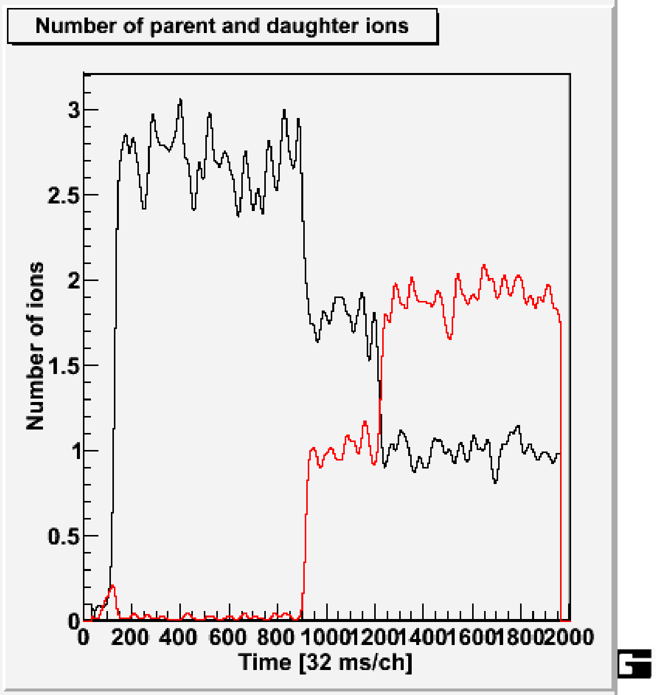


F. Nolden et al., Nucl. Inst. Meth. A659 (2011) 69

Three Parent He-Like ^{142}Pm Ions

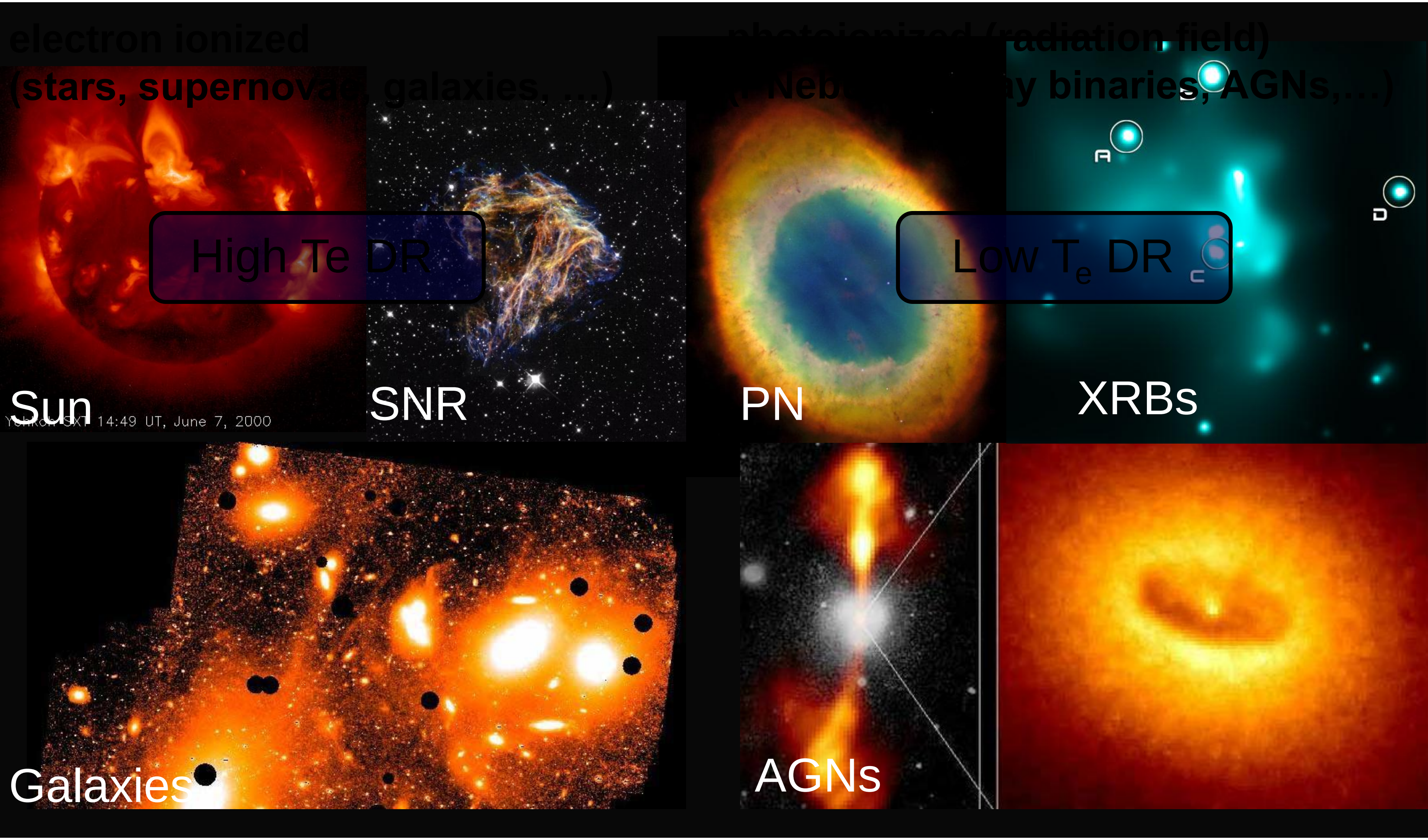

Time-resolved Schotky Spectrum




Number of parent and daughter ions

Photorecombination in cosmic plasmas

Courtesy D.W. Savin, Columbia Astrophysics Lab (CAL), New York, N.Y.



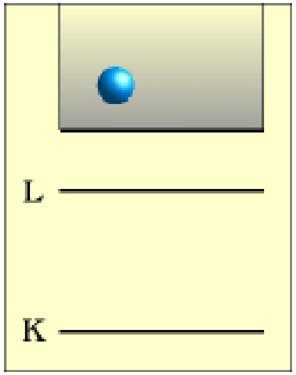
electron ionized
(stars, supernovae, galaxies, ...)

photoionized (radiation field)
(Neb[illegible]ay binaries, AGNs,...)

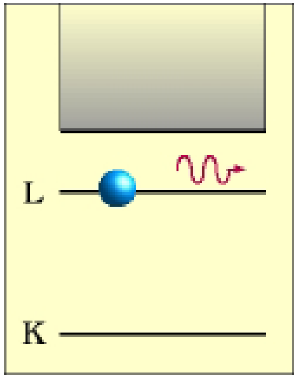
High Te DR

Low T_e DR

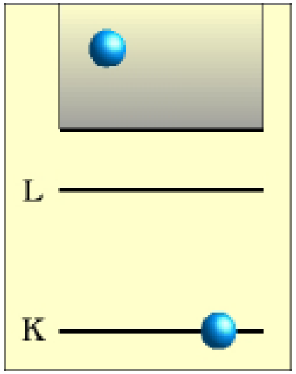
Radiative Recombination, Dielectronic Recombination and Nuclear Excitation by Electron Capture



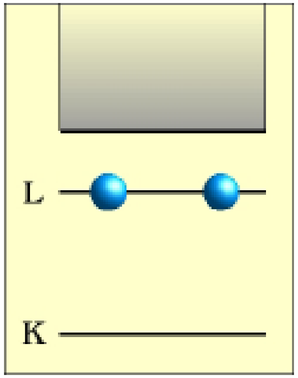
RR



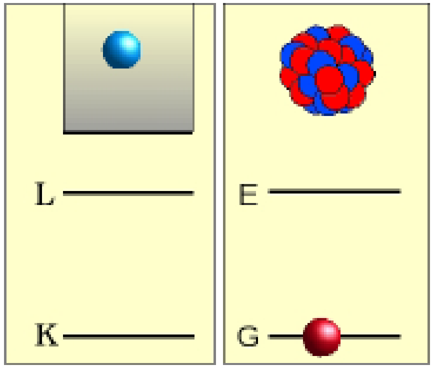
- direct process
- any electron energy
- electron-radiation field



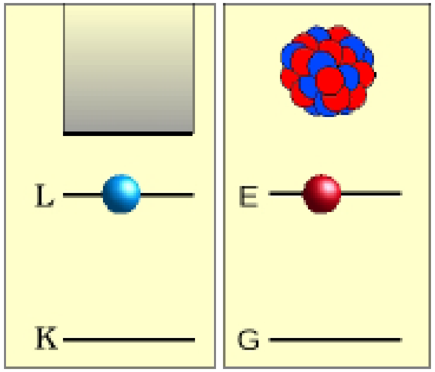
DR



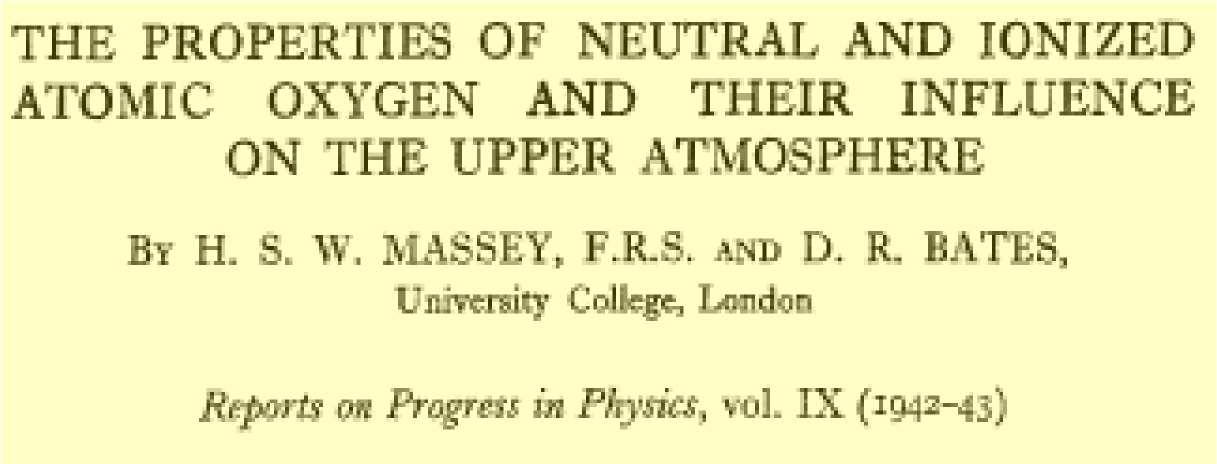
- resonant process
- Coulomb interaction
- Breit interaction



NEEC



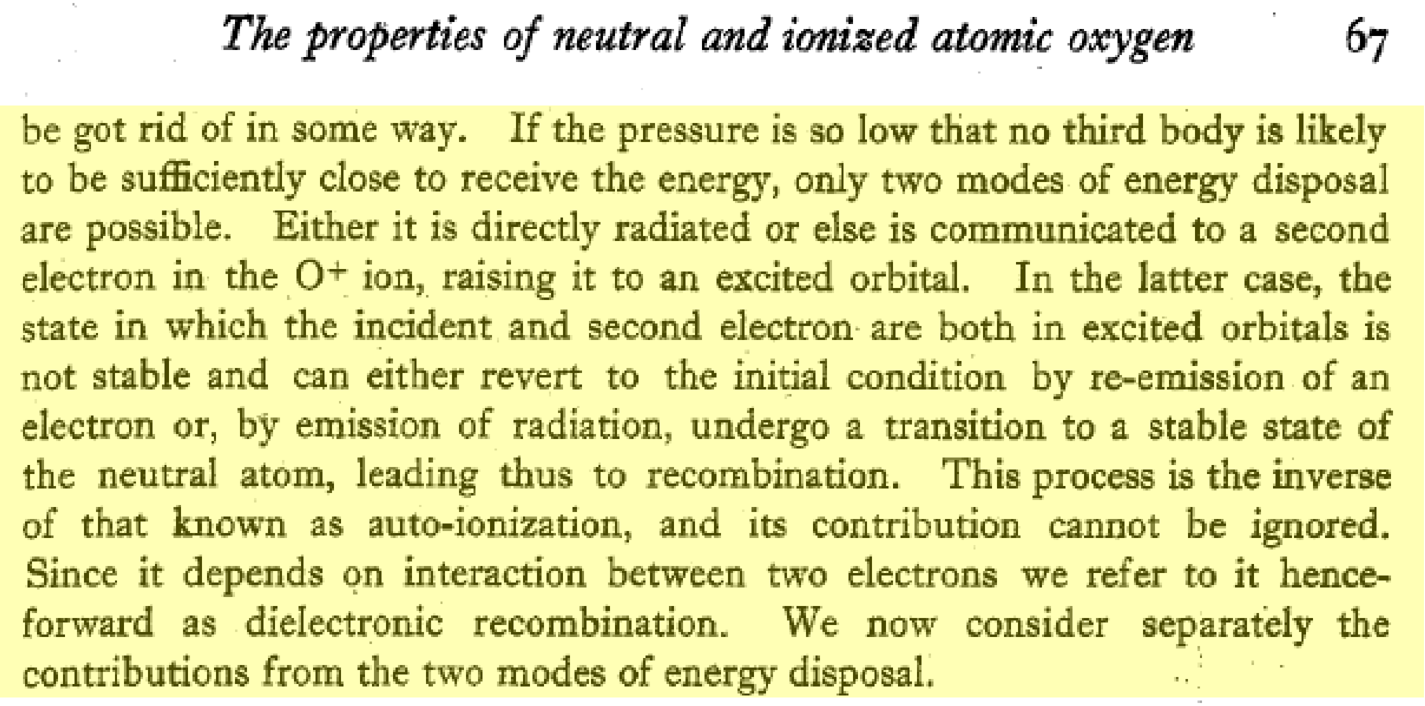
- resonant process
- Coulomb interaction
- current-current interaction



THE PROPERTIES OF NEUTRAL AND IONIZED ATOMIC OXYGEN AND THEIR INFLUENCE ON THE UPPER ATMOSPHERE

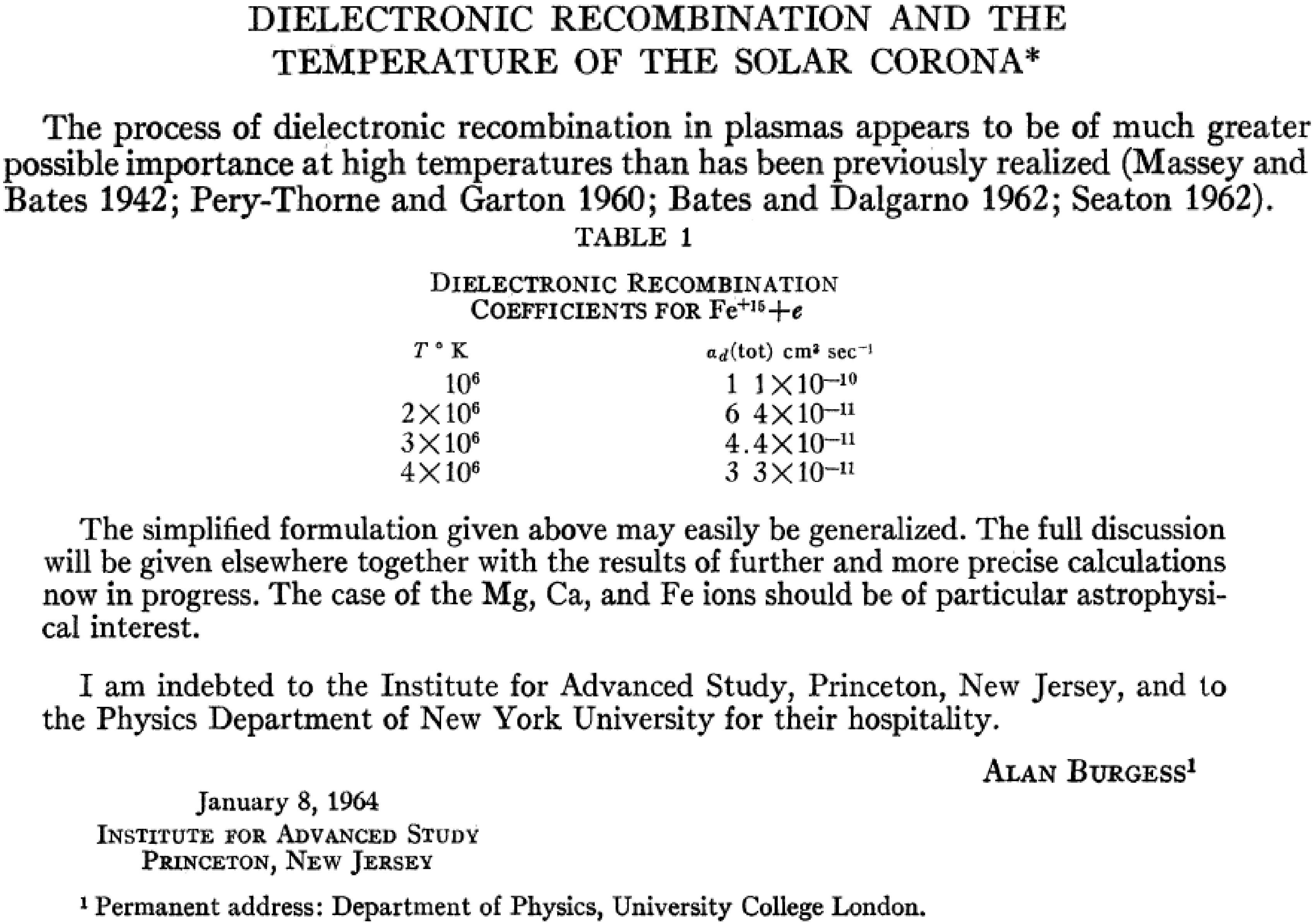
By H. S. W. MASSEY, F.R.S. and D. R. BATES,
University College, London

Reports on Progress in Physics, vol. IX (1942–43)



be got rid of in some way. If the pressure is so low that no third body is likely to be sufficiently close to receive the energy, only two modes of energy disposal are possible. Either it is directly radiated or else is communicated to a second electron in the O^+ ion, raising it to an excited orbital. In the latter case, the state in which the incident and second electron are both in excited orbitals is not stable and can either revert to the initial condition by re-emission of an electron or, by emission of radiation, undergo a transition to a stable state of the neutral atom, leading thus to recombination. This process is the inverse of that known as auto-ionization, and its contribution cannot be ignored. Since it depends on interaction between two electrons we refer to it henceforward as dielectronic recombination. We now consider separately the contributions from the two modes of energy disposal.

20 years later - Astrophys. J. 139, 776 (1964)



DIELECTRONIC RECOMBINATION AND THE TEMPERATURE OF THE SOLAR CORONA*

The process of dielectronic recombination in plasmas appears to be of much greater possible importance at high temperatures than has been previously realized (Massey and Bates 1942; Pery-Thorne and Garton 1960; Bates and Dalgarno 1962; Seaton 1962).

TABLE 1

DIELECTRONIC RECOMBINATION COEFFICIENTS FOR $Fe^{+15}+e$

T ° K	α_d(tot) cm³ sec⁻¹
10^6	$1\ 1\times10^{-10}$
2×10^6	$6\ 4\times10^{-11}$
3×10^6	4.4×10^{-11}
4×10^6	$3\ 3\times10^{-11}$

The simplified formulation given above may easily be generalized. The full discussion will be given elsewhere together with the results of further and more precise calculations now in progress. The case of the Mg, Ca, and Fe ions should be of particular astrophysical interest.

I am indebted to the Institute for Advanced Study, Princeton, New Jersey, and to the Physics Department of New York University for their hospitality.

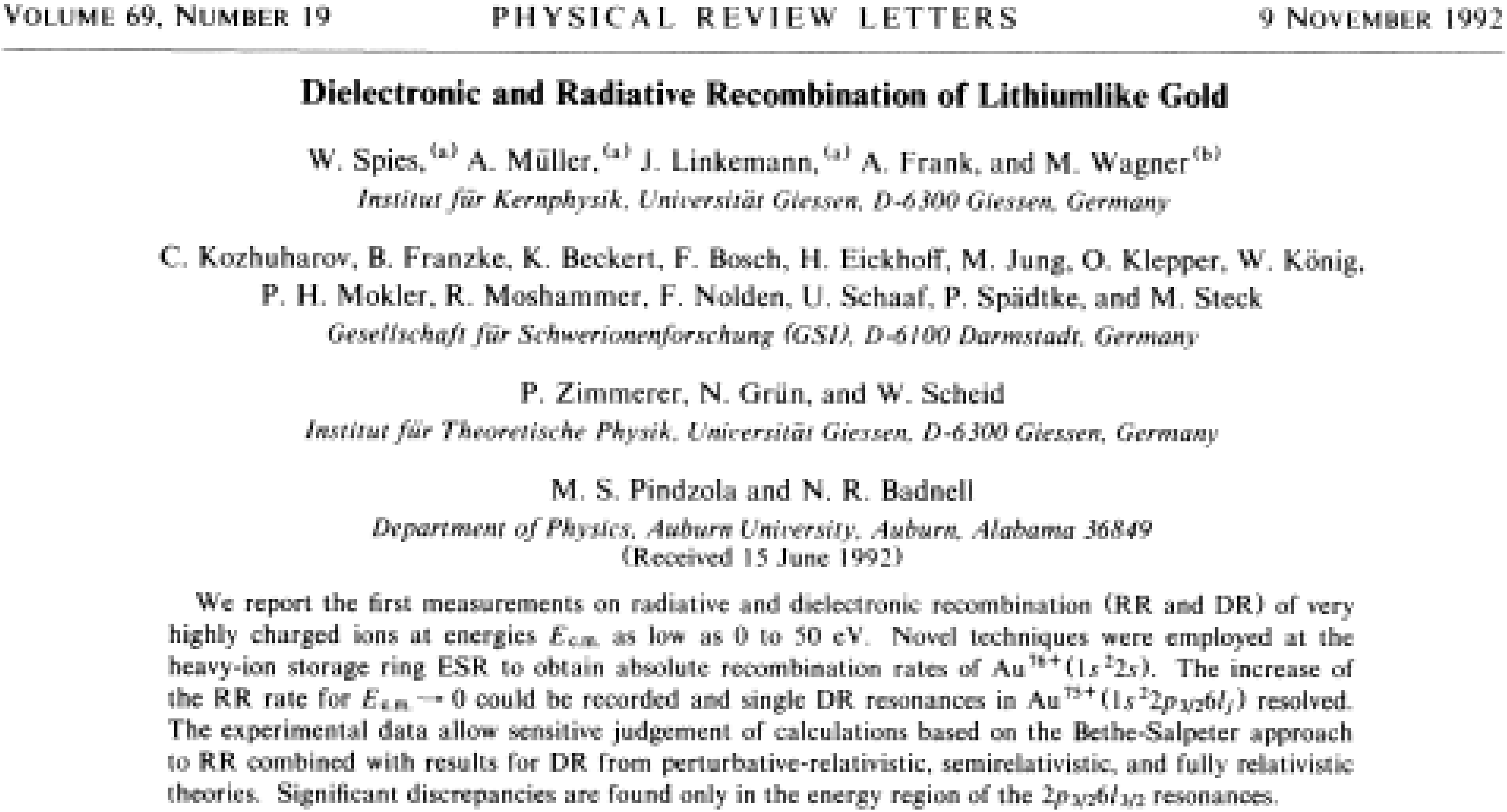
ALAN BURGESS[1]

January 8, 1964
INSTITUTE FOR ADVANCED STUDY
PRINCETON, NEW JERSEY

[1] Permanent address: Department of Physics, University College London.

40 years later – J.B..A. Mitchell et al, PRL. 50, 335 (1983), D.S. Belic et al PRL 50 339 (1983), P.F. Dittner et al. PRL 51 31 (1983) ➔ **first experimental observations**

49 Years later (20 years ago): First GSI-ESR PRL



VOLUME 69, NUMBER 19 PHYSICAL REVIEW LETTERS 9 NOVEMBER 1992

Dielectronic and Radiative Recombination of Lithiumlike Gold

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Gesellschaft für Schwerionenforschung (GSI), D-6100 Darmstadt, Germany

P. Zimmerer, N. Grün, and W. Scheid
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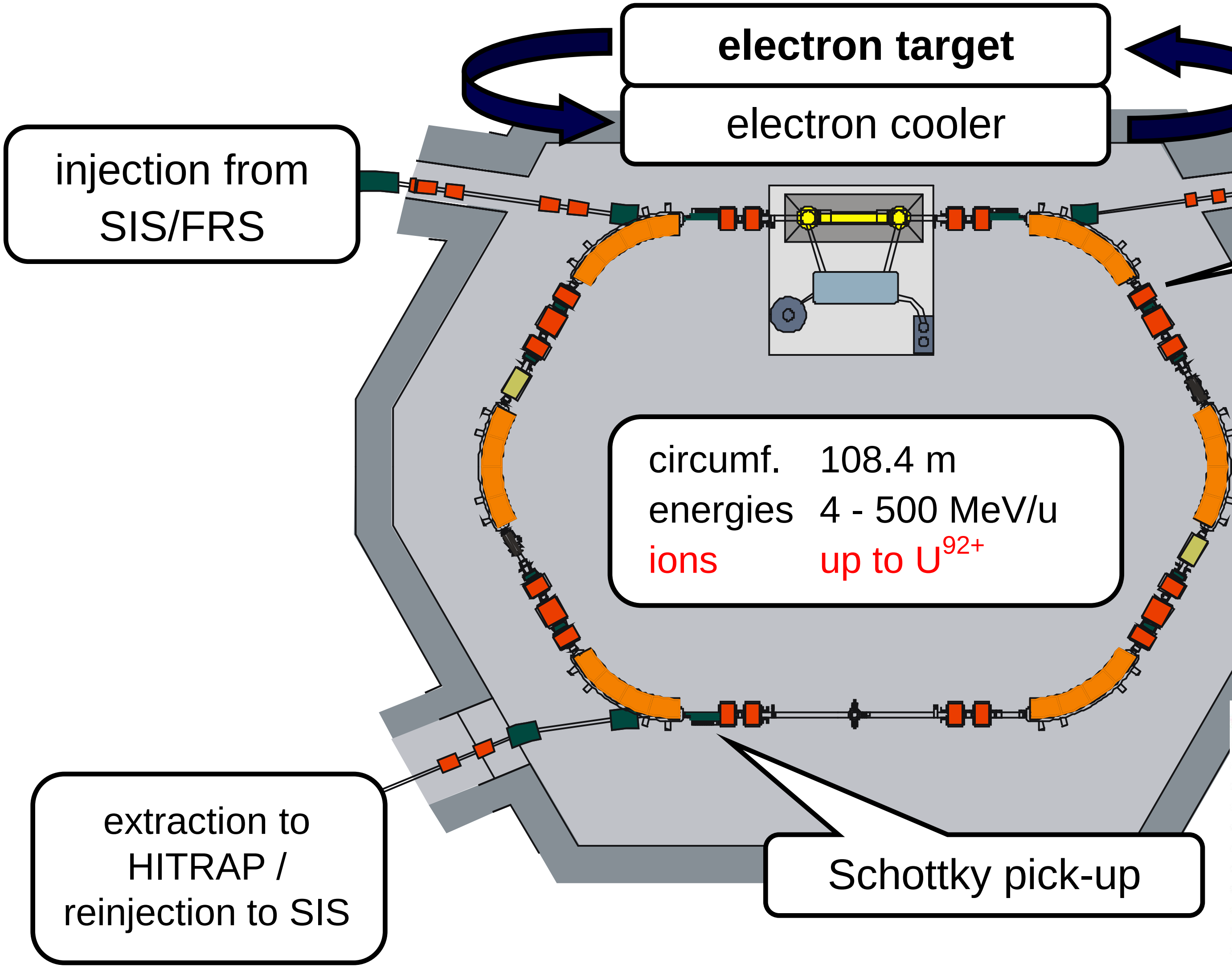
M. S. Pindzola and N. R. Badnell
Department of Physics, Auburn University, Auburn, Alabama 36849

(Received 15 June 1992)

We report the first measurements on radiative and dielectronic recombination (RR and DR) of very highly charged ions at energies $E_{\mathrm{c.m.}}$ as low as 0 to 50 eV. Novel techniques were employed at the heavy-ion storage ring ESR to obtain absolute recombination rates of $\mathrm{Au}^{76+}(1s^2 2s)$. The increase of the RR rate for $E_{\mathrm{c.m.}} \to 0$ could be recorded and single DR resonances in $\mathrm{Au}^{75+}(1s^2 2p_{3/2} 6l_j)$ resolved. The experimental data allow sensitive judgement of calculations based on the Bethe-Salpeter approach to RR combined with results for DR from perturbative-relativistic, semirelativistic, and fully relativistic theories. Significant discrepancies are found only in the energy region of the $2p_{3/2}6l_{3/2}$ resonances.

Experimental Storage Ring



electron target

electron cooler

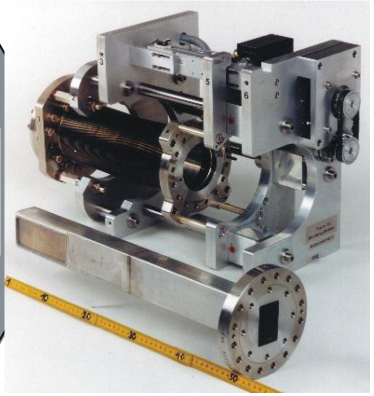
injection from SIS/FRS

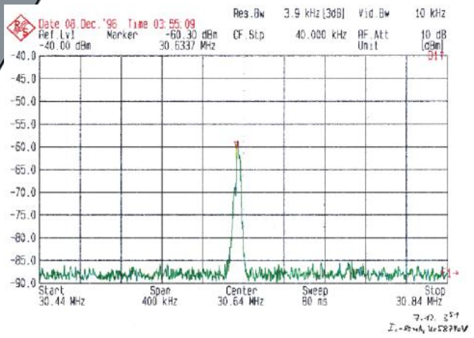
recombination detector

circumf.	108.4 m
energies	4 - 500 MeV/u
ions	up to U^{92+}

extraction to HITRAP / reinjection to SIS

Schottky pick-up



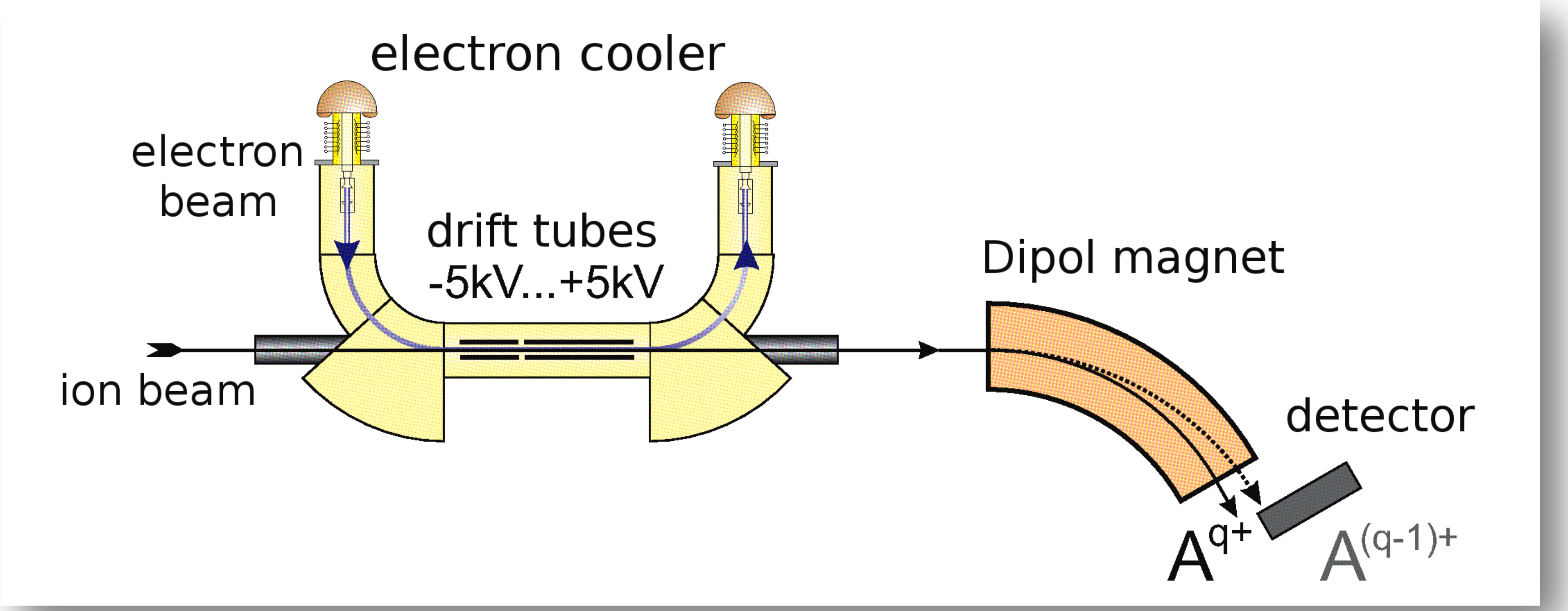


Cooled ion beams in well-defined ionic states

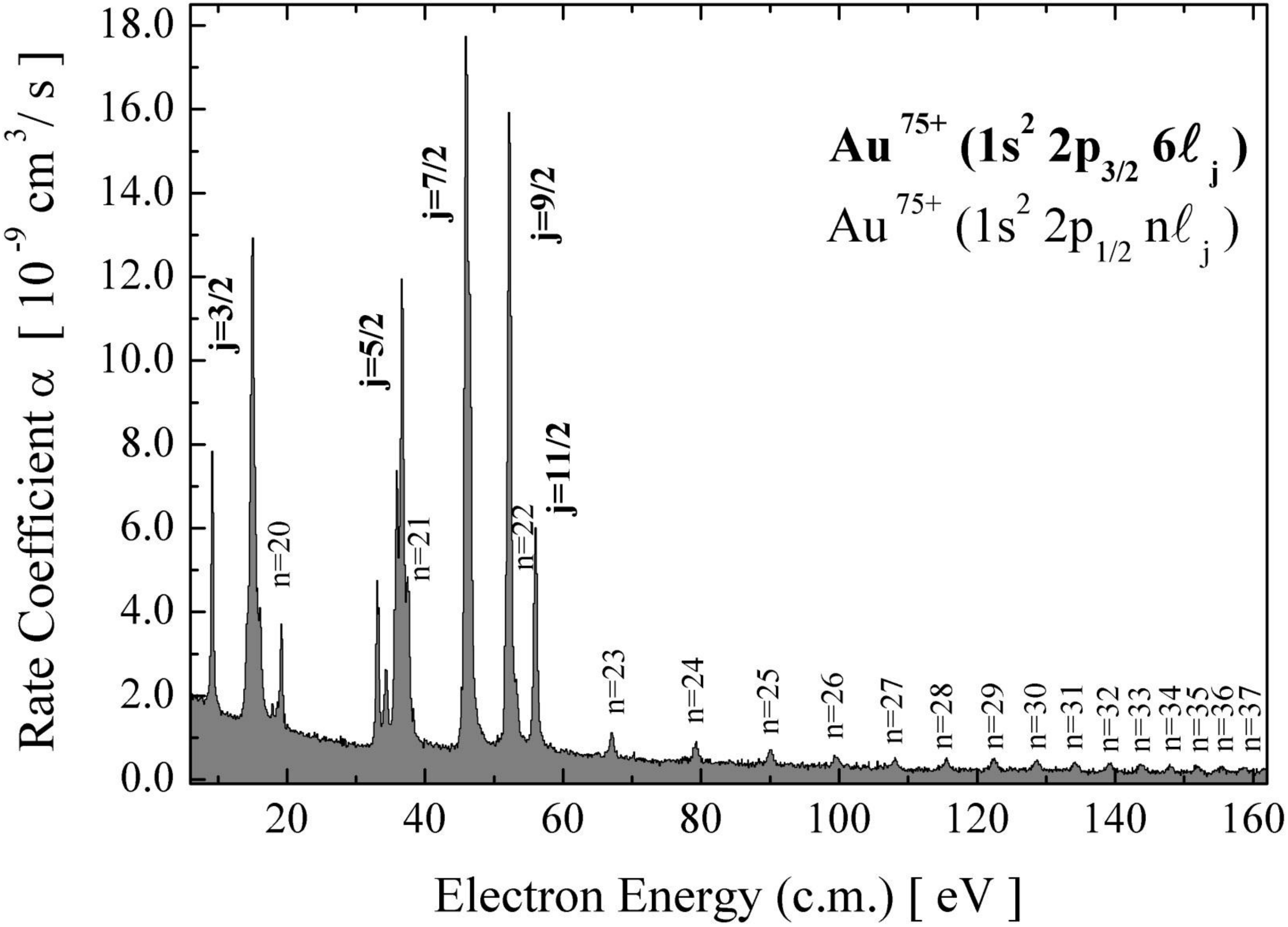
DR-Measurement

- Merged electron and ion beams
- Drift-tube defined variation of the relative ion-electron velocities
- Recombination
- Separation by the ESR dipol magnet
- Single particle detection (4π)

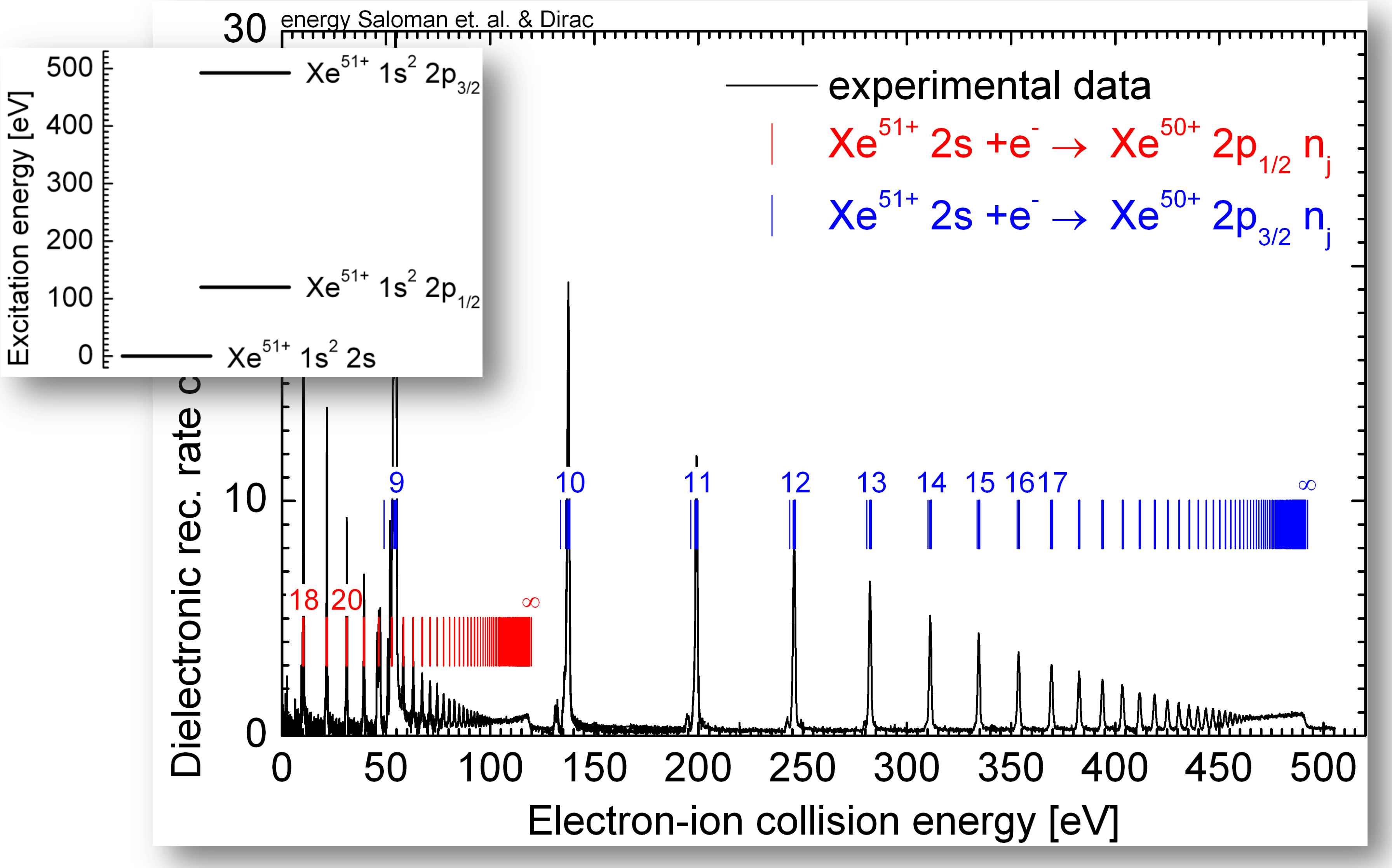
$$\alpha(E_{CM}) = \langle v_{rel}\sigma(E_{CM}) \rangle = \frac{1}{1-\beta_e\beta_i}\frac{R}{N_{Ion}n_e\, {}^{L}\!/\!_{U}}$$



Dielectronic Recombination of Li-like Gold



Li-like Xe^{51+}



energy Saloman et. al. & Dirac
30
10
0
Dielectronic rec. rate c
0
50
100
150
200
250
300
350
400
450
500
Electron-ion collision energy [eV]
experimental data
Xe51+ 2s +e- → Xe50+ 2p1/2 nj
Xe51+ 2s +e- → Xe50+ 2p3/2 nj
9
10
11
12
13
14
15
16
17
∞
18
20
∞
Excitation energy [eV]
500
400
300
200
100
0
Xe51+ 1s2 2p3/2
Xe51+ 1s2 2p1/2
Xe51+ 1s2 2s

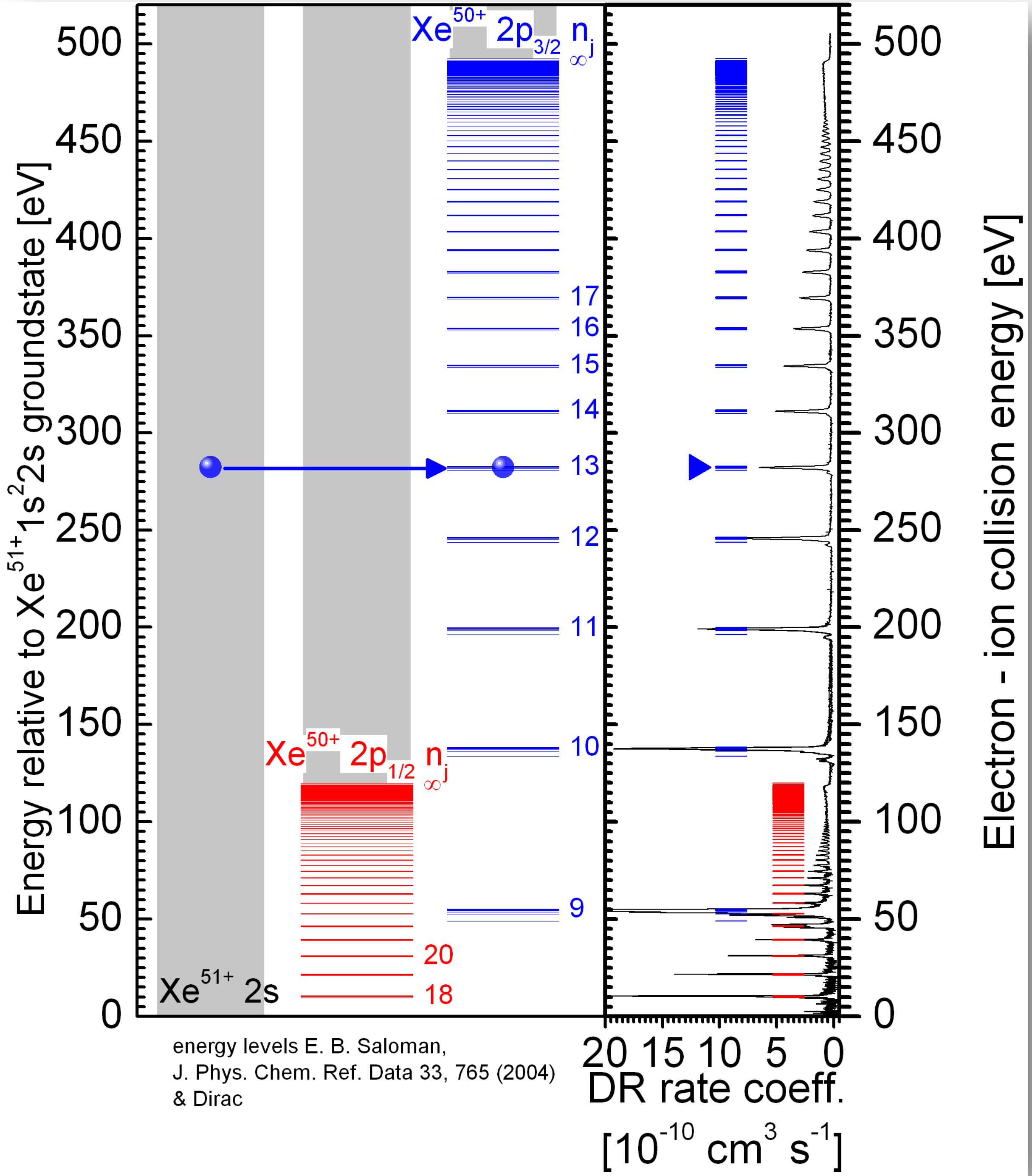
Li-like Xe^{51+}

(preliminary)

Continuum electron are captures into series of Rydberg state up to the series limit for both types of excitation of the 2s electron:

$2s \rightarrow 2p_{1/2}$

$2s \rightarrow 2p_{3/2}$



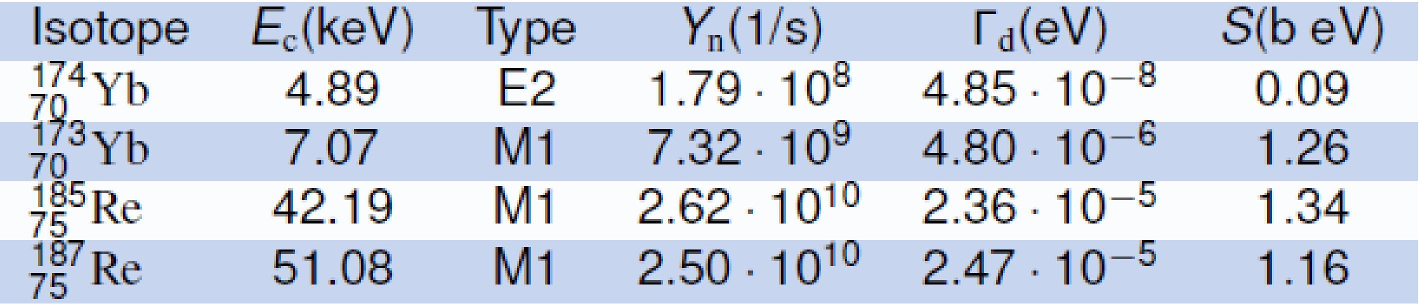
energy levels E. B. Saloman, J. Phys. Chem. Ref. Data 33, 765 (2004) & Dirac

NEEC

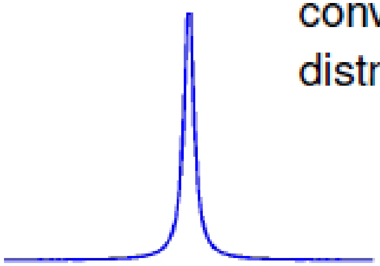
first mentioned by Goldanskii & Namiot Phys. Lett. 62B (1976)

Natural line widths 10^{-8} – 10^{-5} eV
Resonance strength 1 beV

A. Pálffy, Z. Harman, W. Scheidt, PRA 73(2006)012715



Isotope	E_c(keV)	Type	Y_n(1/s)	Γ_d(eV)	S(b eV)
$^{174}_{70}\mathrm{Yb}$	4.89	E2	$1.79 \cdot 10^8$	$4.85 \cdot 10^{-8}$	0.09
$^{173}_{70}\mathrm{Yb}$	7.07	M1	$7.32 \cdot 10^9$	$4.80 \cdot 10^{-6}$	1.26
$^{185}_{75}\mathrm{Re}$	42.19	M1	$2.62 \cdot 10^{10}$	$2.36 \cdot 10^{-5}$	1.34
$^{187}_{75}\mathrm{Re}$	51.08	M1	$2.50 \cdot 10^{10}$	$2.47 \cdot 10^{-5}$	1.16



convolution with realistic electron energy distribution

$$\frac{1}{s\sqrt{2\pi}} \exp\left(-\frac{(E-E_0)^2}{2s^2}\right)$$

Main Idea, Feasibility, Proposal

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Physics Letters B 661 (2008) 330–334
www.elsevier.com/locate/physletb

Nuclear excitation by electron capture followed by fast x-ray emission

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Christoph H. Keitel [a], Werner Scheid [c], Thomas Stöhlker [b,d]

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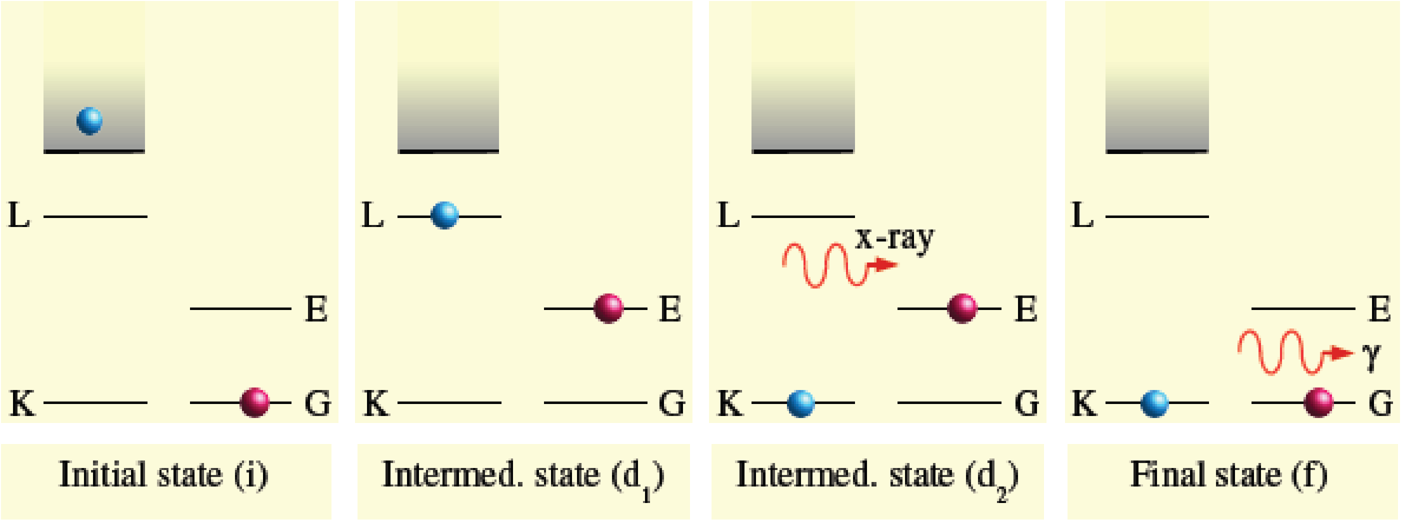
Available online 20 February 2008

Editor: V. Metag

(Challenge - only a few events per minute)

What would happen…

...if capture does not occur into the ground state!



NEECX into L shell of $^{238}_{92}\mathrm{U}$

Basic Idea for a NEECx experiment

- **Illustrative Example: ^{238}U**
- The first excited state in ^{238}U decays predominantly via L-IC (44.9 keV)
- Bare uranium ions bombard cold electron target with the appropriate energy ➔ ➔ an electron is captured into the L shell and the nucleus is excited.
- K-vacancies in uranium decay in 10^{-17} sec, the L-electron goes to the K-shell, i.e. this partial decay width dominates the total one.
- The competing process of radiative recombination, RR, is very fast.
- The excited nucleus leaves the RR-background zone
- The excited nucleus can decay only via gamma emission – i.e. slower by the conversion coefficient (270)
- The gammas can be detected in a background free zone in coincidence with ions which have captured one electron
- The colder the electrons – the better.
- (The experimental proposal is currently being prepared.)

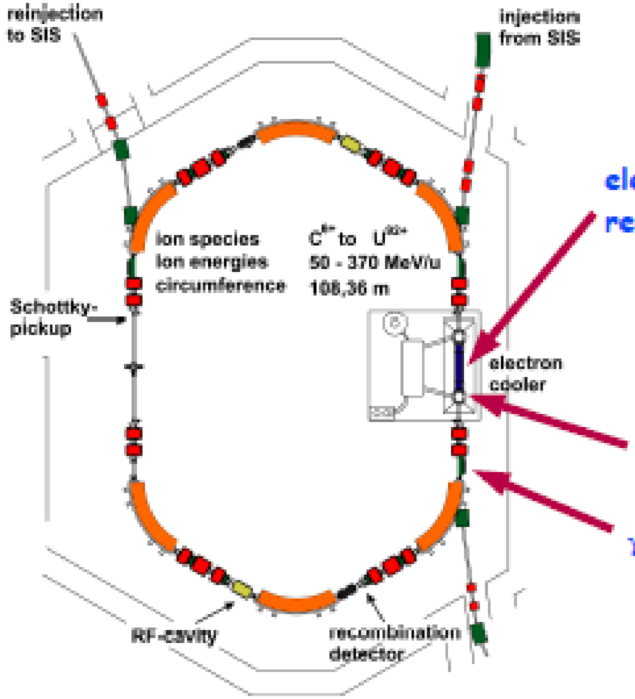
NEEC with and without x-ray

		He-, Be-, C-like ions	bare ions
$^{A}_{Z}\mathrm{X}$	nl_j	S_{NEEC}(b eV)	S_{NEECX}(beV)
$^{238}_{92}\mathrm{U}$	$2s_{1/2}$	8.8×10^{-3}	5.37×10^{-2}
	$2p_{1/2}$	9.2×10^{-3}	1.58
	$2p_{3/2}$	2.7×10^{-3}	1.16
$^{232}_{90}\mathrm{Th}$	$2s_{1/2}$	5.9×10^{-3}	2.04×10^{-2}
	$2p_{1/2}$	7.7×10^{-3}	6.53×10^{-1}
	$2p_{3/2}$	2.6×10^{-3}	5.51×10^{-1}

IC channel is suppressed → gain of two orders of magnitude

Prolongation of nuclear state lifetime via NEECX

	neutral	bare/H-like		Li-, B-, N-like
$^{A}_{Z}\mathrm{X}$	τ_0 (ns)	τ_γ (ns)	nl_j	τ_{nl_j} (ns)
$^{238}_{92}\mathrm{U}$	0.292	185	$2s_{1/2}$	36.2
			$2p_{1/2}$	1.54
			$2p_{3/2}$	0.67
$^{232}_{90}\mathrm{Th}$	0.497	150	$2s_{1/2}$	50.1
			$2p_{1/2}$	2.35
			$2p_{3/2}$	1.04



electron recombination

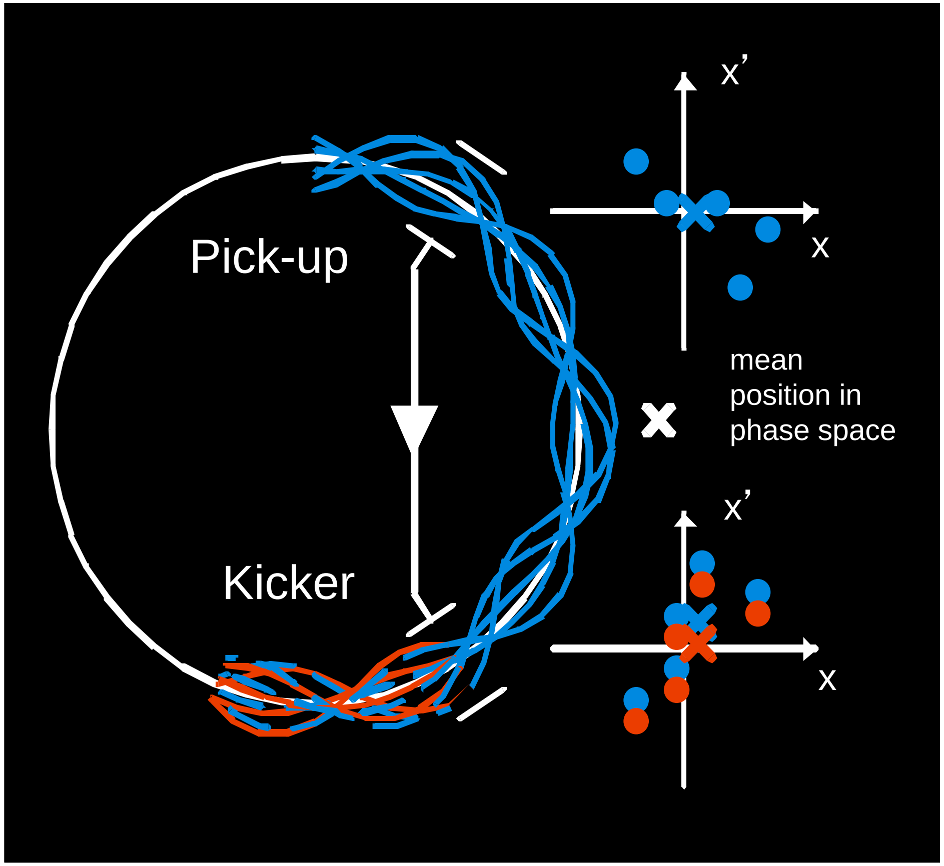
RR photons

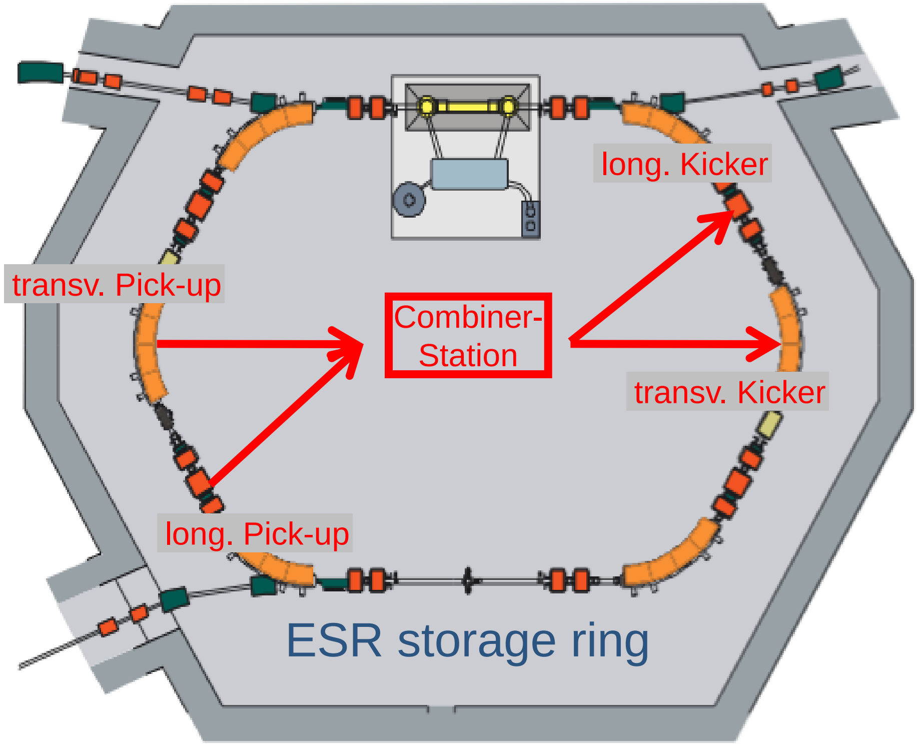
γ photons

- different time scales of NEEC and RR → spatial separation of emitted photons
- RR photons $\simeq 10^{-14} - 10^{-16}$
- γ photons $\simeq 10^{-9} - 10^{-11}$

$$\tau \simeq 10 - 100 \text{ ns} \rightarrow 2 - 20 \text{ m}$$

Stochastic Cooling

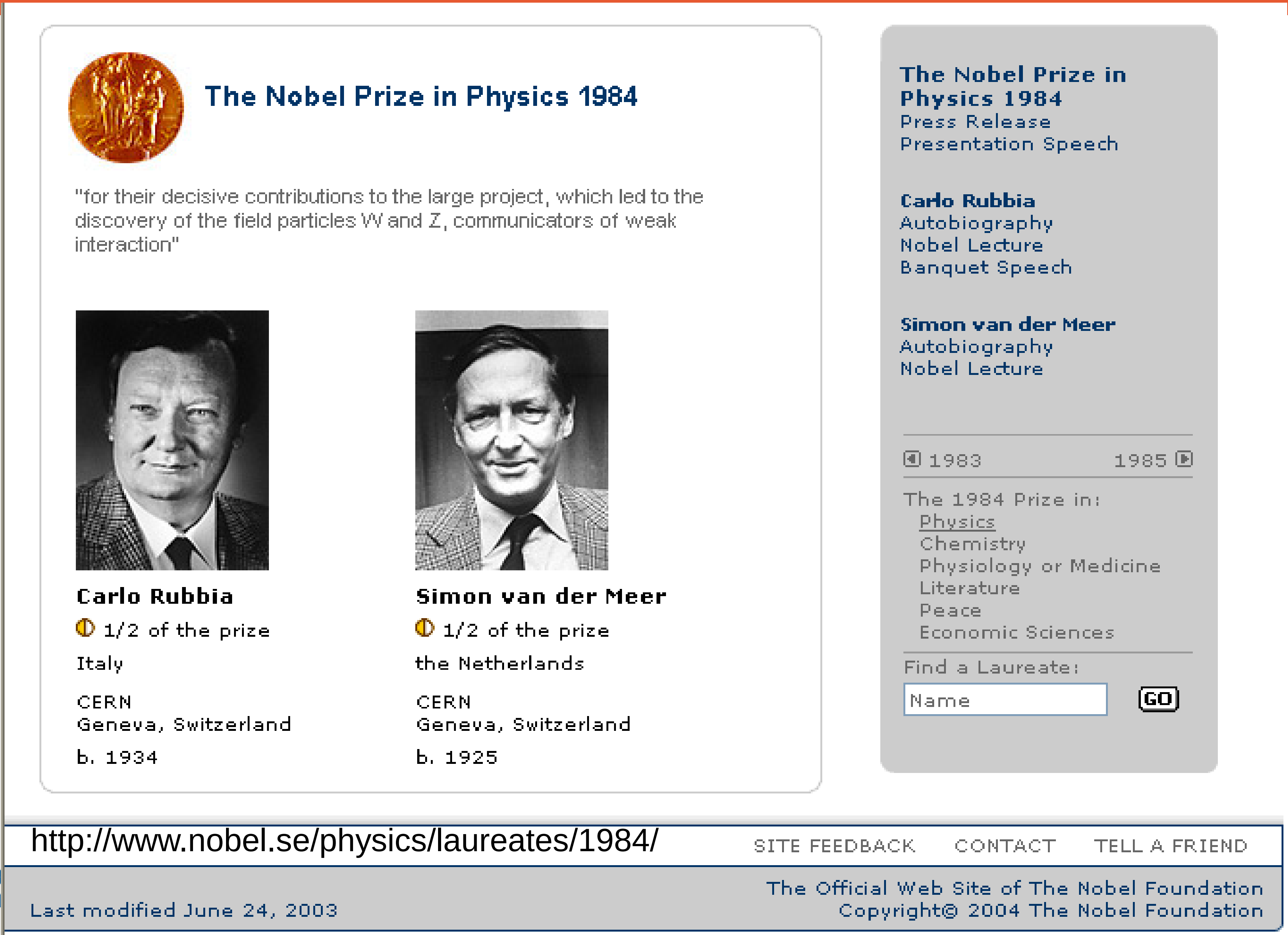




Stochastic cooling is in particular efficient for hot ion beams

Cooling time τ scales as N_{ion} / bandwith

Stochastic cooling (self-correction of trajectory)



The Nobel Prize in Physics 1984

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

Carlo Rubbia

◐ 1/2 of the prize

Italy

CERN
Geneva, Switzerland

b. 1934

Simon van der Meer

◐ 1/2 of the prize

the Netherlands

CERN
Geneva, Switzerland

b. 1925

The Nobel Prize in Physics 1984
Press Release
Presentation Speech

Carlo Rubbia
Autobiography
Nobel Lecture
Banquet Speech

Simon van der Meer
Autobiography
Nobel Lecture

◀ 1983 1985 ▶

The 1984 Prize in:
- Physics
- Chemistry
- Physiology or Medicine
- Literature
- Peace
- Economic Sciences

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Name GO

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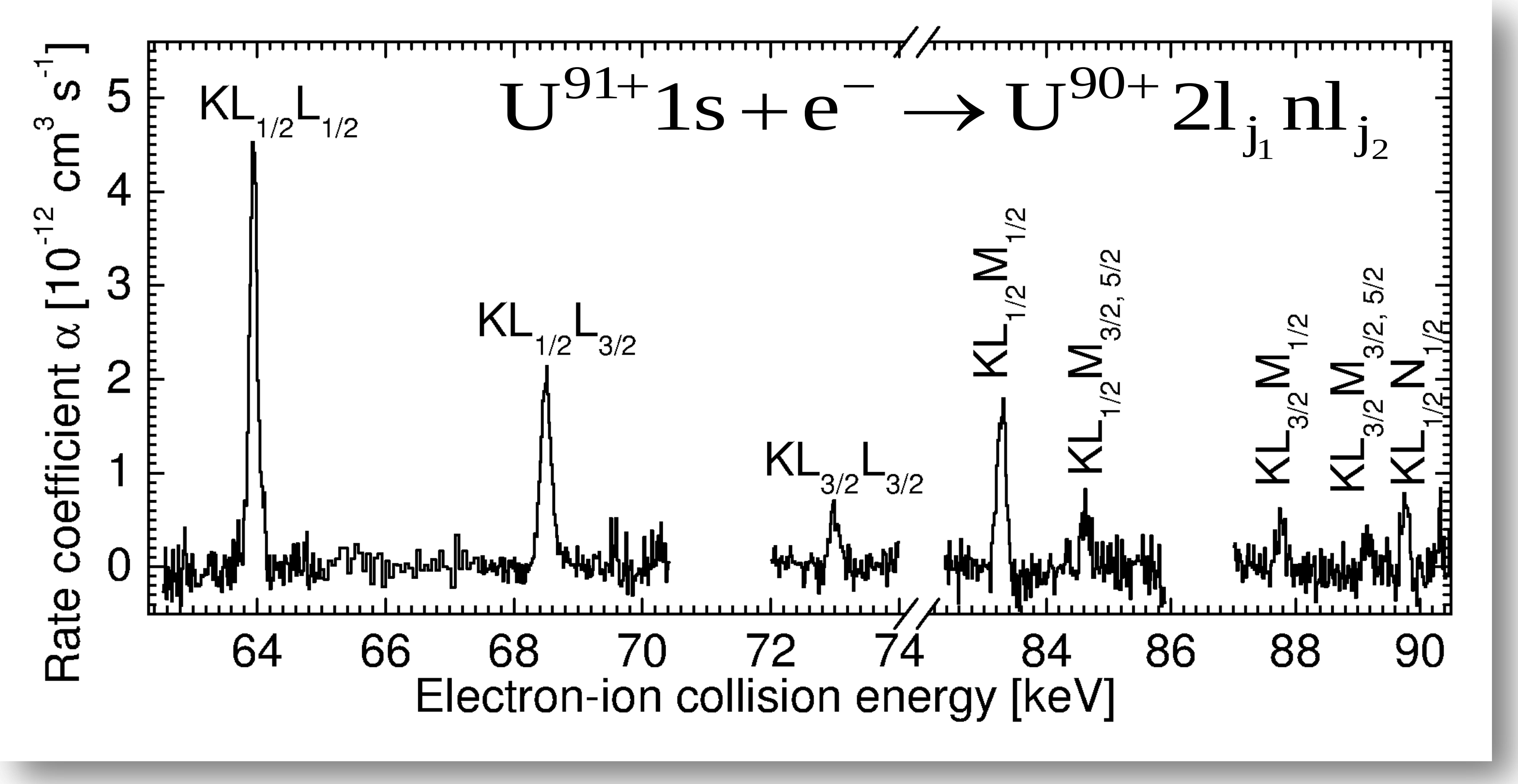
The Official Web Site of The Nobel Foundation

DR of H-like U^{91+}

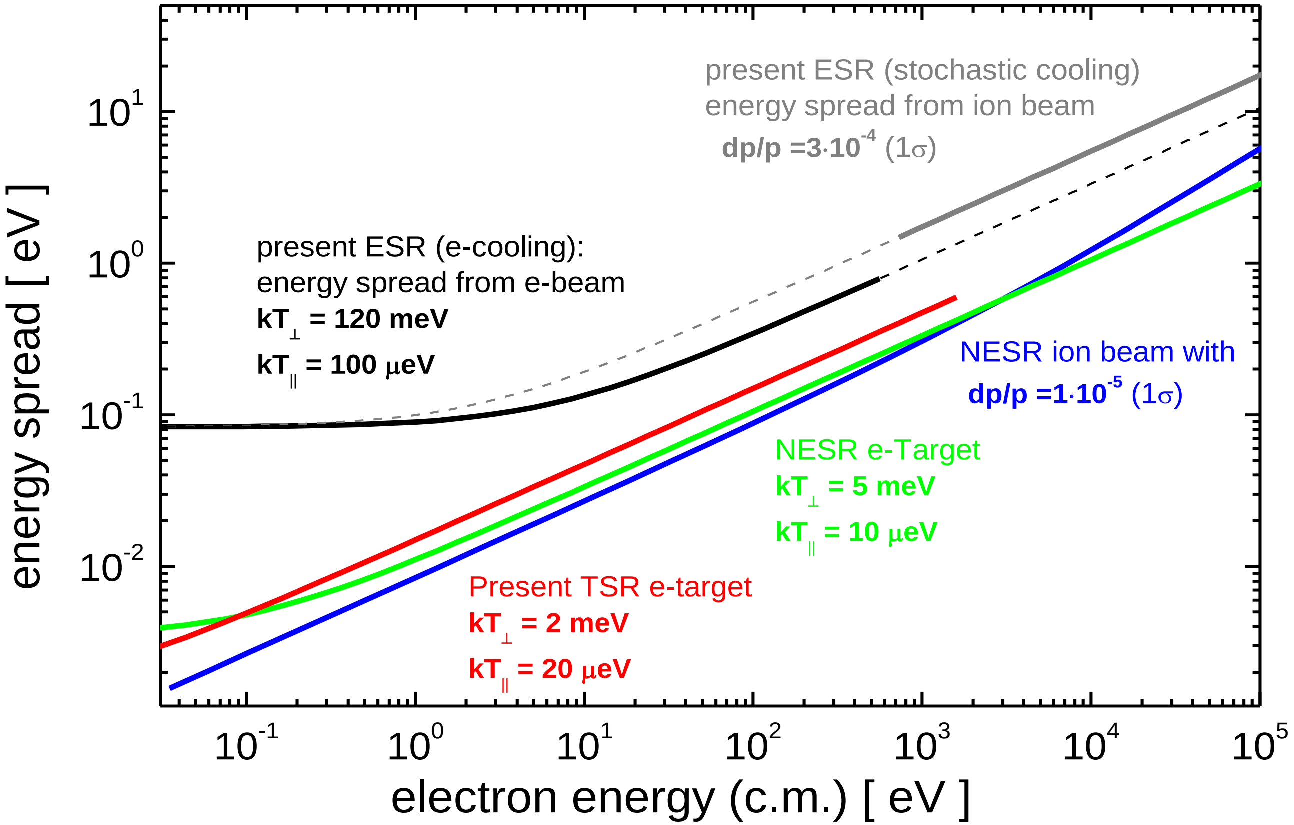
D. Bernhardt et al. Phys. Rev. A83 020701(R) (2011)

Breit Interaction in dielectronic recombination of hydrogenlike uranium



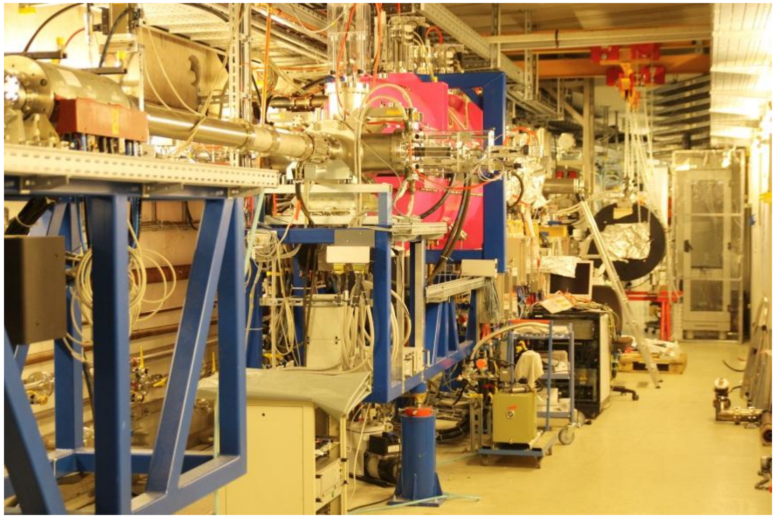
Energy Resolution at ESR

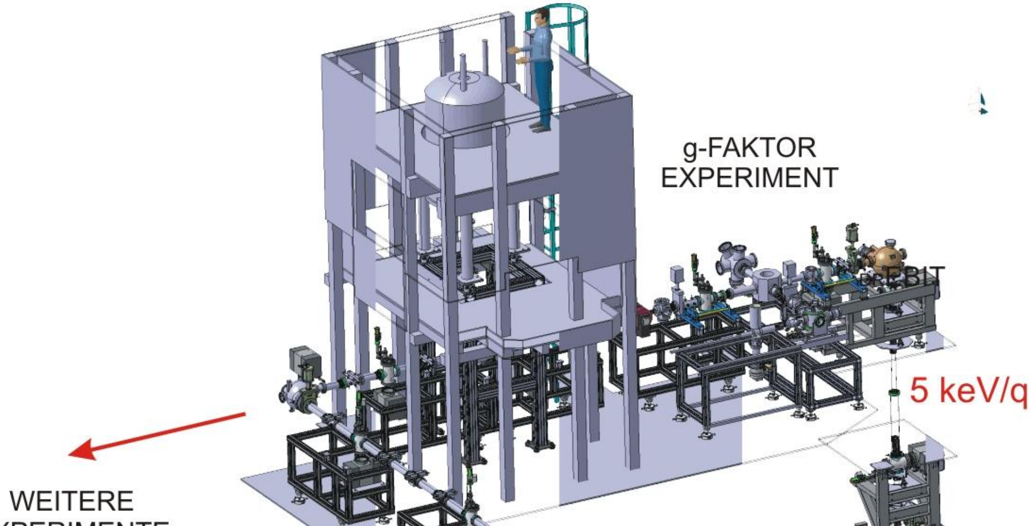
collision energies from meV to sub MeV

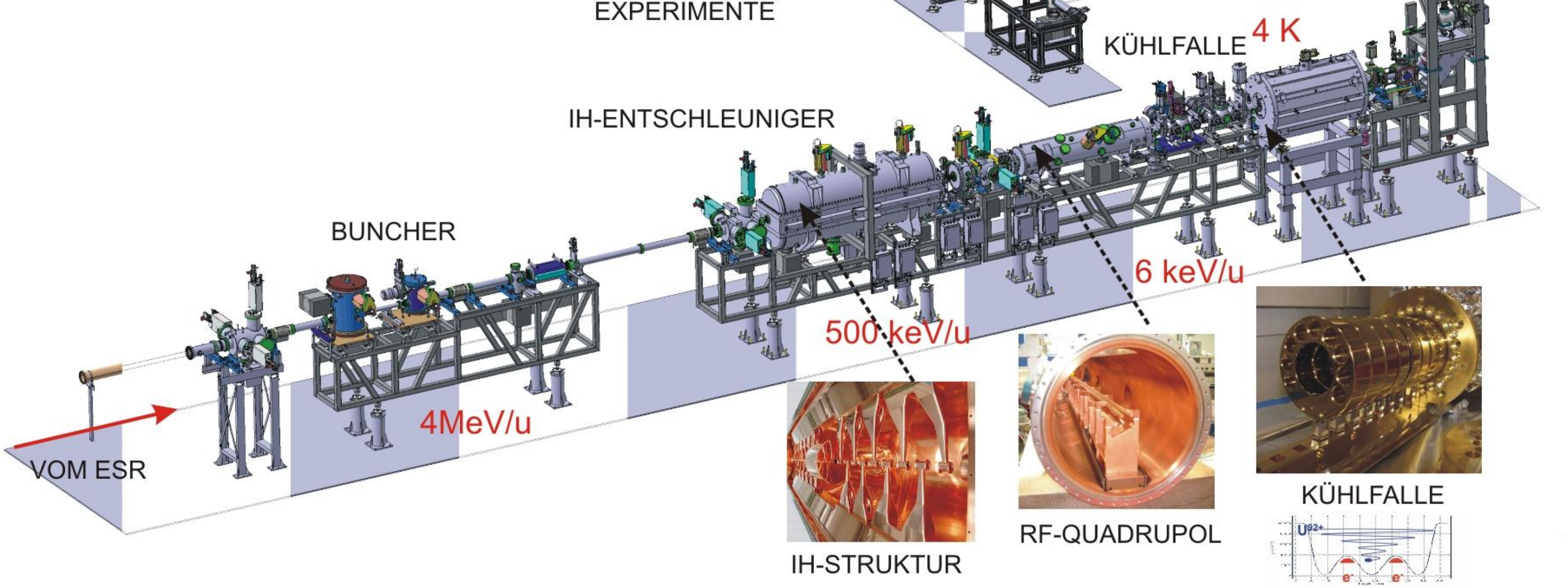


resolution ~10 meV to ~10 eV

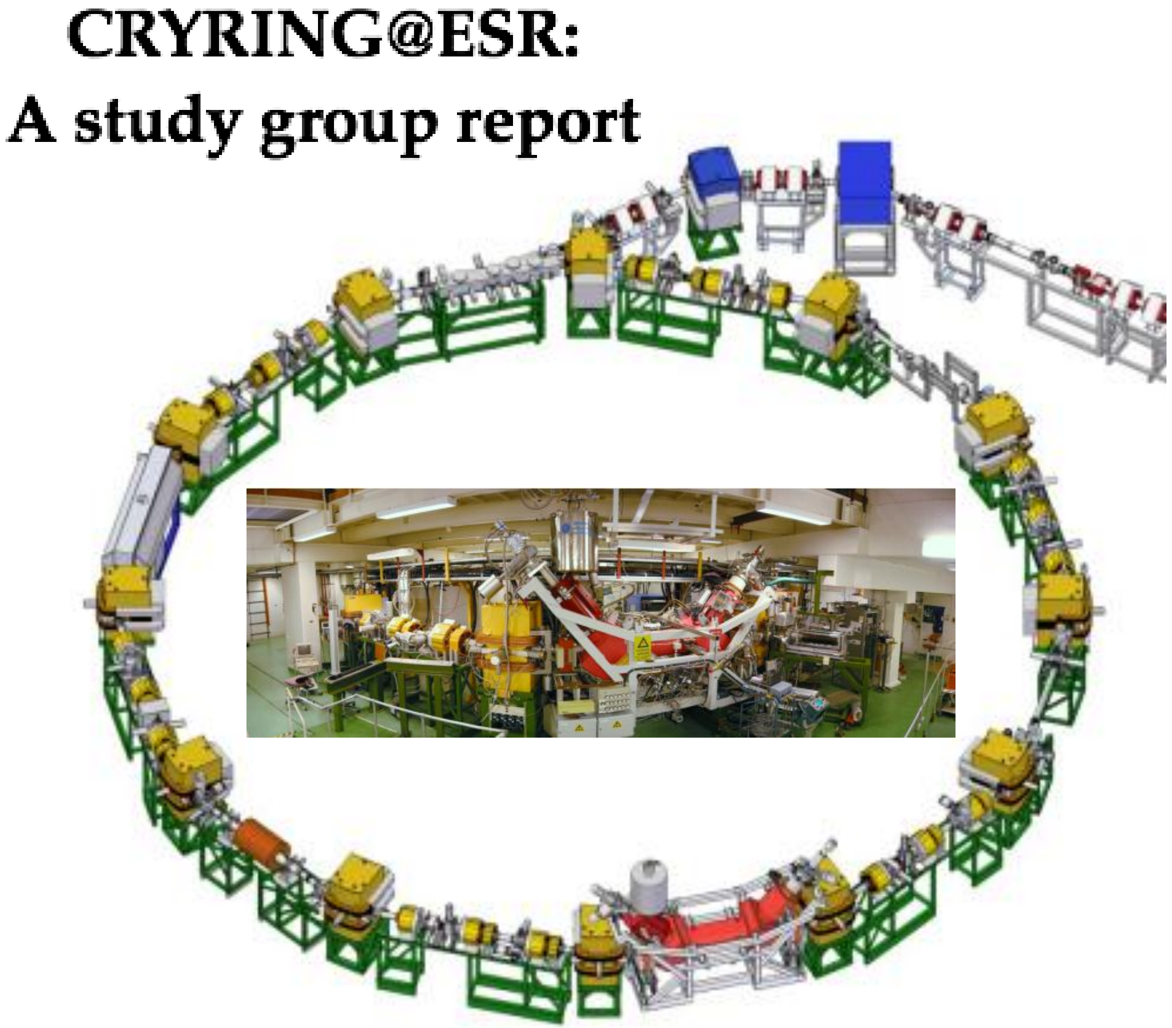
HITRAP so far built / designed







CRYRING@ESR



Study Group

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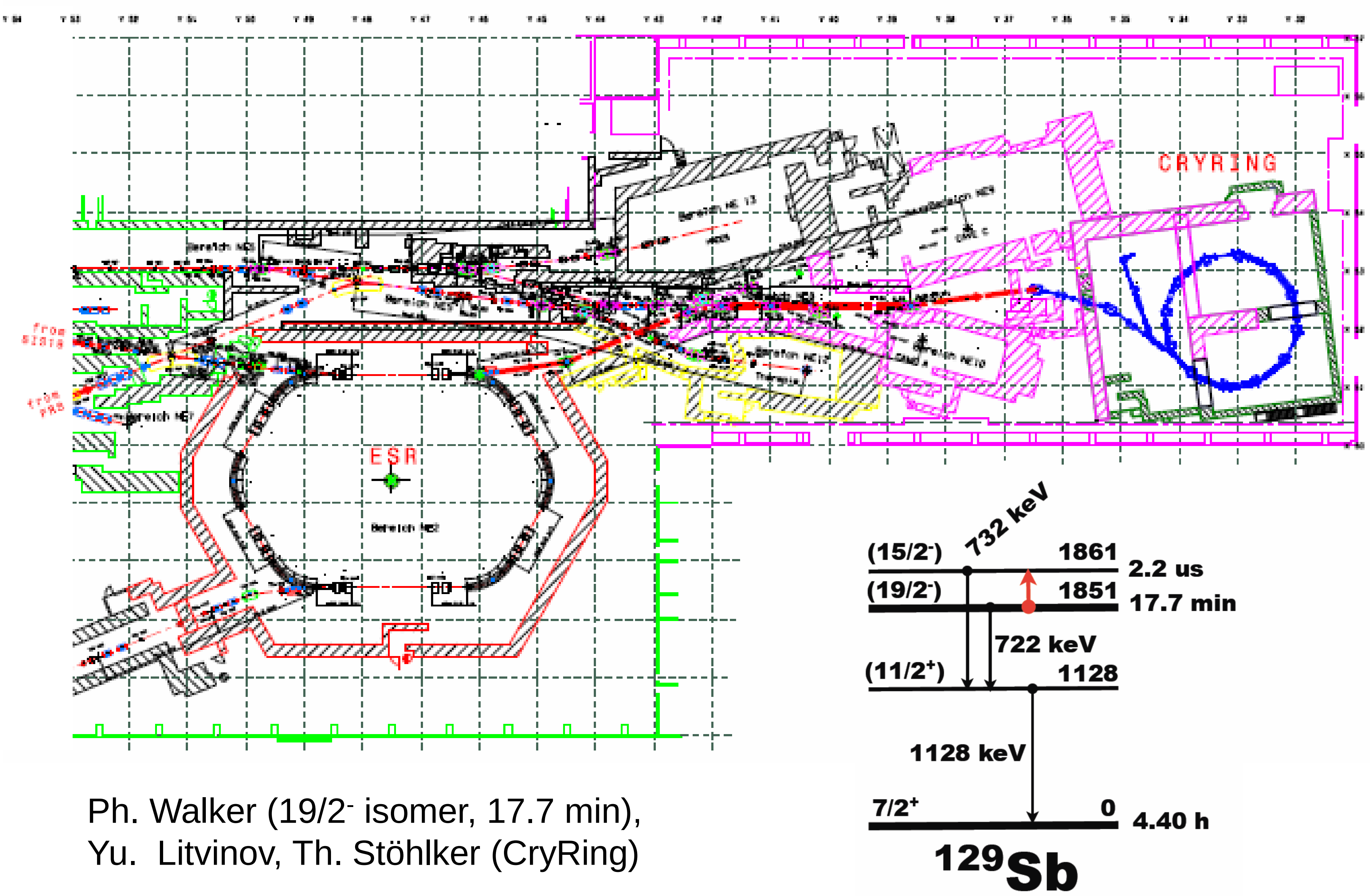
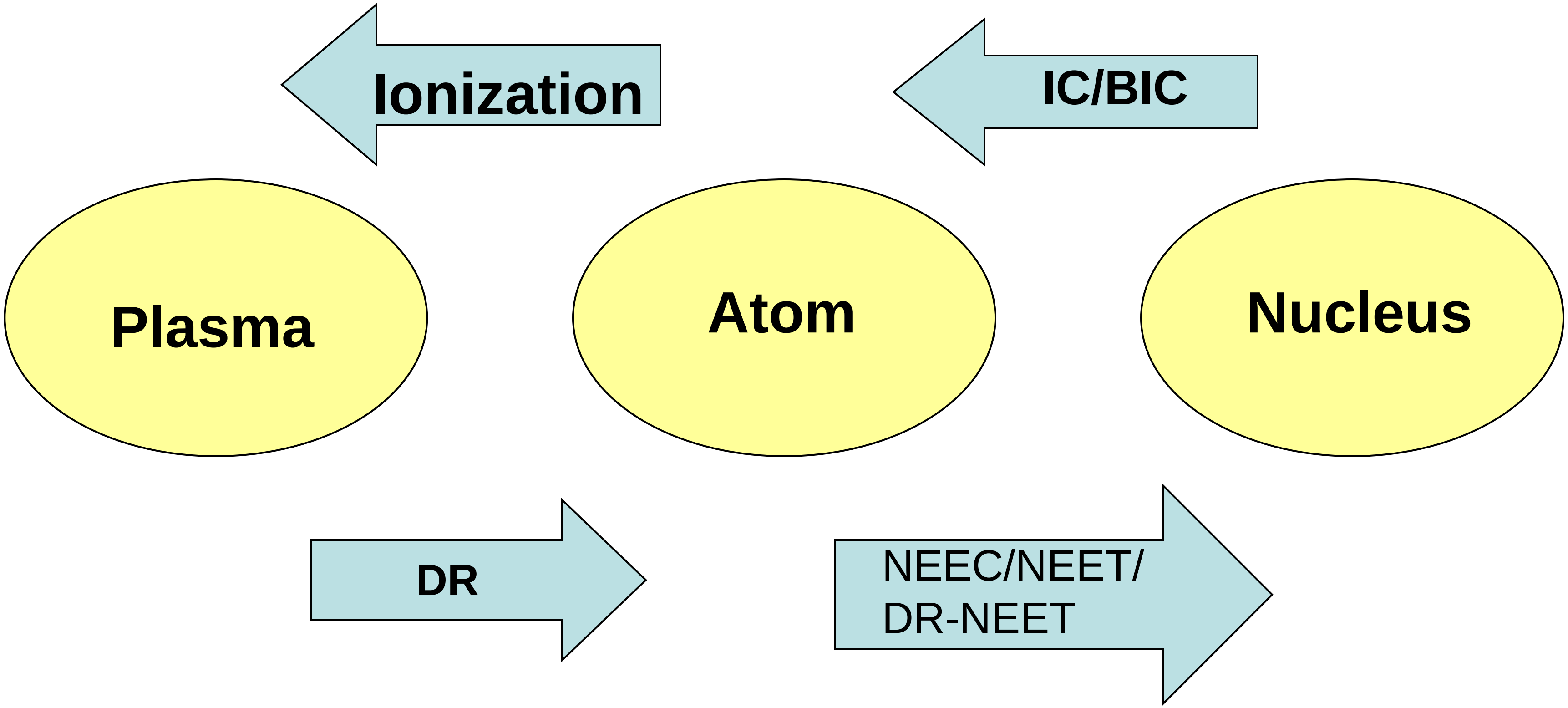
Mats Engström
Bernhard Franzke
Anders Källberg
Oliver Kester
Michael Lestinsky
Yuri Litvinov
Markus Steck
Thomas Stöhlker

2nd Realistic Scenario for a NEEC Experiment



Ph. Walker (19/2⁻ isomer, 17.7 min),
Yu. Litvinov, Th. Stöhlker (CryRing)

Basic Idea



IC – internal (electron) conversion

BIC – bound internal conversion

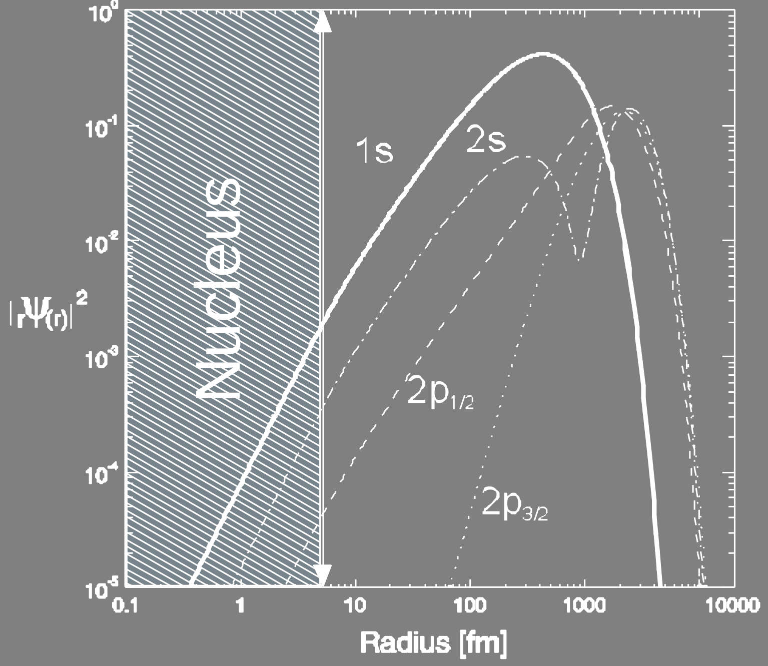
DR – dielectronic recombination

NEEC – nuclear excitation by electron capture

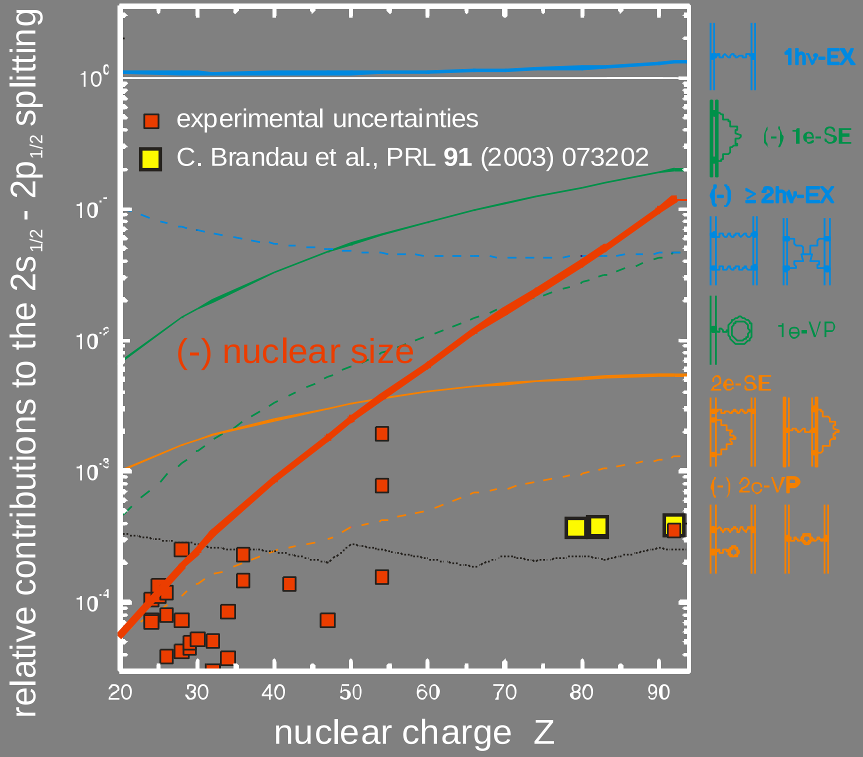
NEET – nuclear excitation by electron transition

Why Li-Like Heavy-Ions?

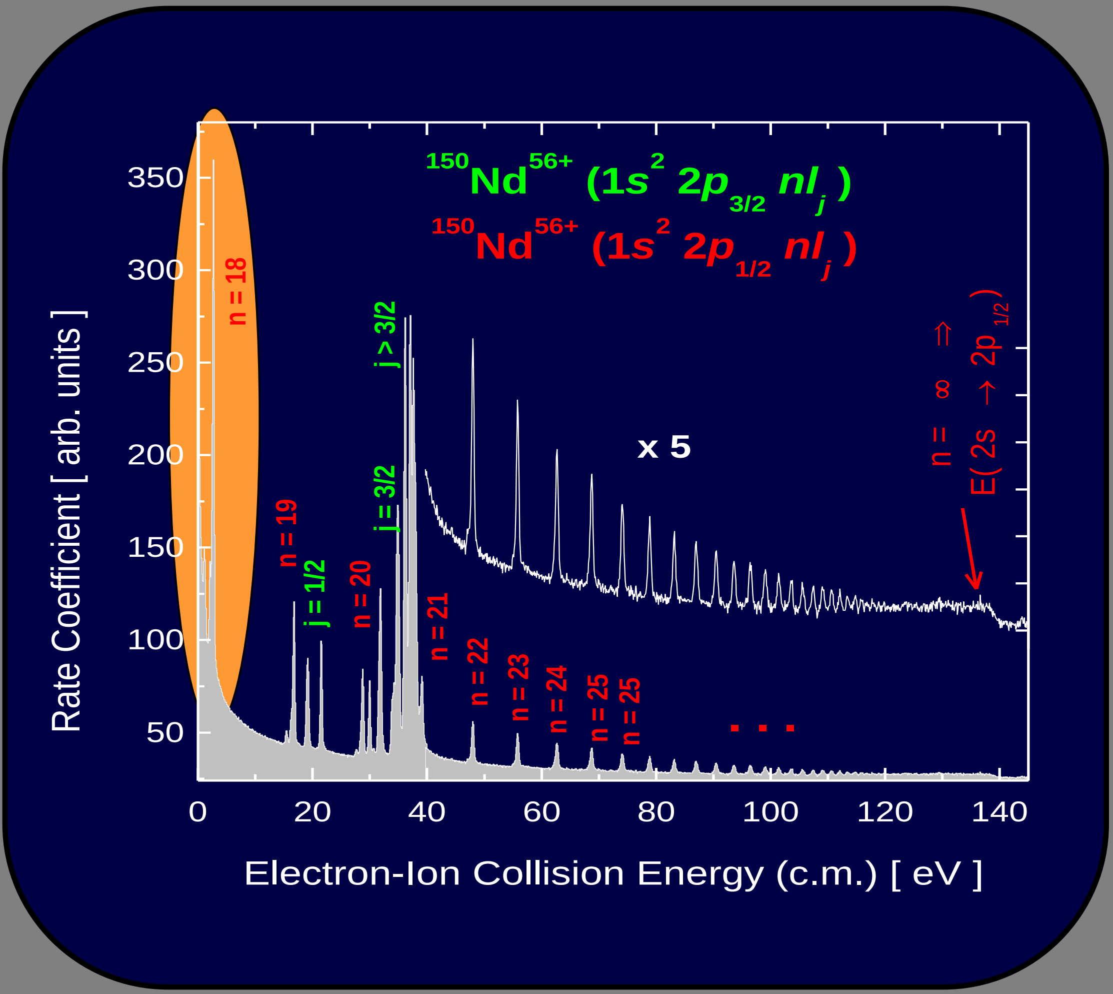
Radial density distribution of low-lying electron orbitals in U^{91+}



$2s_{1/2}$ -$2p_{1/2}$ Energy Splitting for Li-like Ions



Low-Energy PR Spectrum of Li-like Neodymium ($^{150}\text{Nd}^{57+}$)



Li-like ion (Δn = 0)

2 series of resonances:

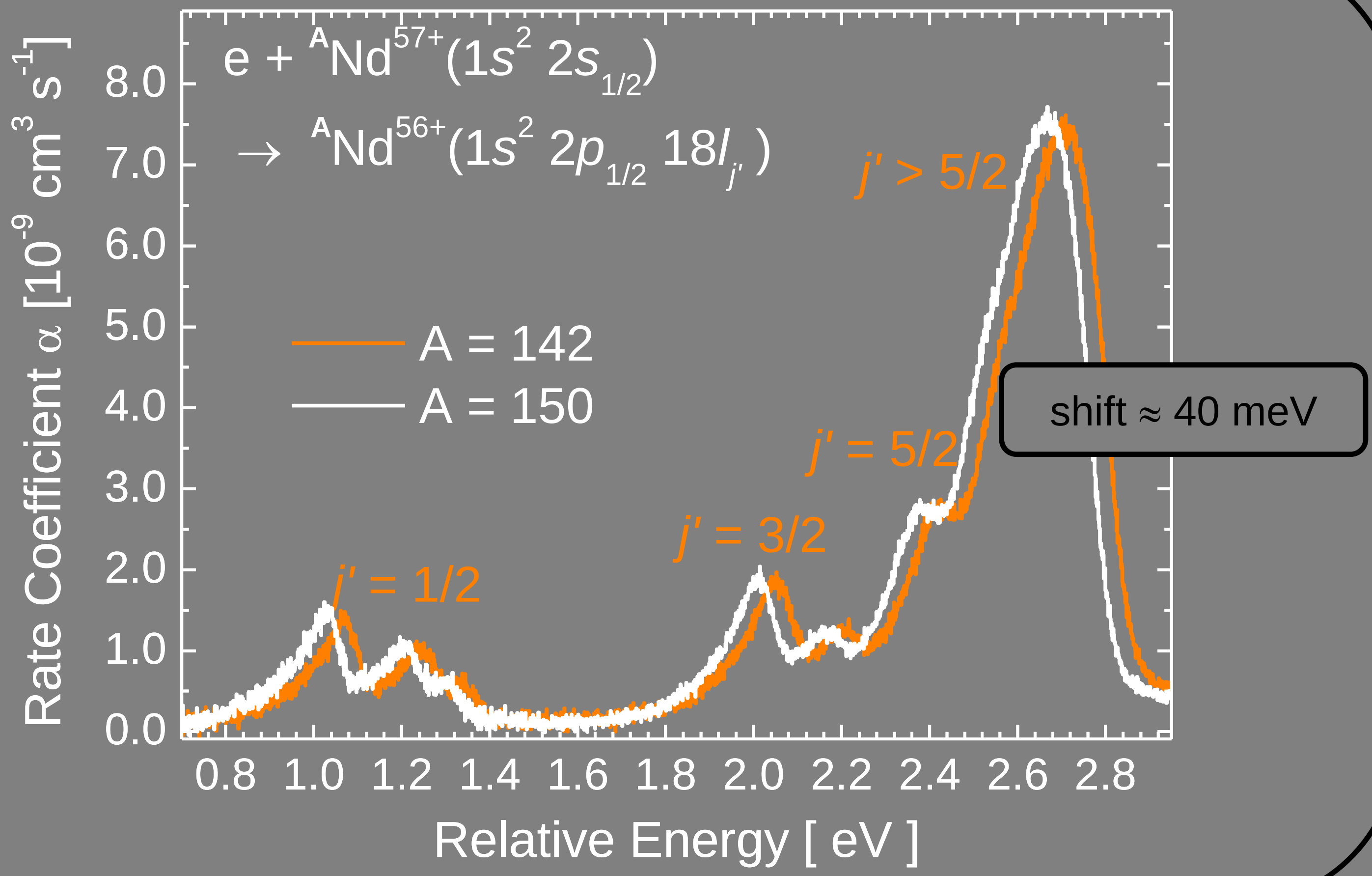
$E\,(2s_{1/2} \to 2p_{1/2}) = 139.2$ eV
$\Rightarrow\ n_{min} = 18$

and to

$E\,(2s_{1/2} \to 2p_{3/2}) = 729.1$ eV
$\Rightarrow\ n_{min} = 8$

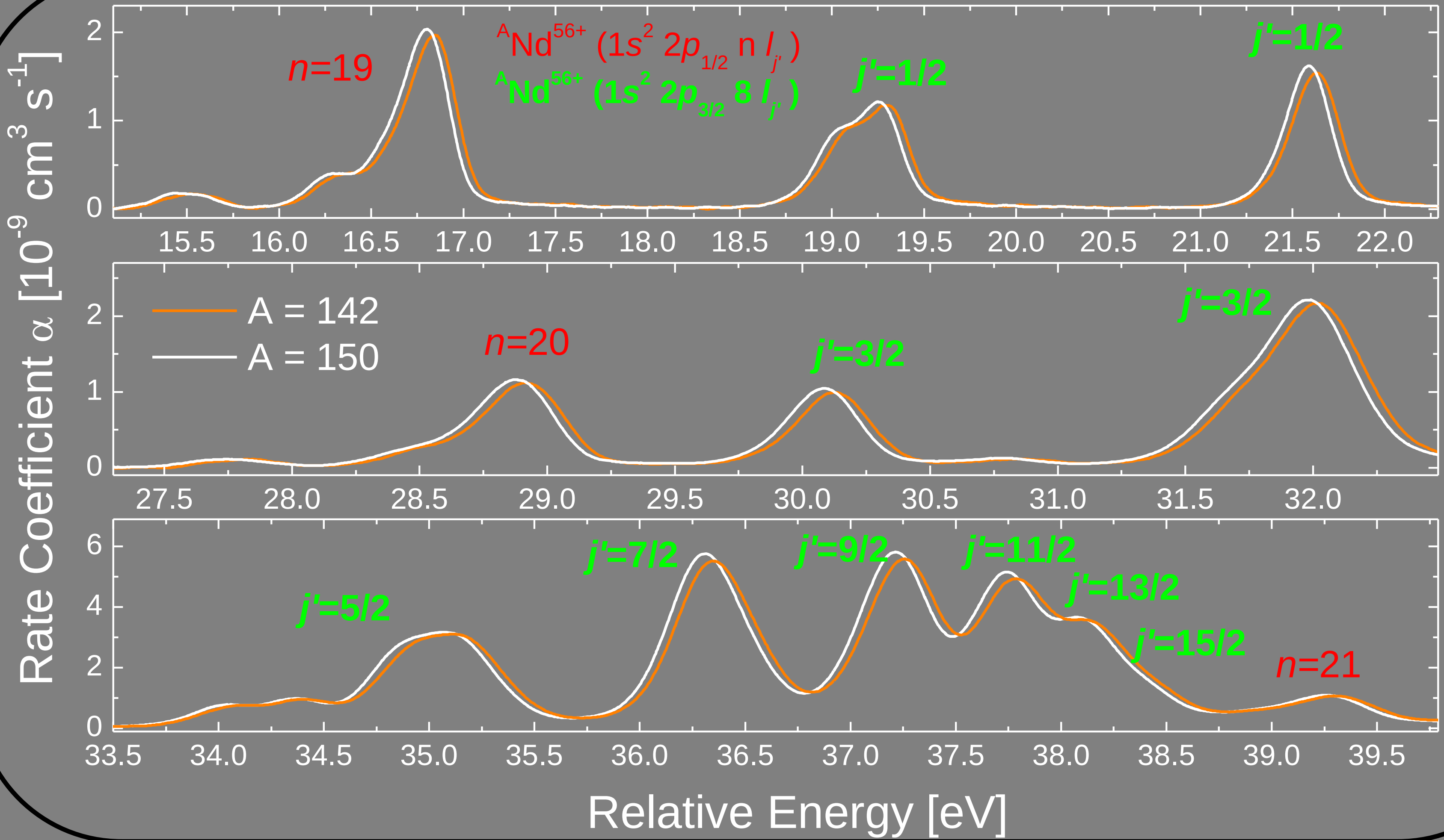
different overlap of 2s and 2p wavefunctions with the nucleus
=> shift of a whole pattern of resonances.

Li-like $^{142}\mathrm{Nd}^{57+}$ vs. $^{150}\mathrm{Nd}^{57+}$



C. Brandau, et al., PRL **100** (2008) 073201

Li-like $^{142}Nd^{57+}$ vs. $^{150}Nd^{57+}$



C. Brandau, et al., PRL **100** (2008) 073201

${}^{A}Nd^{57+}$ DR-IS and Change in Mean Square Radius

from maxima, minima and inflection points:

154 values for $2s_{1/2} - 2p_{1/2}$ $\Rightarrow$ ΔE = 40.2 (3)(6) meV

45 values for $2s_{1/2} - 2p_{3/2}$ $\Rightarrow$ ΔE = 42.3 (12)(25) meV

+ full QED calculations

+ NP 0.3 meV for A=150

$\Rightarrow \delta\langle r^2 \rangle(142\text{-}150) = 1.36\ (1)(3)\ \mathrm{fm}^2$

C. Brandau, et al., PRL **100** (2008) 073201.

Y.S. Kozhedub, et al., PRA **77** (2008) 032501.

Z. Harman, et al., in preparation.

Production of Li-like (!) Exotic Ions

1×10^9 ^{238}U ions @ 370 MeV/u in SIS

⇓

Be-target (1 cm „stripping foil“ = 1850 mg/cm^2)

⇓

3.5×10^5 Li-like ^{237}U^{89+} @ ~169 MeV/u (total ^{237}U^{q+}: 2×10^6)

complexities :

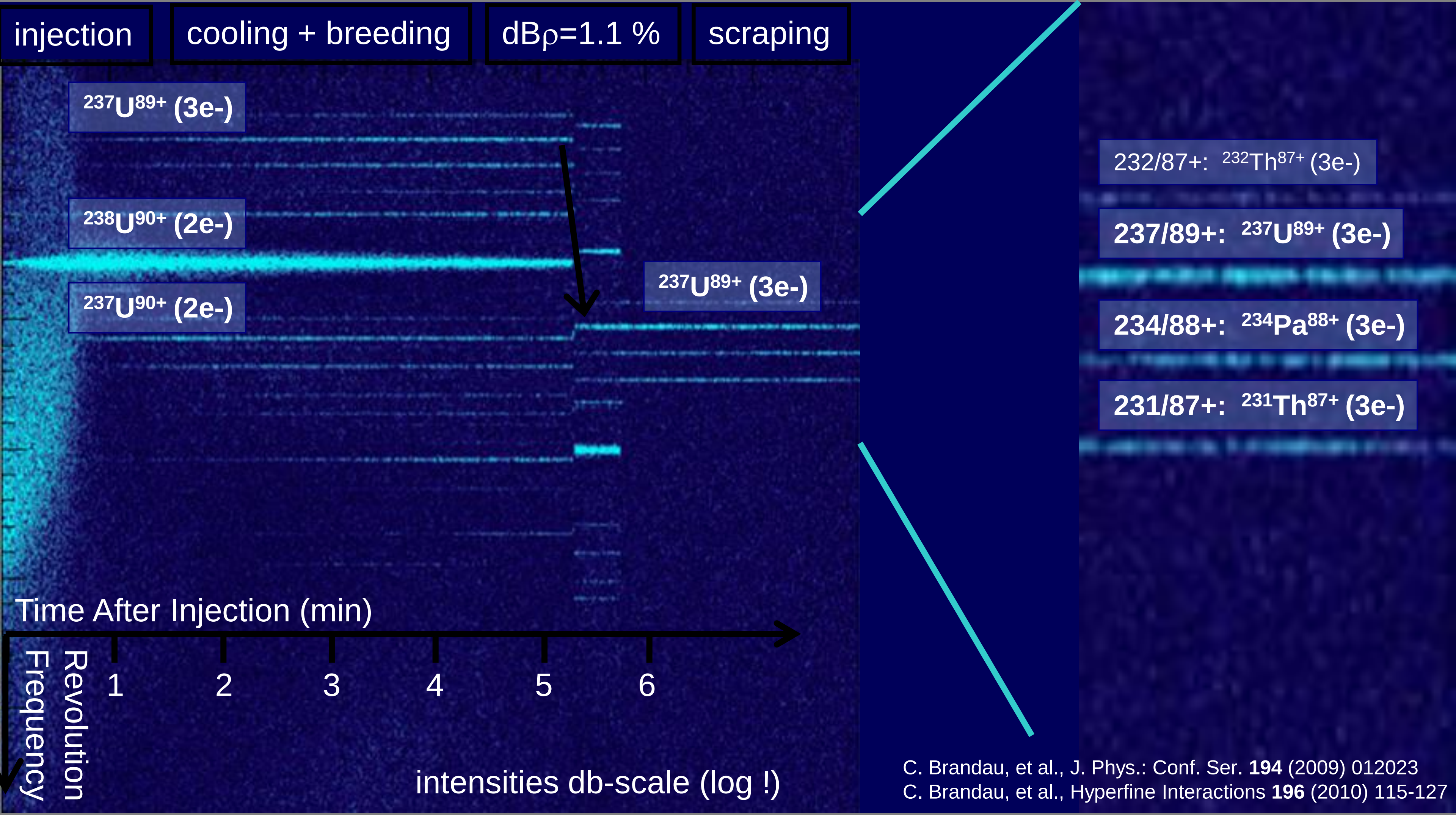
+ energy loss and straggling in thick target

+ distribution of charge states

+ cooling times ~ 1-5 min (for hot fragments far off β_{Cool} ?)

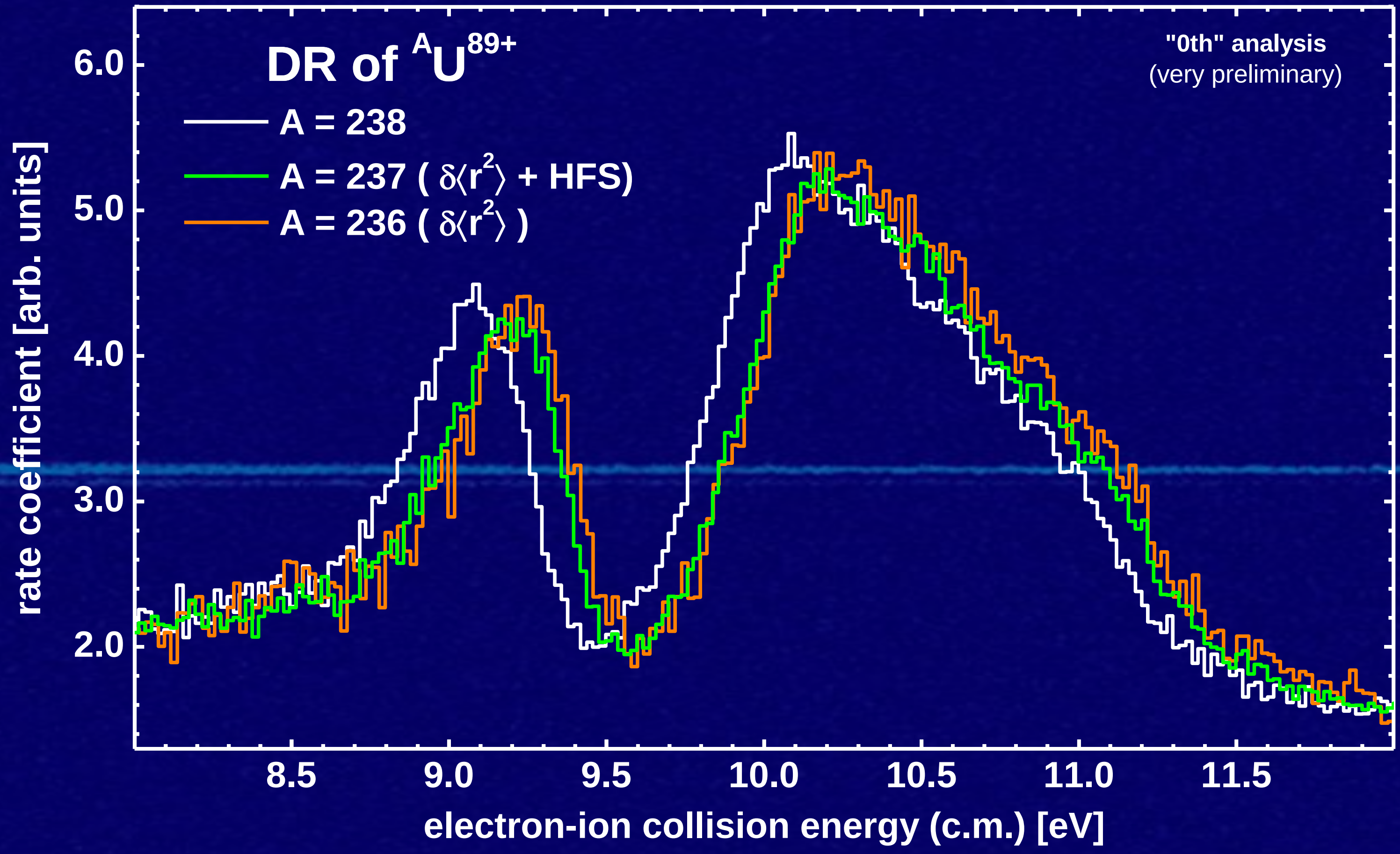
=> beam loss due to recombination in cooler (~95 % after 5 min)

Preparation of Li-like Exotic Beams in the ESR
or: the Storage Ring as an Isotope Separator

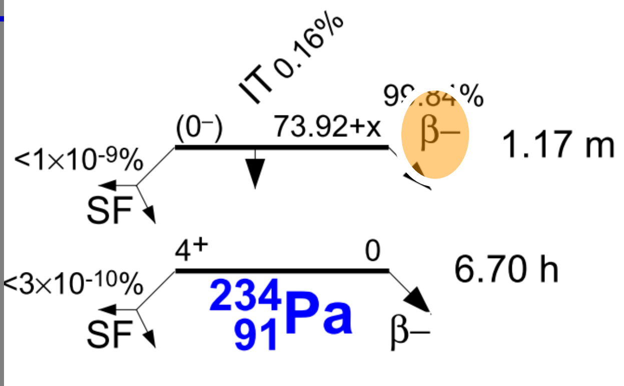


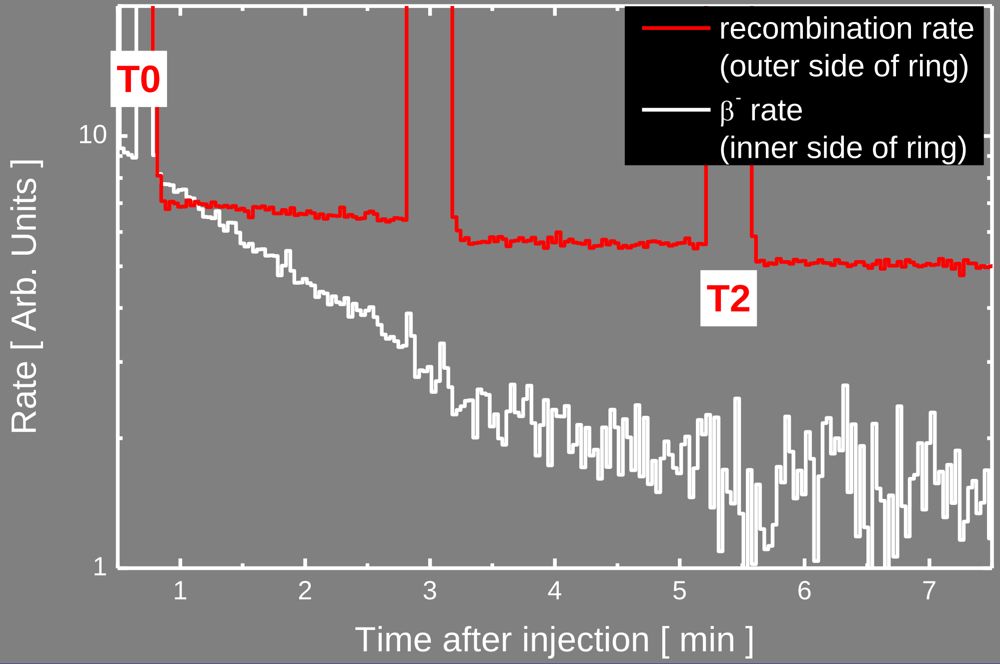
C. Brandau, et al., J. Phys.: Conf. Ser. **194** (2009) 012023
C. Brandau, et al., Hyperfine Interactions **196** (2010) 115-127

Isotope Shift and Hyperfine Effects in the Dielectronic Recombination of In-Flight Synthesized $^{A}U^{89+}$ (A=236, 237, 238)



Nov 2010 Test Run: Brevium - ^{234m}Pa





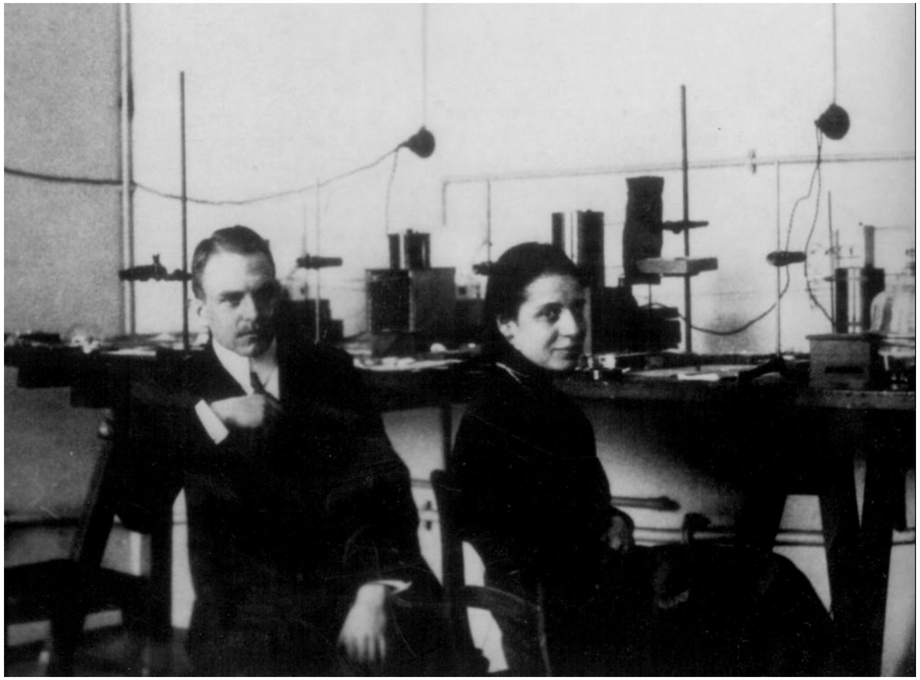
preliminary

Kazimierz Fajans

Brevium, 1913

Otto Hahn and Lise Meitner

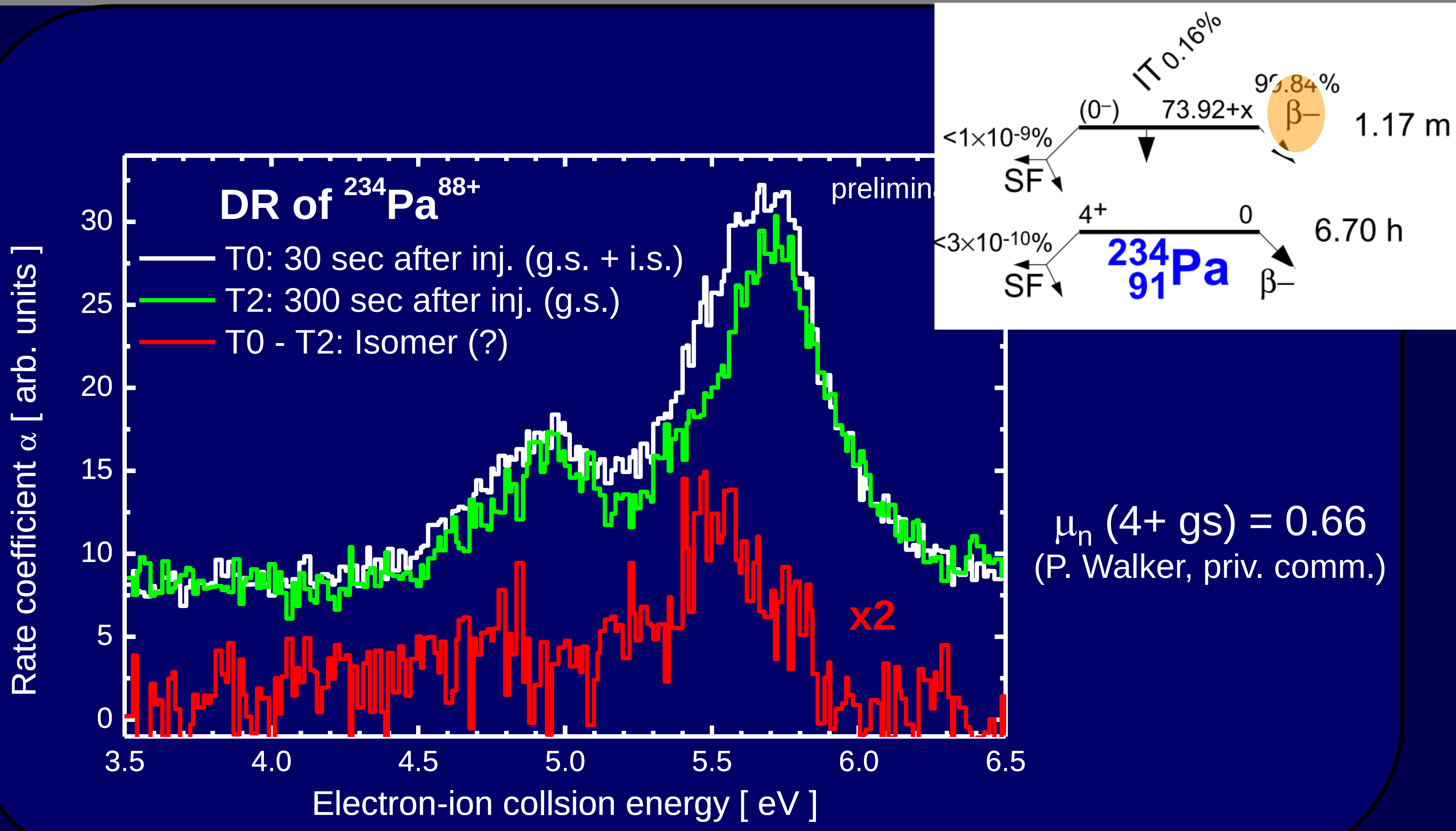
Protoactinium, 1917 (1918)



Latin. Man's natural language. Spoils your style. Useful for reading the inscriptions on public fountains. Beware of quotations in Latin: they always conceal something improper.

Gustave Flaubert

DR of 0^-- Isomers in $^{234}Pa^{88+}$



μ_n (4+ gs) = 0.66
(P. Walker, priv. comm.)

preliminary

Conclusions

- A storage ring for high-Z ions in well-defined charge states, equipped with electron cooling capabilities for well-defined ion velocities and furnished with some nice instrumentation is a very good tool for nuclear and atomic physics studies.
- GPAC-accepted ^{229m}Th-LoI and proposal.
- Beam Time!?
- PhD students?