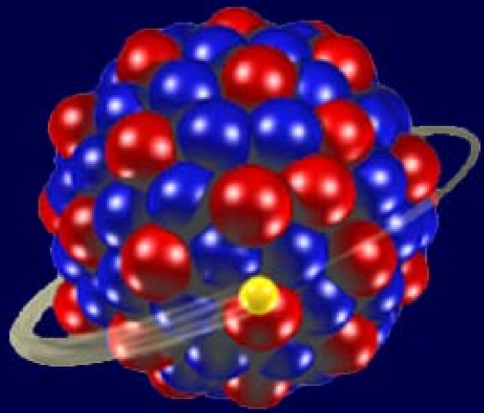
Carsten Brandau
JLU Giessen / GSI, Darmstadt

EMMI Workshop
Eisenach, 28/06/10

Resonant Photo-Recombination of Highly-Charged Radioisotopes at the ESR

GSI, Darmstadt	F. Bosch, D. Boutin, C. Dimopoulou, B. Franzke, A. Gumberidze, M. Heil, H.-J. Kluge, C. Kozhuharov, Yu.A. Litvinov, R. Märtin, P. H. Mokler, F. Nolden, R. Reuschl, H. Simon, U. Spillmann, M. Steck, Th. Stöhlker, G. Weber, D. Winters
JLU, Giessen	D. Bernhardt, S. Böhm, C. Böhme, J. Jacobi, S. Kieslich, H. Knopp, A. Müller, W. Scheid, S. Schippers
University of Oulo	S. Fritzsche
Uni Mainz	M. Lochmann, W. Nörthershäuser
LLNL Livermore	L.A. Bernstein, D. Schneider, M. Wiedeking
JKU, Kielce	D. Banas
INP, Krakau	Z. Stachura
MPI-K, Heidelberg	A. Wolf , Z. Harman, U.D. Jentschura, A. Pálffy, C.-H. Keitel
St.Petersburg State University	Y.S. Kozhedub, V.M. Shabaev, I.I. Tupitsyn
QUB, Belfast	F.J. Currell, B.E. O'Rourke
TU Munich	R. Krücken



within the SPARC collaboration (www.gsi.de/sparc)
SPARC: Stored Particles Atomic Research Collaboration

Outline

- nuclear data in AP experiments
- resonant channel of photo-recombination: DR
- storage ring DR experiments (ESR)

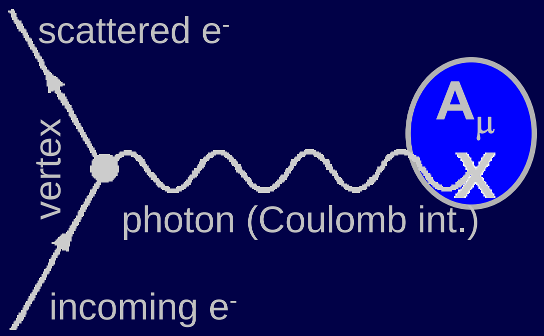
DR as a tool at interface of atomic and nuclear physics:

- isotope shift / HFS studies with stable ions
- DR experiments with radioisotopes
- nuclear metastable states (isomers)

The Nucleus as Seen Through the Eyes of an Atomic Physicist

the nucleus provides the central binding potential for the electrons

or more generally (in terms of QED):
the nucleus is the source of a strong EM field A_μ

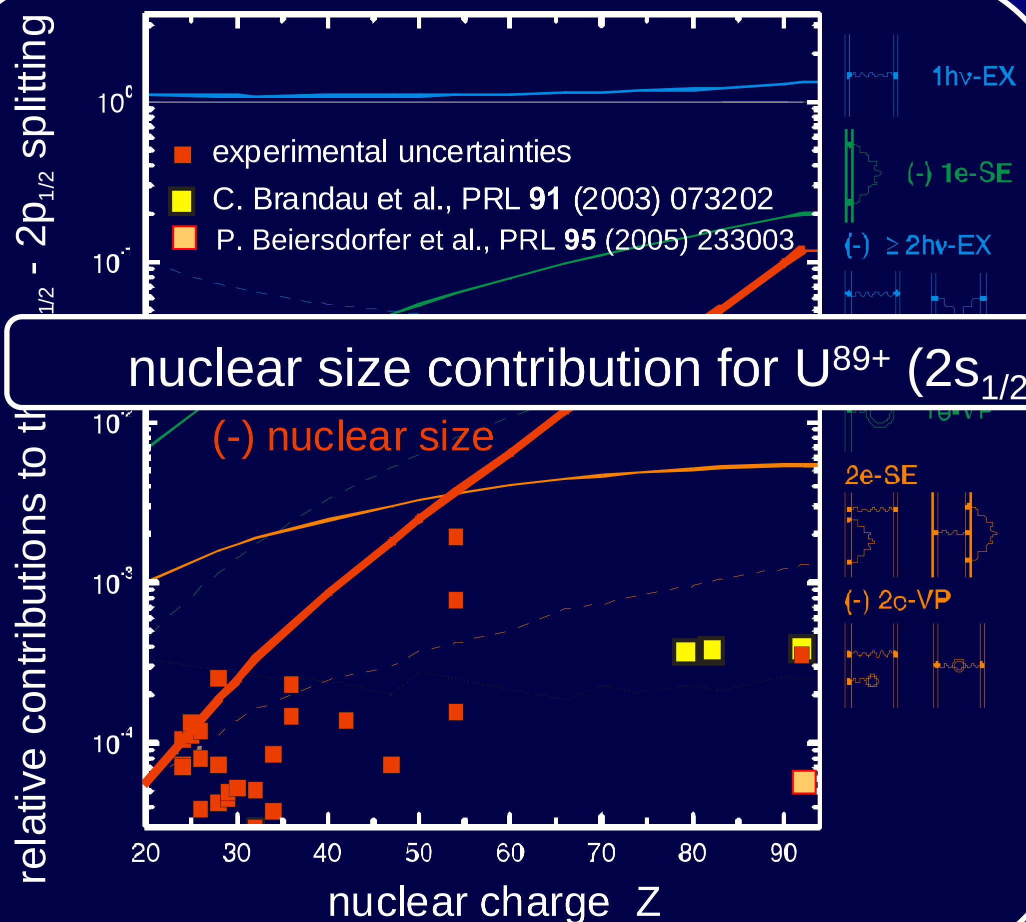


… (un)fortunately the nucleus has a finite size, spin, magnetic moment and structure

Nucleus as a Nuisance:

Nuclear Size Contribution in Precision Experiments

(Here: $2s_{1/2}$ - $2p_{1/2}$ Splitting in Li-like Ions)



nuclear size contribution for U^{89+} ($2s_{1/2} - 2p_{1/2}$) ~ 15 %

Sensitivity DR :

0,5 % of „QED“
< 7 % of QED in order α^2
< 3 % of „nuclear size“ contributions
(on an absolute scale)

with respect to nuclear physics ^{208}Pb is an ideal candidate for QED tests

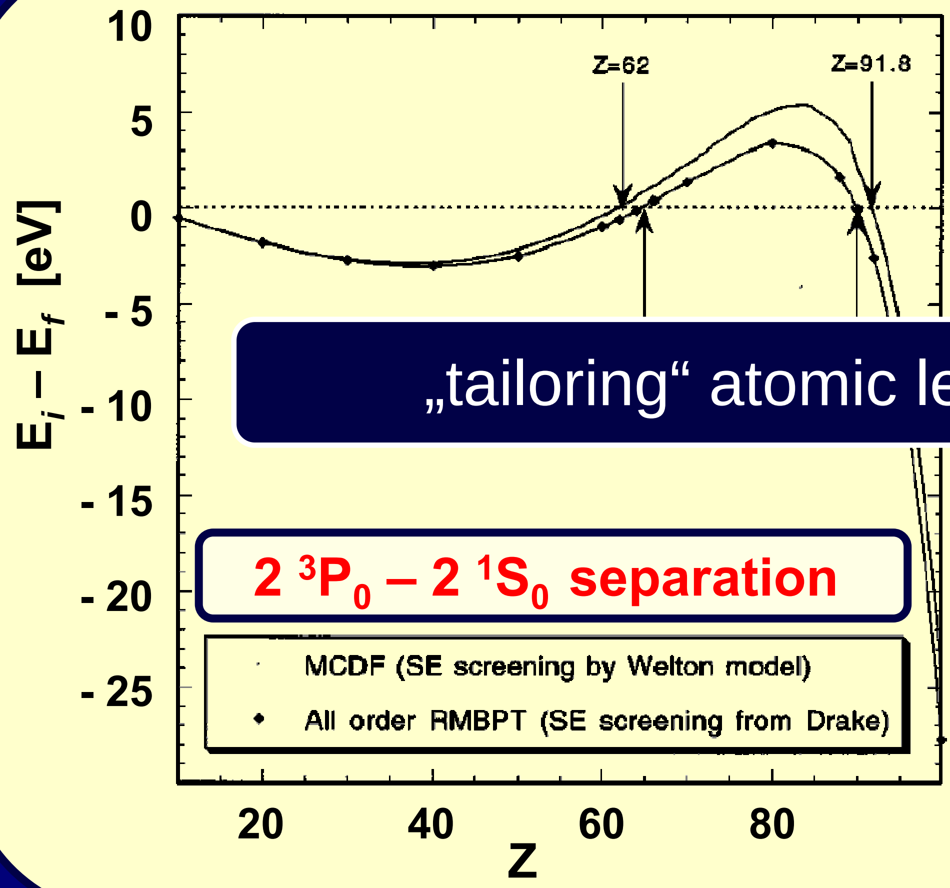
QED: Yerokhin et al. (2001,2002)

experimental uncertainties from:
Bosselmann et al. (1999)
Feili et al. (2000)

Nucleus as a Benefit:

Isotopic Fine Tuning of the 2 $^3P_0$ – 2 $^1S_0$ Energy Splitting

(Enhancing Parity Violation Effects in Heavy He-like Ions)

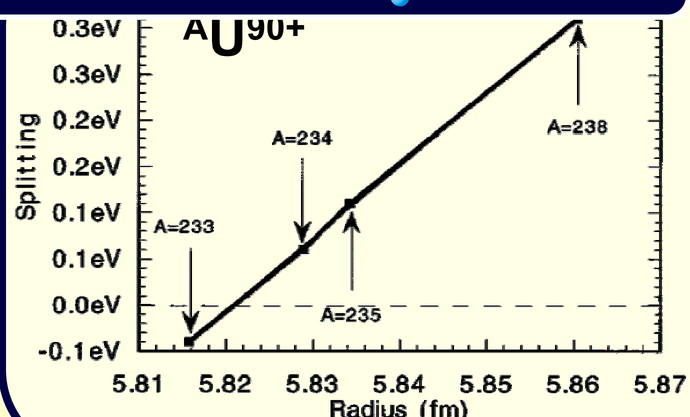


2 $^3P_0$ – 2 $^1S_0$ separation

parity admixture η

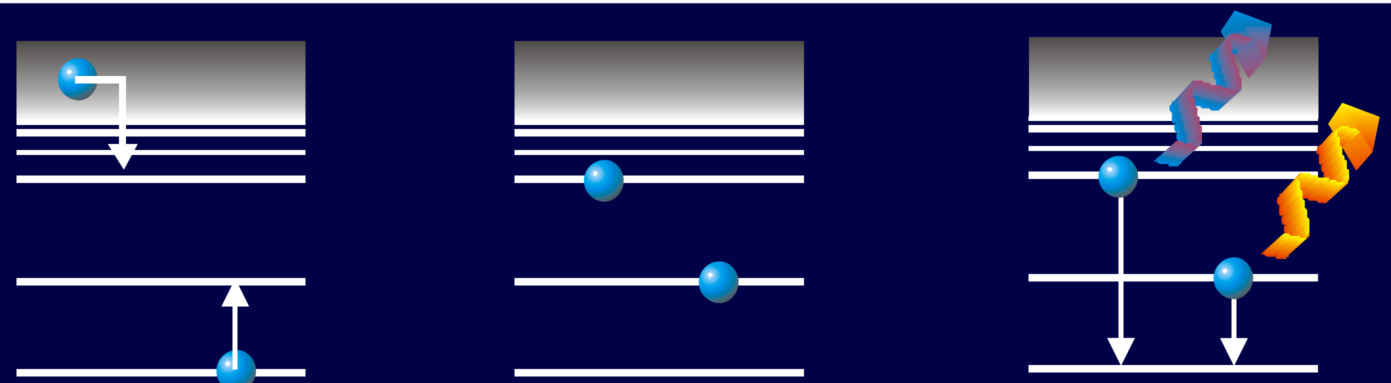
$$\eta = \frac{\left\langle i \left| \frac{G_F}{2\sqrt{2}} \left(1 - 4\sin^2\vartheta_W - \frac{N}{Z}\right)\rho\,\gamma_5 \right| f \right\rangle}{E_i - E_f}$$

„tailoring“ atomic level energies



e.g.: A. Schäfer et al., PRA **40** (1989) 7362; M. Maul et al., PRA **53** (1996) 3915

The Tool -- Dielectronic Recombination: „Inverse“ Auger Spectroscopy



$$A^{q+} + e^{-} \rightarrow [A^{(q-1)+}]^{**} \rightarrow A^{(q-1)+} + n \cdot h\nu$$

kinetic energy of e-

Dielectronic Capture (DC) →

← Auger emission (time-reverse)

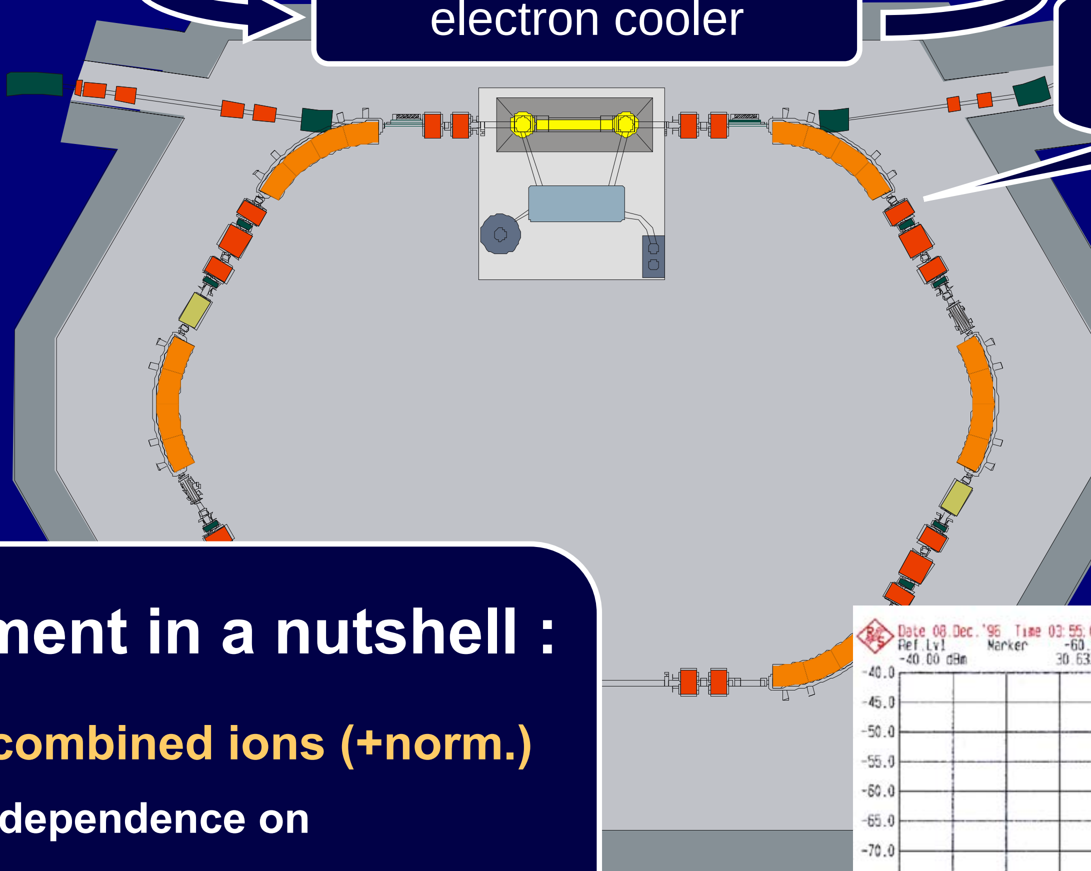
Radiative Stabilization
(in competition to Auger emission)

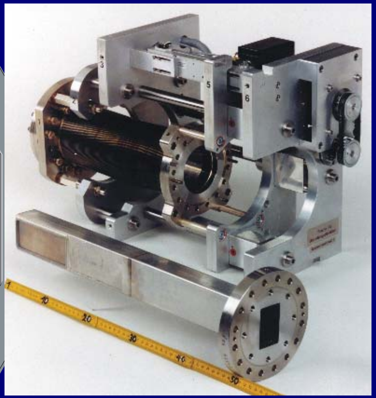
Experimental Storage Ring (ESR)

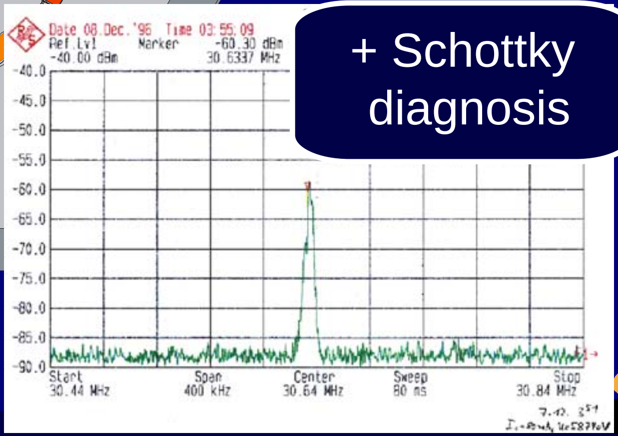
electron target

electron cooler

recombination detector ε ~ 1







+ Schottky diagnosis

DR experiment in a nutshell :

counting recombined ions (+norm.)

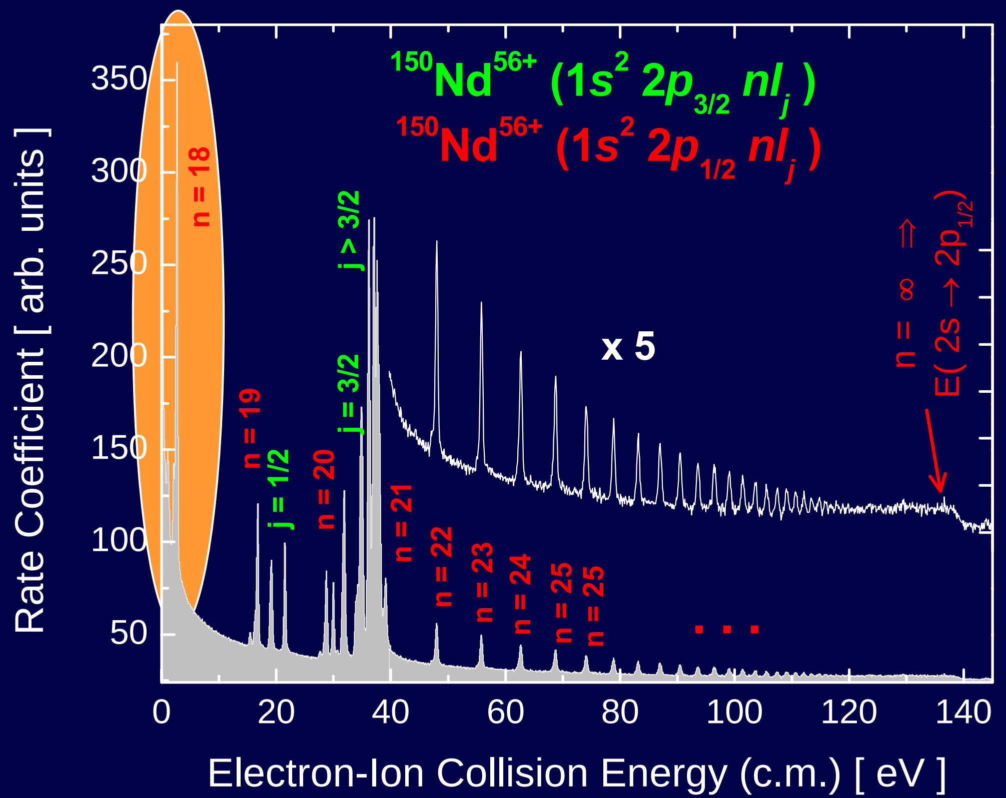
in dependence on

relative electron-ion collision energy

DR Investigations of Nuclear Properties

- **isotope shift / hfs studies with stable isotopes**
- DR experiments with exotic beams
- nuclear metastable states (isomers)

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



Li-like ion ($\Delta n = 0$)

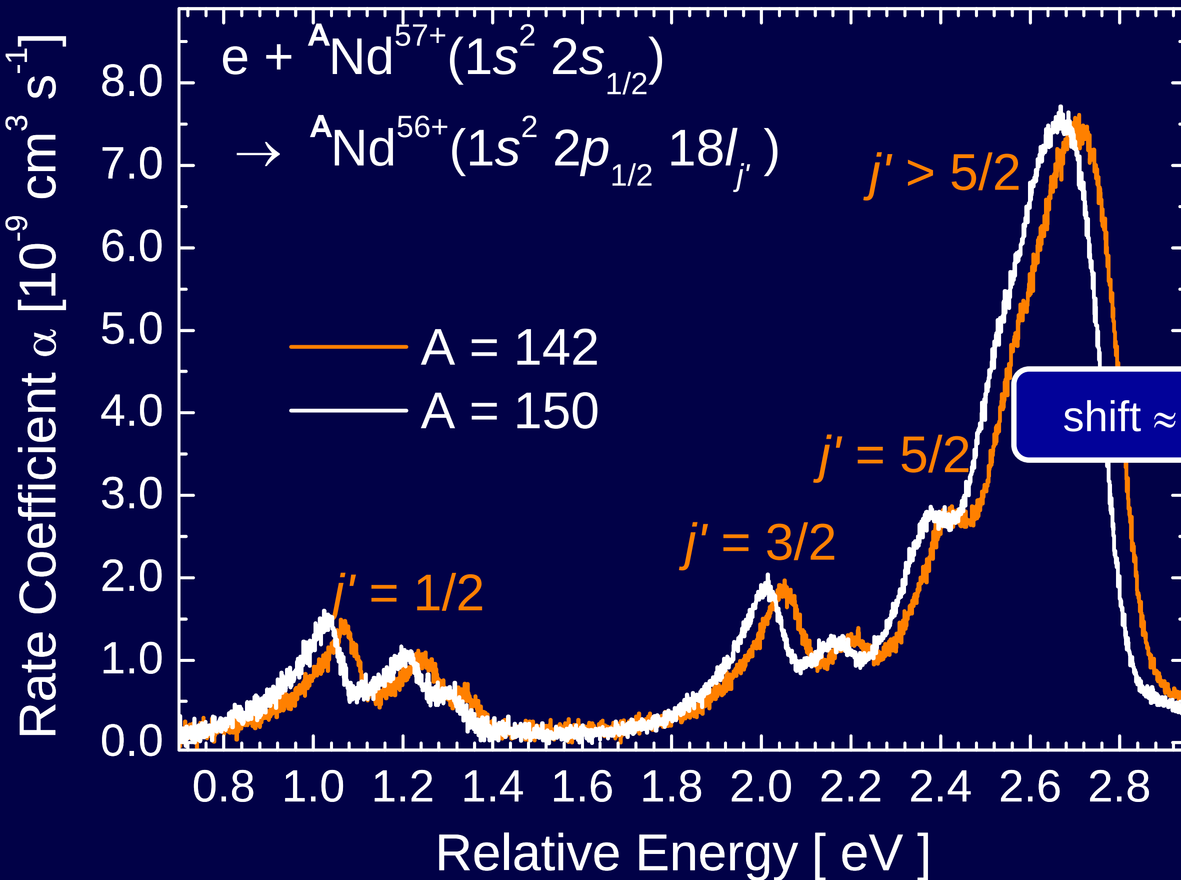
2 series of resonances:

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

and to

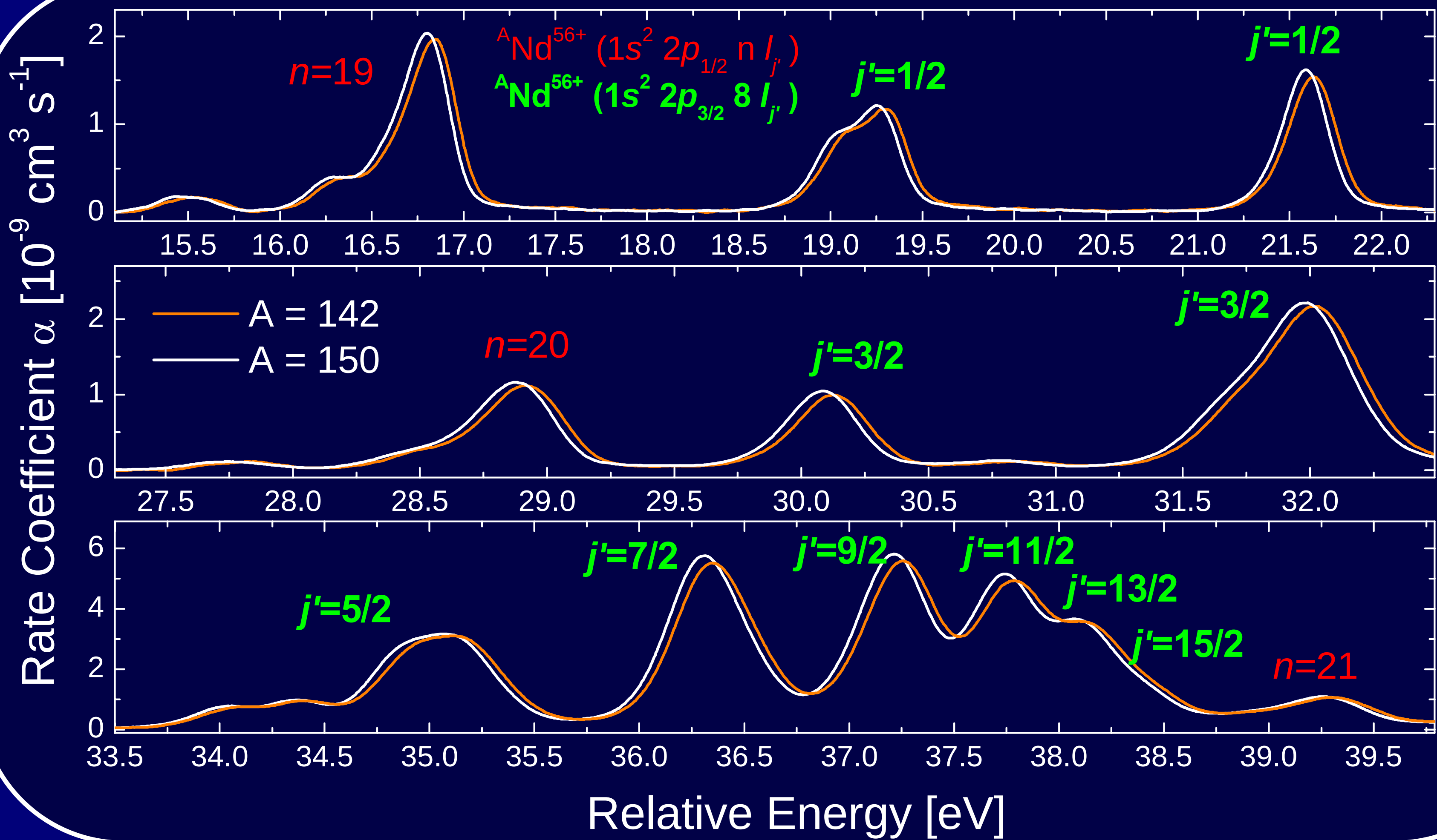
E ($2s_{1/2} \rightarrow 2p_{3/2}$) = 729.1 eV
$\Rightarrow$ n_{min} = 8

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



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

main benefit: simple atomic configuration !!!

\+ NP 0.3 meV for A=150

$\Rightarrow$ **$\delta\langle r^2 \rangle$(142-150) = 1.36 (1)(3) fm^2**

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

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

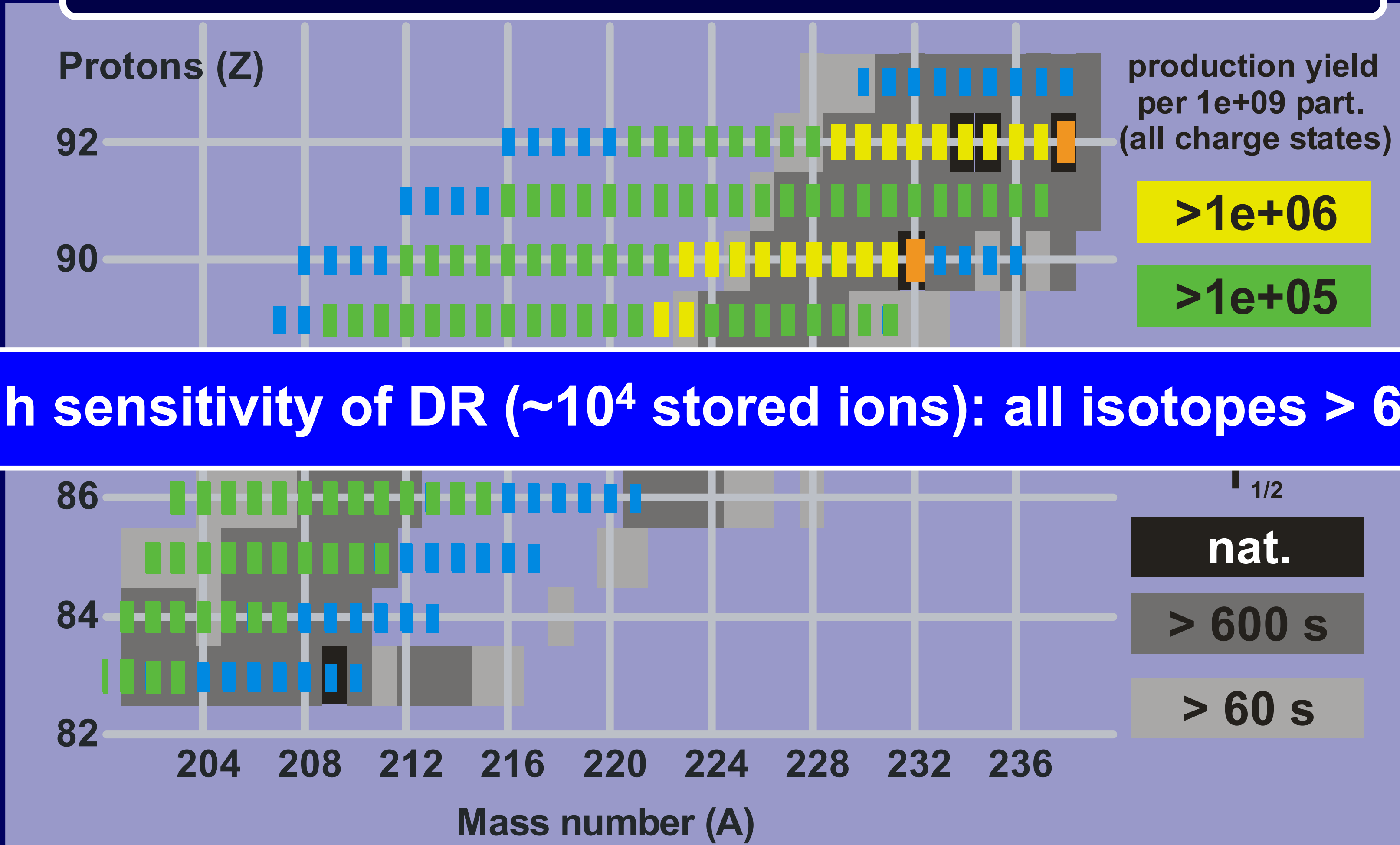
Z. Harman, et al., in preparation.

DR Investigations of Nuclear Properties

- isotope shift / hfs studies with stable isotopes
- **DR experiments with exotic beams**
- nuclear metastable states (isomers)

How Far Can We Go (Present ESR) ?

$^{238}U/^{232}Th$ ions @ 370 MeV/u in SIS ⇒ 1cm Be-target (1850 mg/cm^2)



high sensitivity of DR (~10^4 stored ions): all isotopes > 60s

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

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})

<u>complexities :</u>

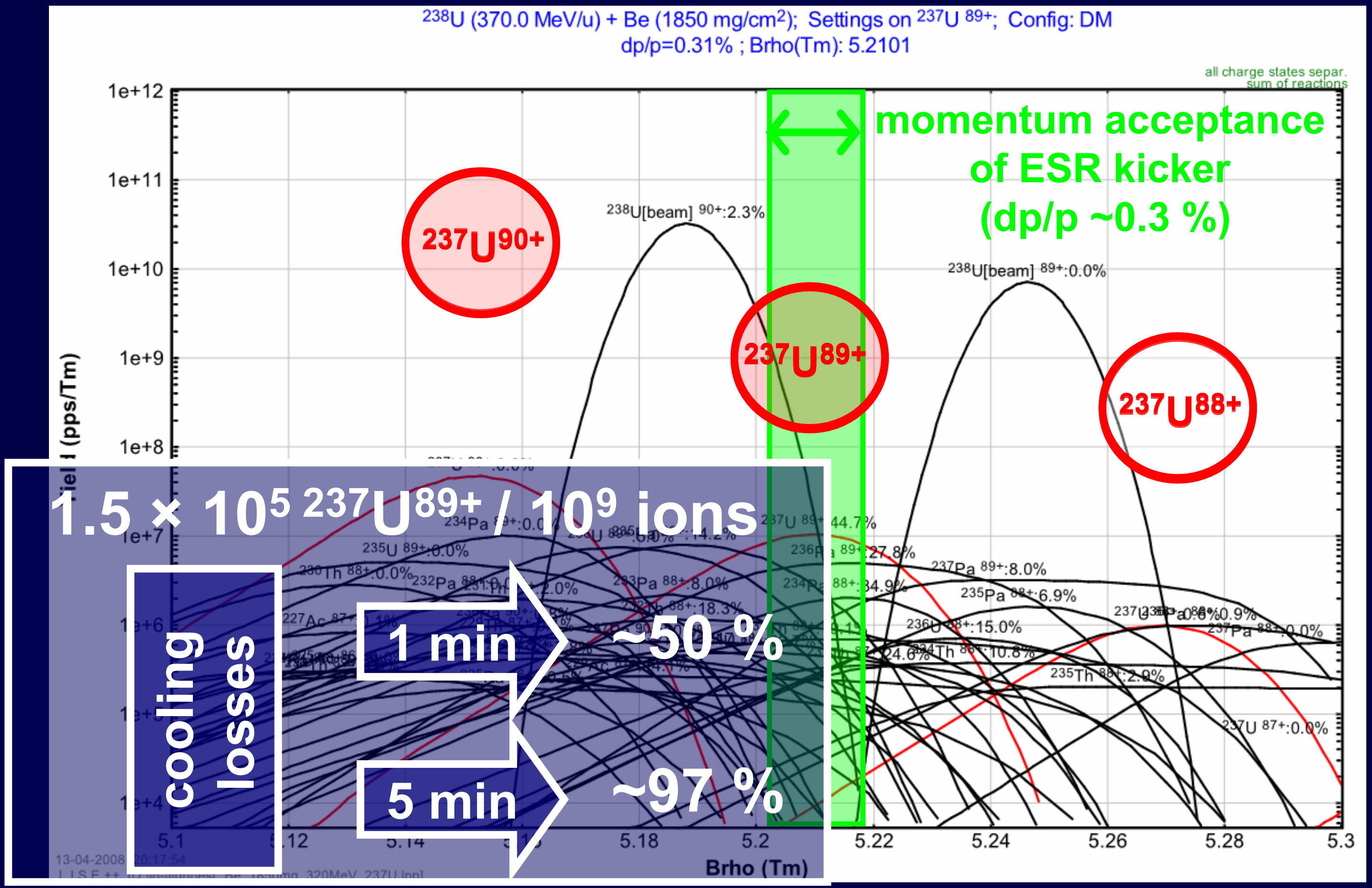
+ production of an isotope cocktail => separation w/o FRS (?)

+ energy loss and straggling in thick target

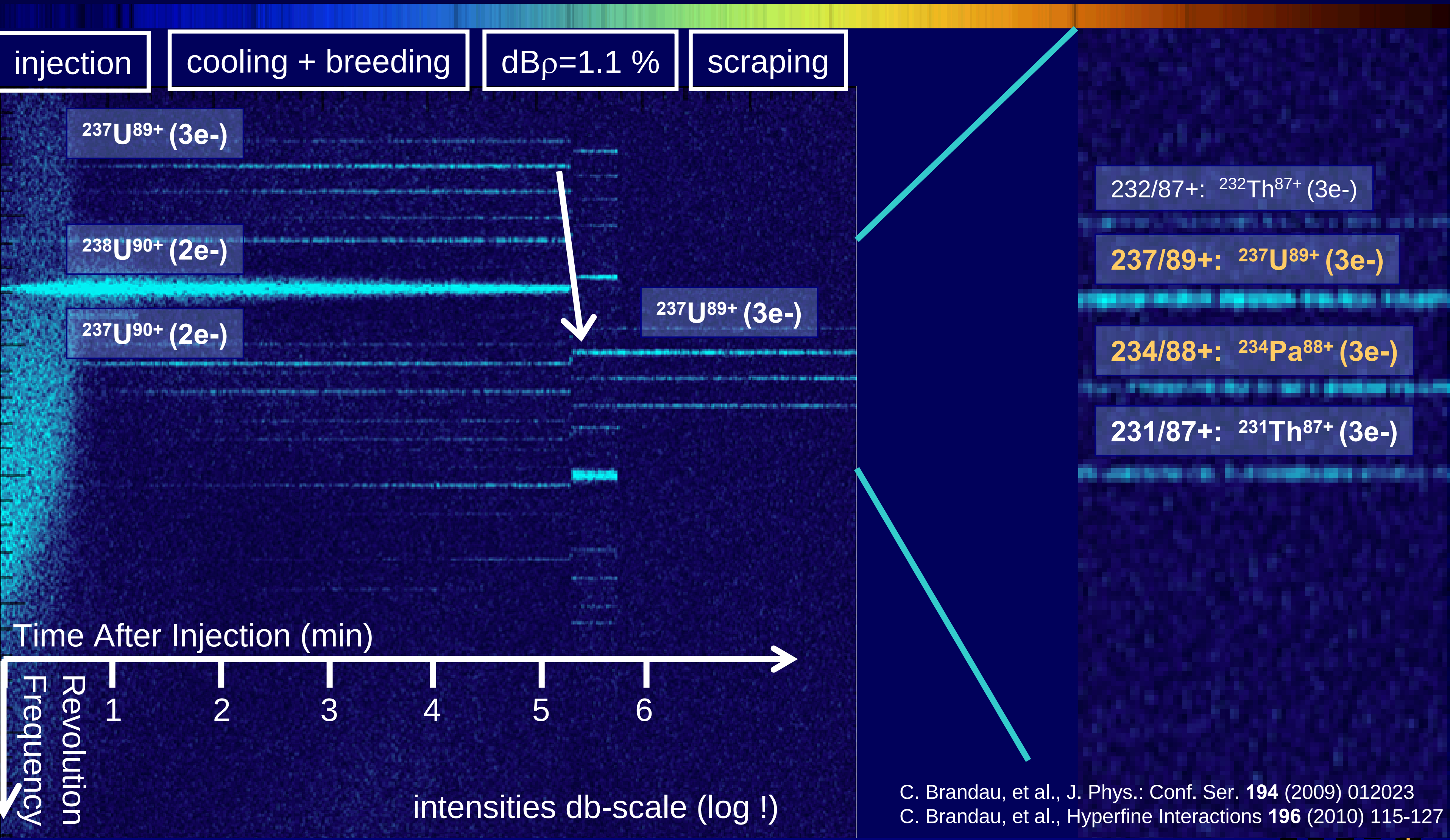
+ cooling times ~ 1-5 min (for hot fragments far off β_{Cool} ?)

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

^{238}U ions @ 370 MeV/u in SIS ⇒ 1cm Be-target (1850 mg/cm^2)

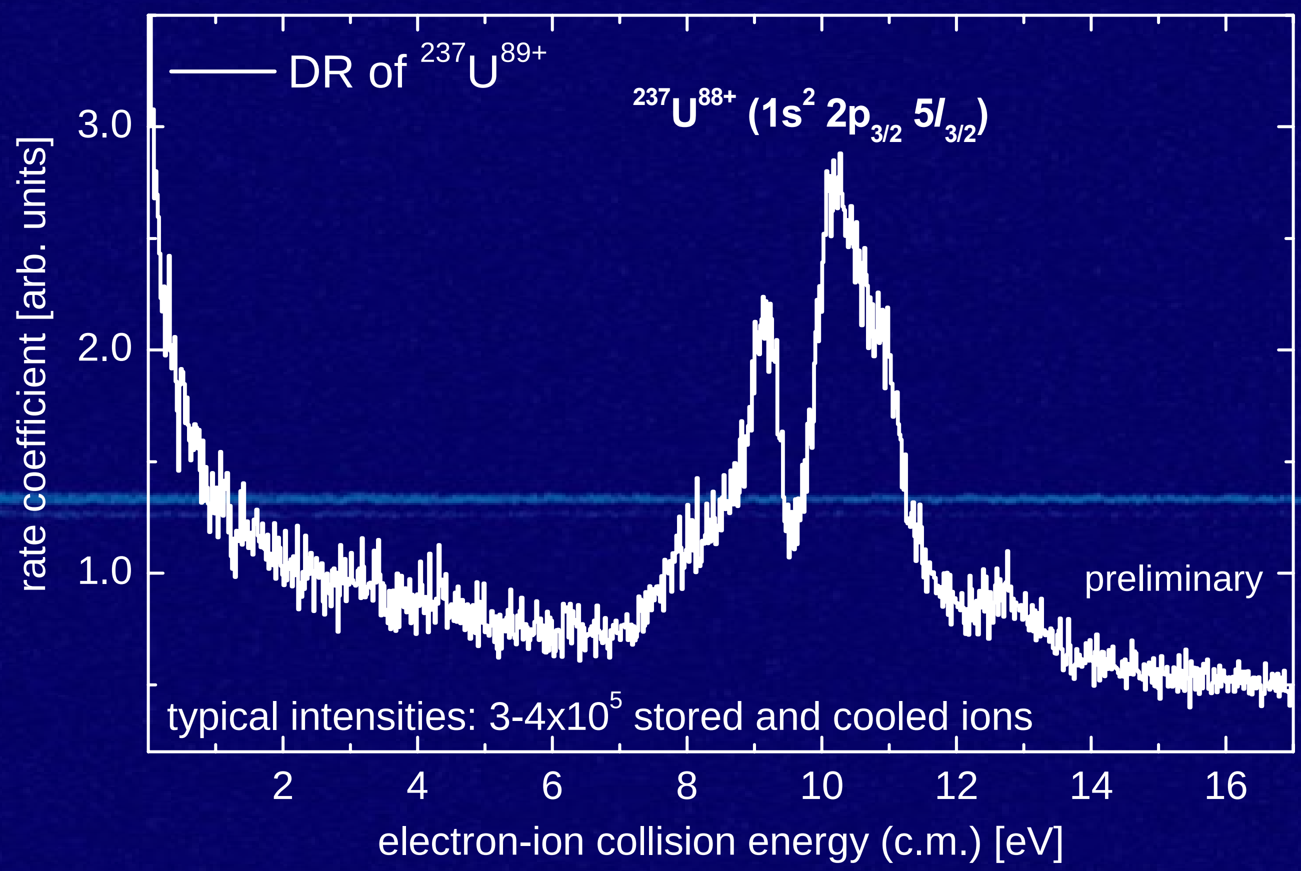


Preparation of Li-like Exotic Beams in the ESR



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

$^{237}U^{89+}$ - DR

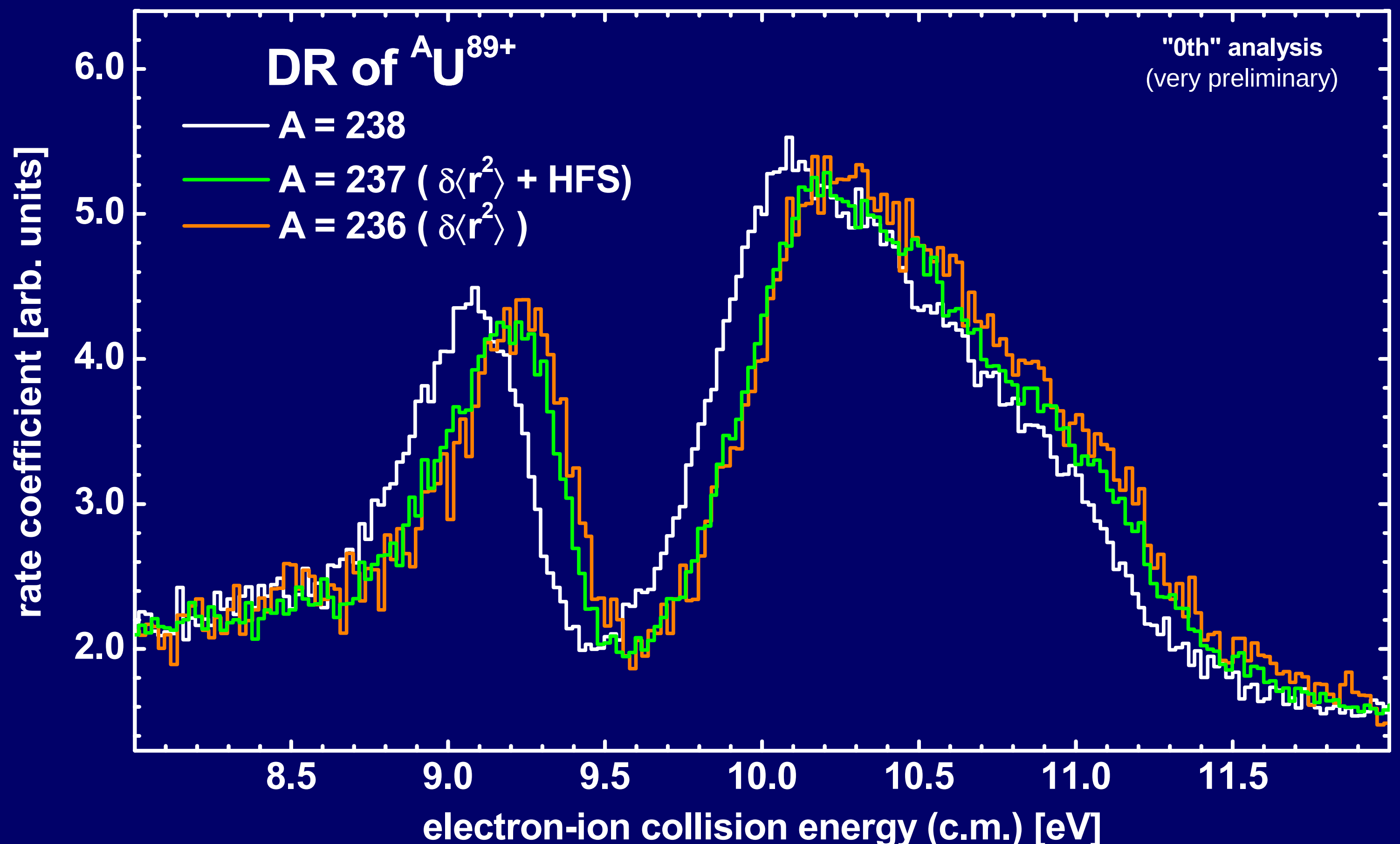


C. Brandau, et al., J. Phys.: Conf. Ser. **194** (2009) 012023

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)

(First Preliminary Results of the Oct 2009 Beamtime)



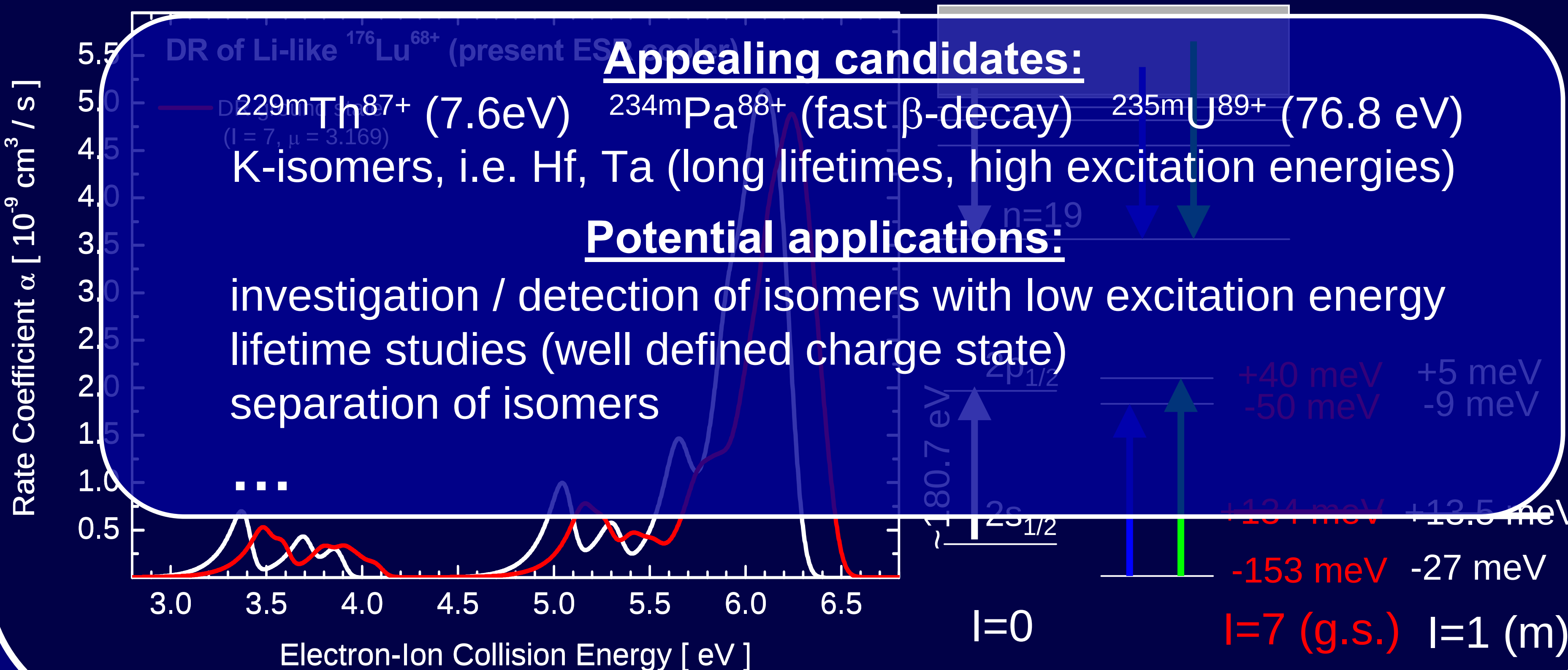
DR Investigations of Nuclear Properties

- isotope shift / hfs studies with stable isotopes
- DR experiments with exotic beams
- **nuclear metastable states (isomers)**

DR of Nuclear Metastable States (Isomers)

Li-like: $^{176g,m}Lu^{68+}$ ($1s^2\ 2p_{1/2}\ 19\ n\ l_j$)

E_{cm} = 3 – 6.5 eV (+nucl size (~1 meV) + magn. hfs effects)



Appealing candidates:

$^{229m}Th^{87+}$ (7.6eV) $^{234m}Pa^{88+}$ (fast β-decay) $^{235m}U^{89+}$ (76.8 eV)

K-isomers, i.e. Hf, Ta (long lifetimes, high excitation energies)

Potential applications:

investigation / detection of isomers with low excitation energy

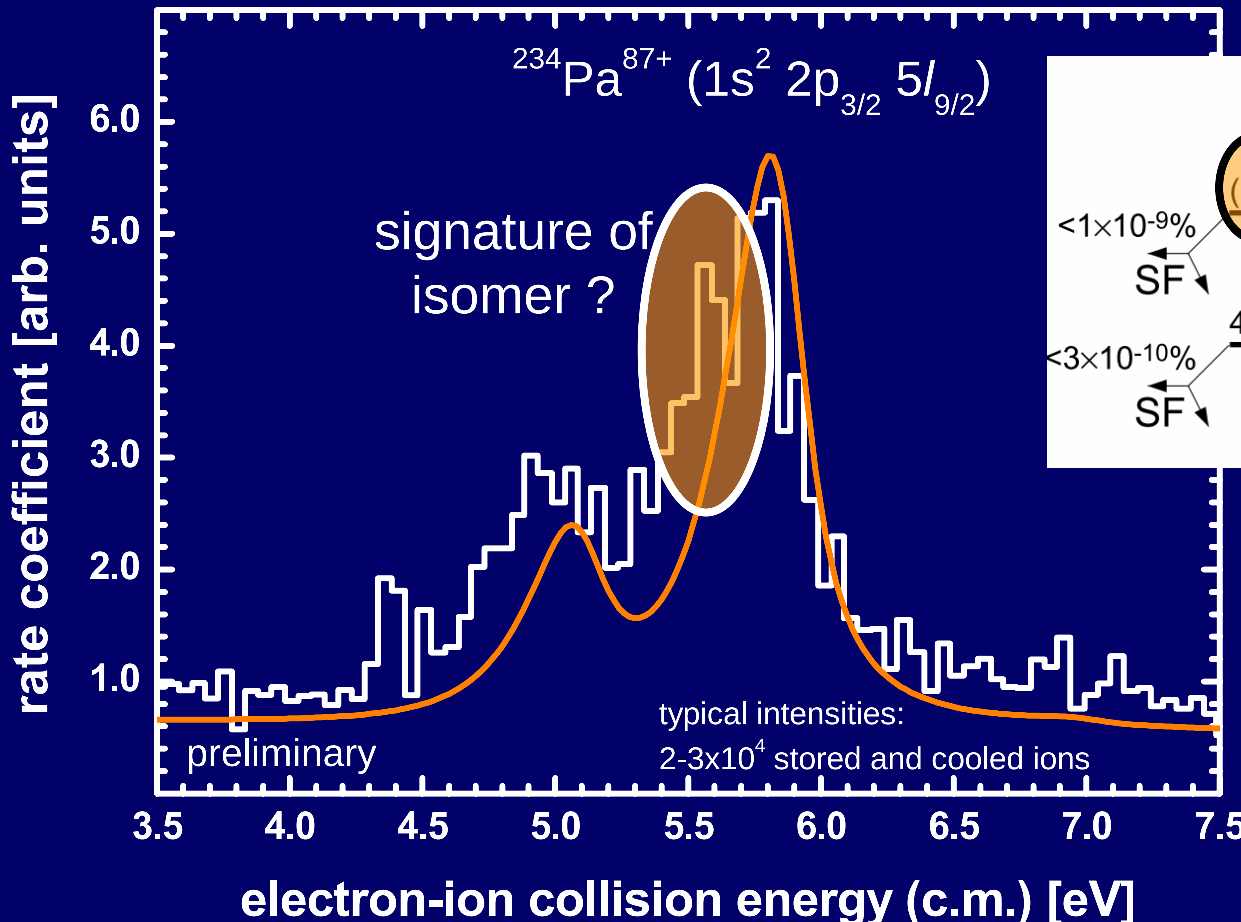
lifetime studies (well defined charge state)

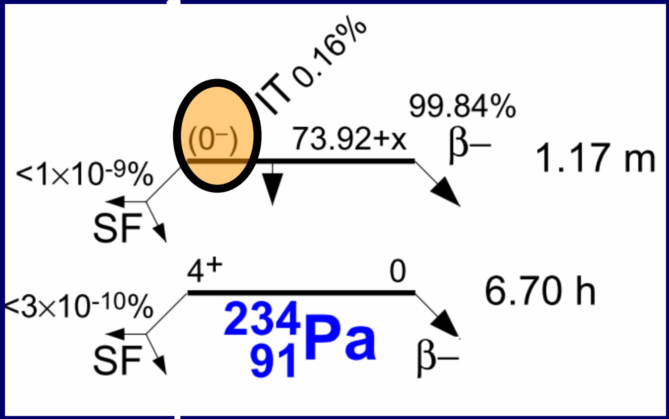
separation of isomers

...

$^{176g,m}Lu$: 7^- g-state: 3.8 x 10^{10}y 1^- m state β^- -decay (3.6h !); cosmochronometer

Isomers in $^{234}Pa^{88+}$



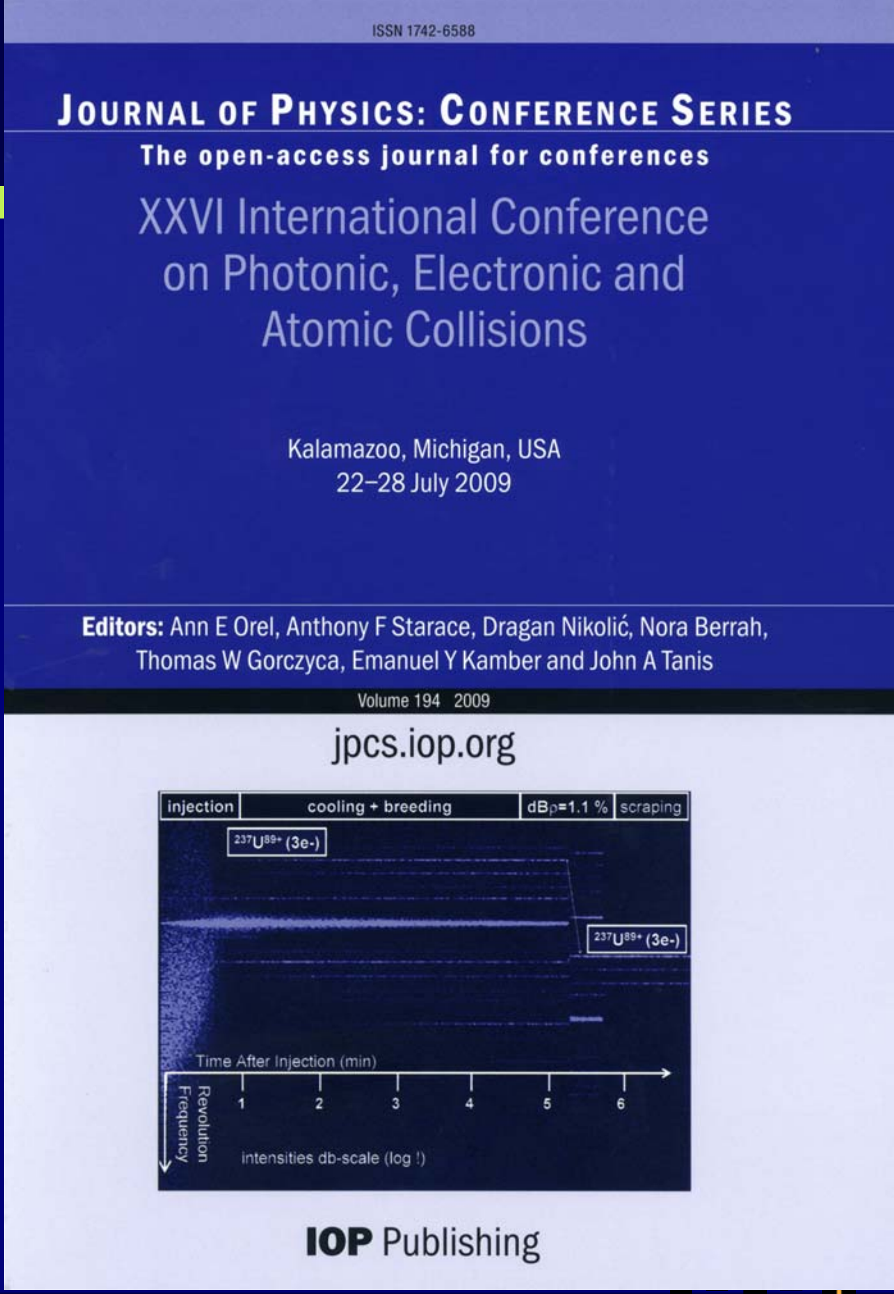


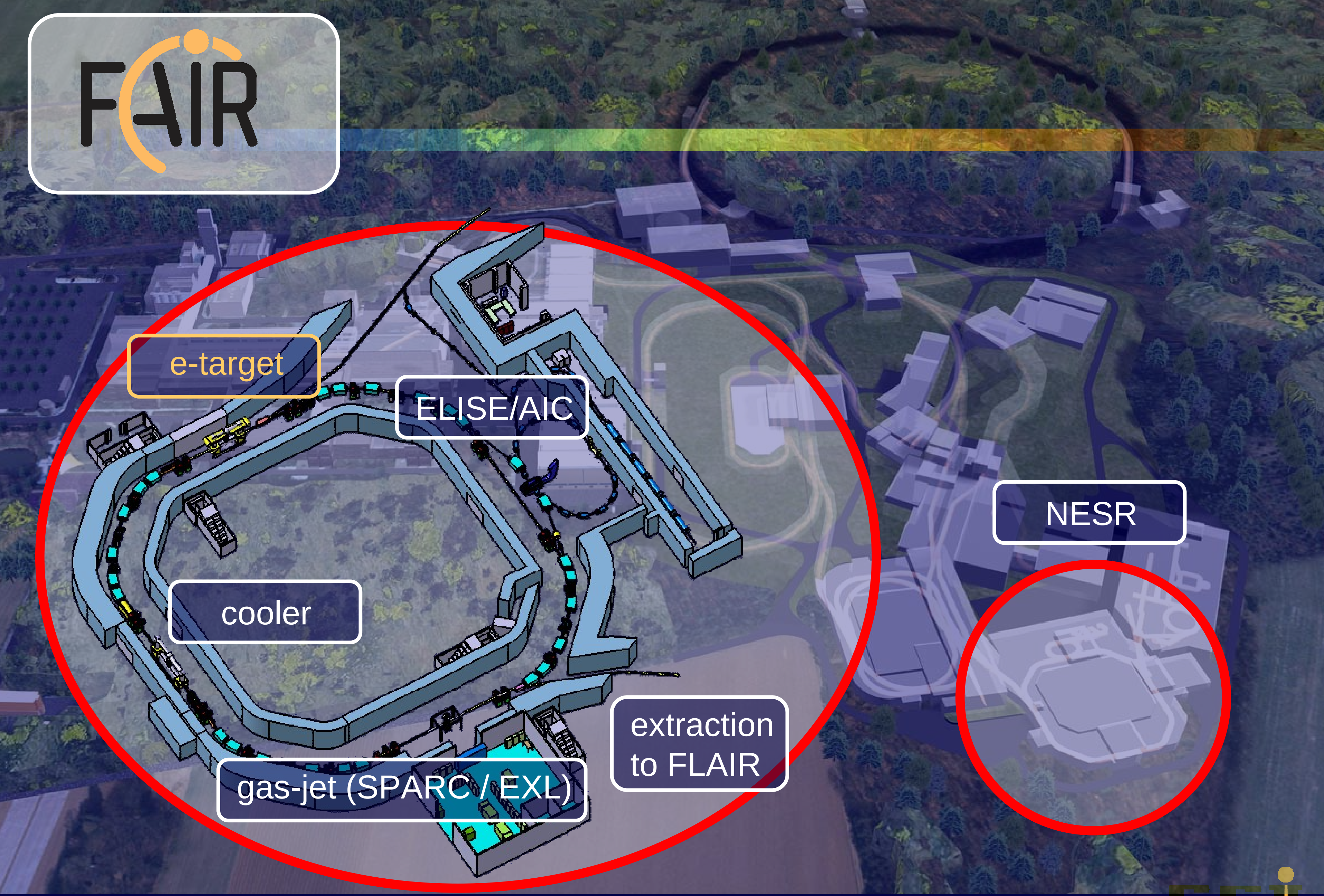
μ_n (4+ gs) = 0.7

(P. Walker, priv. comm.)

Summary and Outlook

- DR method for isotope shift of few-electron ions established
- Li-like vs. Be-like: switching the sign of the HFS contribution
- Intense radioisotope beams for AP studies (in paralllel to FRS)
- Successful DR experiment with $^{A}U^{89+}$ radioisotope beams
- Future improvements:
  - optimize radioisotope yield
  - normalization at low intensities
- Isomers: running proposal 3 days test beamtime acknowledged (full proposal soon)




FAIR
e-target
ELISE/AIC
cooler
NESR
extraction
to FLAIR
gas-jet (SPARC / EXL)

Thank you for your attention !

Isotope Shift Measurements by Means of DR

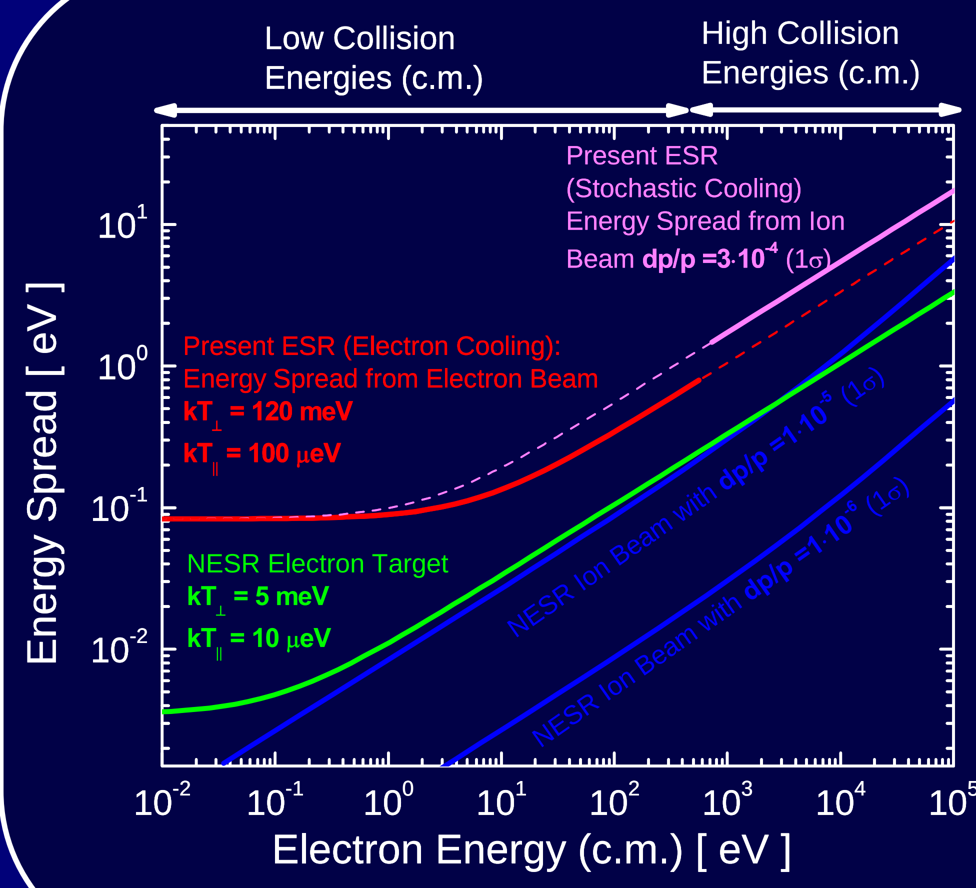
„Accessing Nuclear Properties with Large Atomic Cross Sections“

- novel method with large FAIR potential
- very effiicient approach to $\delta\langle r^2 \rangle$, I, μ_I and $T_{1/2}$
- radioisotopes / isomers
- isotopically pure (or cocktail) beam, single charge state
- few-electron system (**Li-like**, …):
  - $\Rightarrow$ reliable theoretical description (full QED !)
  - $\Rightarrow$ negligible specific mass shift
- whole pattern of well-resolved resonance structures
  - $\Rightarrow$ **Li-like (2 excitations)** : 2s $\rightarrow$ $2p_{1/2}$, 2s $\rightarrow$ $2p_{3/2}$
- **nuclear size ~ $Z^{5…6}$; HFS ~Z^4 $\Rightarrow$ well suited for heavy systems (Z>50)**

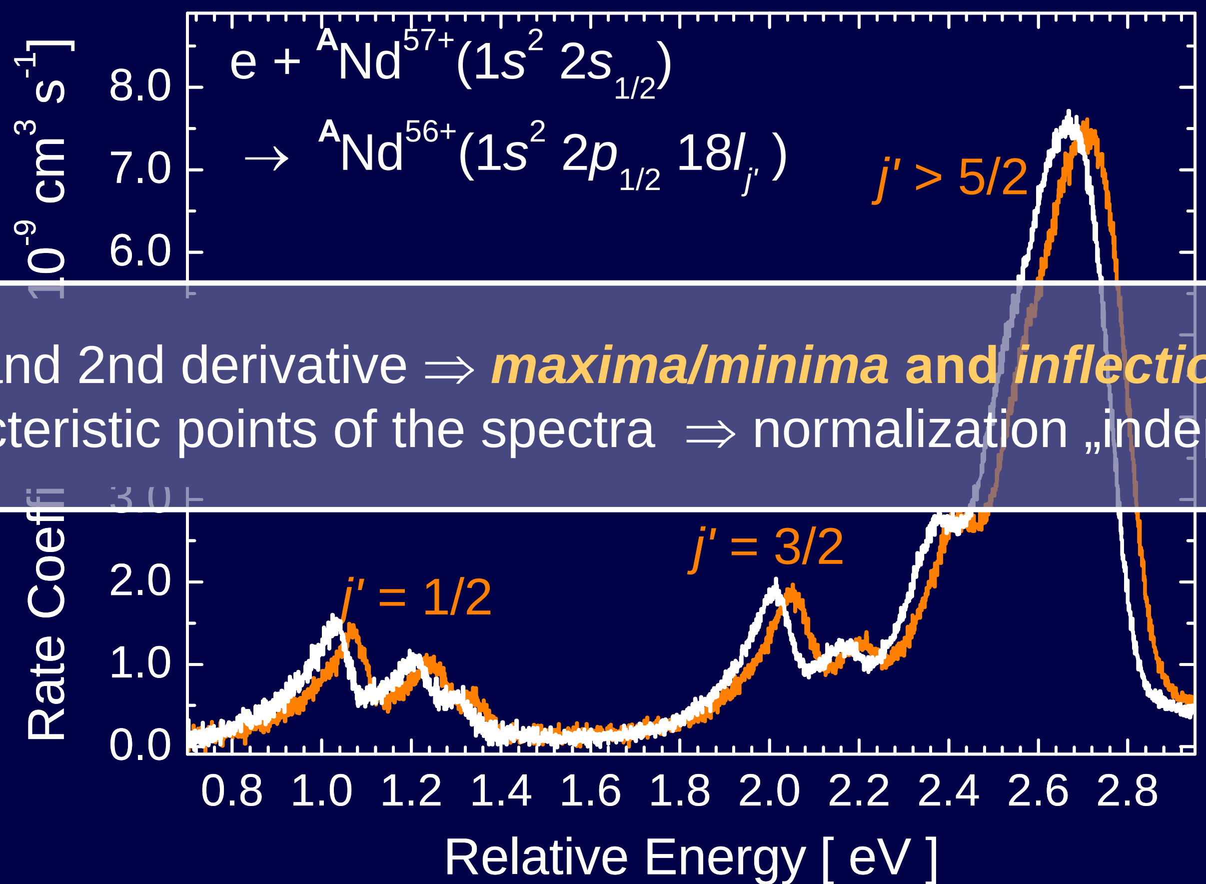
GSI

Outlook

- production run on IS / HFS with in-flight produced uranium isotopes (sept. 2009)
- isomers / lifetimes ?
- are more exotic processes (e.g. NEEC) feasible ??
- DR @ FAIR (within SPARC) ⇒ a dedicated ‚ultracold' electron target



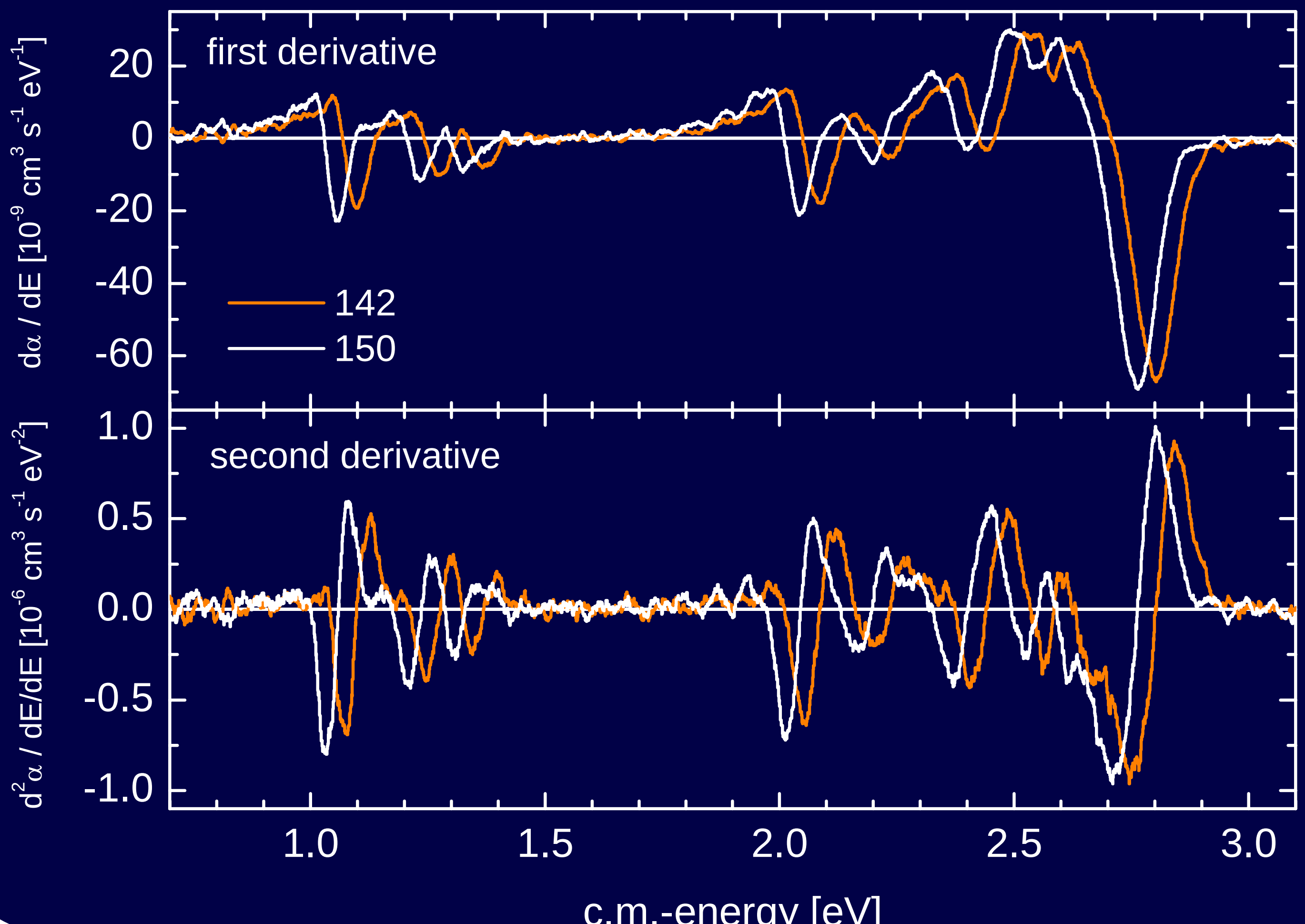
So Many Nice Resonant Features
How to Get the Energy Shift ?



Idea: 1st and 2nd derivative ⇒ ***maxima/minima and inflection points***
(characteristic points of the spectra ⇒ normalization „independent“)

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

Derivatives of the DR Spectra for the $^{A}Nd^{56+}(1s_2\ 2s_{1/2}\ 18\ l_j)$ Group



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

Non-comprehensive List of $\delta\langle r^2 \rangle$ Values for the Isotope Pair ^{142}Nd - ^{150}Nd

about 20 publications (optical, muonic, K_α x-ray, e-scattering), a few examples :

Method	$\delta\langle r^2 \rangle$
„combined“ analysis:	**1.291 fm² [1]**
muonic atoms:	1.324 fm² [2]
e-scattering, high energy:	1.345 fm² [3]
e-scattering, low energy:	-0.569 fm² [4]
e-scattering, reanalysed:	0.765 fm² [5]
e-scattering, low energy (II):	0.220 fm² [6]
optical IS	1.205 fm² [7]
optical IS	1.259 fm² [8]
optical IS ($\lambda \rightarrow \delta\langle r^2 \rangle$)	1.220 fm² [9]
optical IS (λ ?)	1.205 fm² [10]
K_α x-ray ($\lambda \rightarrow \delta\langle r^2 \rangle$)	1.259 fm² [11]
K_α x-ray	1.353 fm² [12]
DR-IS (this work)	1.36(1)(3) fm²

[1] I. Angeli, ADNDT 87 (2004) 185
[2] G. Fricke, et al., ADNDT 60 (1995) 177
[3] N.P. Heisenberg, et al., NPA 164 (1971) 340
[4] D.W. Madsen, et al., NPA 169 (1971) 97
[5] L.S. Cardman, et al., NPA 216 (1973) 285
[6] R. Maas, et al., Phys. Lett. B 48 (1974) 212
[7] E. W. Otten, Treat on Heavy-ion Sci., Vol.8
[8] M. Wakasugi, et al., J Phys. Soc. Jap, 59 (1990) 2700
[9] W.H. King et al., Z Phys 265 (1973) 207
[10] M. Hongliang, et al., PRA 44 (1991) 1843 / J Phys B, 30 (1997) 3355
[11] S.K. Battacherjee, et al., PR 188 (1969) 188
P.L. Lee and F. Boehm, PRC 8 (1973) 819
[12] O.I. Sumbaev, et al., Sov. J. Nucl. Phys. 5 (1967) 387

Systematic Errors

Study of Systematic Errors (Re-Run of Analysis under the Assumption of Alternative Input Parameters):
($2p_{1/2}$ only)

ion energy:	~0.1 meV
misalignment (0.2 mrad)	<0.1 meV
Normalization/RR & BG subtraction):	~0.4 meV
DT voltage calibration	~0.1 meV
number of points for S/G:	~0.4 meV
Total:	0.6 meV

additionally for radius determination:
Nuclear Polarization (130 keV 2+ state in A=150) ~0.3 meV

Non-comprehensive List of $\delta\langle r^2 \rangle$ Values for the Isotope Pair ^{142}Nd - ^{150}Nd

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[5] L.S. Cardman, et al., NPA 216 (1973) 285
[6] R. Maas, et al., Phys. Lett. B 48 (1974) 212
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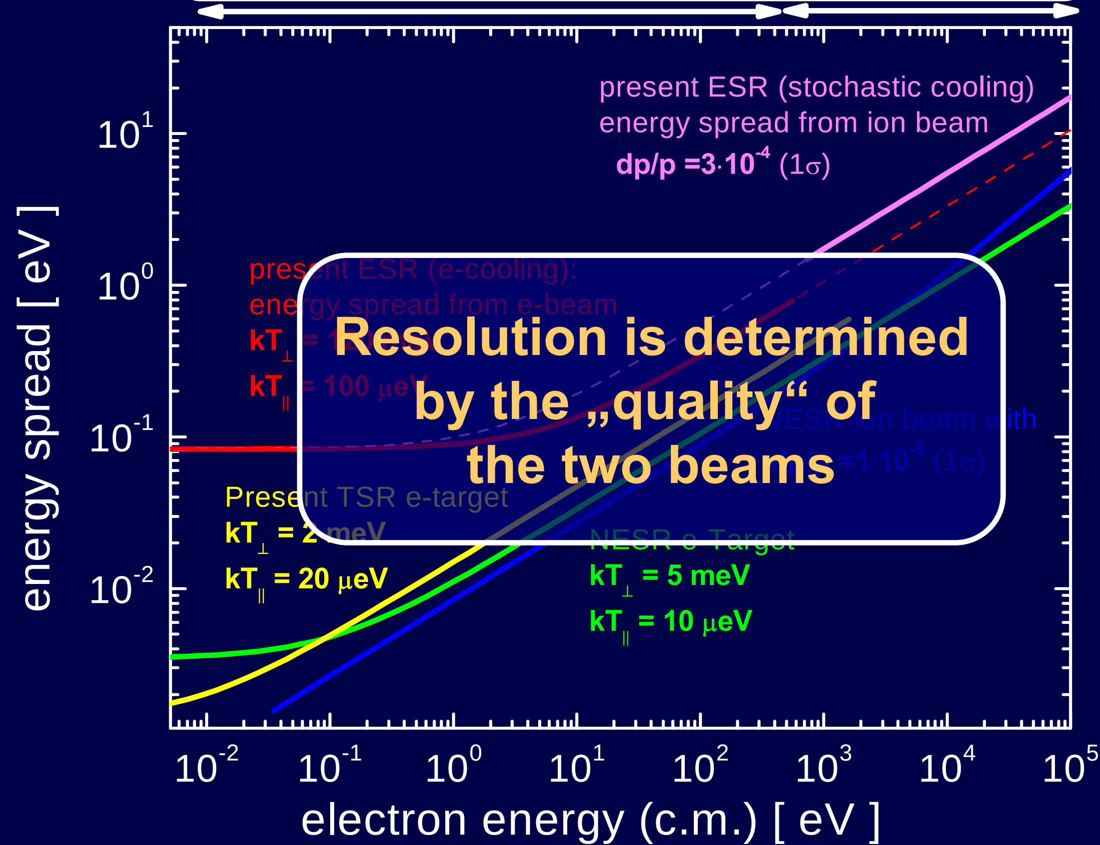
[10] M. Hongliang, et al., PRA 44 (1991) 1843 / J Phys B, 30 (1997) 3355
[11] S.K. Battacherjee, et al., PR 188 (1969) 188 P.L. Lee and F. Boehm, PRC 8 (1973) 819
[12] O.I. Sumbaev, et al., Sov. J. Nucl. Phys. 5 (1967) 387

Energy Resolution in DR Experiments ESR / TSR and NESR

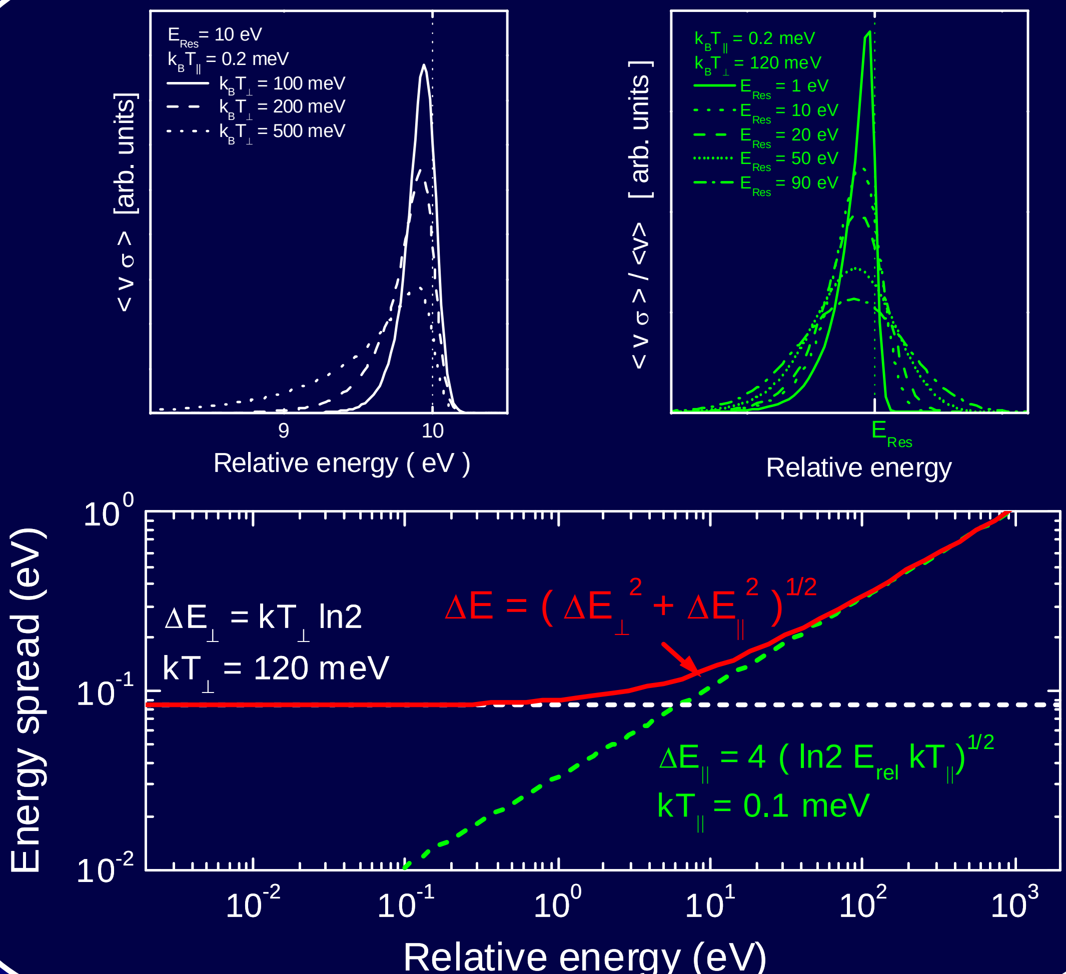
collision energies from meV to sub MeV



Resolution is determined by the „quality“ of the two beams

resolution ~1 meV to ~10 eV

Experimental Response Function and Resolution



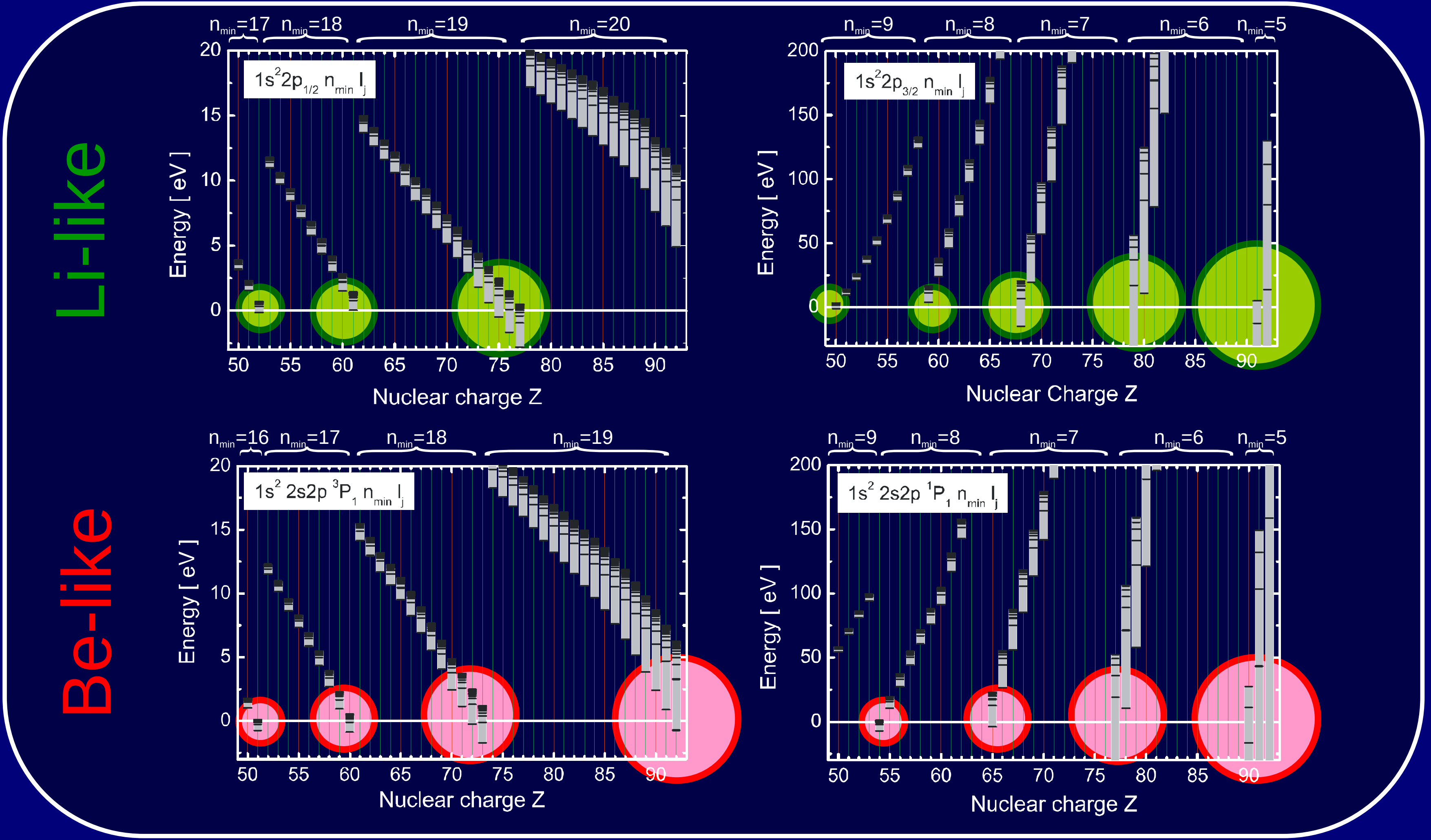
experimental resolution is mainly determined by the velocity spread of the cooler/target electron beam.

=> 2-parameter Maxwell-Boltzmann distribution ($kT_\perp >> kT_\parallel$)

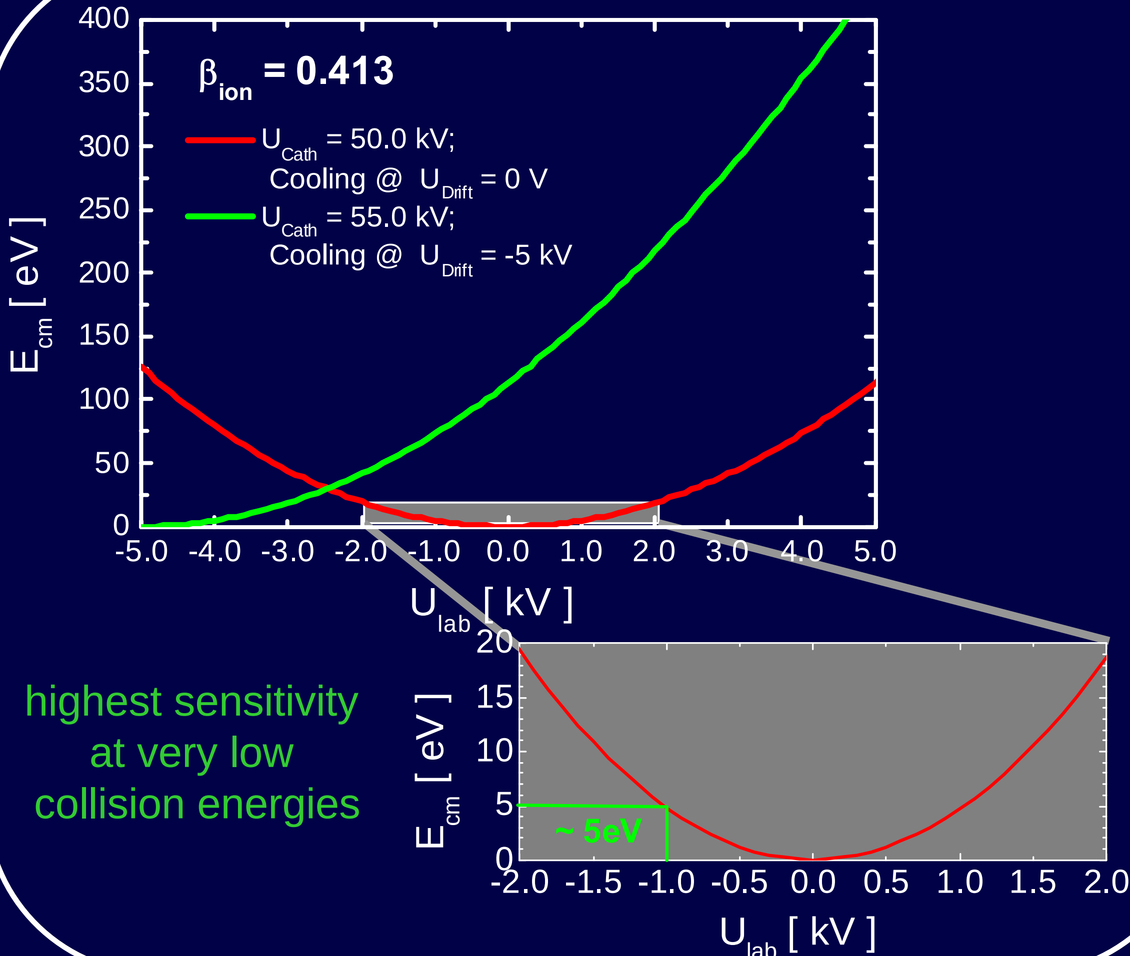
$kT_\perp$:
energy independent
asym. broadening
on low energy side

$kT_\parallel$:
energy dependent
symmetric broadening

Strong Low-Lying DR Resonances of Li-like and Be-like Ions



Resonance Reaction Spectroscopy
(GSI Electron Cooler as a Target)



highest sensitivity
at very low
collision energies

merged circulating
ion-beam and
cooler electron-beam

variation of E_{rel}:
fast energy scan
(approx. 8000 pts. à 35 ms
with intermediate cooling)

detection of the
recombined ions **A** $^{(q-1)+}$
with single particle detector

$\Rightarrow$ rate coeffizient $\alpha(E_{rel})$
on an absolute scale

co-propagating beams
$\Rightarrow$ $0 \leq E_{rel} \leq 1000$ eV
@ $0 \leq \Delta U_{lab} \leq 10000$ V

Contributions of the Nuclear Charge Radius to the 2s -2p$_{1/2}$ Energy Splitting (Total Values and Uncertainties)

2s-2p$_{1/2}$ energy splitting (QED) in 3 electron systems (Li-like):
experimental error vs. theoretical uncertainty (QED)

	$^{197}Au^{76+}$	$^{208}Pb^{79+}$	$^{238}U^{89+}$
	216.167**(29)(67)** eV	230.650**(30)(51)** eV	280.516**(34)(65)** eV [1]
Yerokhin et al., (2001)	216.170(130)(110) eV	230.680(60)(130) eV	280.640(110)(200) eV
Fin. nucl.	-7.680**(120)** eV[a]	-10.670**(20)** eV	-33.350**(70)** eV
$\langle r^2 \rangle^{1/2}$	5.437 fm	5.504(4) fm	5.860(2) fm

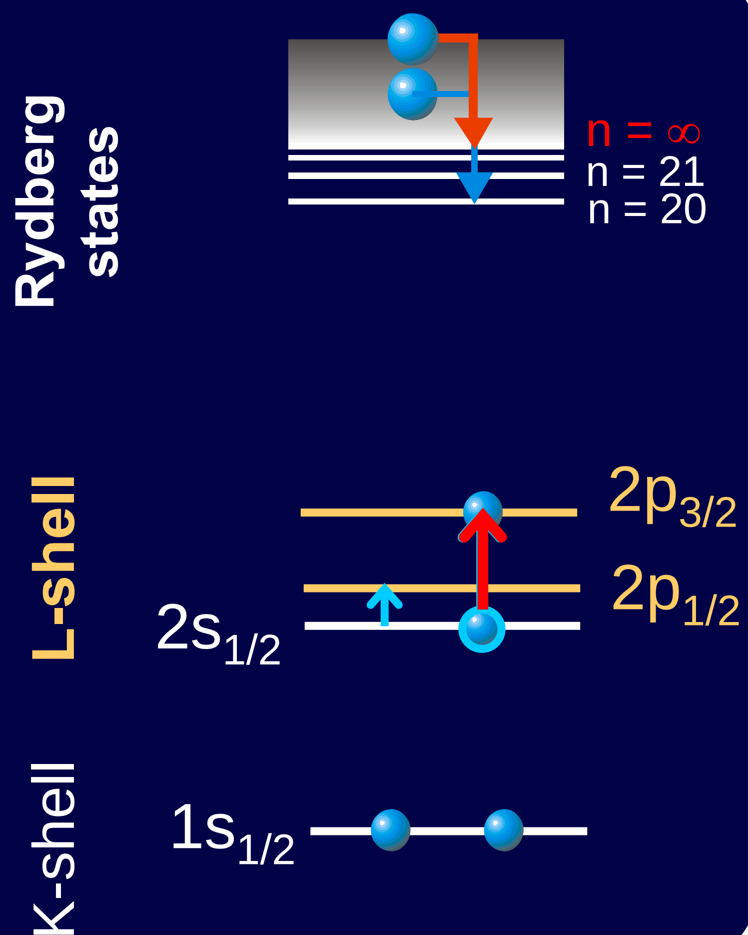
example $^{238}U^{89+}$: $\langle r^2 \rangle^{1/2}$ = 5.8604(23) fm (muonic atoms) [2]
uncertainty of 0.0023 fm => ΔE = 0.020 eV

but: $\langle r^2 \rangle^{1/2}$ = 5.8507(74) fm (combined analysis) [3]
=> δE(Fin.Nucl.) ≈ 0.085 eV and ΔE(Fin.Nucl.) ≈ 0.06 eV

[1] C. Brandau et al.,PRL **91**(2003)073202
[2] J.D. Zumbro et al.,PRL **53**(1984)1888
[3] I. Angeli, ADNDT 87(2004)187
[4] P. Beiersdorfer et al., PRL **95**(2005)233003

GSI

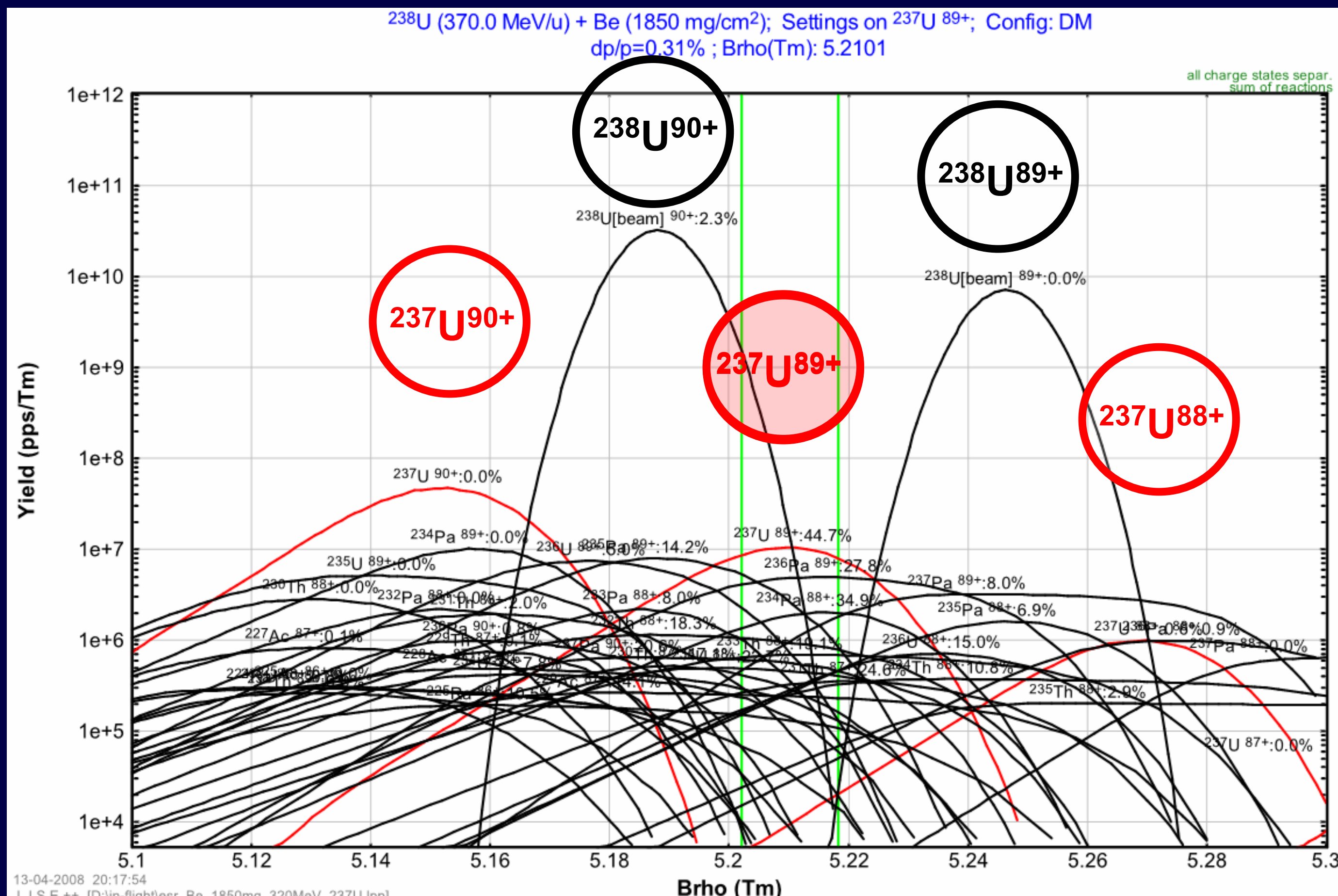
Low Energy – DR ($\Delta n = 0$)



schematically – not to scale

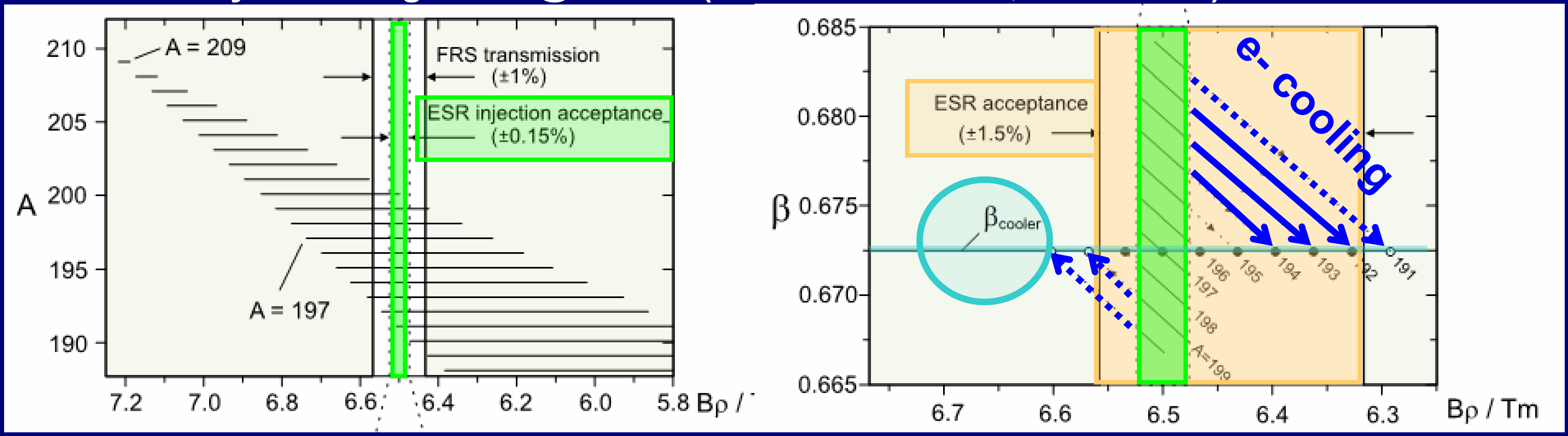
- at least 3 e- (Li-like)
- intra-shell transitions ($\Delta n = 0$)
  $2s_{1/2} \rightarrow 2p_{1/2}$ and **$2s_{1/2} \rightarrow 2p_{3/2}$**
- capture to high-Rydberg states (Rydberg series)
- partial (or near) cancellation of excitation and binding energy
  => **E_{kin} very low / low**
  => high precision measurements with very high resolution

^{238}U ions @ 370 MeV/u in SIS $\Rightarrow$ 1cm Be-target (1850 mg/cm^2)



Injection of an Isotope Cocktail into the ESR

schematically: ^{209}Bi fragments @ 6.5 Tm (from: Yu. Litvinov, PhD thesis)



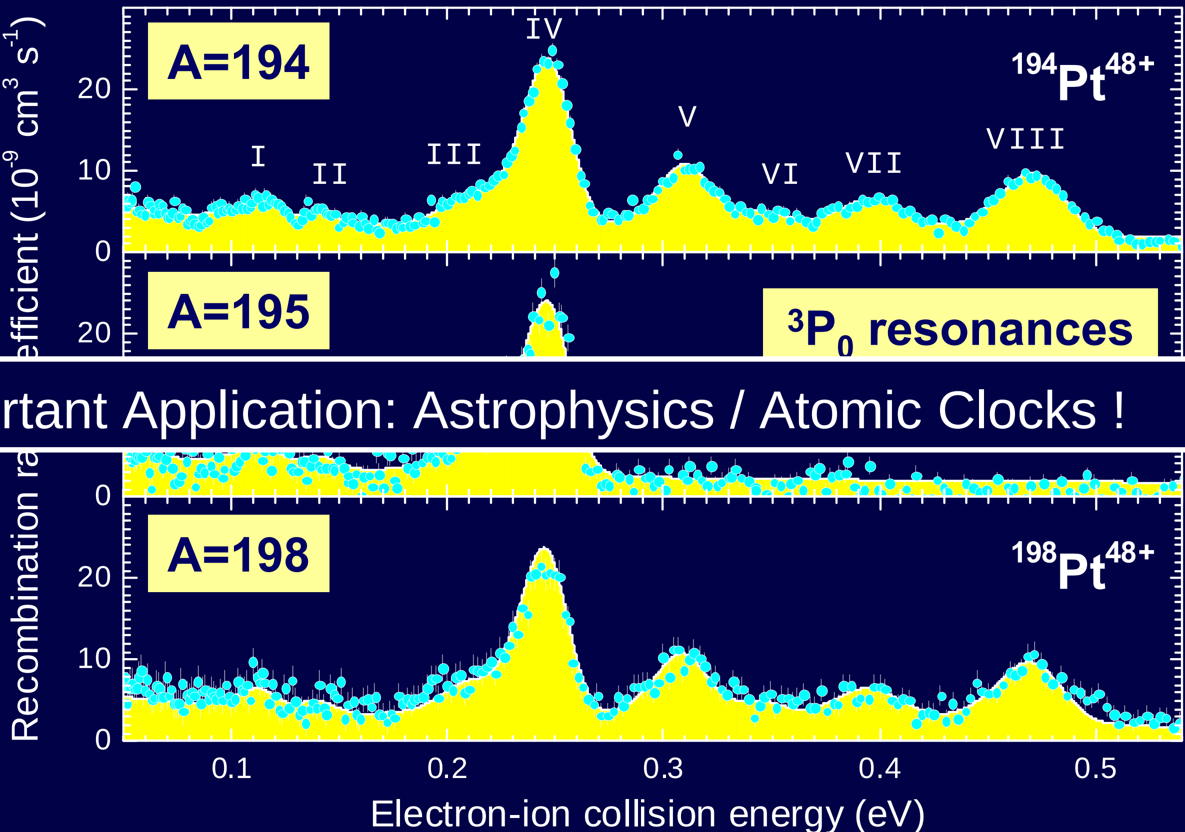
same Bρ – different energies => Cooling => fixed velocity (β_{Cooler}) - different Bρ

separation in ESR

septum	cooling	scrapers
Bρ	ΔE	Bρ

Nucleus Altering Atomic Transition Rates:

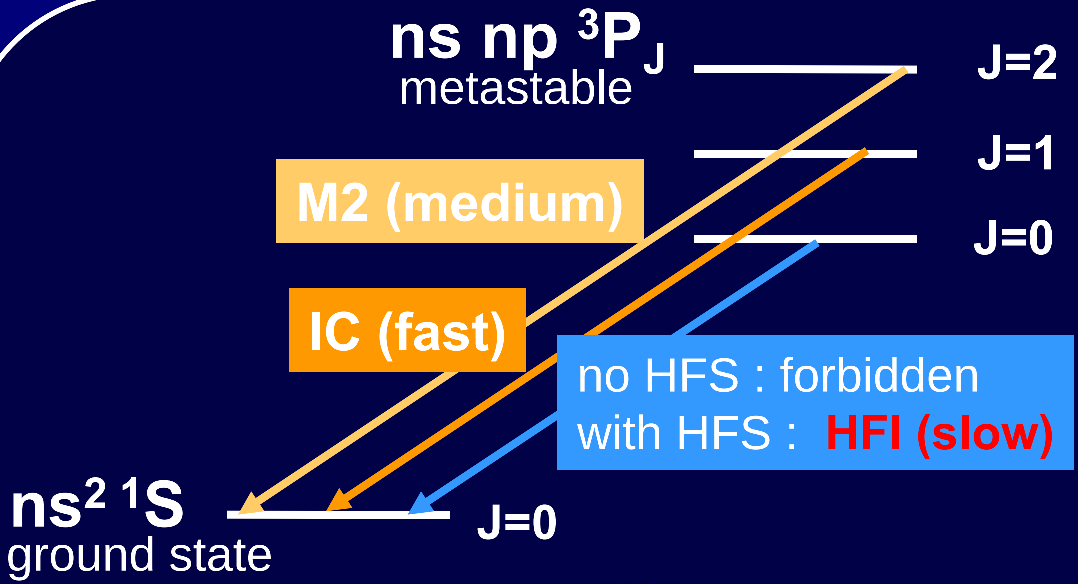
Hyperfine-Quenching in Atomic Metastable Ions (here: Zn-like Pt^{48+})



Important Application: Astrophysics / Atomic Clocks !

S. Schippers, et al., NIMB **235** (2005) 265

Lifetime Measurements Using DR:
Hyperfine-Induced Transitions of Metastable States



2 valence electrons

n=2: Be, (-like)

n=3: Mg, (-like)

n=4: Ca, Zn (-like)

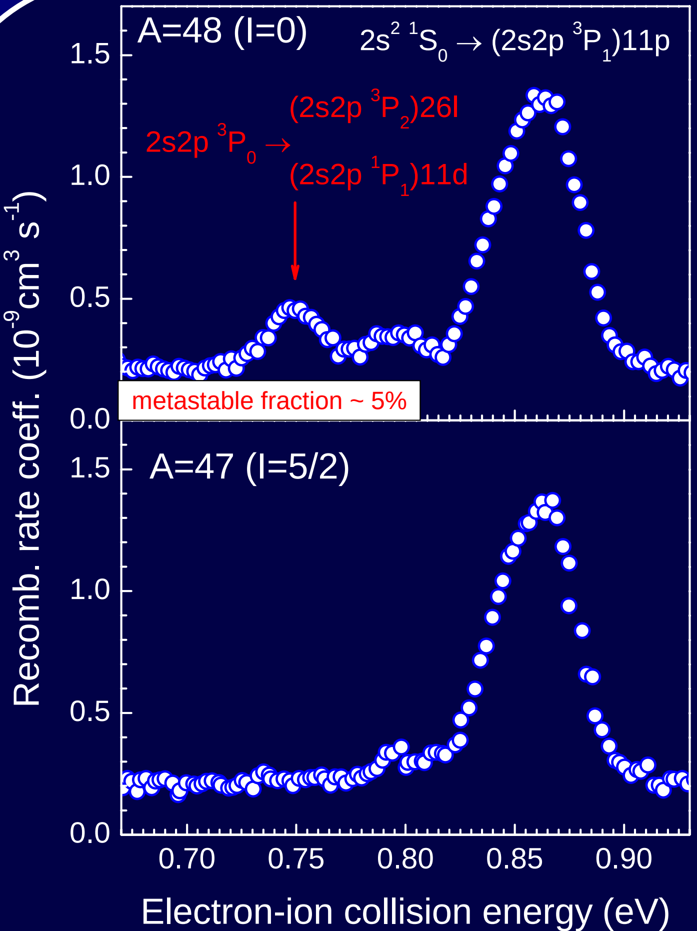
n=5: Sr, Cd (-like)

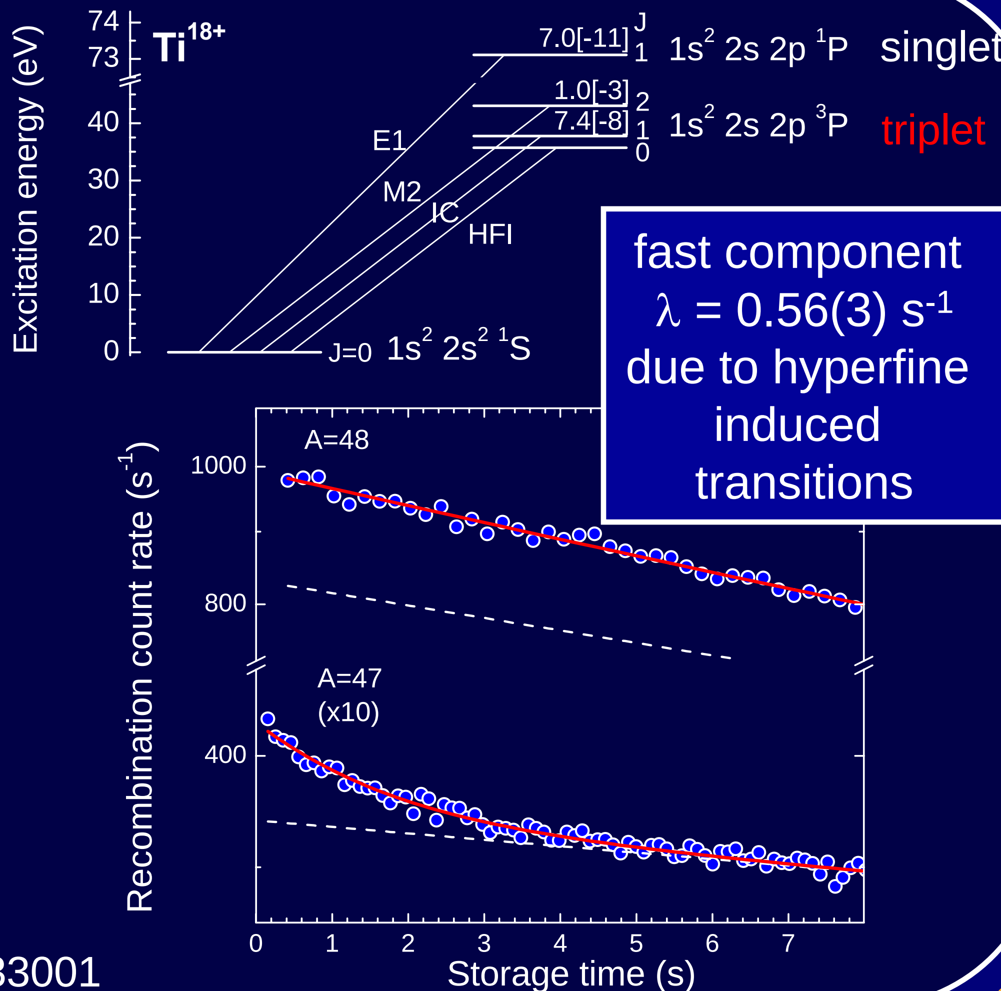
n=6: Ba, Hg (-like)

n=7: Ra (-like)

- nucleosynthesis/astrophysics (HFI signal, => ^{13}C, (^{14}N) abundance), see e.g.:
  R.H. Rubin et al., Astroph. J. **605** (2004) 784;
  T. Brage et al., PRL. **89** (2002) 281101
- atomic clock (e.g. In+, natural width 0.8 Hz),
  Th. Becker et al., Phys. Rev. A **63** (2001) 051802

Lifetime Measurements Using DR: Hyperfine Quenching of Atomic Metastable States (Be-like $^{A}Ti^{18+}$ at the Storage Ring TSR)





fast component
λ = 0.56(3) s⁻¹
due to hyperfine induced transitions

S. Schippers et al., PRL **98** (2007) 033001