National Nuclear Physics Summer School 2019

Precision Mass Measurements of Short-lived Nuclei at the HIRFL-CSR facility:

N = 32 subshell closure in Scandium

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Outline

1. Introduction: Mass Measurements
2. Motivation: Magic number N=32
3. IMS Experiment: Setup, Analysis
4. Results and Discussion
5. Future Improvements

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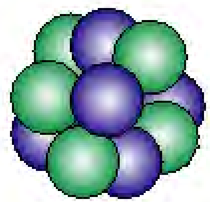
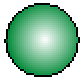
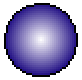
Atomic Mass

Mass → Binding Energy → Interaction

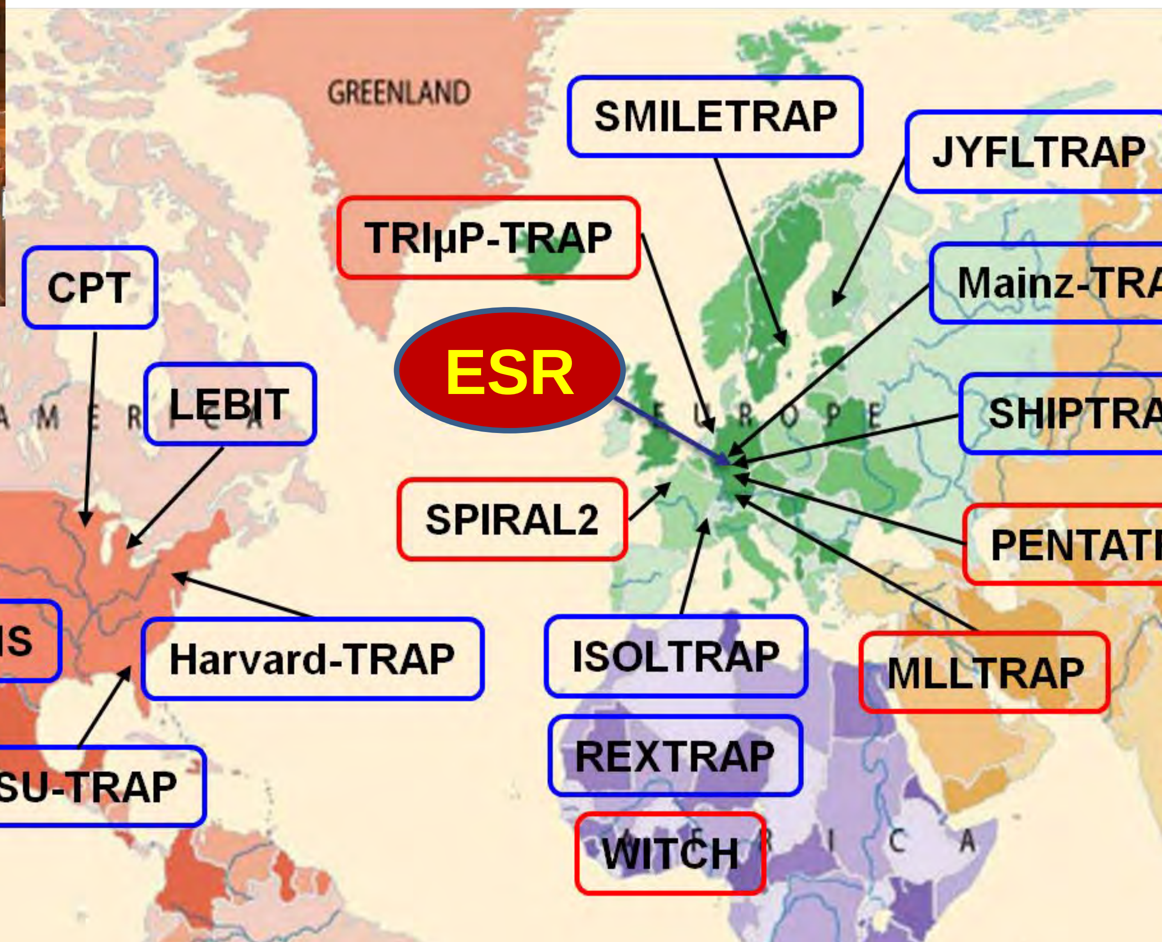
 = N×  +Z× 

- Binding Energy

	Filed of application	Required uncertainty
	Chemistry: identification of molecules	10^{-5}–10^{-6}
Nuclear Mass Measurement	Nuclear physics: shells, sub-shells, pairing	10^{-6} ~100 keV
	Nuclear structure: deformation, halos	10^{-7}–10^{-8}
	Astrophysics: r-process, rp-process, waiting points	10^{-7} ~10 keV
	Nuclear models and formulas: IMME	10^{-7}–10^{-8}
	Weak interaction studies: CVC hypothesis, CKM unitarity	10^{-8} ~1 keV
	Atomic physics: binding energies, QED	10^{-9}–10^{-11}
	Metrology: fundamental constants, CPT	10^{-10}

K. Blaum, Physics Reports 425 (2006) 1–78

Penning Traps & Storage Rings



Penning Trap:
Highest precision（10^{-5}-10^{-11} ）
Lifetime: ~ s
Phase-Imaging Tech (~ 100 ms)

Storage ring:
High precision（10^{-5}-10^{-7}）
Short-lived (>100us),
low production

Atomic Mass Evaluation (AME)

The NUBASE2016 evaluation of nuclear properties, Chinese Physics C Vol. 41, No. 3 (2017) 030001

The AME 2016 atomic mass evaluation (1): evaluation of input data, adjustment procedures, Chinese Physics C Vol. 41, No. 3 (2017) 030002

The AME 2016 atomic mass evaluation (2): tables, graphs and references, Chinese Physics C Vol. 41, No. 3(2017) 030003

"ATOMIC MASS DATA CENTER"

http://amdc.impcas.ac.cn/

Andoid: Google Play Store request "Nucleus Amdc"

Win: http://amdc.impcas.ac.cn/web/nubdisp_en.html

Storage-ring Mass Spectrometry

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

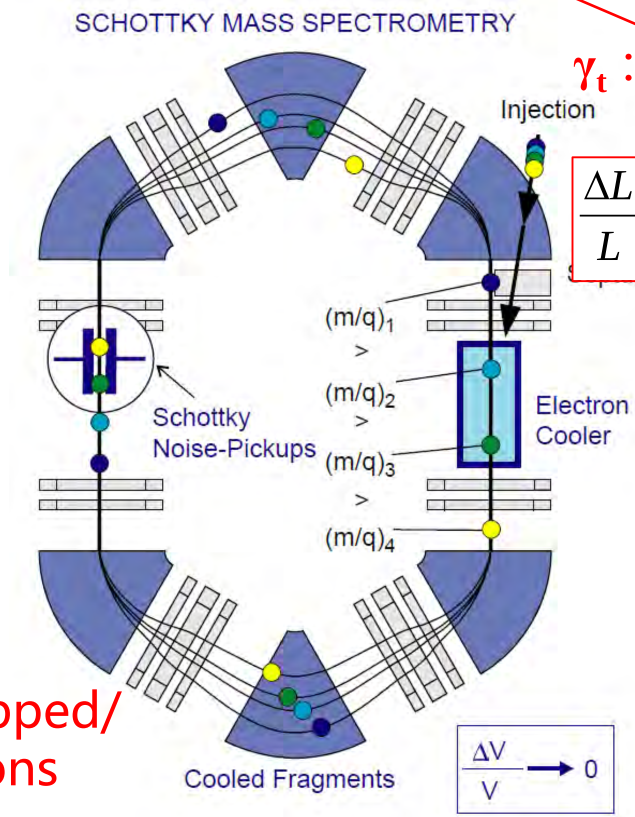
Frequency → f

γ : Lorentz factor

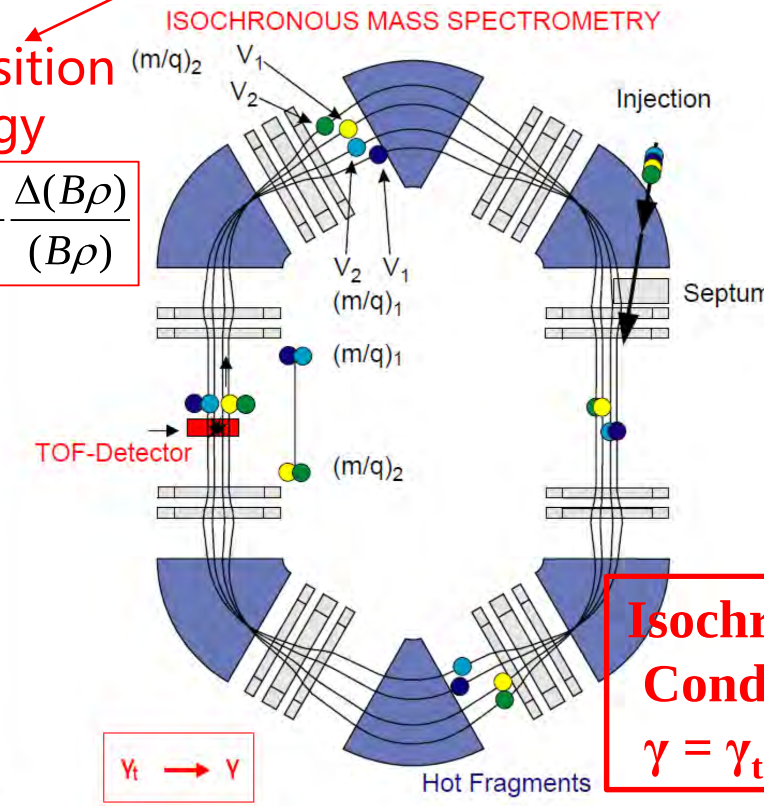
Velocity → v

γ_t : Transition Energy

$$\frac{\Delta L}{L} = -\frac{1}{\gamma_t^2}\frac{\Delta(B\rho)}{(B\rho)}$$



Fully stripped/ H⁺-like ions

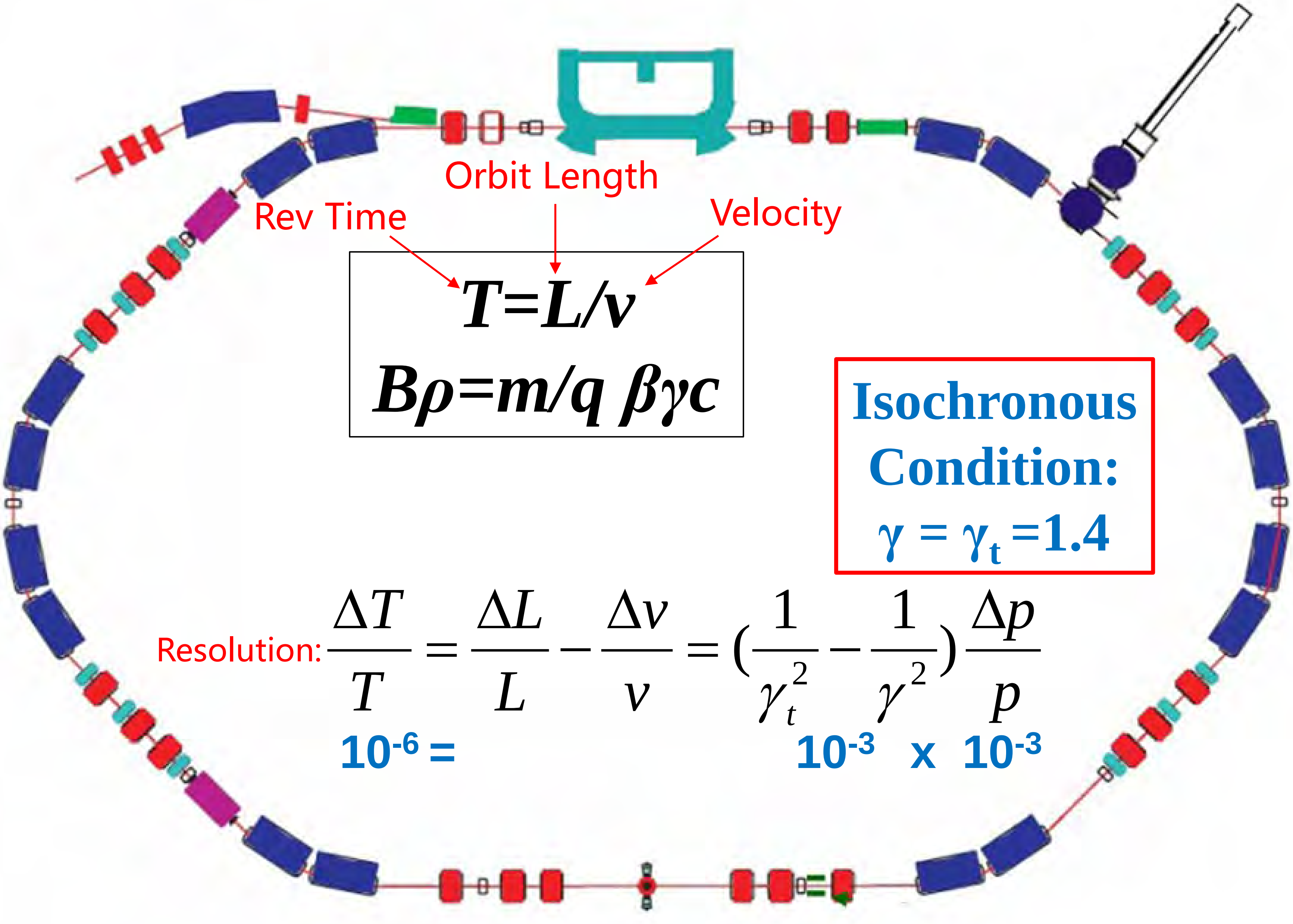


Isochronous Condition:
$\gamma = \gamma_t = 1.4$

Schottky Mass Spectrometry (SMS):
Relative High precision（10^{-7}-10^{-8} ）
Lifetime: ~ s

Isochronous Mass Spectrometry (IMS) :
precision（10^{-5}-10^{-7}）
Short-lived: >100us

Basic Principle of IMS



Rev Time — Orbit Length — Velocity

$$T = L/v$$

$$B\rho = m/q\ \beta\gamma c$$

Isochronous Condition:

$\gamma = \gamma_t = 1.4$

Resolution: $$\frac{\Delta T}{T} = \frac{\Delta L}{L} - \frac{\Delta v}{v} = \left(\frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}\right)\frac{\Delta p}{p}$$

$10^{-6} = \quad 10^{-3} \times 10^{-3}$

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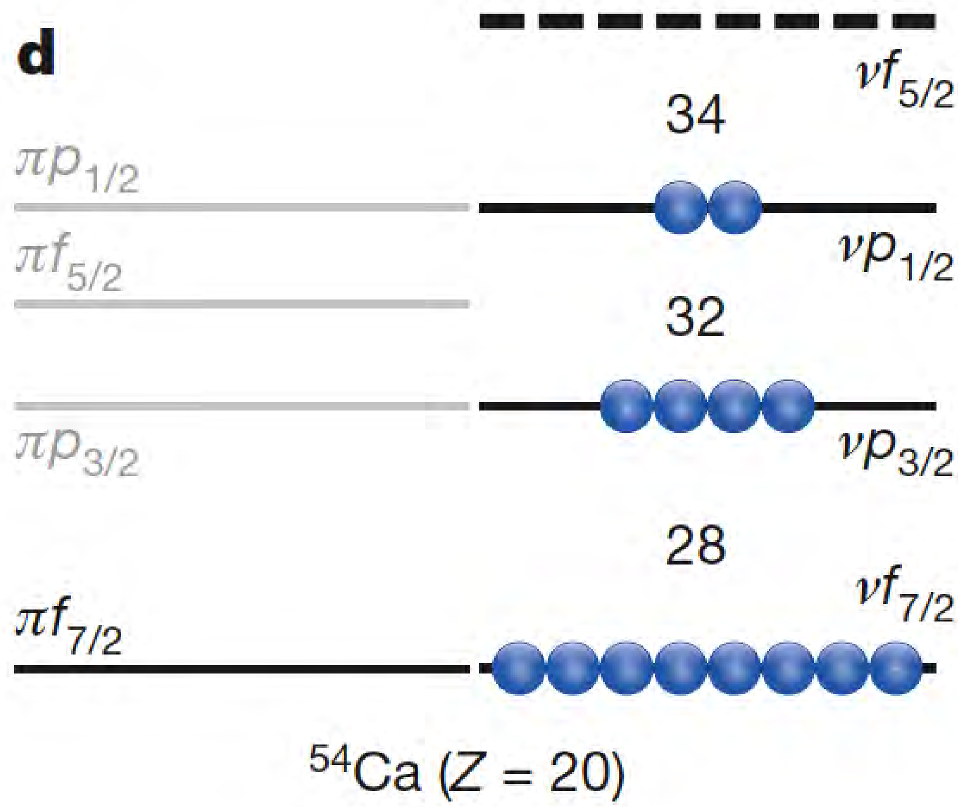
Shell Evolution in Neutron-rich Nuclei

Otsuka, et al, Evolution of Nuclear Shells due to the Tensor Force, PRL 95, 232502 (2005)

$$j_> = l + 1/2 \qquad j_< = l - 1/2$$



D. Steppenbeck1, et al, NATURE 502, 207 (2013)

Experimental evidence of magic number

- **Enhanced excitation energies of first 2^+ states**

  D. Steppenbeck et al., Phys. Rev. Lett. 114, 252501 (2015).

  A. Huck, et. Al., Phys. Rev. C 31, 2226 (1985).

  R. V. F. Janssens et al., Phys. Lett. B 546, 55 (2002).

  J. I. Prisciandaro et al., Phys. Lett. B 510, 17 (2001).

- **Reduced gamma-ray transition probabilities**

  D.-C. Dinca et al., Phys. Rev. C 71, 041302(R) (2005).

  A. Büeger et al., Phys. Lett. B 622, 29 (2005).

- **S_{2n} and Empirical shell gap**

  A. T. Gallant et al., Phys. Rev. Lett. 109, 032506 (2012).

  F. Wienholtz et al., Nature (London) 498, 346 (2013).

  M. Rosenbusch et al., Phys. Rev. Lett. 114, 202501 (2015).

  E. Leistenschneider et al., Phys. Rev. Lett. 120, 062503 (2018).

  M. P. Reiter et al., Phys. Rev. C 98, 024310 (2018).

  C. Guenaut et al., J. Phys. G: Nucl. Part. Phys. 31, S1765 (2005).

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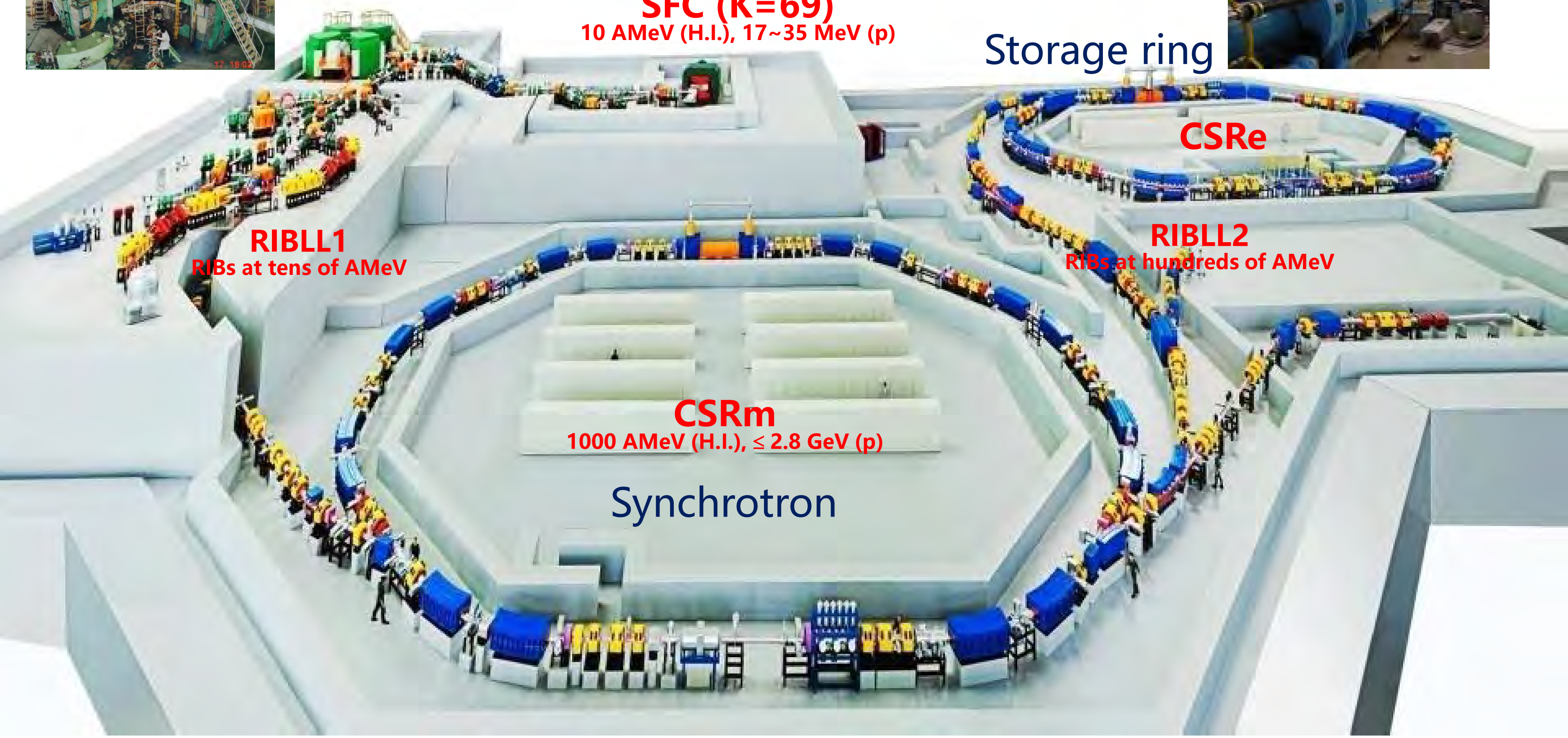
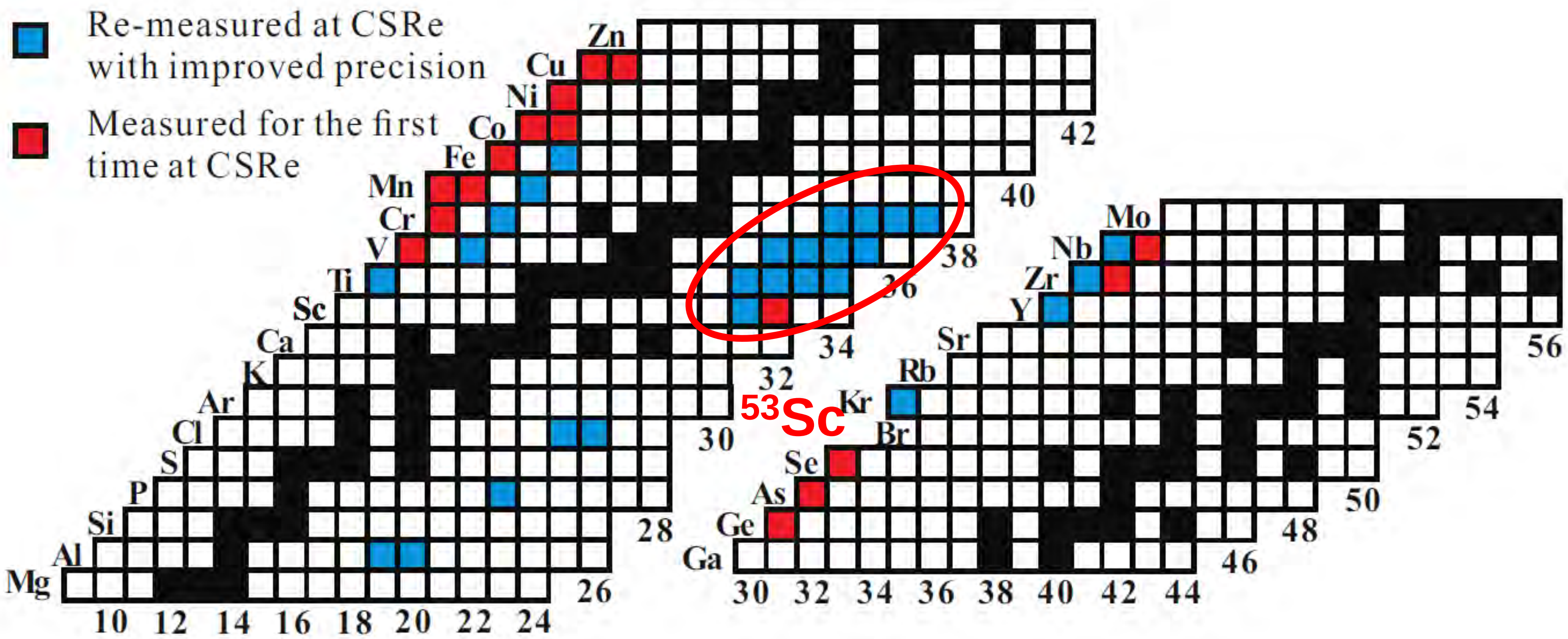
HIRFL-CSR Facility

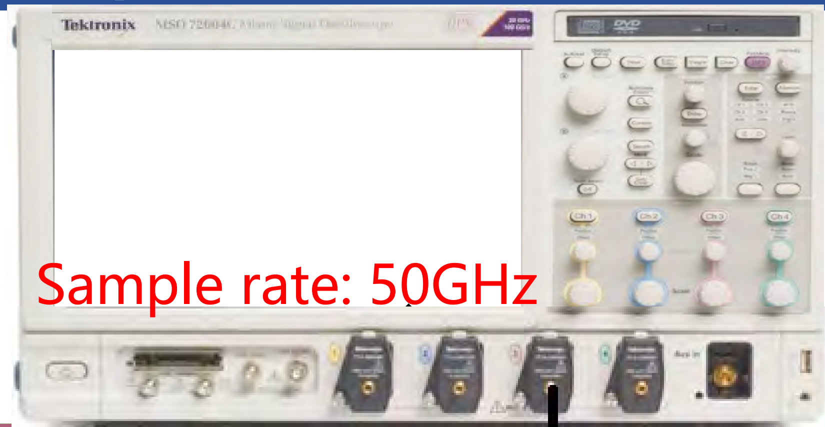
Heavy Ion Research Facility in Lanzhou & Cooler Storage Ring Facility

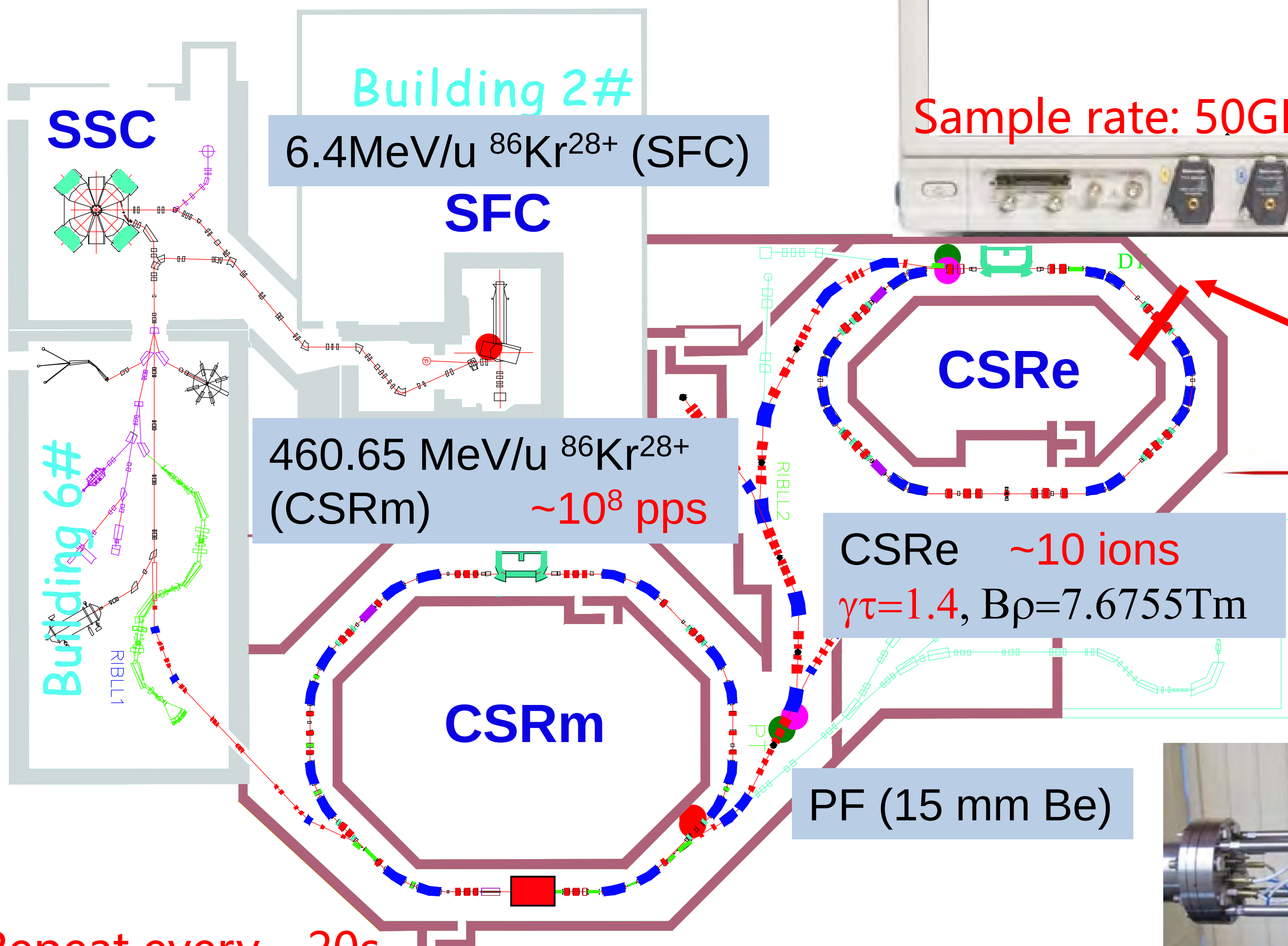


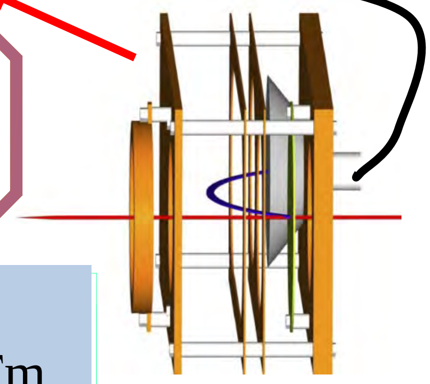
Experiment Objective



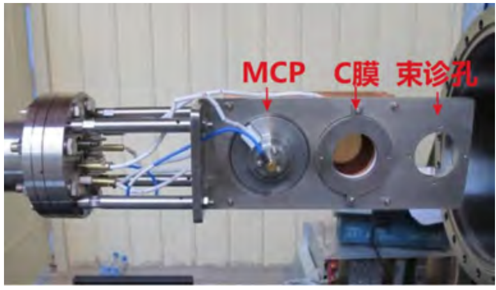
IMS experiment procedure





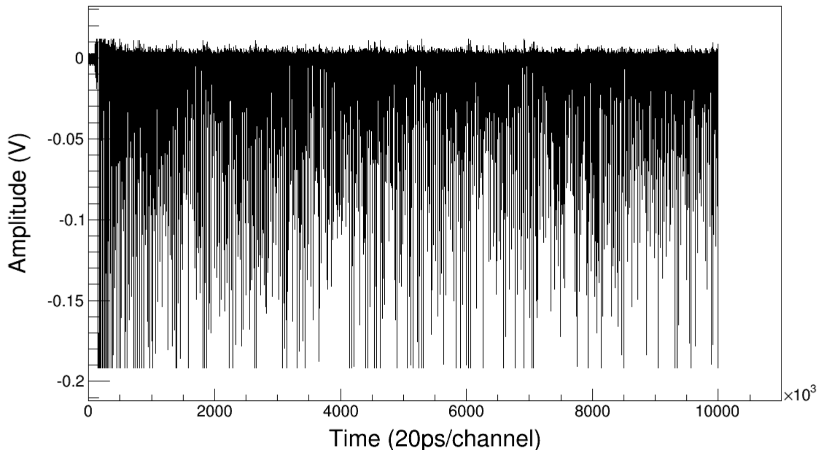


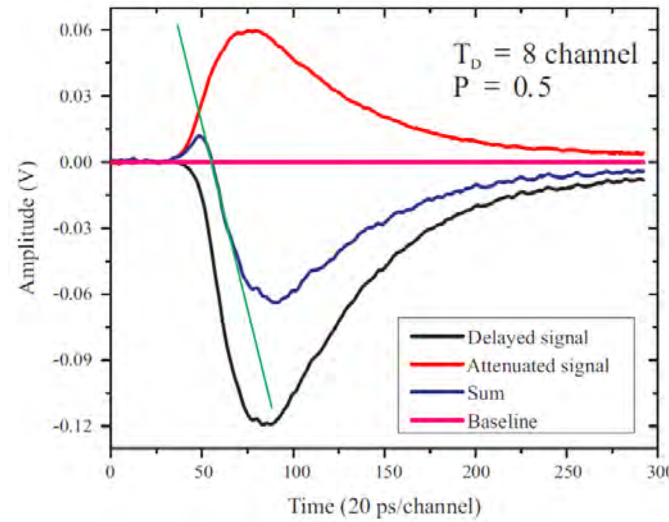
DAQ 200us

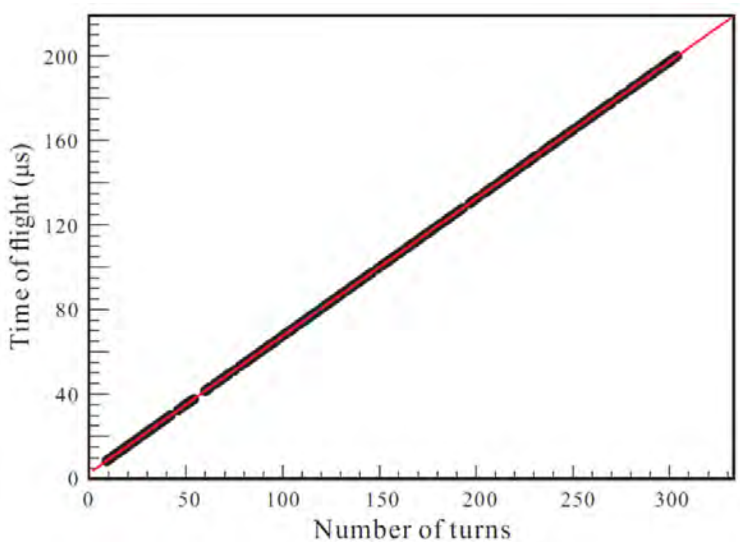


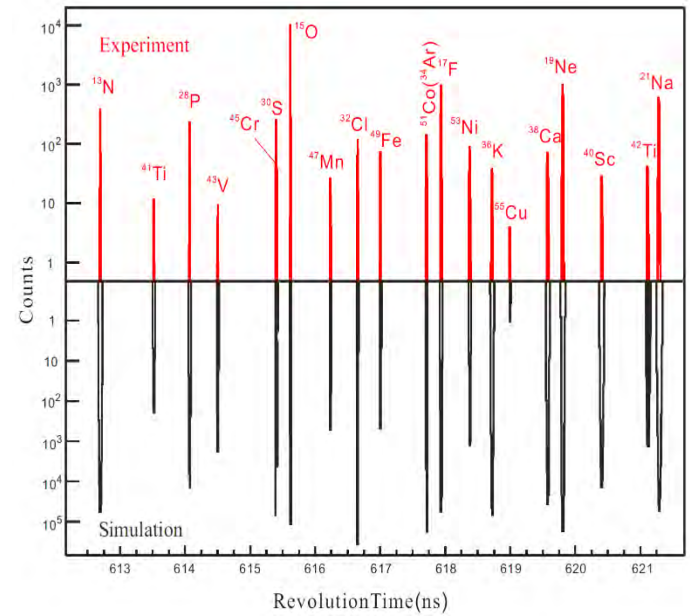
Repeat every ~20s

IMS Data Analysis

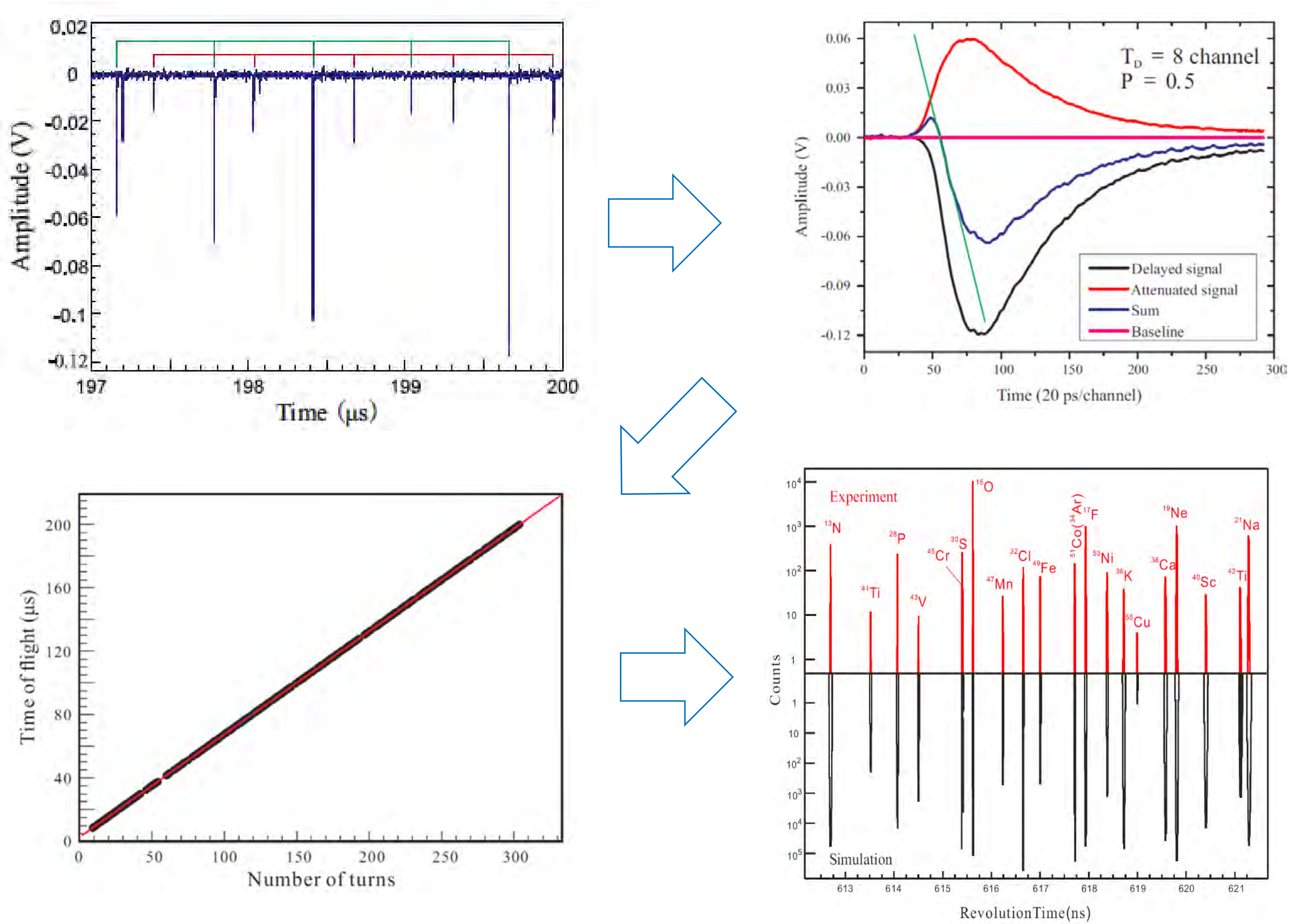




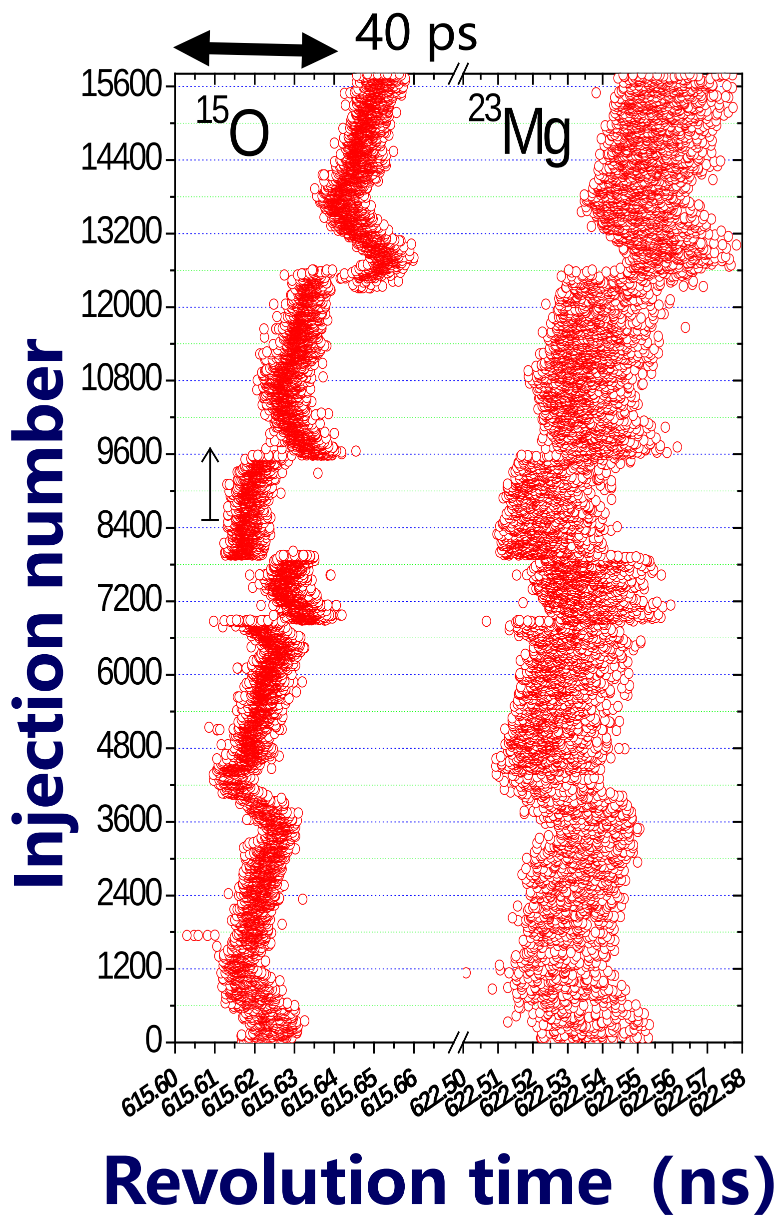


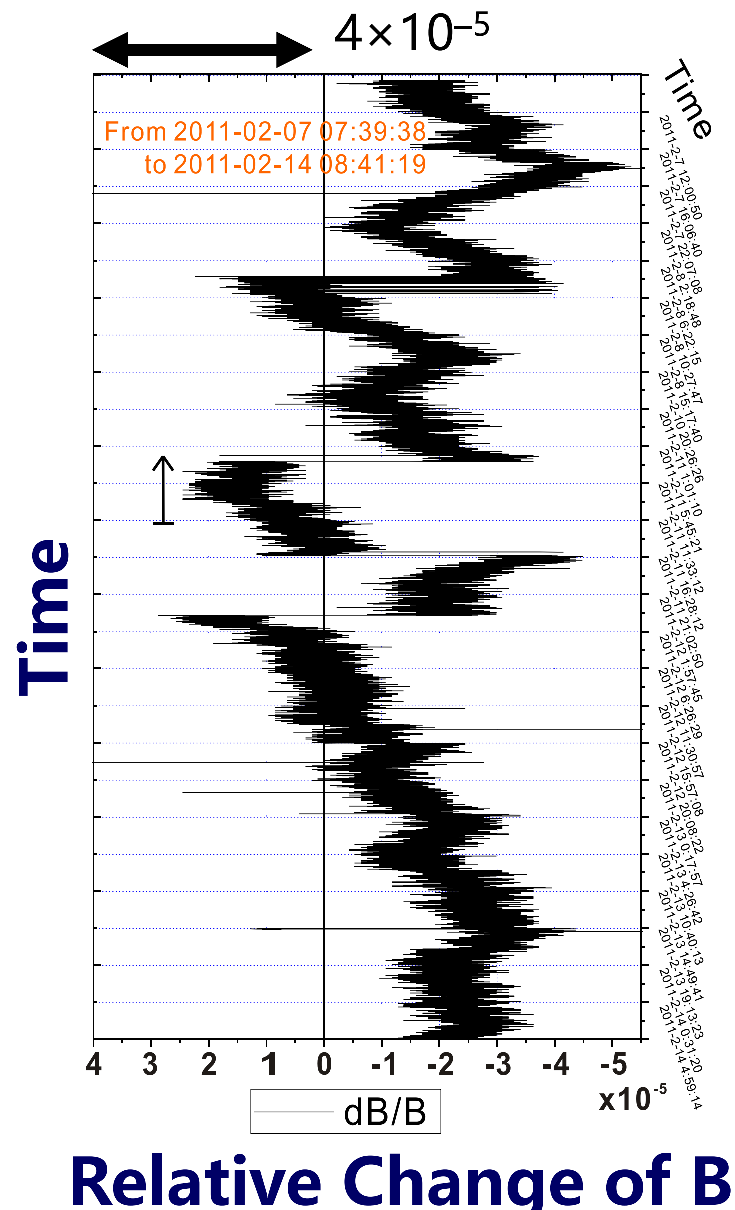


IMS Data Analysis



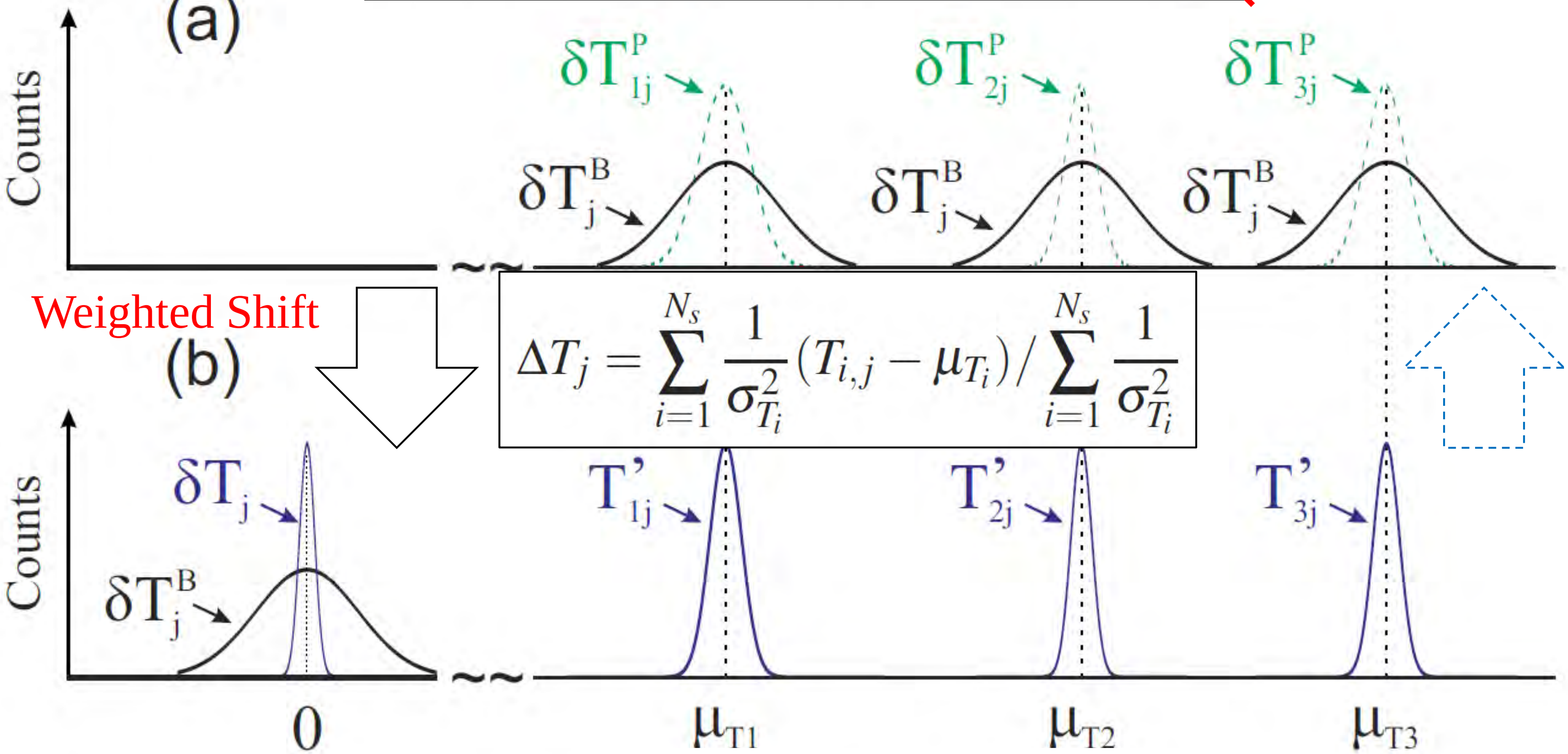
Unstable Magnetic field





Weighted Shift Correction

$$T_{i,j} = \mu_{T_i} + \delta T^P_{i,j} + \delta T^B_j$$



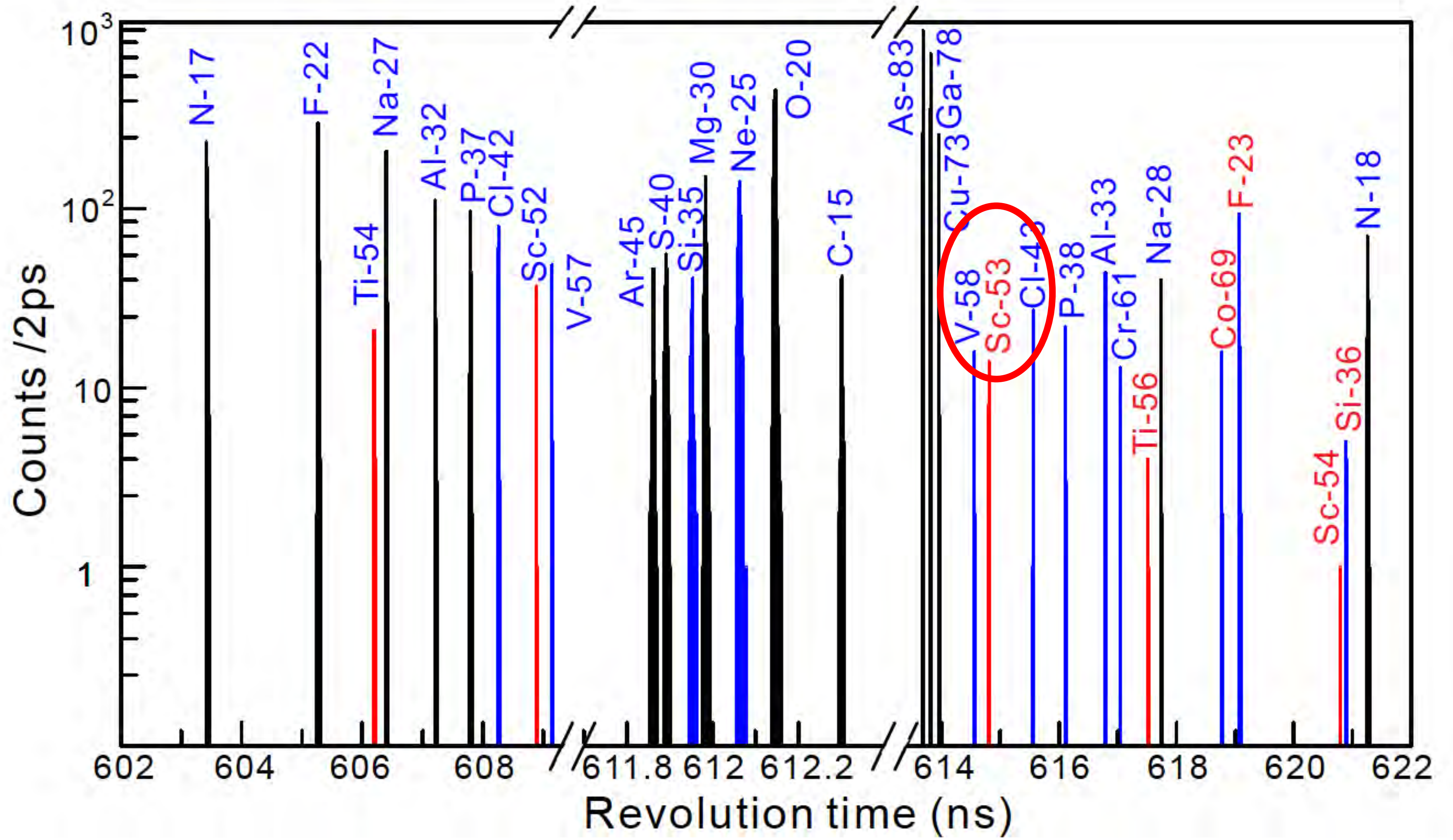
$$\Delta T_j = \sum_{i=1}^{N_s} \frac{1}{\sigma^2_{T_i}} (T_{i,j} - \mu_{T_i}) \Big/ \sum_{i=1}^{N_s} \frac{1}{\sigma^2_{T_i}}$$

$$\sigma^2_{T_i} = s^2_{T'_i} + \frac{1}{\frac{1}{\sigma^2_{T_1}} + \frac{1}{\sigma^2_{T_2}} + \cdots + \frac{1}{\sigma^2_{T_{N_s}}}}$$

Mass Calibration

$$m/q = a + bT + cT^2 + dT^3$$

T: Rev. Time



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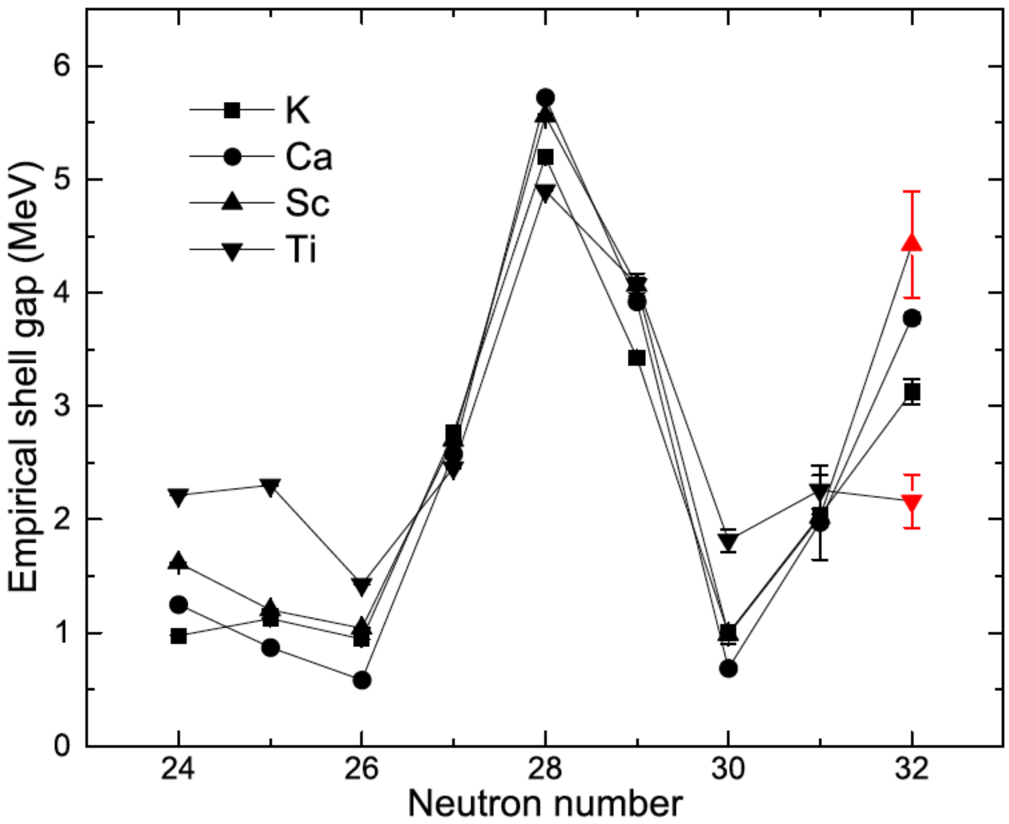
S_{2n} and Empirical shell gap



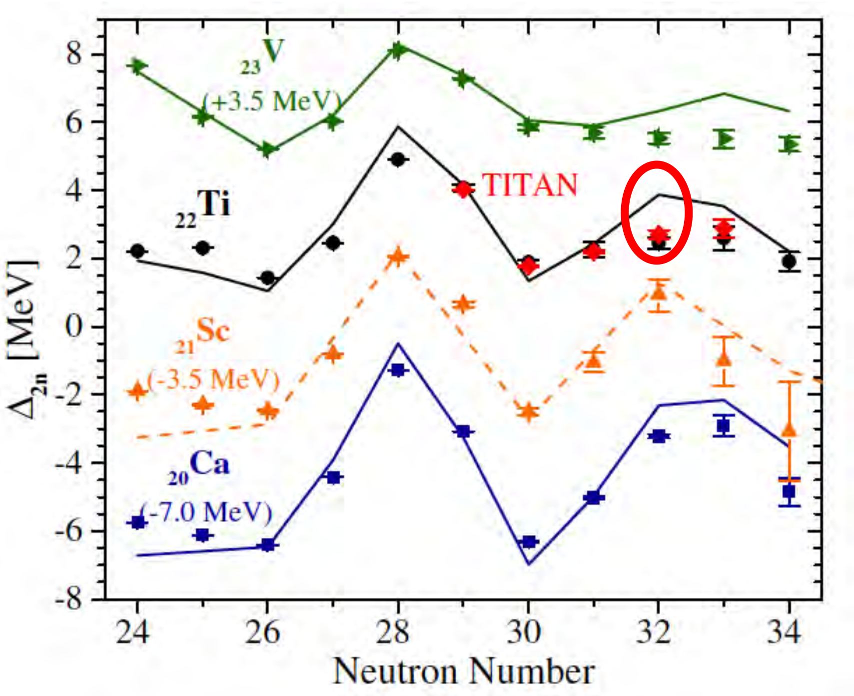
$$S_{2n}(N,Z) = M_a(Z,N-2) + 2M_n - M_a(N,Z)$$

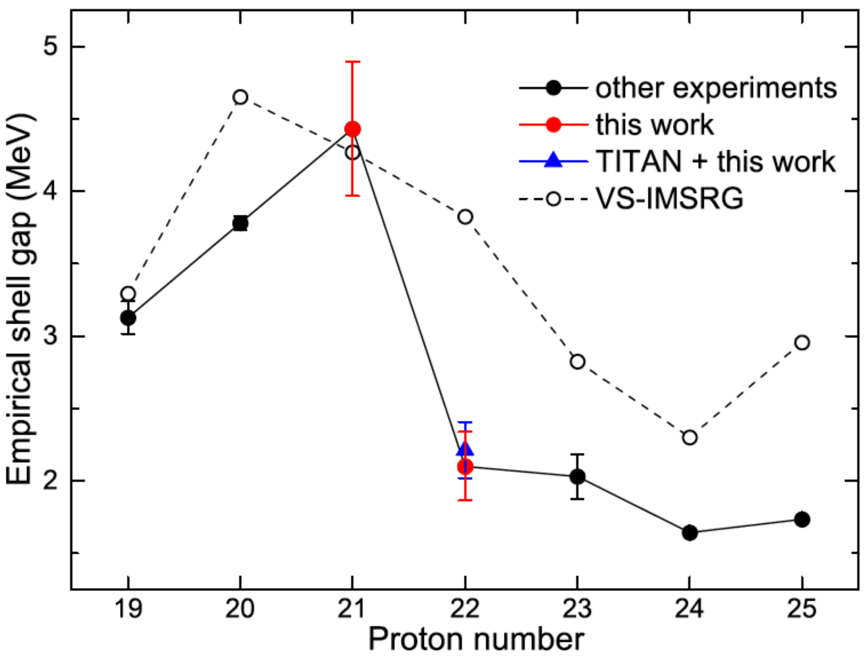
$$\Delta_{2n}(N,Z) = S_{2n}(N,Z) - S_{2n}(N+2,Z)$$

X. Xu, et al, PHYSICAL REVIEW C 99, 064303 (2019)

VS-IMSRG prediction

valence-space in-medium similarity renormalization group





E. Leistenschneider, et al, PRL 120, 062503 (2018)

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1. Introduction: Mass Measurements
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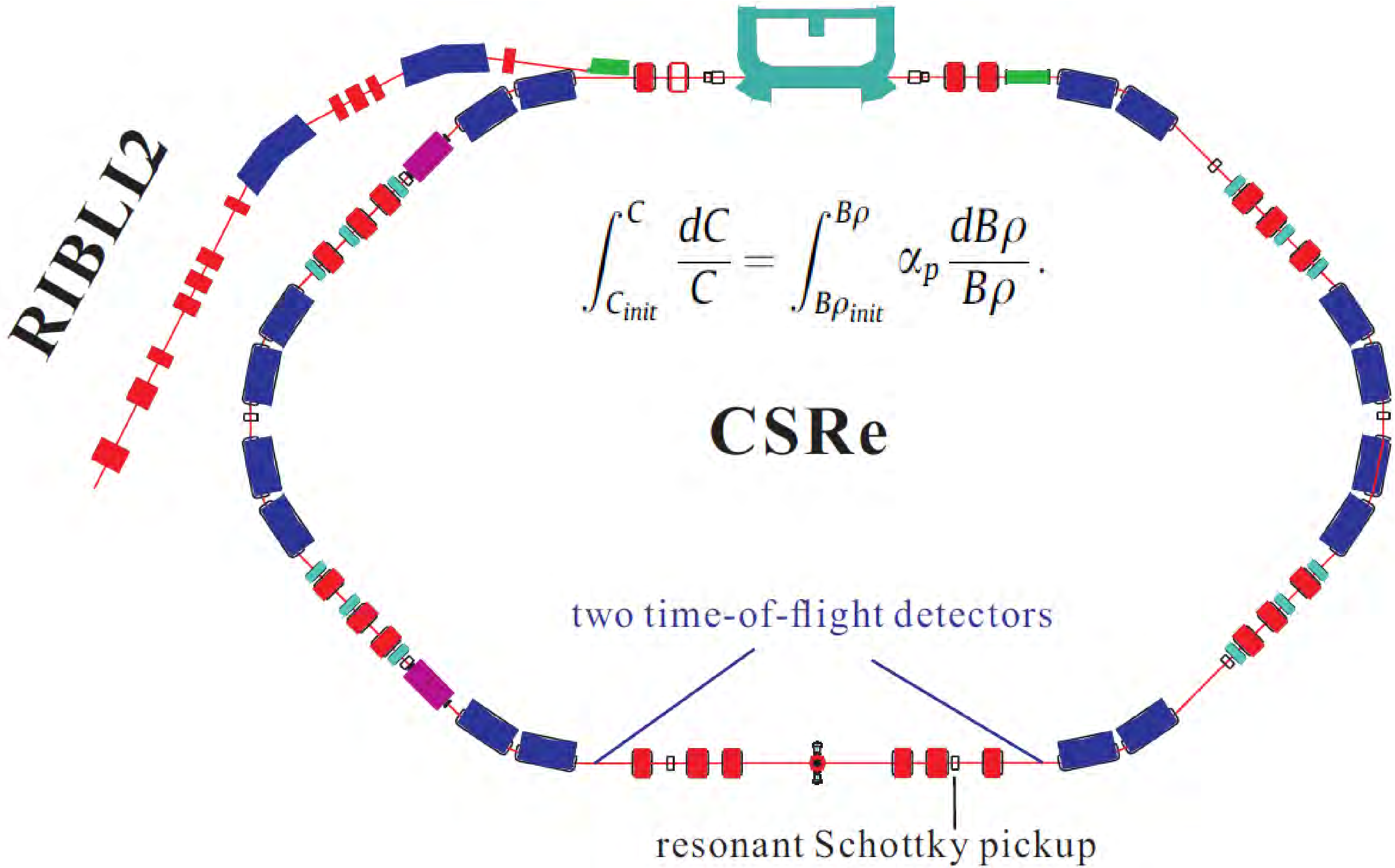
Double TOF IMS: Velocity Measurements

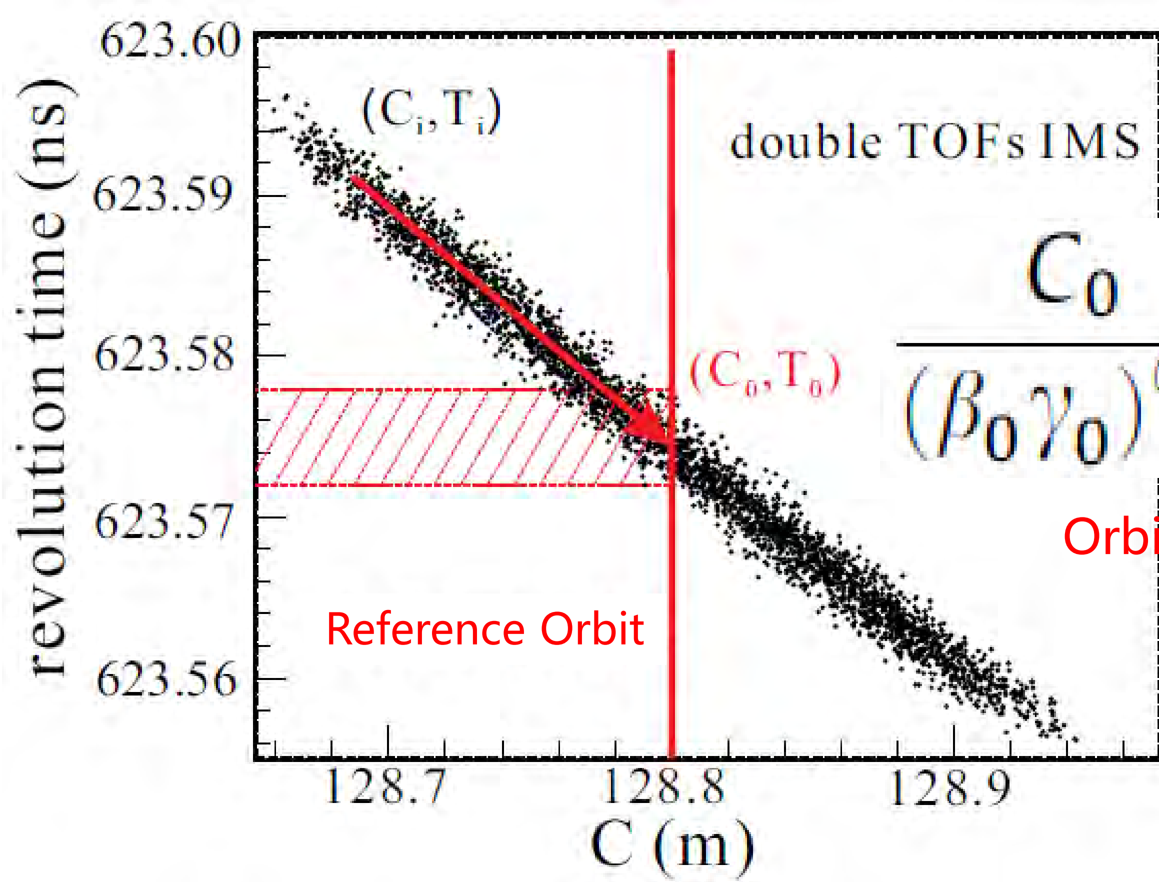


$$\int_{C_{init}}^{C} \frac{dC}{C} = \int_{B\rho_{init}}^{B\rho} \alpha_p \frac{dB\rho}{B\rho}.$$

P. Shuai, et al., Nucl. Instr. Meth. B 376 (2016) 311–3

Double TOF IMS

Simulation data



$$\frac{C_0}{(\beta_0\gamma_0)^{\alpha_{p0}}} = \frac{C_i}{(\beta_i\gamma_i)^{\alpha_{p0}}} = K.$$

Orbit Length

Velocity

$$C = Tv$$

Rev Time

$$\alpha_{p0} = 1/\gamma_t^2$$

P. Shuai, et al., Nuc. Instr. Meth. B 376 (2016) 311–3

Summary

- Isochronous mass spectrometry in storage ring is an ideal tool to measure the masses of short-lived nuclei:
  - no cooling required
  - single ion sensitivity
  - short half-live ~100 us

- Masses of 86Kr PF in fp-shell have been measured in HIRFL-CSR facility in Lanzou.

- Validate N=32 subshell closure in Sc isotopes.

- Shell model with tensor force between proton f7/2 and neutron f5/2, and ab initio calculation using the VS-IMSRG approach with NN and 3N interactions can reproduce magic number N=32 very well.

Collaborators

H. S. Xu, Y. H. Zhang, M. Wang, R. J. Chen, X. C.Chen, C. Y. Fu, B. S. Gao, M.Z. Sun, X. L.Tu, Y.M. Xing, X. Xu, X. L. Yan, Q. Zeng, X. H. Zhou, Y. J. Yuan, J. W. Xia, J. C. Yang, Z. G. Hu, S. Kubono, X. W. Ma, R. S. Mao, B. Mei, G. Q. Xiao, H. W. Zhao, T. C. Zhao, W. L. Zhan (IMP-CAS, Lanzhou, China)

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T. Yamaguchi (Saitama University, Saitama, Japan)

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