Precision mass measurement for shot-lived nuclides at HIRFL-CSR

Meng WANG
Institute of Modern Physics, Chinese Academy of Sciences

- Introduction
- IMS experiment
- New results
- Double-TOF IMS

CSRe IMS Collaboration

Y. H. Zhang, M. Wang, H. S. Xu, R. J. Chen, X. Zhou, C. Y. Fu, B. S. Gao, X. C.Chen, Y.H. Lam, P. Shuai, M.Z. Sun, X. L.Tu, Y.M. Xing, X. Xu, X. L. Yan, Q. Zeng, P. Zhang, 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)

Yu.A. Litvinov, S. A. Litvinov, S.Typel (GSI, Darmstadt, Germany)

K. Blaum (MPIK, Heidelberg, Germany)

Baohua SUN (Beihang University)

Y. Sun (Shanghai Jiao Tong University, Shanghai, China)

F.R. Xu (Beijing University, China)

H. Schatz, B. A. Brown (MSU, USA)

G. Audi (CSNSM-IN2P3-CNRS, Orsay, France)

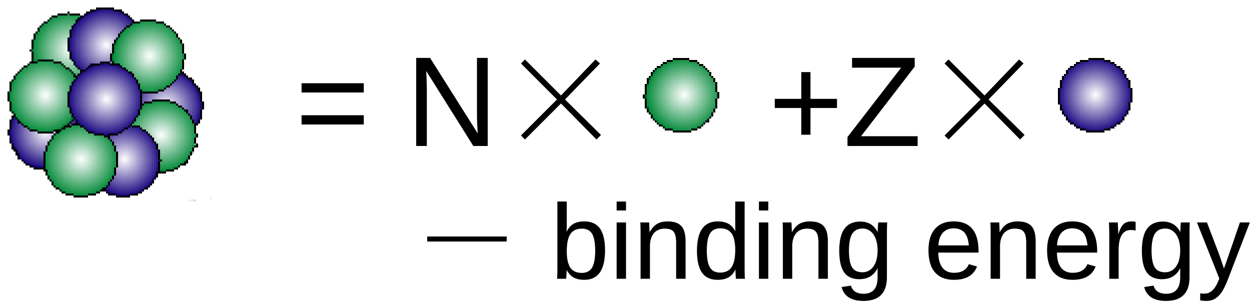
A. Ozawa (University of Tsukuba, Japan)

T. Yamaguchi (Saitama University, Saitama, Japan)

T. Uesaka, S. Naimi, Y. Yamaguchi (RIKEN, Saitama, Japan)

Nuclear Mass

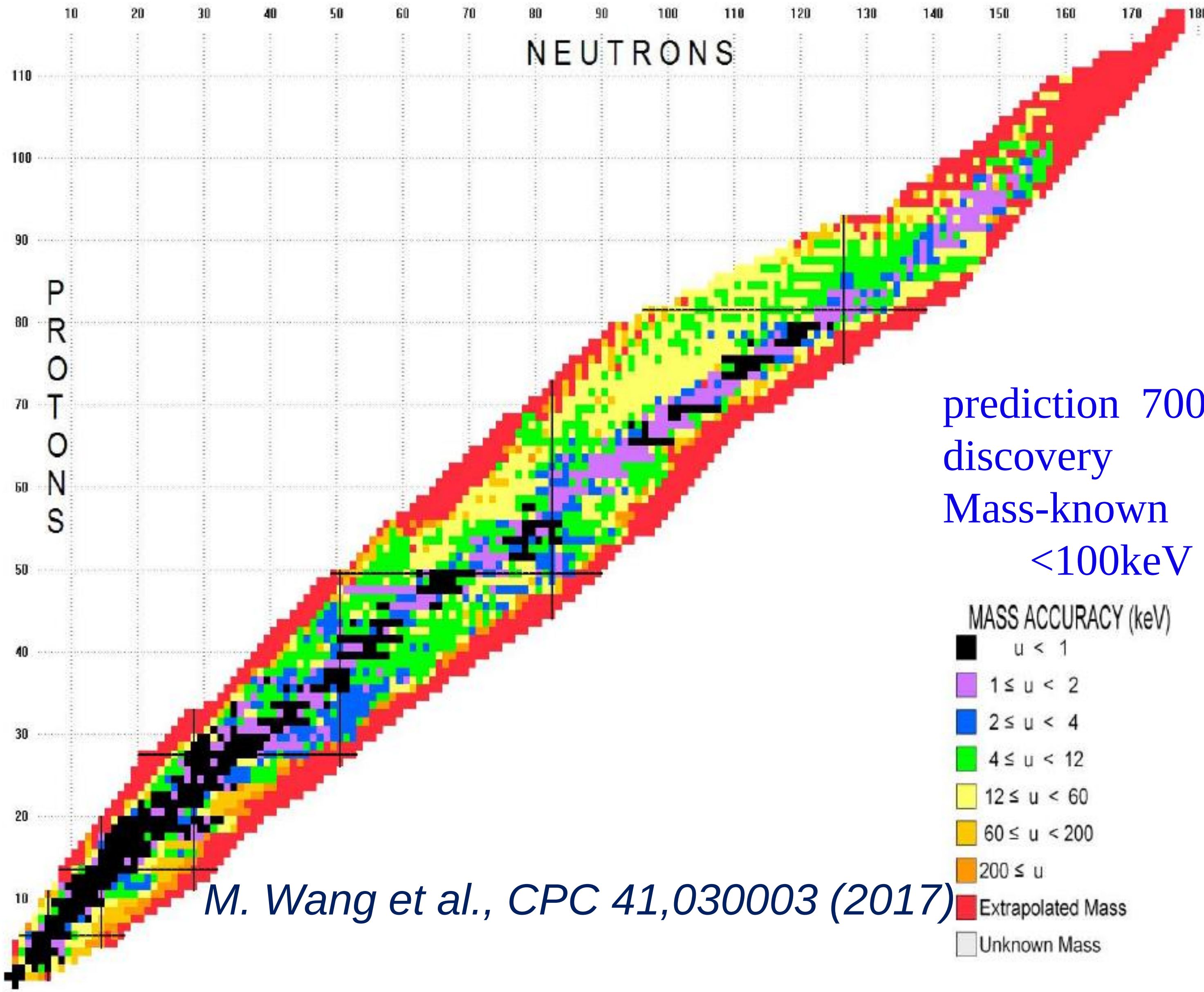
Mass → binding energy → interaction



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

K. Blaum, Physics Reports 425 (2006) 1-

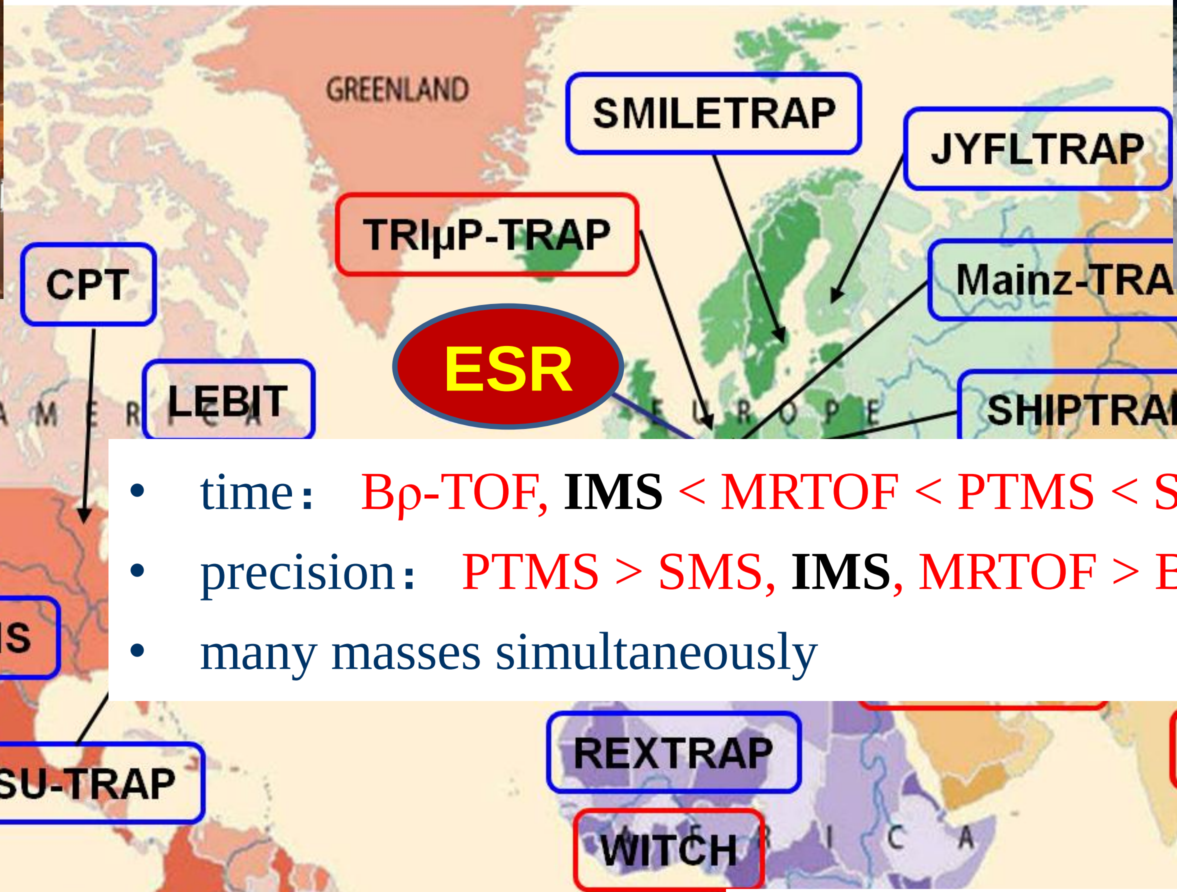
Nuclear Mass



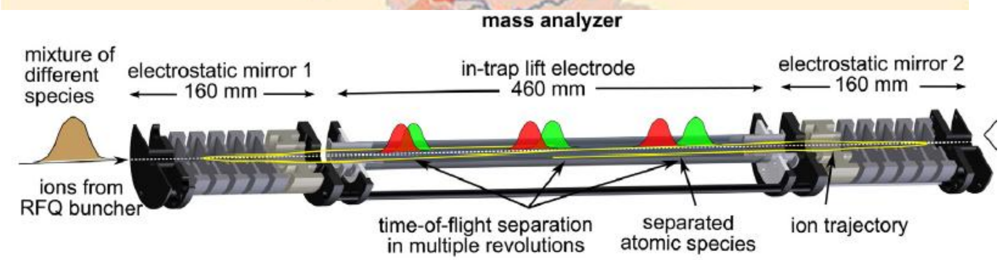
prediction 7000-9000
discovery ~3400
Mass-known ~2500
<100keV ~2300

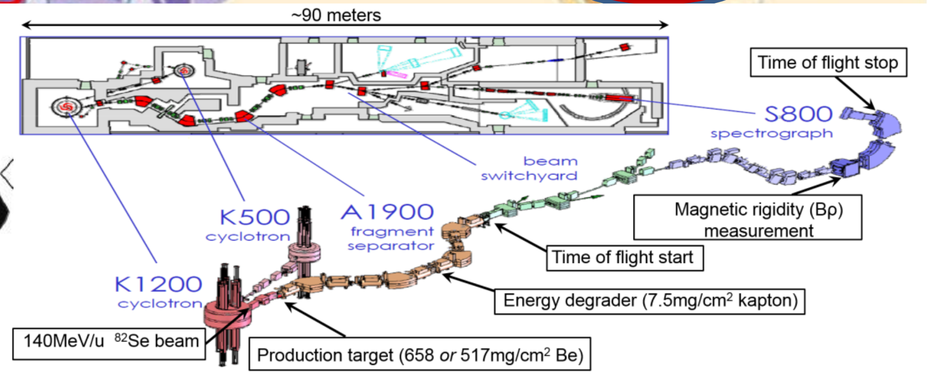
M. Wang et al., CPC 41,030003 (2017)

Present activities



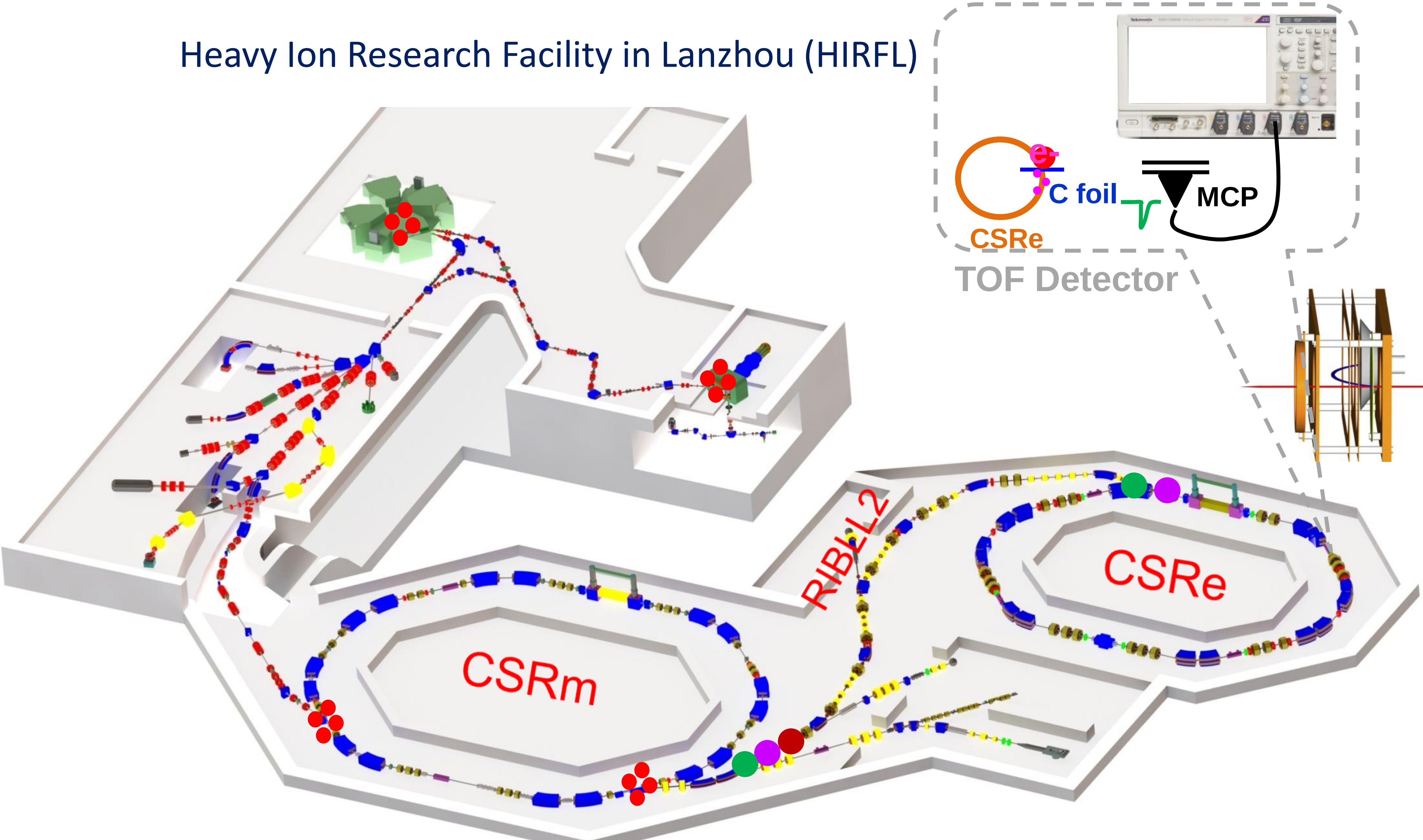
- time： Bρ-TOF, **IMS** < MRTOF < PTMS < SMS
- precision： PTMS > SMS, **IMS**, MRTOF > Bρ-TOF
- many masses simultaneously

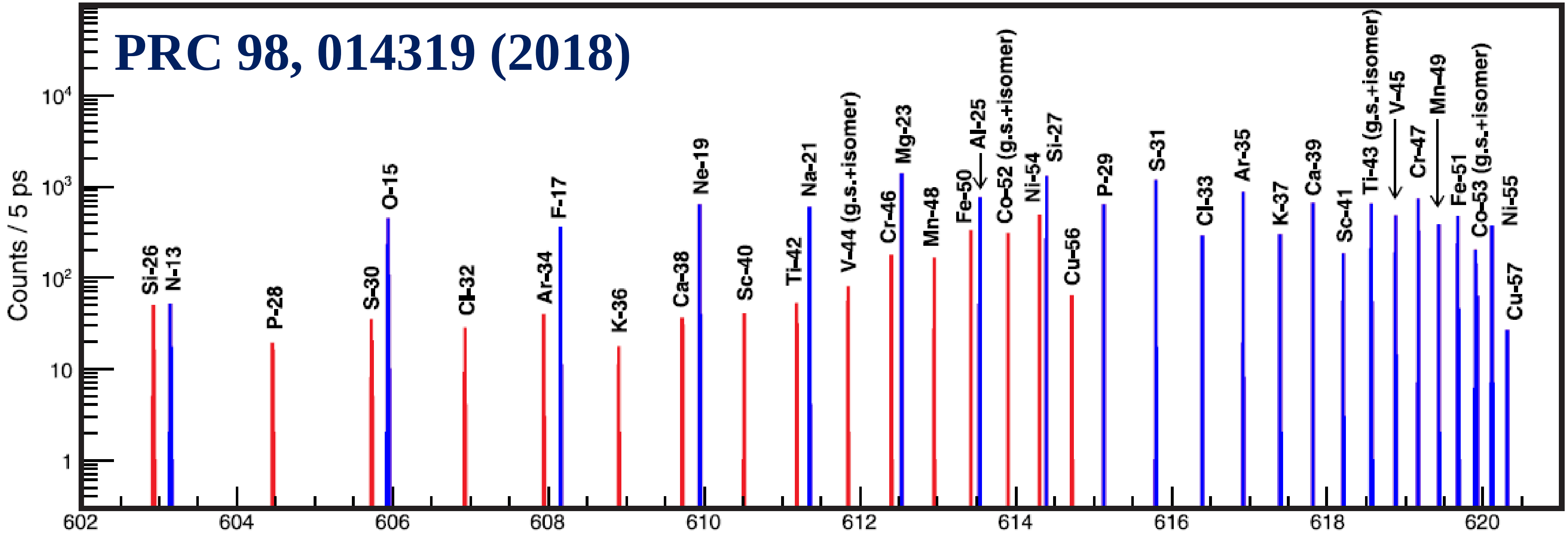


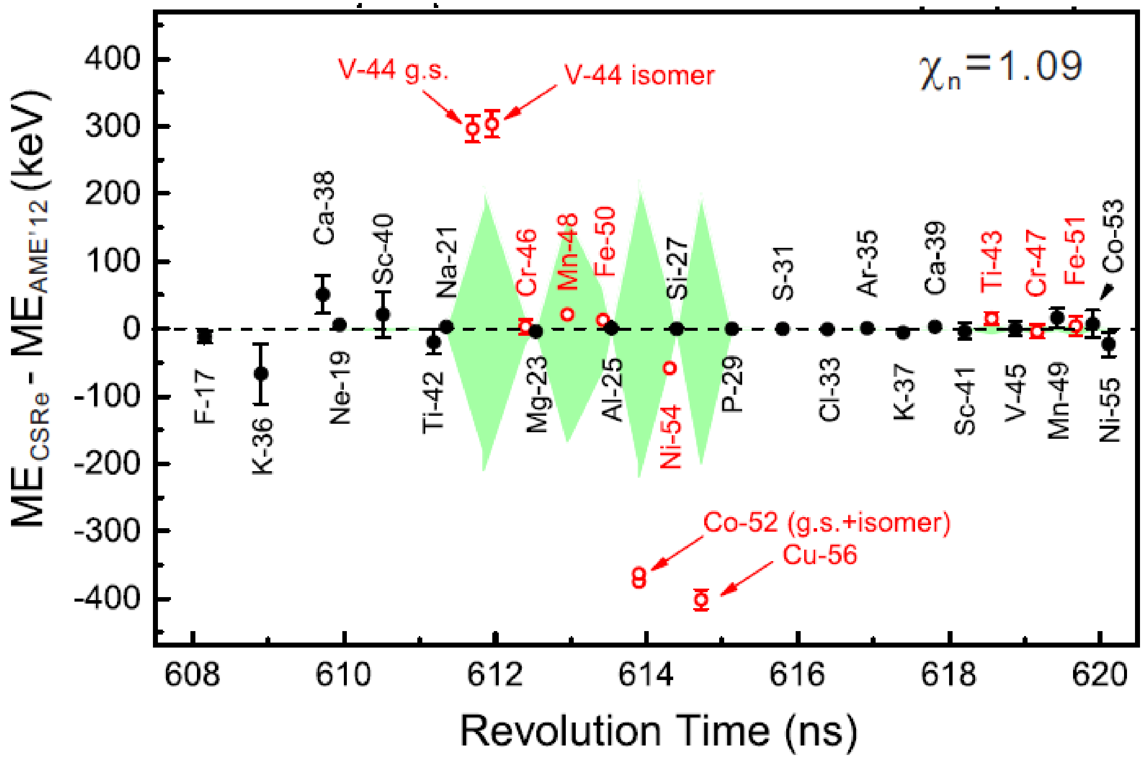


Mass measurement at CSR, Lanzhou

Heavy Ion Research Facility in Lanzhou (HIRFL)

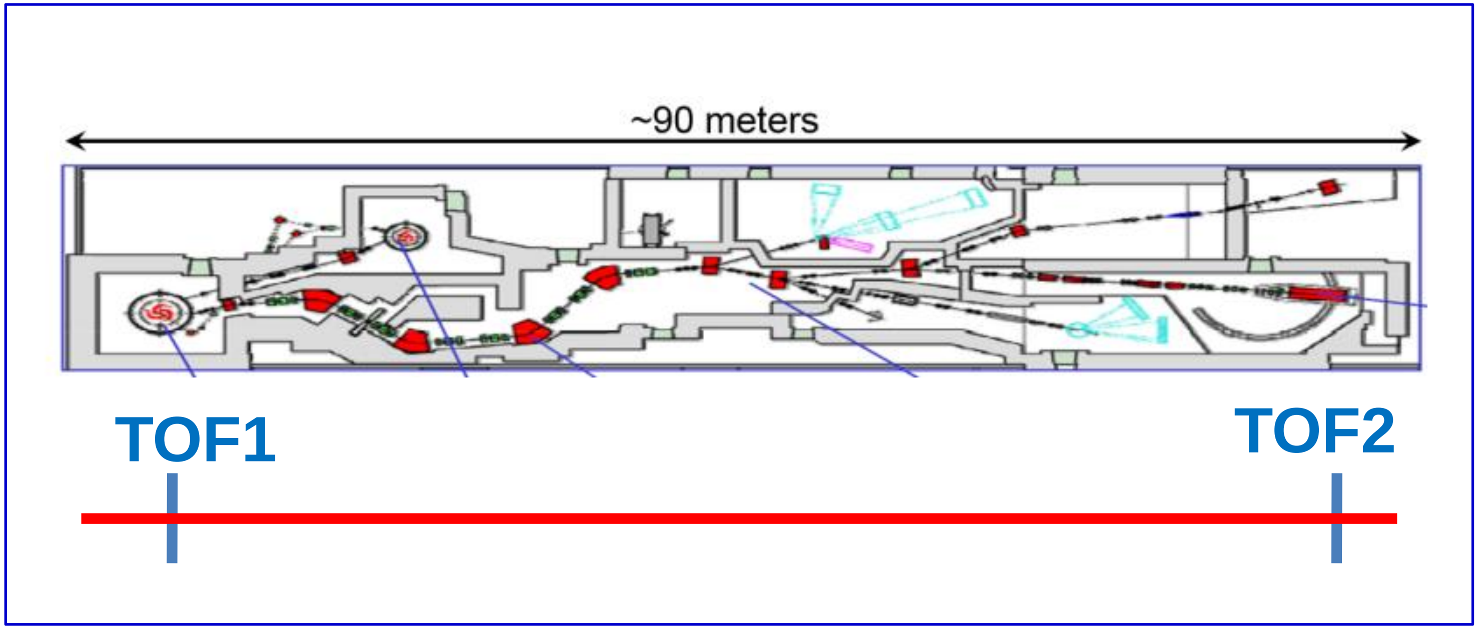






$$m/q = a_0 + a_1 * t + a_2 * t^2 + a_3 * t^3$$

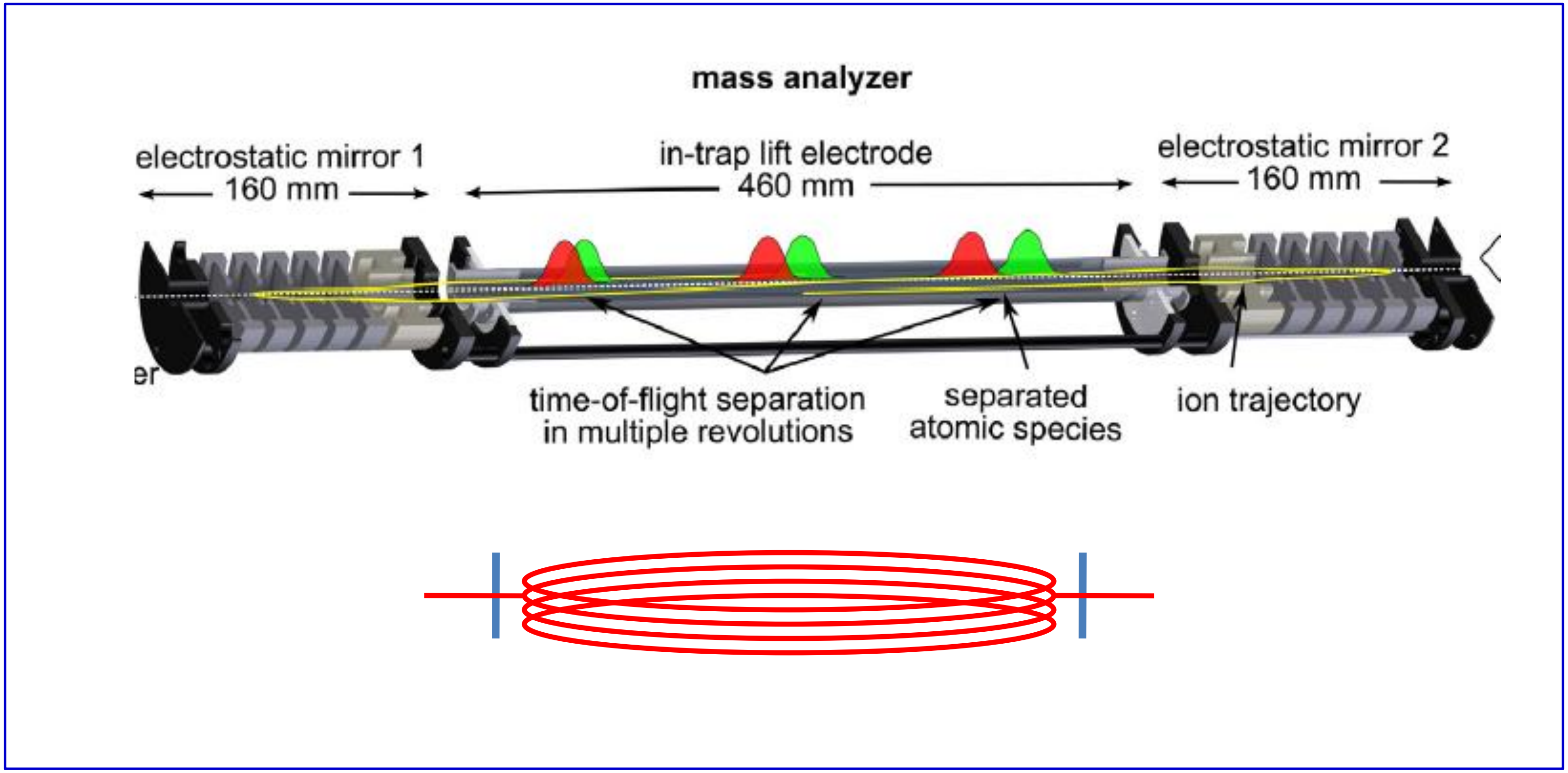
Measurement time and precision



$$\frac{\delta T}{T} = \frac{\sqrt{2}\sigma_t}{T} \approx \frac{50ps}{500ns} = 10^{-4}$$

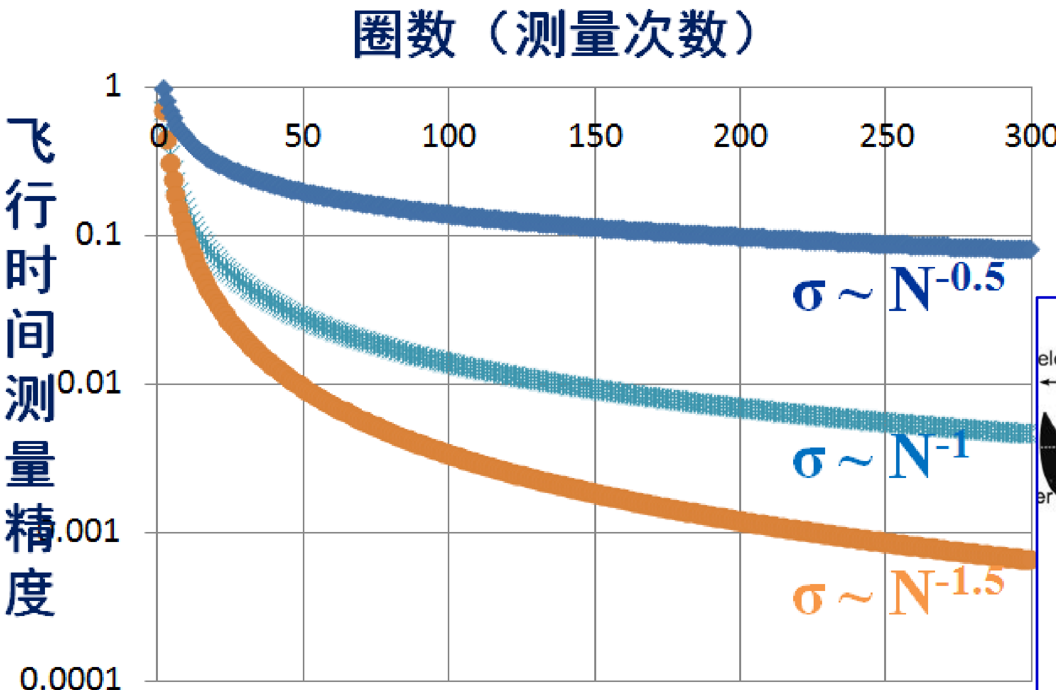
$$\delta T = \frac{\sqrt{2}\,\sigma_t}{\sqrt{N}}$$

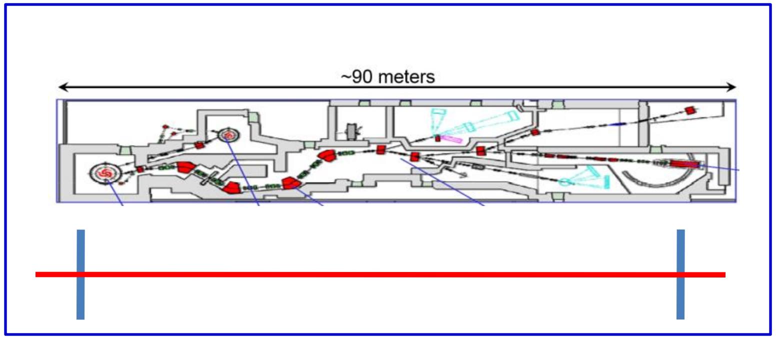
Measurement time and precision

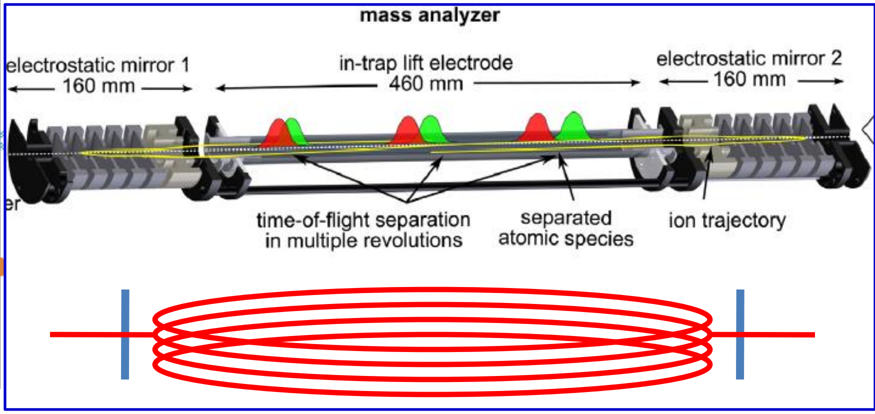


$$\frac{\delta T}{T} = \frac{\sqrt{2}\sigma_t}{TN}$$

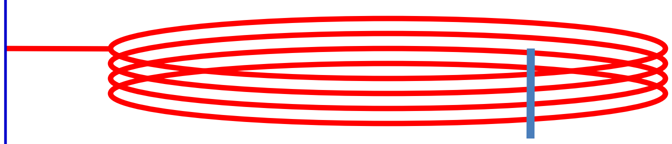
Measurement time and precision

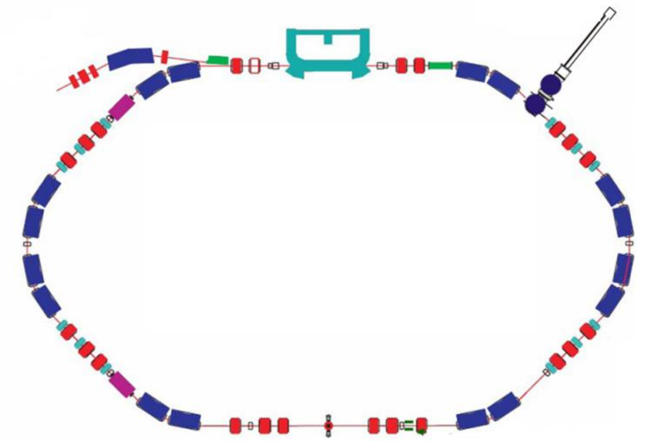






$$\frac{\delta T}{T} = \frac{\sqrt{12}\sigma_t}{\sqrt{\eta N^3}}$$



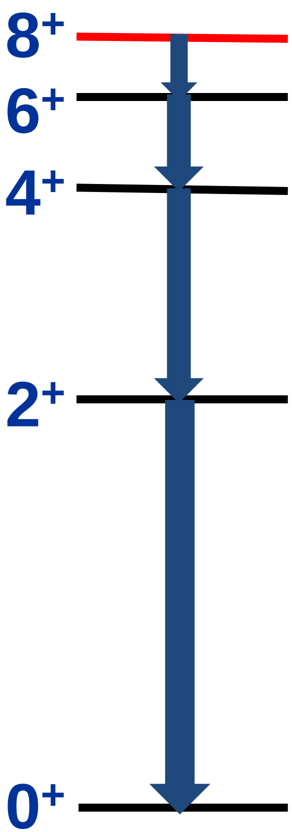


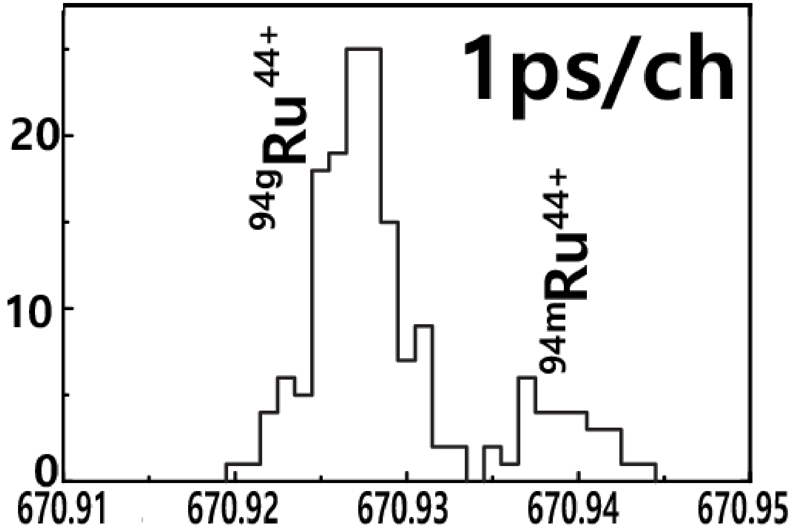
Measurement time and precision

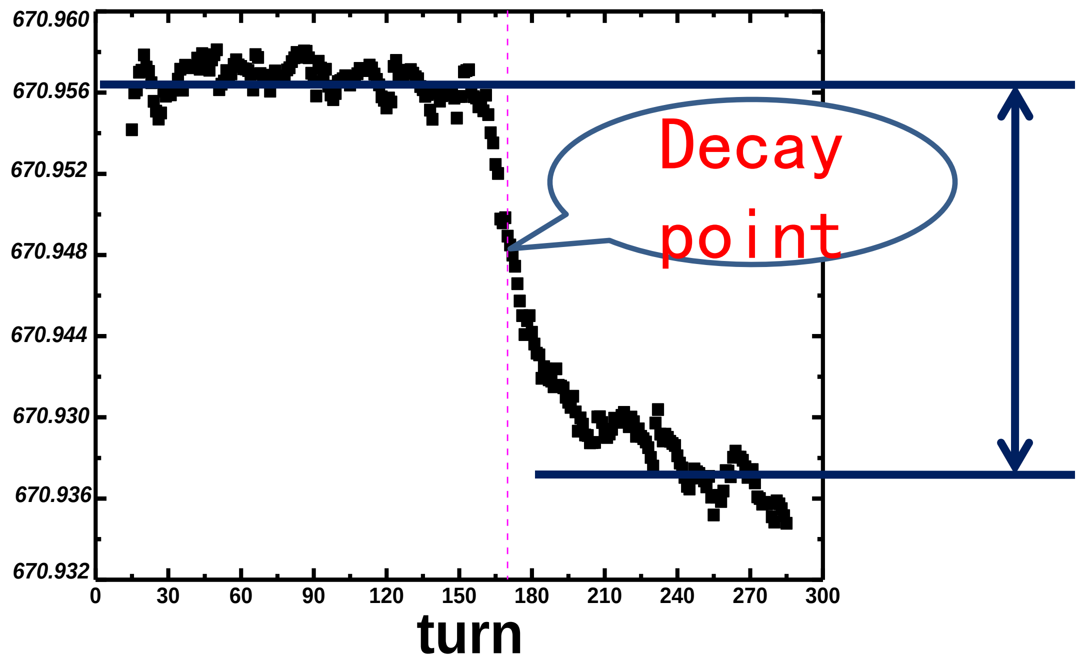
^{94m}Ru

$T_{1/2} = 71\ \mu s$

Ex=2645 keV

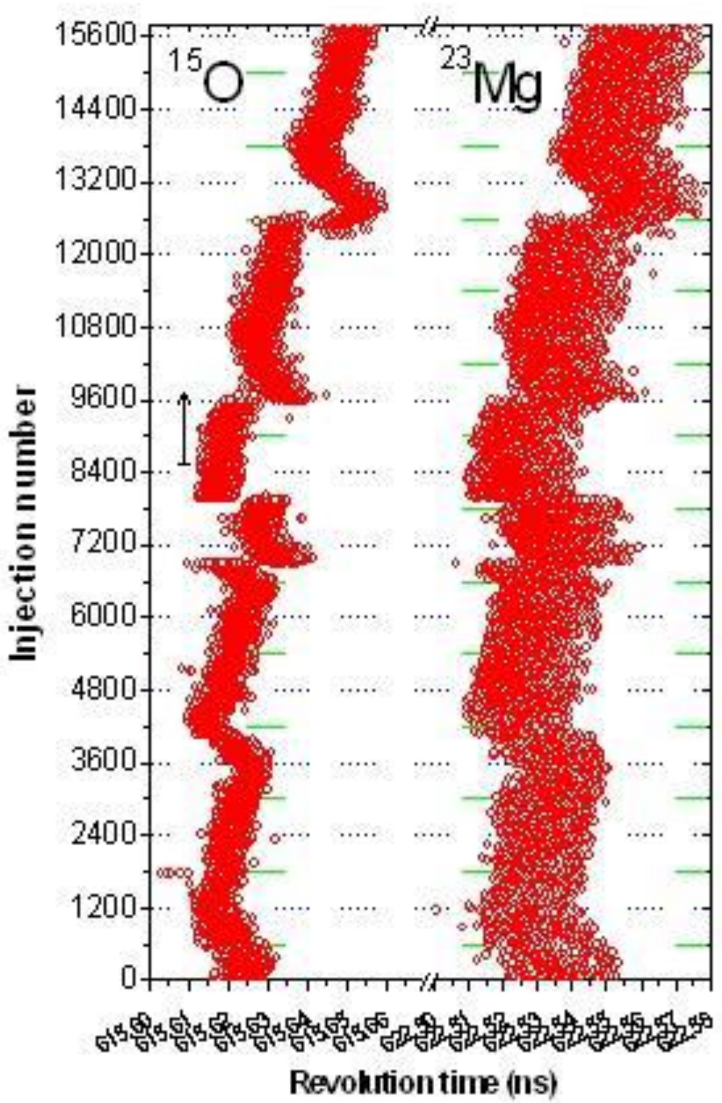


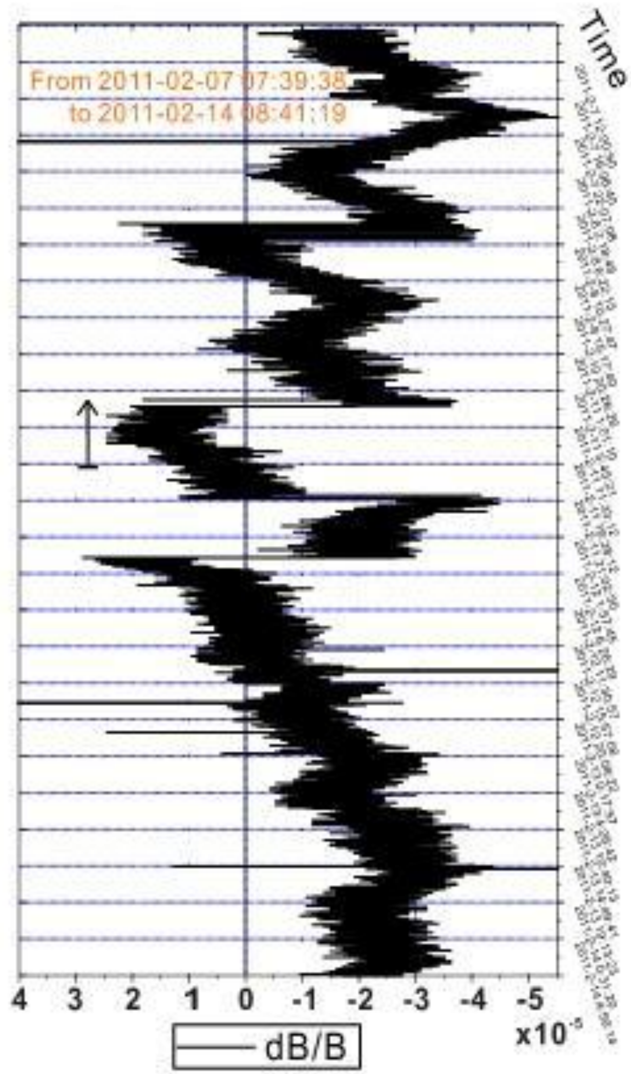




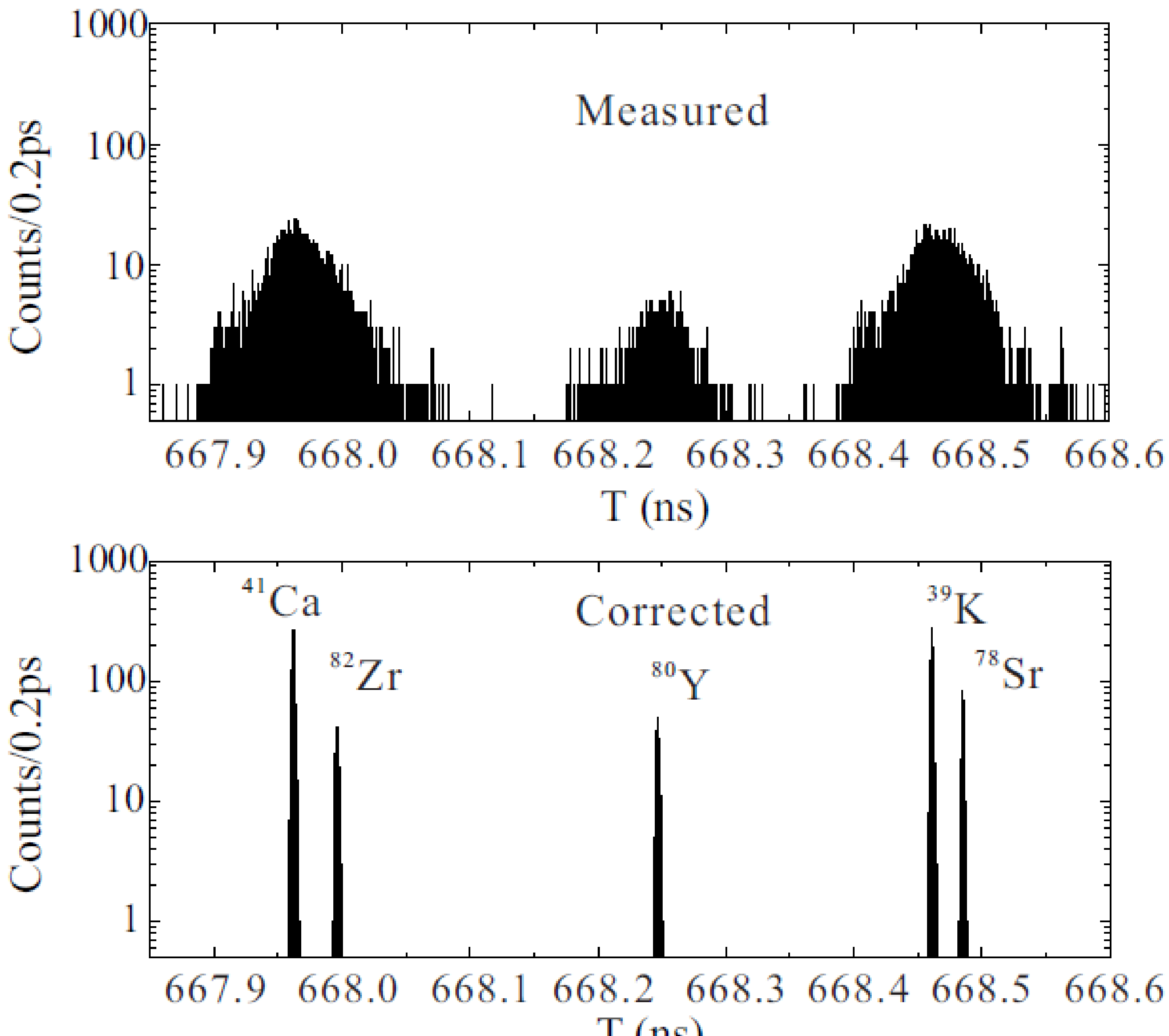
Q. Zeng , M. Wang* et al., PRC (R) 96, 031303 (2017)

Correction for magnetic-field drift





Correction for magnetic-field drift

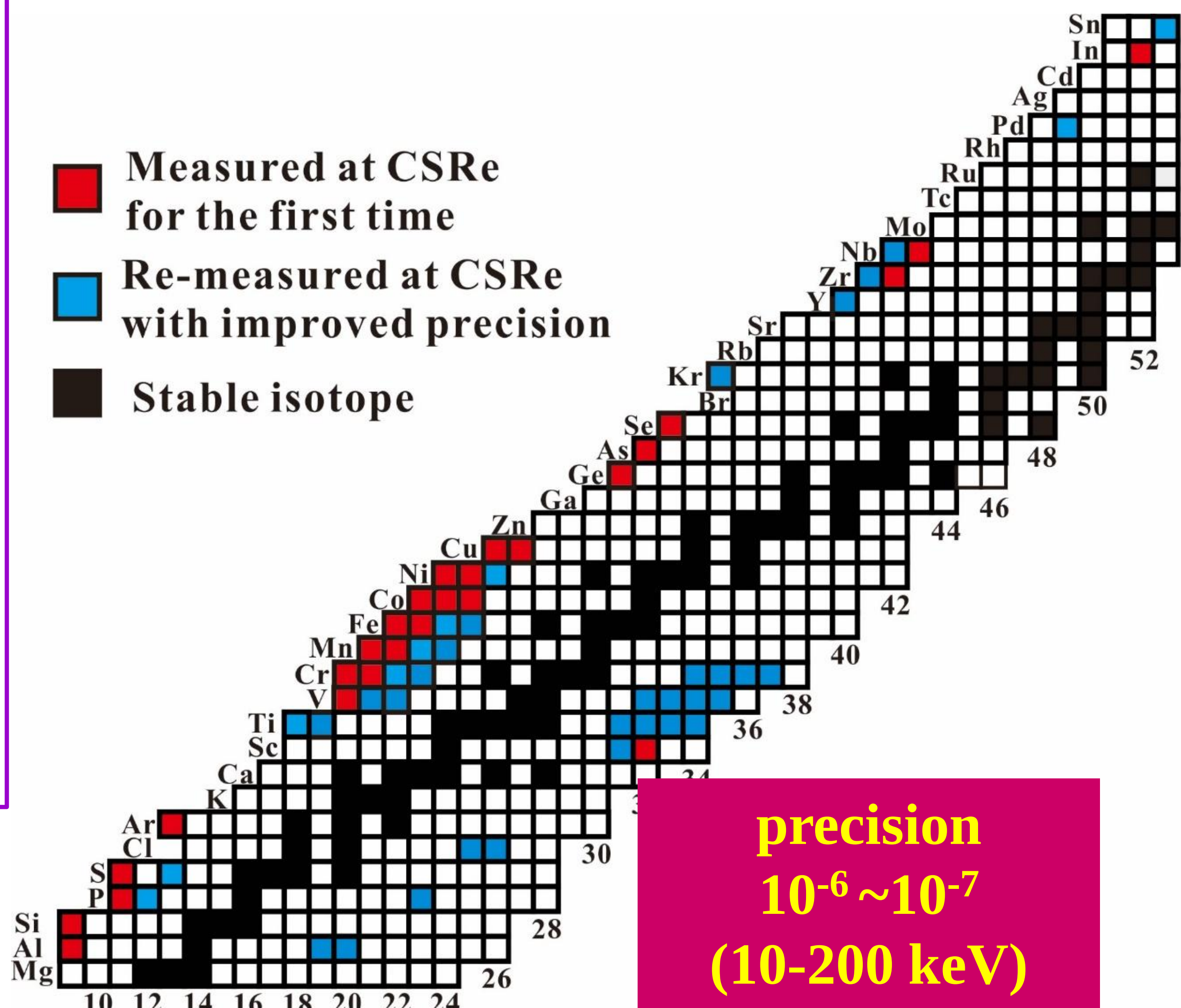


Y.M. Xing, Y.H. Zhang*, M. Wang* et al., NIM A 941 (2019) 162331

Overview of CSR results

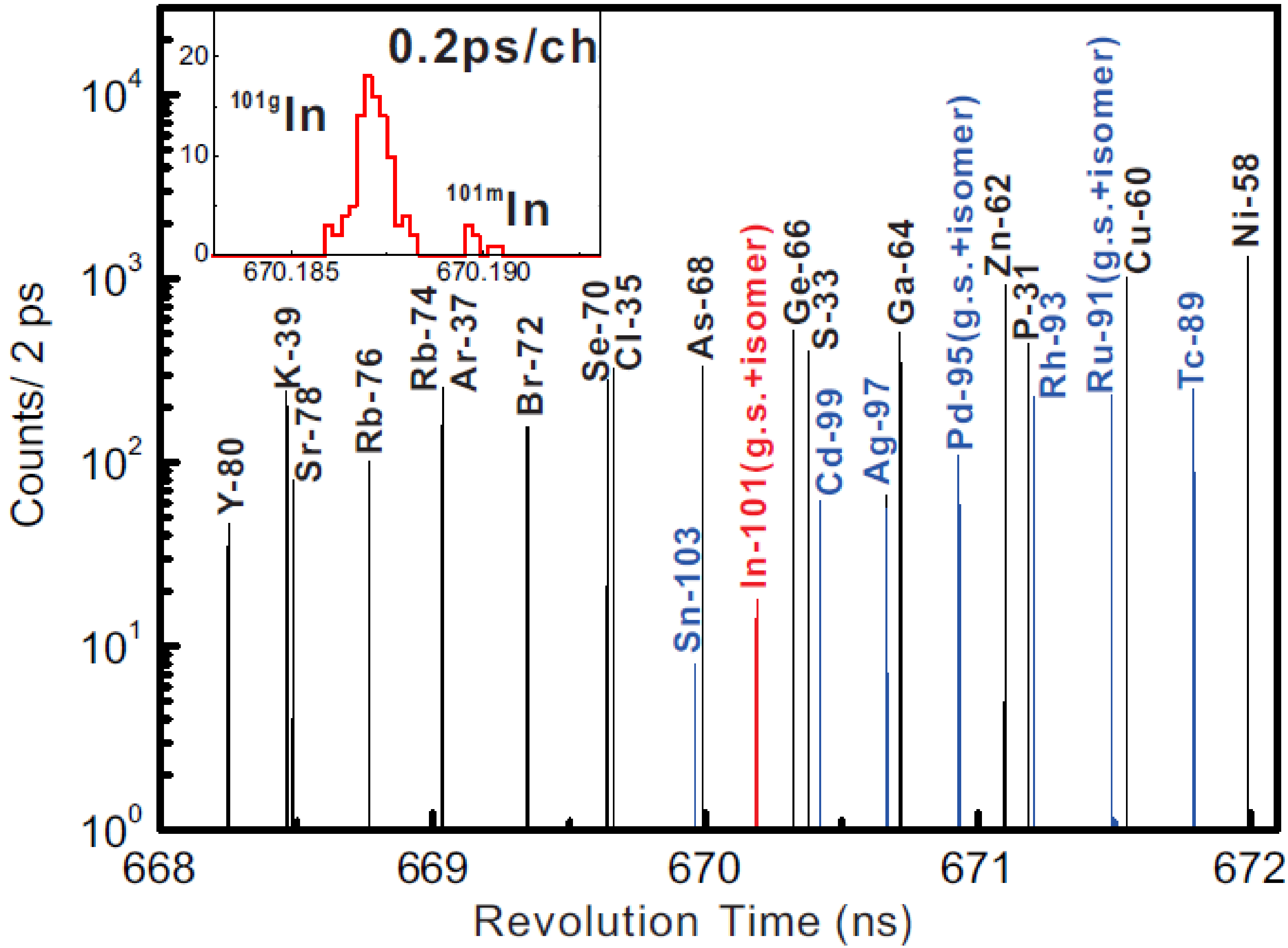
1. M. Wang et al., IJMP E 18, 352 (2009)
2. B. Mei et al., NIM A 624, 109 (2010)
3. X. L. Tu et al., PRL 106, 112501 (2011)
4. X. L. Tu et al., NIM A 654, 213 (2011)
5. Y. H. Zhang et al., PRL 109, 102501 (2012)
6. X. L. Yan et al. ApJL 766, L8 (2013)
7. H. S. Xu et al., IJMS 349, 162 (2013)
8. X. L. Tu et al., JPG 41, 025104 (2014)
9. W. Zhang et al., NIM A 755, 38 (2014)
10. W. Zhang et al., NIM A 756, 1 (2014)
11. B. Mei et al., PRC 89, 054612 (2014)
12. P. Shuai et al., PLB 735,327 (2014)
13. J.J. He et al., PRC 89, 035802 (2014)
14. X. Xu et al., CPC 39, 104001 (2015)
15. X. Xu et al., CPC 39, 106201 (2015)
16. R.J. Chen et al., PS T166, 014044 (2015)
17. Y.M. Xing et al., PS T166, 014010 (2015)
18. Y.H. Lam et al., APJ 818, 78 (2016)
19. P. Shuai et al., NIM B 376, 311 (2016)
20. X.L. Tu et al., NPA 945, 89 (2016)
21. B. Mei et al., PRC 94,044615 (2016)
22. X. Xu et al., PRL 117, 182503 (2016)
23. P. Zhang et al., PLB 767, 20 (2017)
24. X.L. Tu et al., PRC 95, 014610 (2017)
25. Q. Zeng et al., PRC (R) 96, 031303 (2017)
26. Y.H.Zhang et al., PRC 98, 014319 (2018)
27. C. Y. Fu et al., PRC 98, 014315 (2018)
28. Y.M.Xing et al., PLB 781, 358 (2018)
29. X. Xu et al., PRC 99, 064303 (2019)

Primary beams: ^{78}Kr, ^{36}Ar, ^{58}Ni, ^{86}Kr, ^{112}Sn



precision
10^{-6} ~10^{-7}
(10-200 keV)

Masses of $^{101g,m}In$



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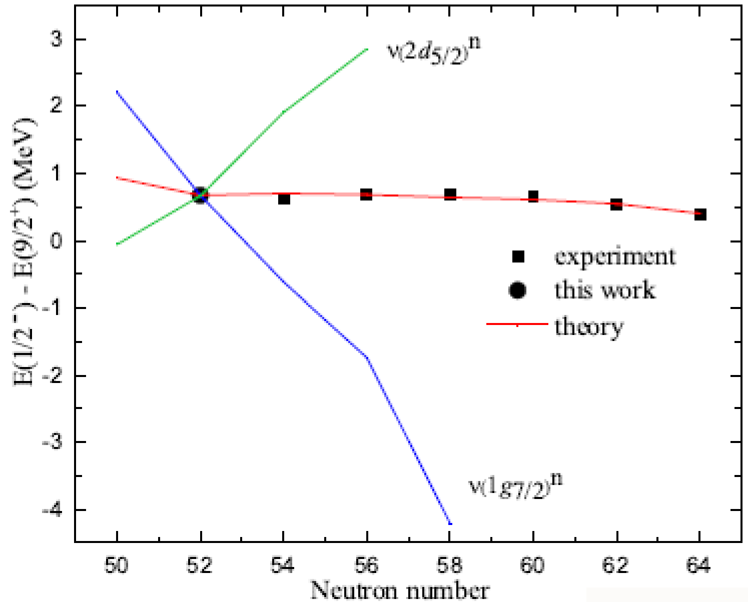
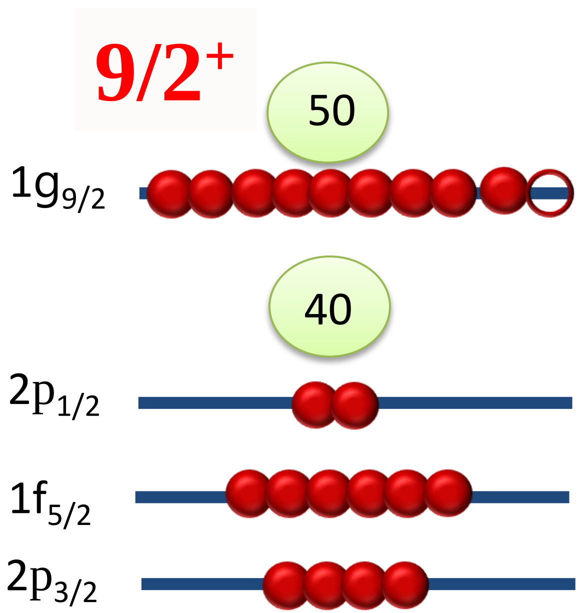
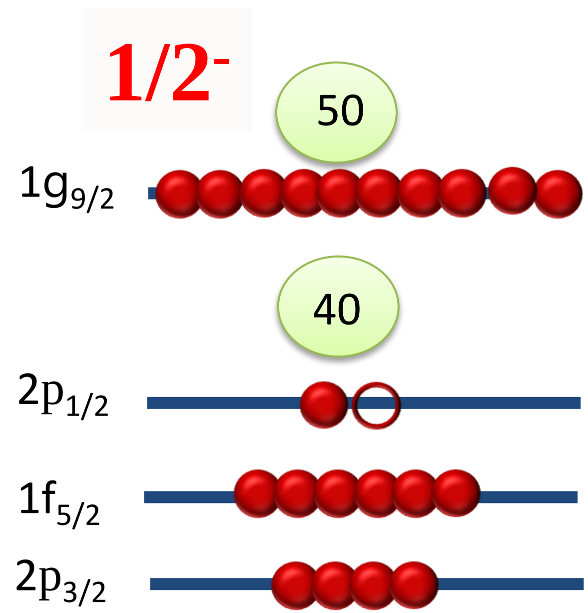
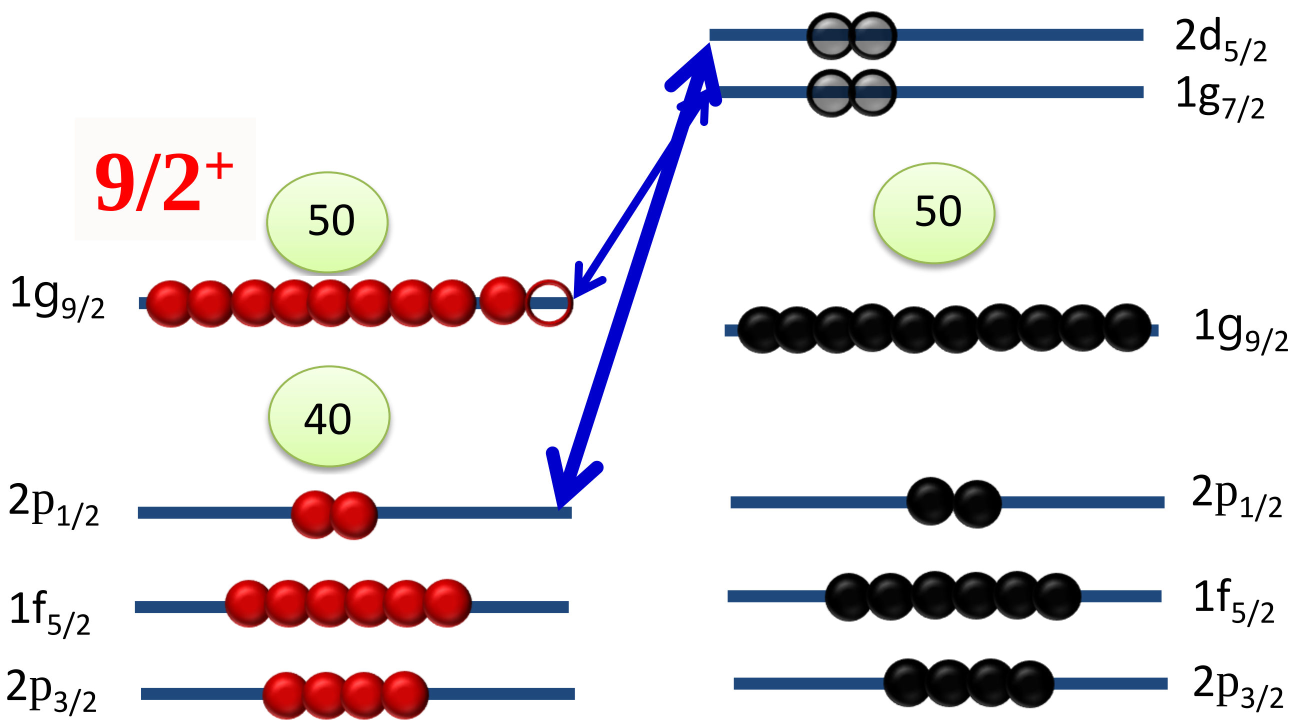






Masses of $^{101g,m}In$



T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005)

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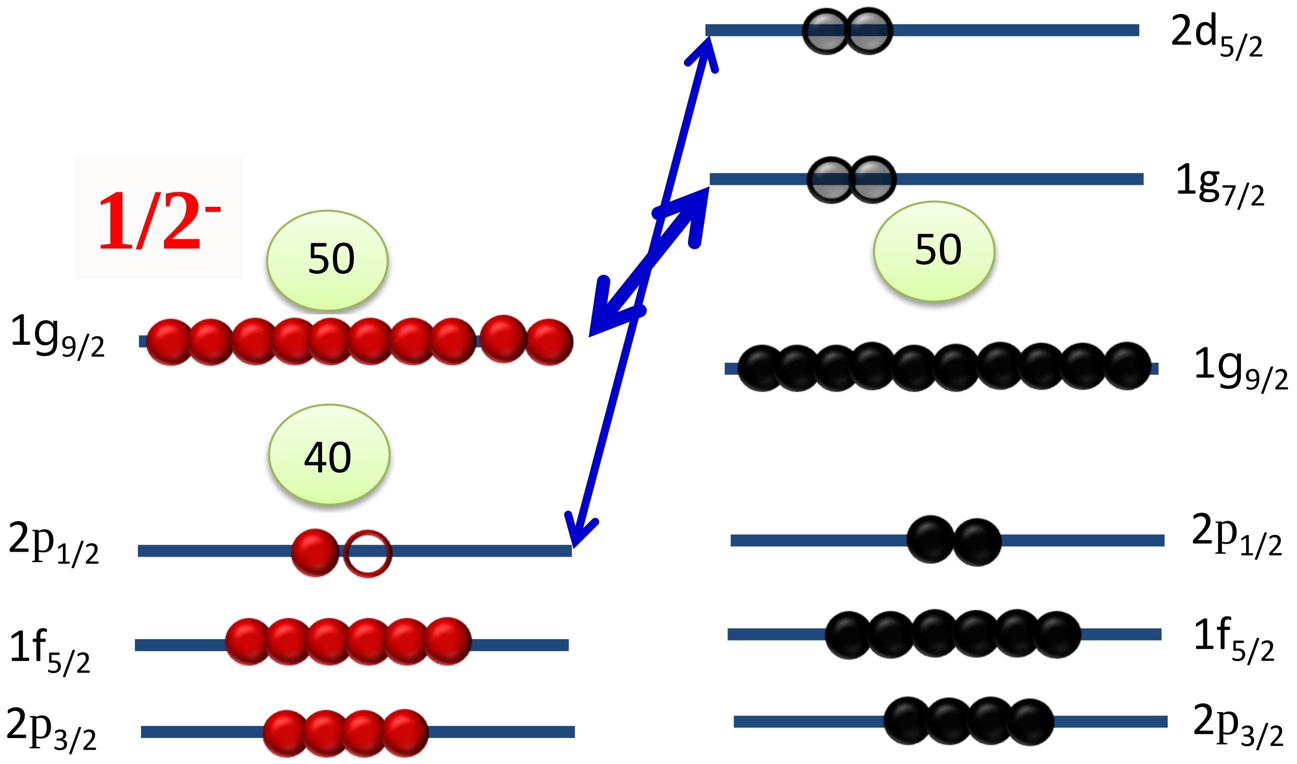

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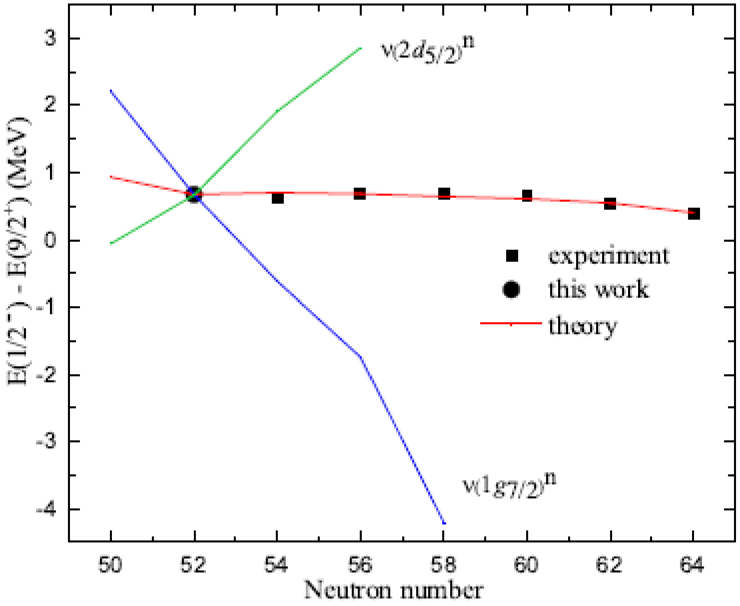
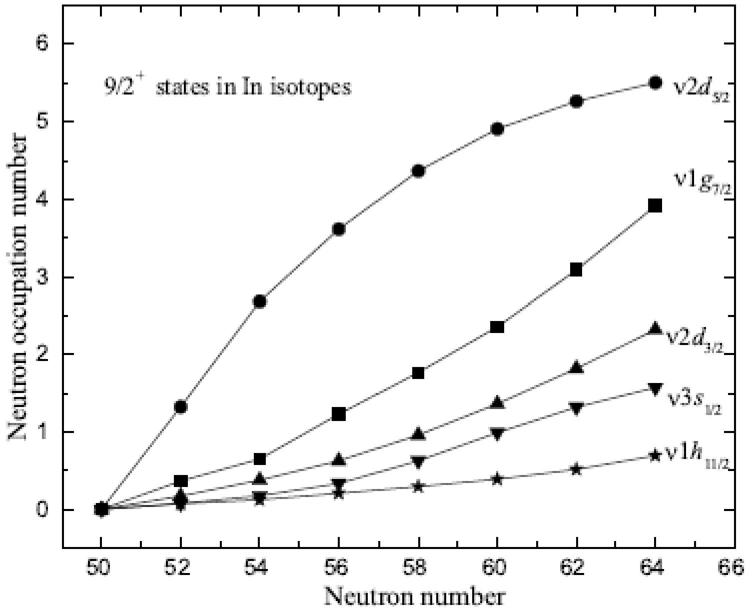
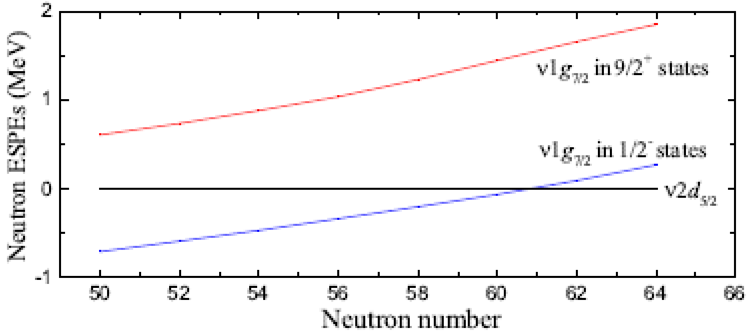
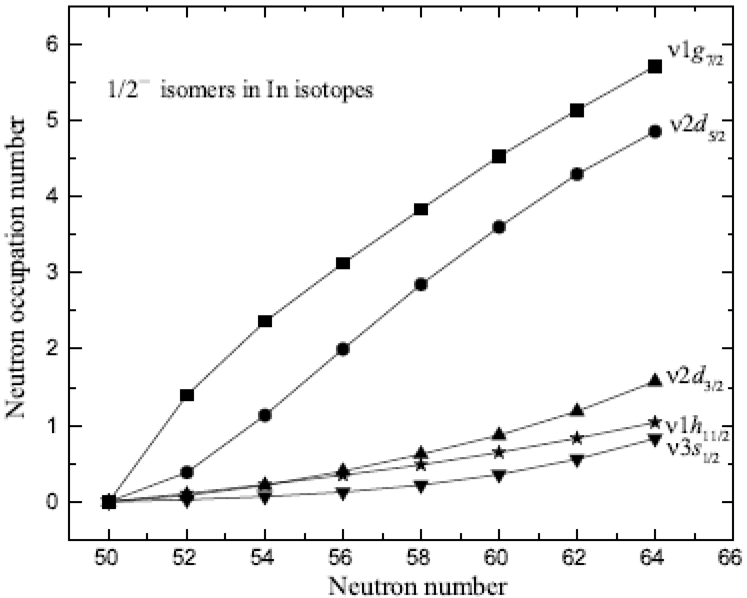








Masses of ^{101g,m}In

Masses of ground and isomeric states of ^{101}In and configuration-dependent shell evolution in odd-*A* indium isotopes

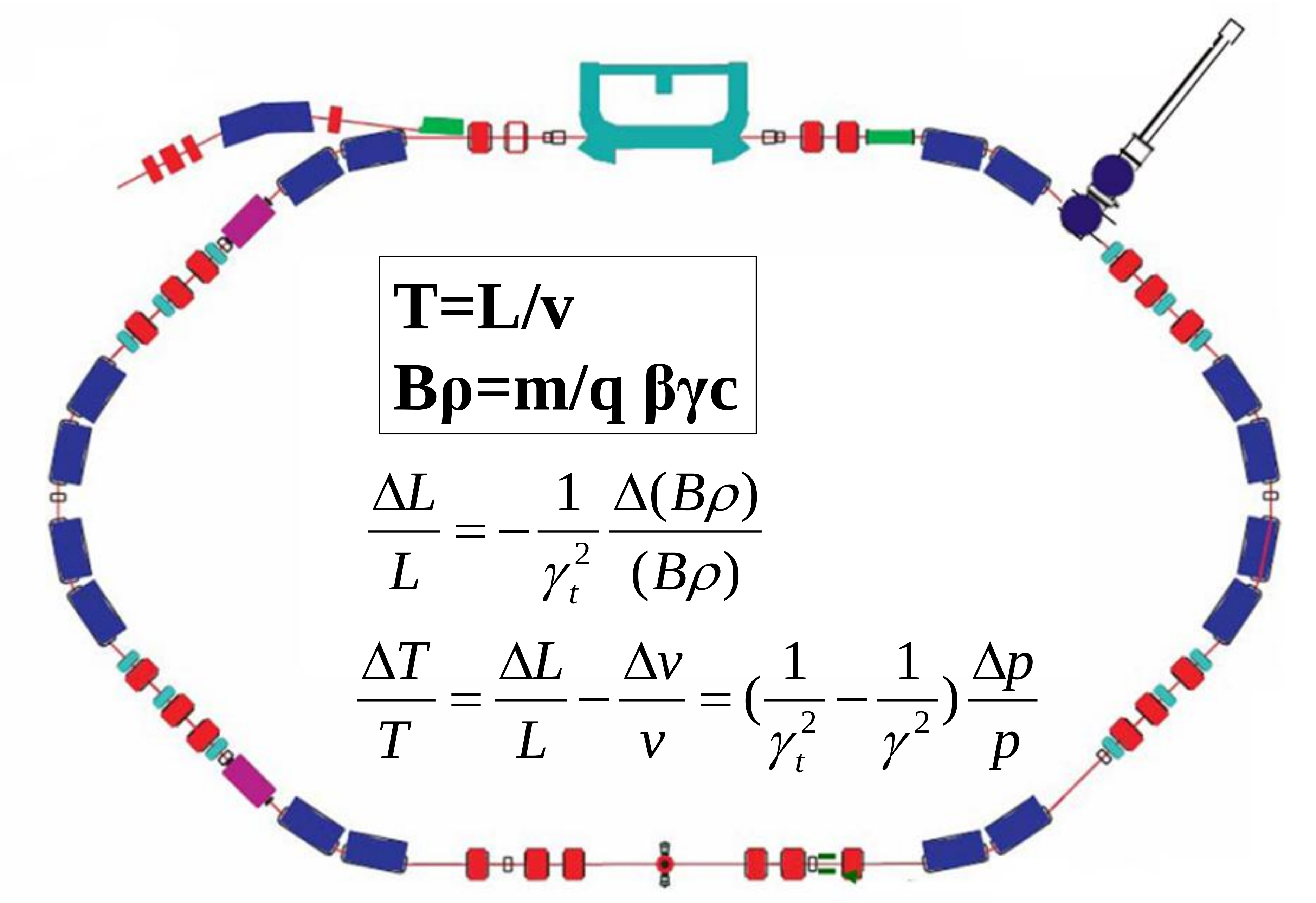
X. Xu,[1,2] J. H. Liu,[1,3] C. X. Yuan,[4] Y. M. Xing,[1] M. Wang,[1,3,*] Y. H. Zhang,[1,3,†] X. H. Zhou,[1,3] Yu. A. Litvinov,[1,5] K. Blaum,[6] R. J. Chen,[1] X. C. Chen,[1] C. Y. Fu,[1] B. S. Gao,[1,3] J. J. He,[7,1] S. Kubono,[1] Y. H. Lam,[1] H. F. Li,[1,3] M. L. Liu,[1,3] X. W. Ma,[1,3] P. Shuai,[1] M. Si,[1,3] M. Z. Sun,[1,3] X. L. Tu,[1,3] Q. Wang,[1,3] H. S. Xu,[1,3] X. L. Yan,[1] J. C. Yang,[1,3] Y. J. Yuan,[1,3] Q. Zeng,[1,8] P. Zhang,[1,3] X. Zhou,[1,3] W. L. Zhan,[1] S. Litvinov,[5] G. Audi,[9] S. Naimi,[10] T. Uesaka,[10] Y. Yamaguchi,[10] T. Yamaguchi,[11] A. Ozawa,[12] B. H. Sun,[13] K. Kaneko,[14] Y. Sun,[15,1] and F. R. Xu[16]

[1]Key Laboratory of High Precision Nuclear Spectroscopy and Center for Nuclear Matter Science, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2]School of Science, Xi'an Jiaotong University, Xi'an 710049, China
[3]School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China
[4]Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-Sen University, Zhuhai 519082, China
[5]GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, Darmstadt, 64291 Germany
[6]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[7]Key Laboratory of Beam Technology of Ministry of Education, College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, China
[8]School of Nuclear Science and Engineering, East China University of Technology, Nanchang, 330013, China
[9]CSNSM, Univ Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, 91405 Orsay, France
[10]RIKEN Nishina Center, RIKEN, Saitama 351-0198, Japan
[11]Department of Physics, Saitama University, Saitama 338-8570, Japan
[12]Insititute of Physics, University of Tsukuba, Ibaraki 305-8571, Japan
[13]School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China
[14]Department of Physics, Kyushu Sangyo University, Fukuoka 813-8503, Japan
[15]School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China
[16]State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China

(Dated: July 11, 2019)

arXiv:1907.04584

Double-TOF IMS at CSRe



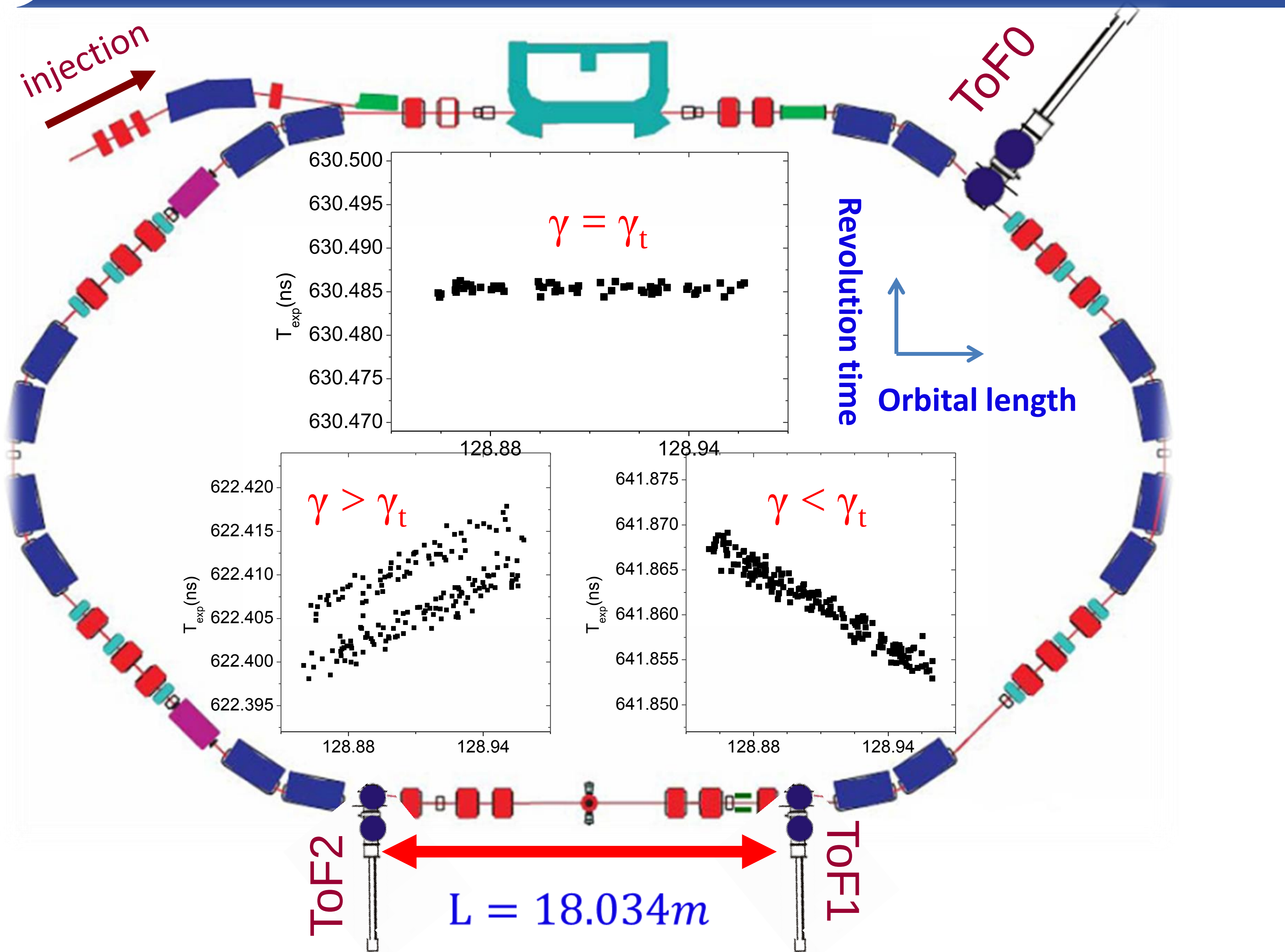
T=L/v

Bρ=m/q βγc

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

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

Double-TOF IMS at CSRe



Double-TOF IMS at CSRe

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **31** (2005) S1779–S1783 doi:10.1088/0954-3899/31/10/072

Precision experiments with relativistic exotic nuclei at GSI

H Geissel[1,2] and Yu A Litvinov[1,2]

the narrow range where the isochronous conditions are fulfilled. The analysis with only one time-of-flight (ToF) detector positioned inside the ESR lattice [26] requires, in principle, a strong restriction on the accepted mass-to-charge ratio. A solution is to measure the velocity of each fragment in addition to the revolution time. This will provide a correlation to account for the deviations from the strict isochronous condition. For this purpose, additional detectors could be placed within the FRS, inside the ESR, and behind the extraction channel from the ESR. Within the FRS both magnetic rigidity and time-of-flight measurements are possible. However, a restriction is certainly the higher particle rate compared to the actually stored ions in the ESR. The advantage with a second ToF detector within the ESR is the turn-by-turn velocity correlation measurement. The velocity measurement of the extracted beam after many revolutions in the ESR also has advantages. For example, the velocity can be measured

Double-TOF IMS at CSRe

- **2013**: Installation of two TOF detectors
- **2013**: D-TOF IMS with ^{78}Kr, test of detectors
- **2015**: D-TOF IMS with ^{36}Ar, optical setting of CSRe
- **2016**: D-TOF IMS with ^{40}Ar, optical setting of CSRe
- **2017**: D-TOF IMS with ^{58}Ni
- **2018**: D-TOF IMS with ^{58}Ni

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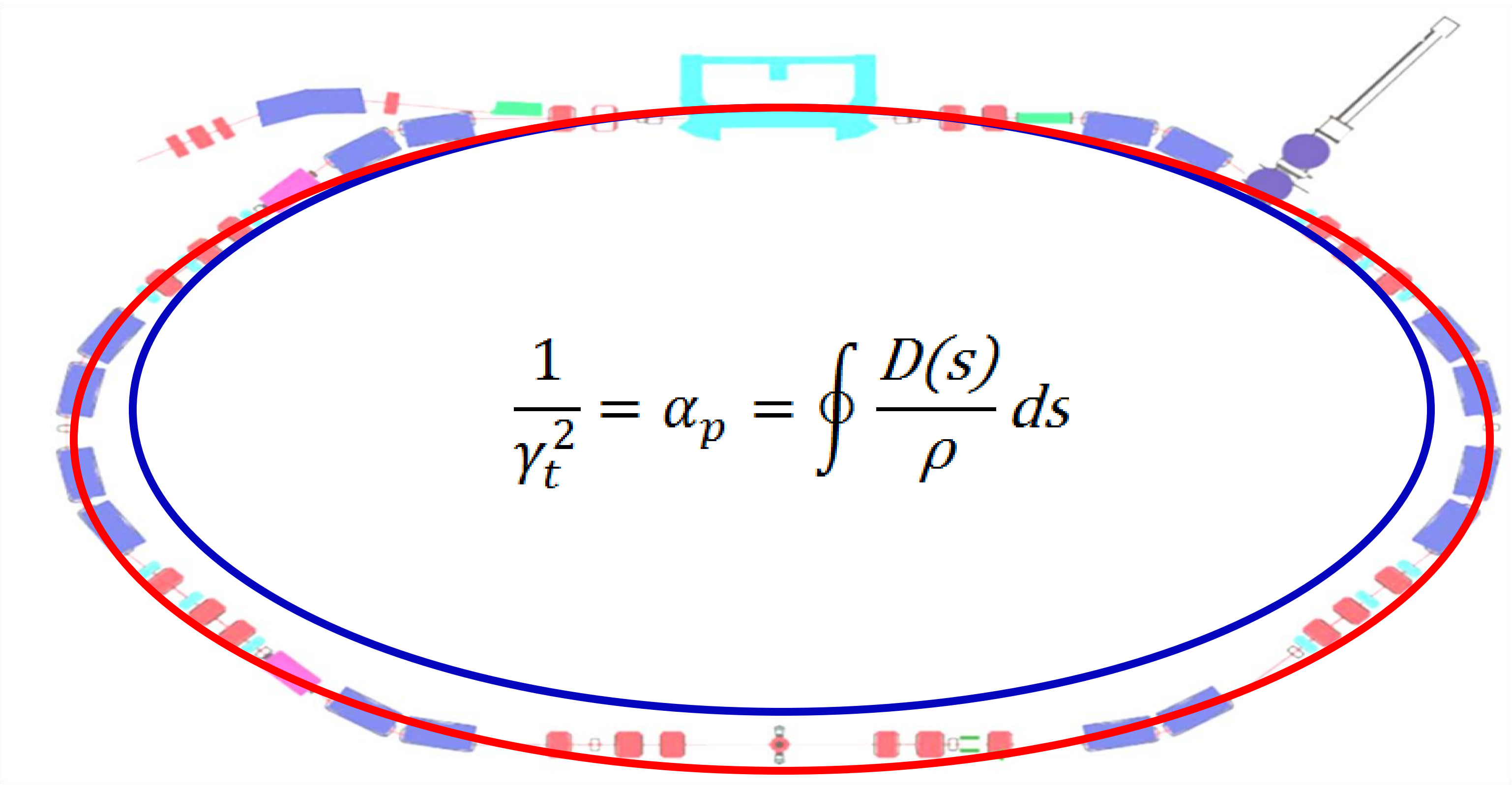
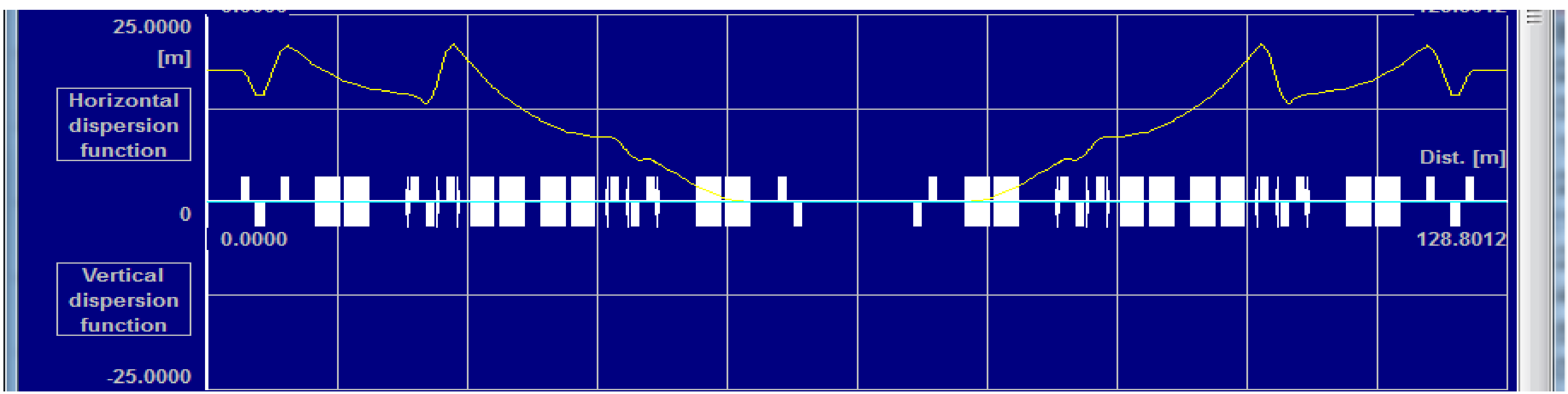
- W. Zhang et al., NIM A 756 (2014) 1
- Y. M. Xing et al., Phys. Scr. T166 (2015) 014010;
- X. Xu et al.,CPC 39(2015)2015

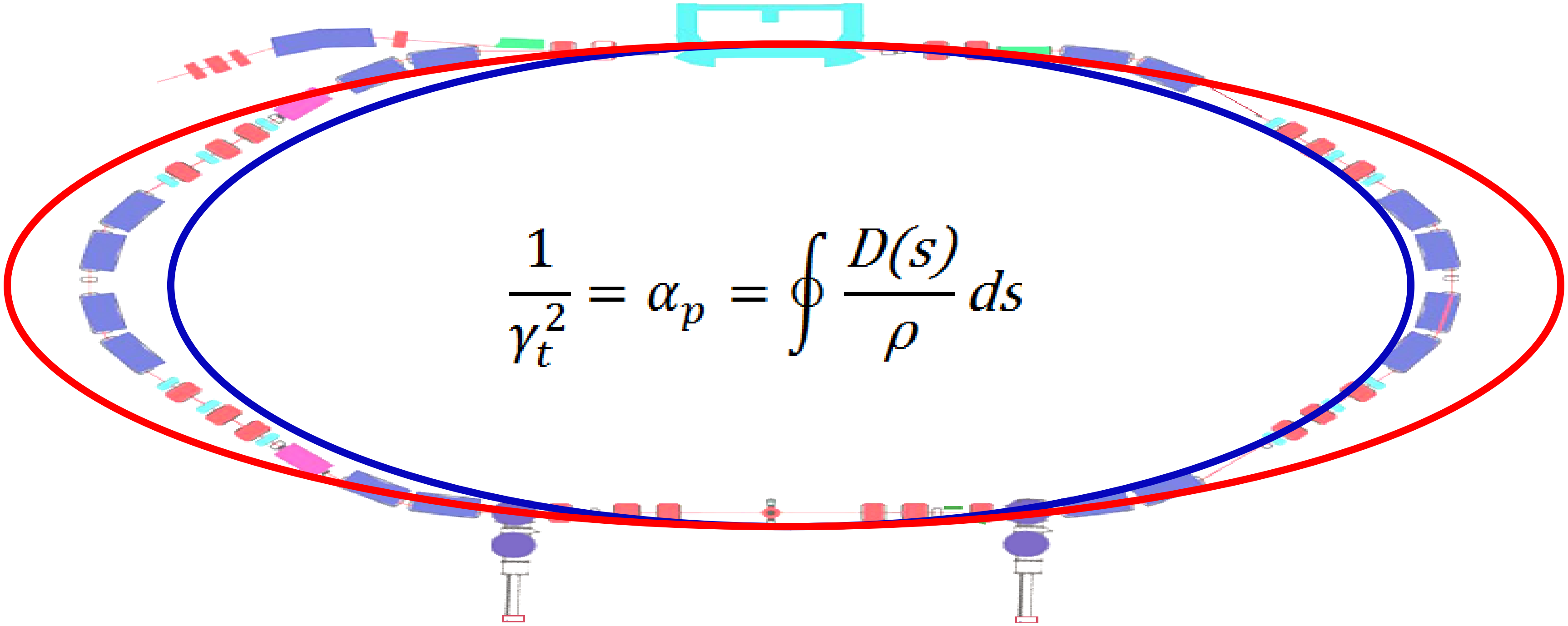
Double-TOF IMS at CSRe



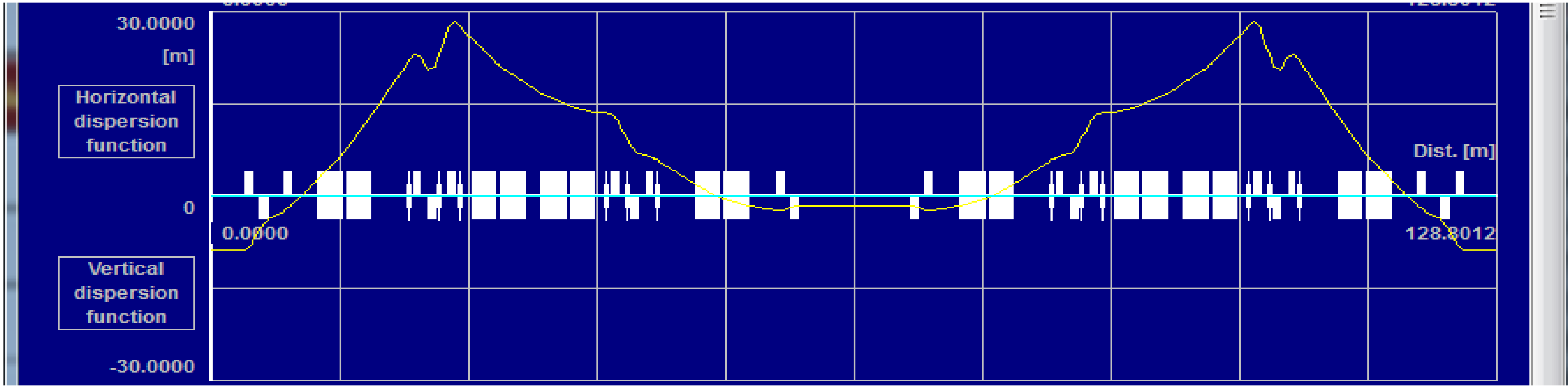
$$\frac{1}{\gamma_t^2} = \alpha_p = \oint \frac{D(s)}{\rho} ds$$



Double-TOF IMS at CSRe



$$\frac{1}{\gamma_t^2} = \alpha_p = \oint \frac{D(s)}{\rho} ds$$



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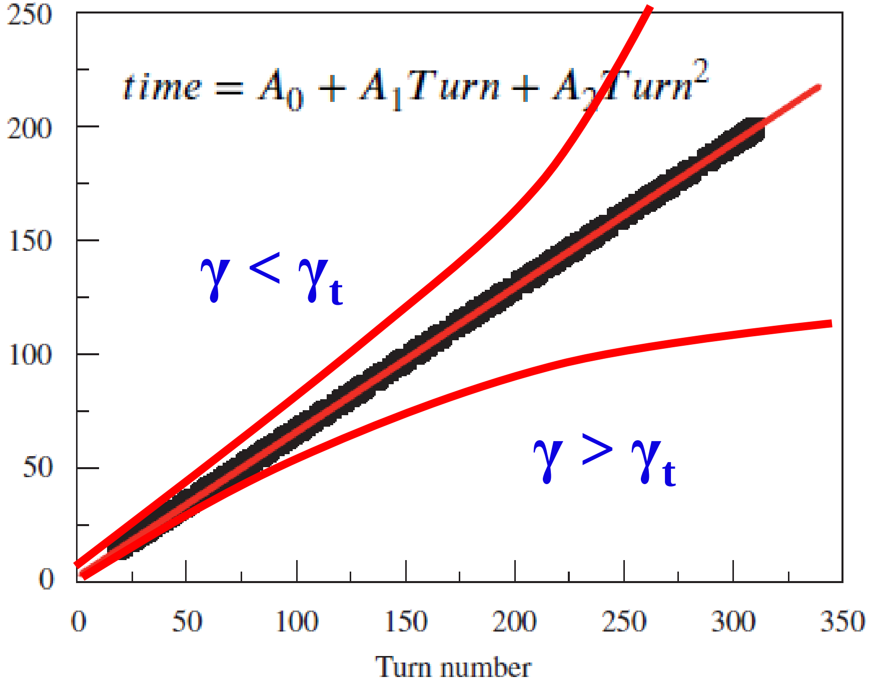
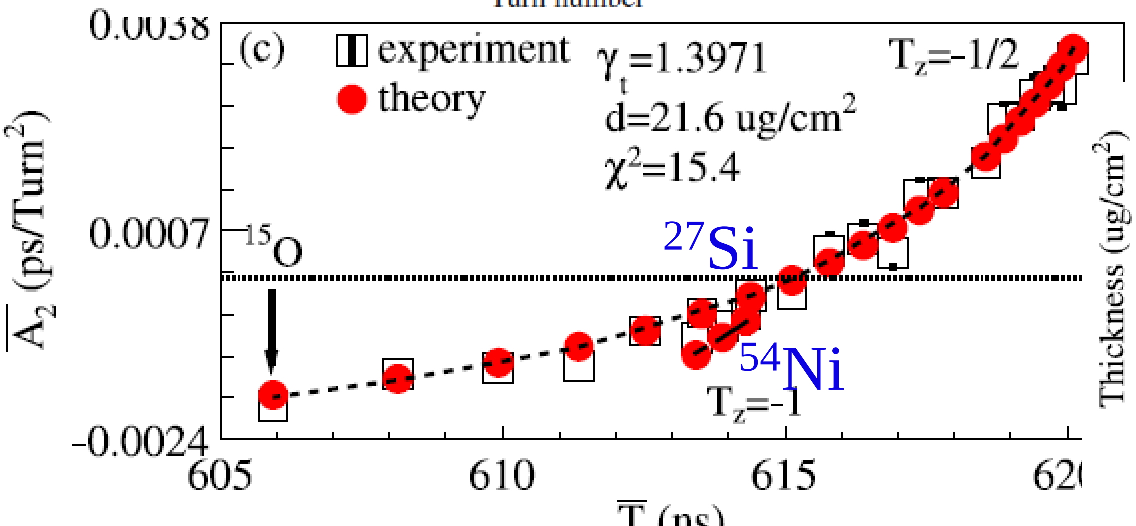
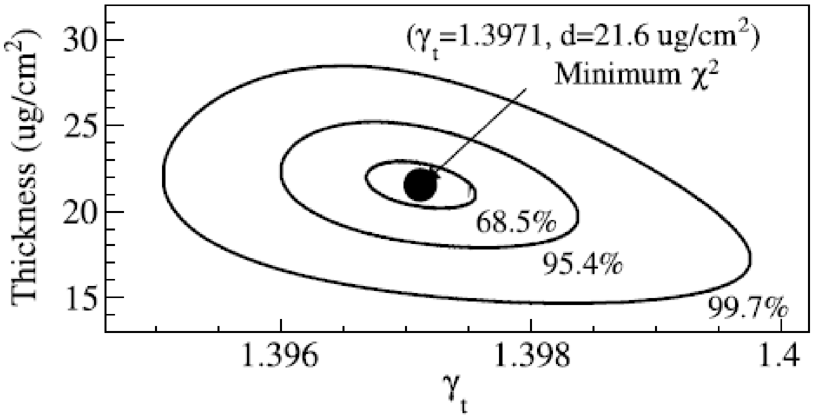


$$\frac{\Delta T}{T} = -\eta \frac{\Delta P}{P} = -\left(\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}\right)\frac{\Delta P}{P}$$

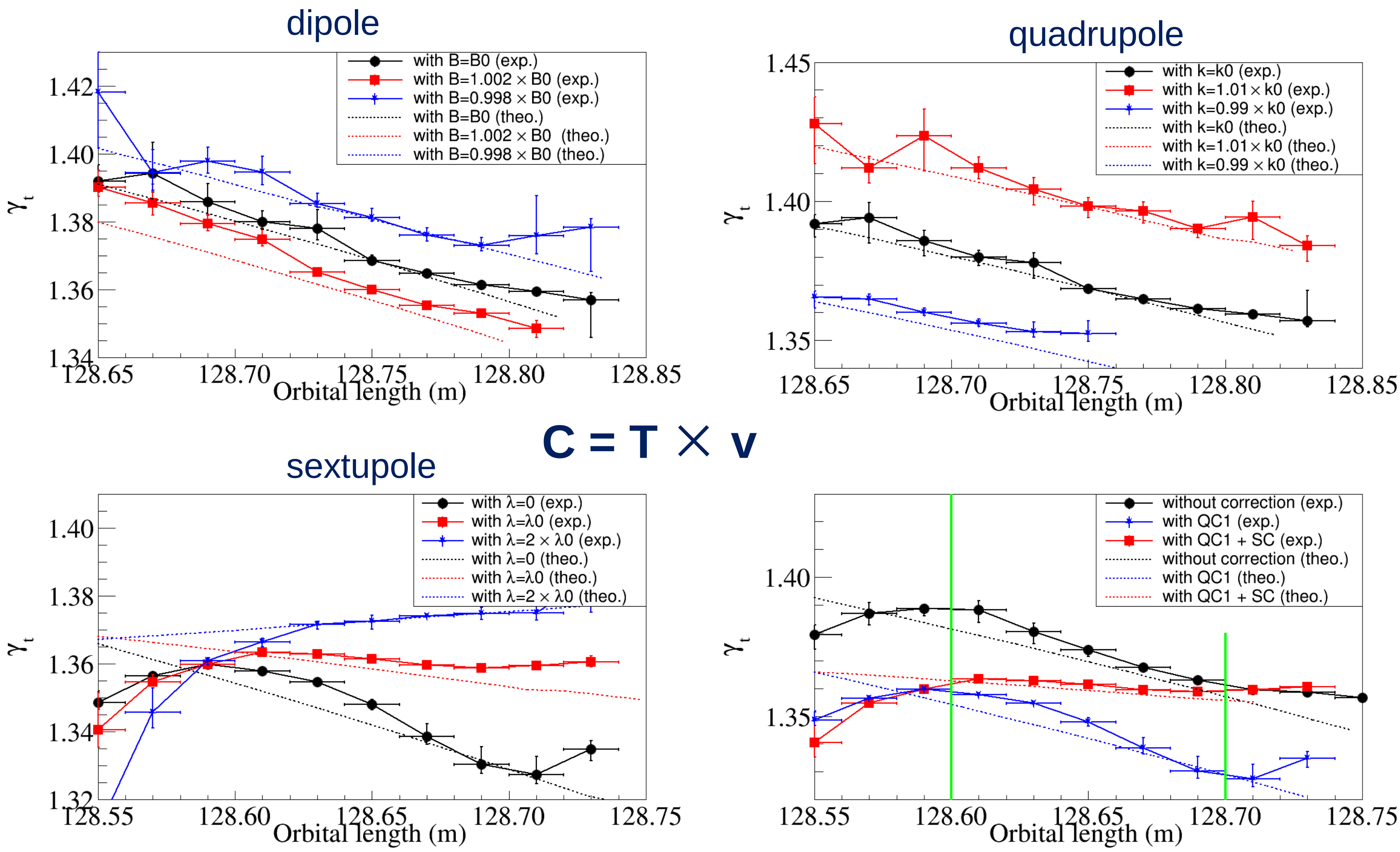
$$A_2 = -\frac{1}{2}\left(\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}\right)\frac{\gamma}{\gamma+1}\frac{\delta E_k}{E_k}T$$





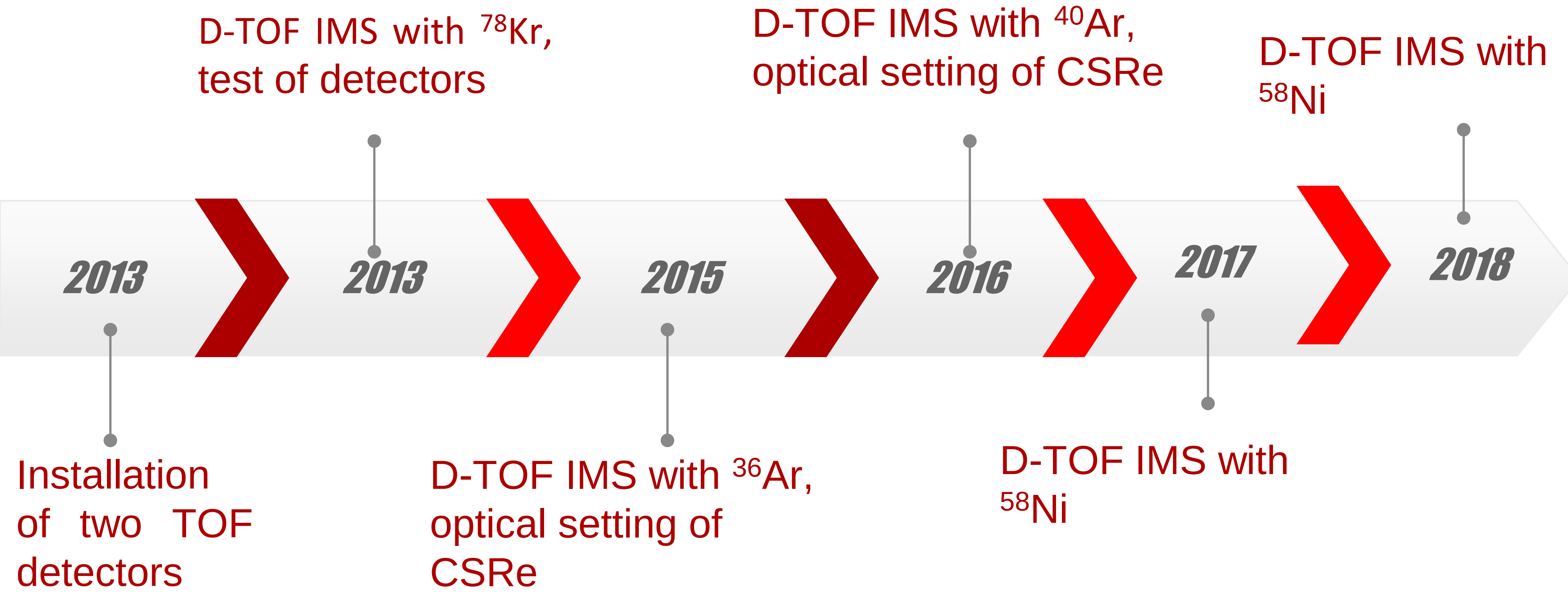
R.J.Chen, X.L.Yan, W.W.Ge, Y.J.Yuan*, M. Wang* et al., NIM A 898 (2018) 111.

Double-TOF IMS at CSRe



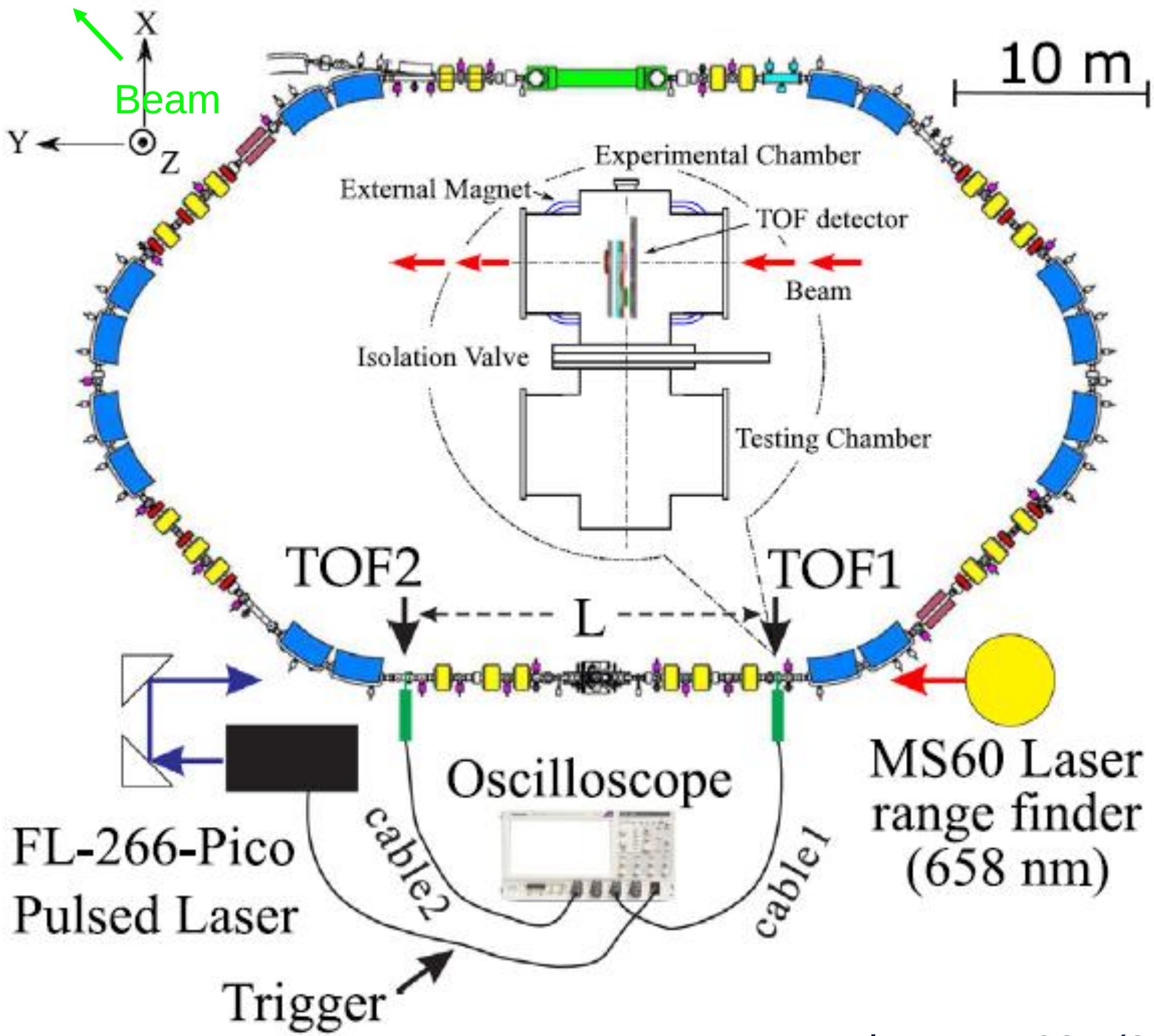
W.W. Ge et al., NIM A 908 (2018) 388-393

Double-TOF IMS at CSRe



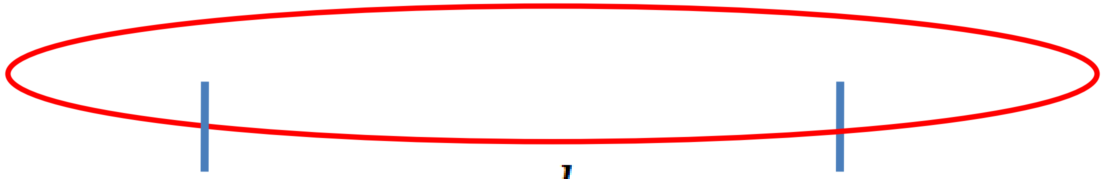
- W. Zhang et al., NIM A 756 (2014) 1
- Y. M. Xing et al., Phys. Scr. T166 (2015) 014010;
- X. Xu et al.,CPC 39(2015)2015
- R. J. Chen et al., NIM A 898 (2018) 111.
- W.W. Ge et al., NIM A 908 (2018) 388-393

Double-TOF IMS at CSRe



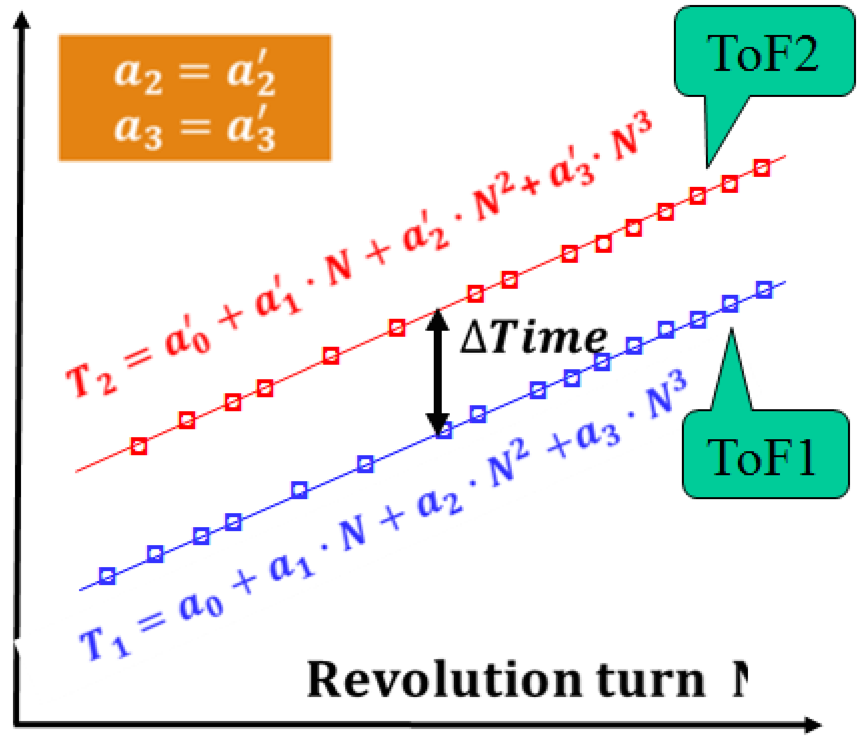
X. L.Yan et al., NIM A 931 (2019) 52

Double-TOF IMS at CSRe



$$v = \frac{l}{t}$$

	Uncertainty	Example：$\sigma_1=\sigma_2=30$ ps，$\eta_1=\eta_2=20\%$，N=400
Coincident signals	$\sqrt{\frac{\sigma_1^2}{n\eta_1\eta_2}+\frac{\sigma_2^2}{n\eta_1\eta_2}}$	10.5 ps，1.2×10^{-4}
Independent fitting	$2\sqrt{\frac{\sigma_1^2}{n\eta_1}+\frac{\sigma_2^2}{n\eta_2}}$	9.5 ps， 1.1×10^{-4}
Combined fitting	$\sqrt{\frac{\sigma_1^2}{n\eta_1}+\frac{\sigma_2^2}{n\eta_2}}$	4.7 ps, 5.6×10^{-5}



Double-TOF IMS at CSRe

2013
Installation of two TOF detectors

2013
D-TOF IMS with ^{78}Kr, test of detectors

2015
D-TOF IMS with ^{36}Ar, optical setting of CSRe

2016
D-TOF IMS with ^{40}Ar, optical setting of CSRe

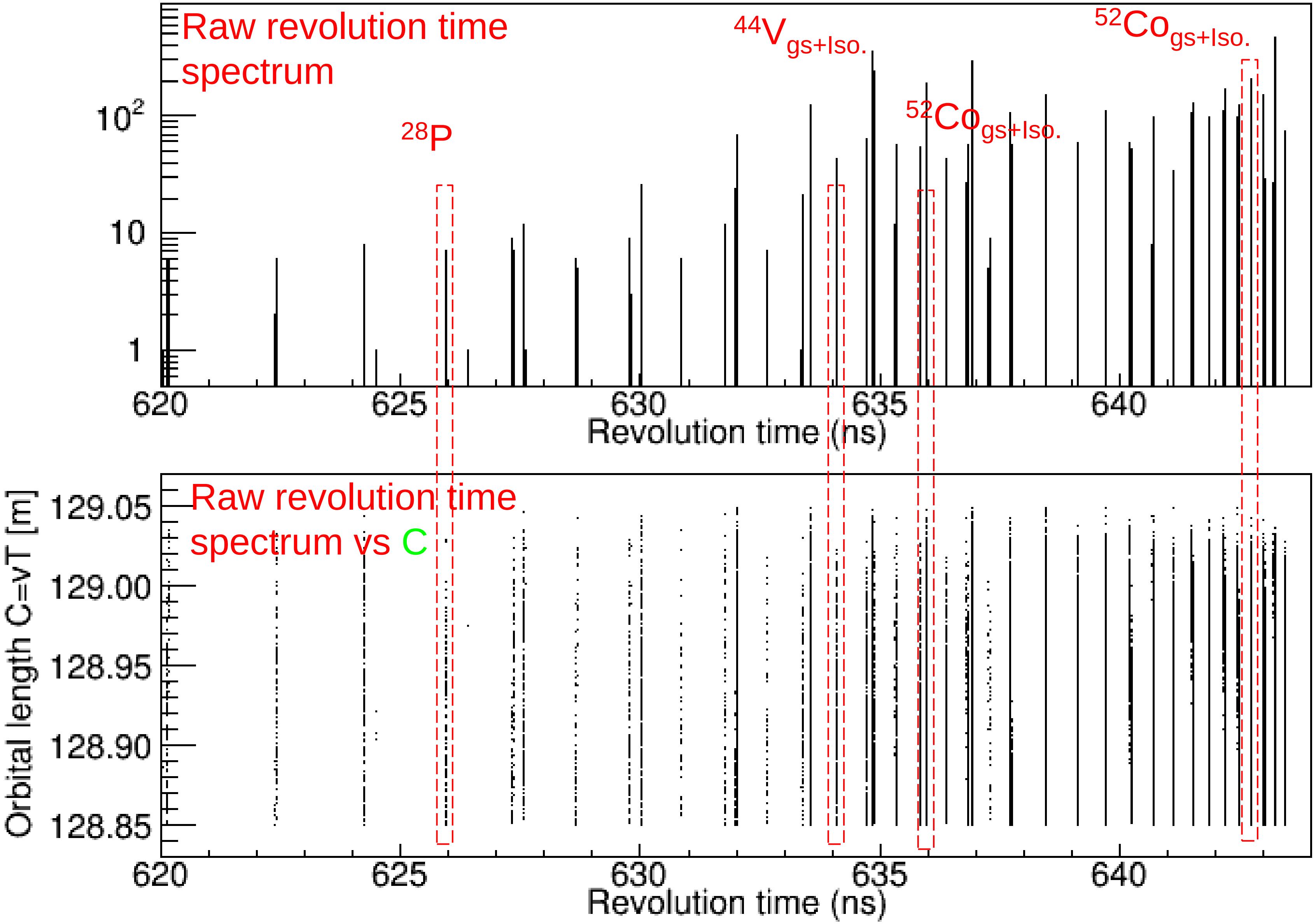
2017
D-TOF IMS with ^{58}Ni

2018
D-TOF IMS with ^{58}Ni

- W. Zhang et al., NIM A 756 (2014) 1
- Y. M. Xing et al., Phys. Scr. T166 (2015) 014010;
- X. Xu et al.,CPC 39(2015)2015
- R. J. Chen et al., NIM A 898 (2018) 111.
- W.W. Ge et al., NIM A 908 (2018) 388-393
- X. L.Yan et al., NIM A 931 (2019) 52

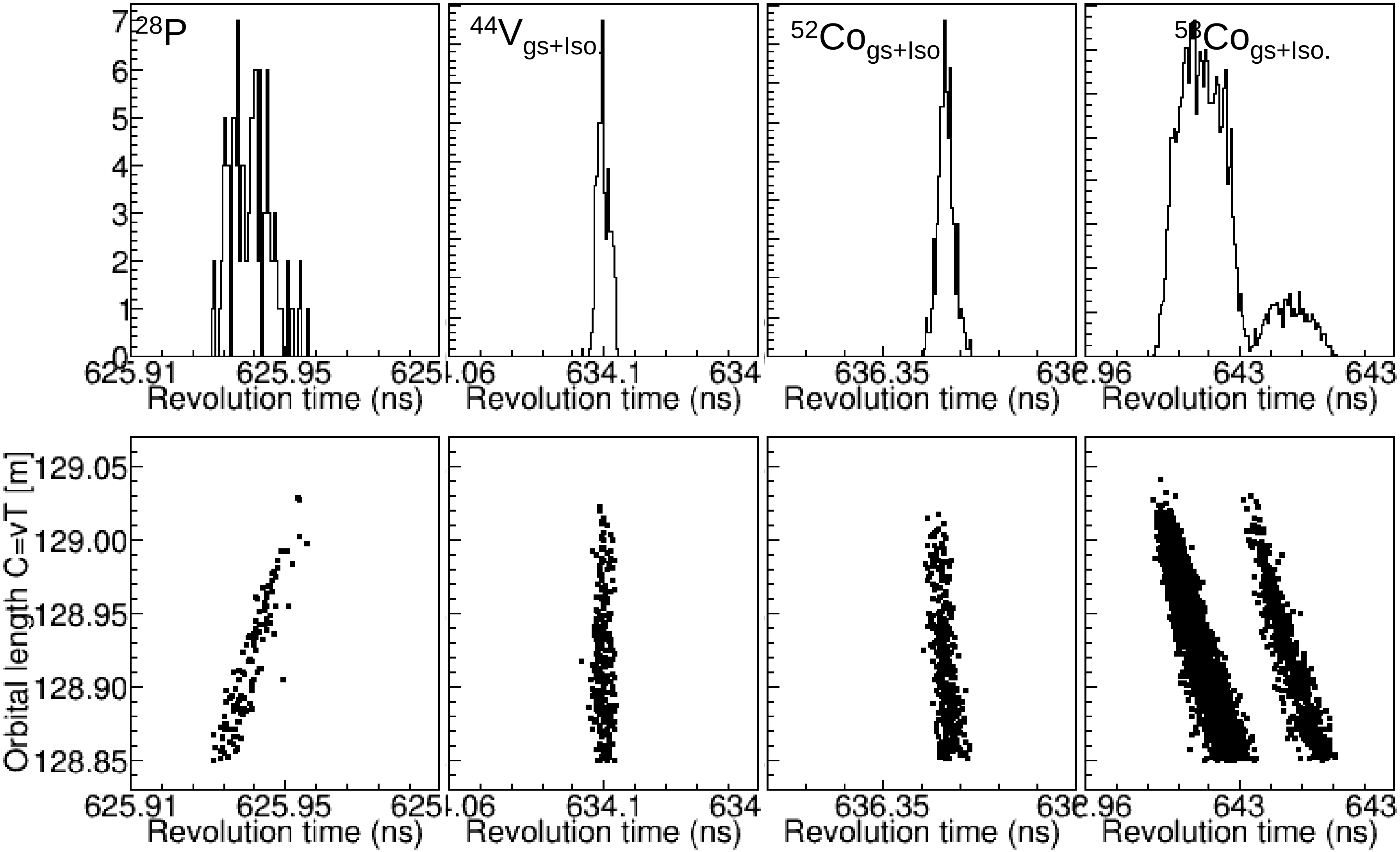
Double-TOF IMS at CSRe

Primary beam : ^{58}Ni, Dec. 2017



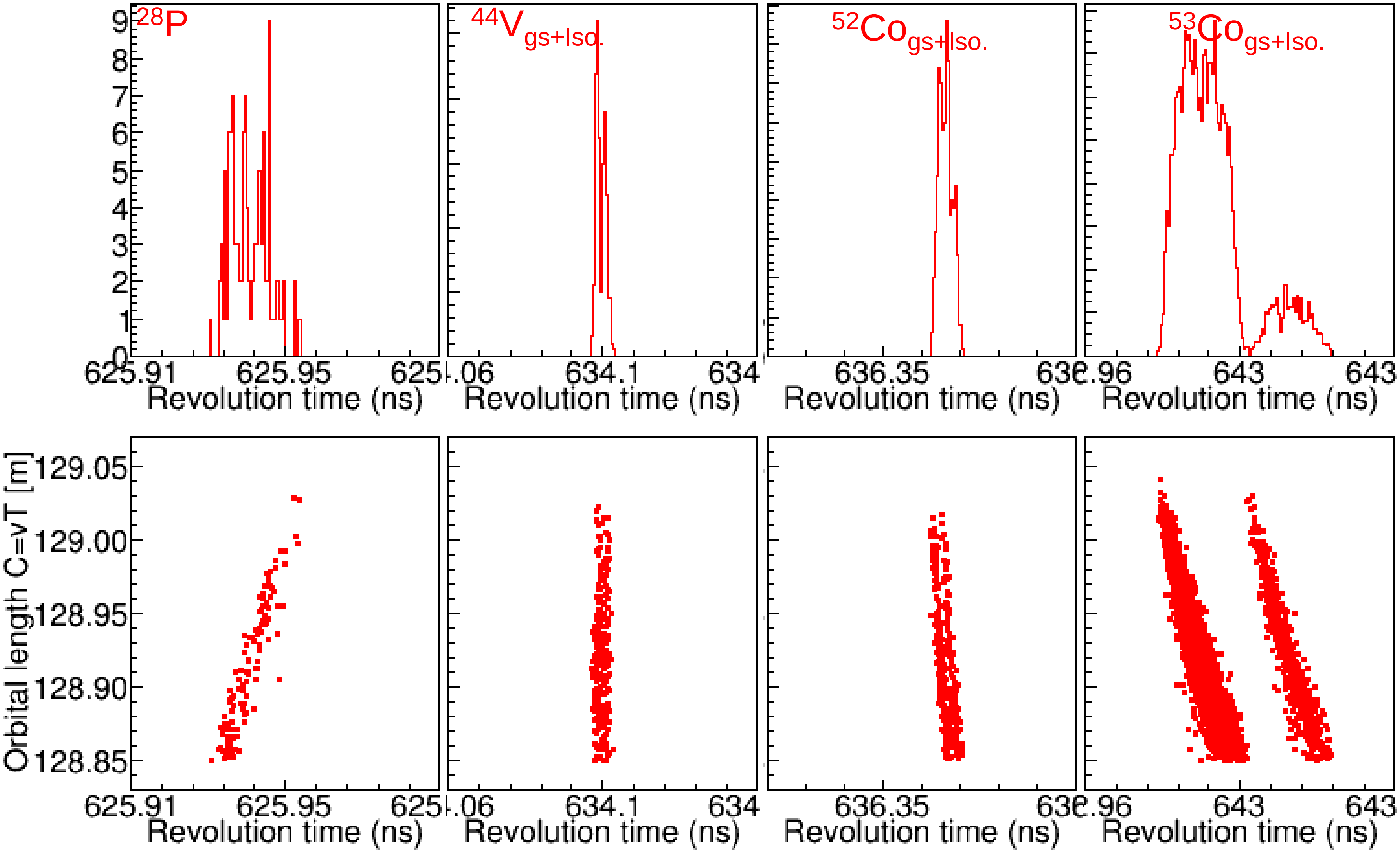
Double-TOF IMS at CSRe

Raw data



Double-TOF IMS at CSRe

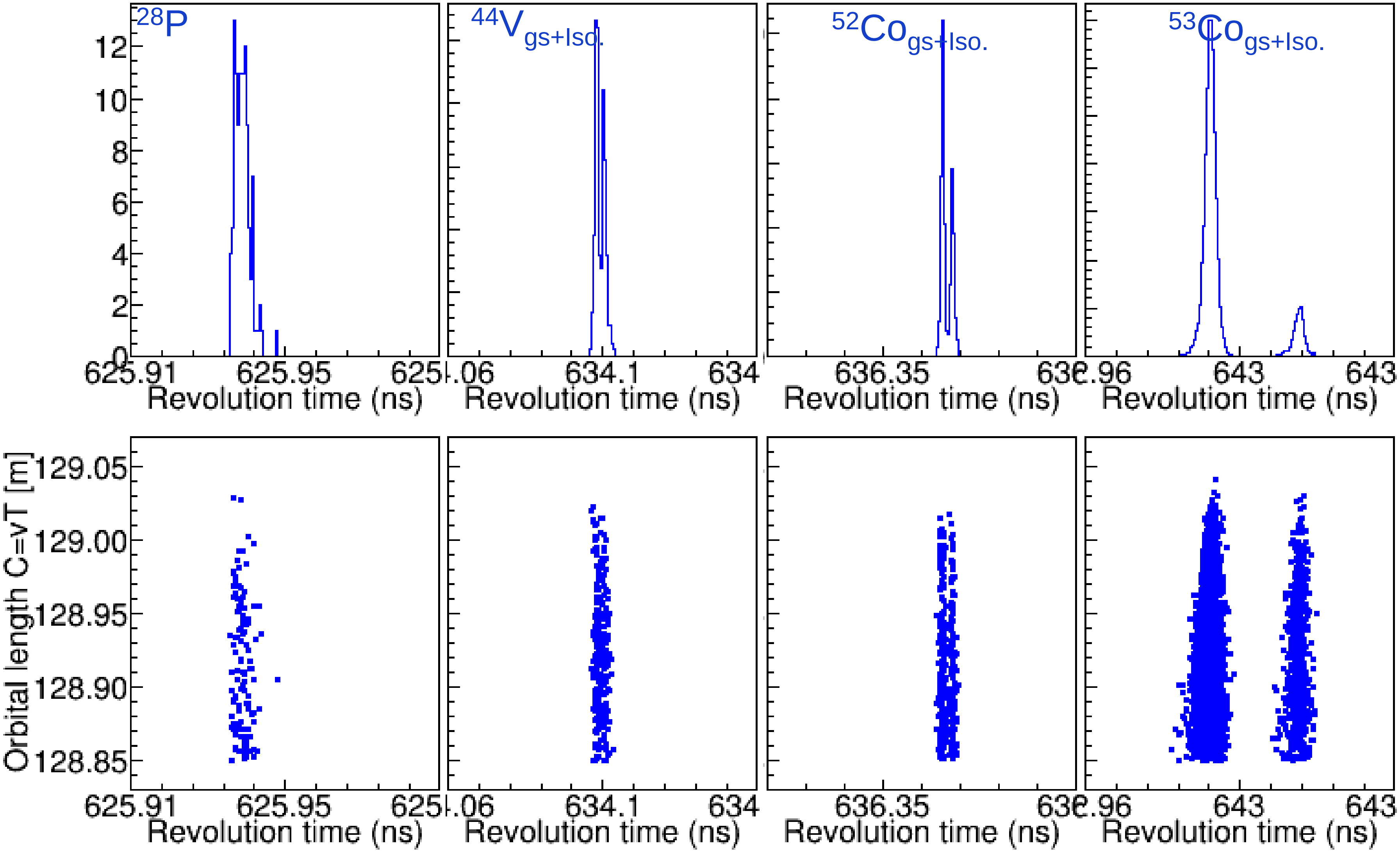
Magnetic correction



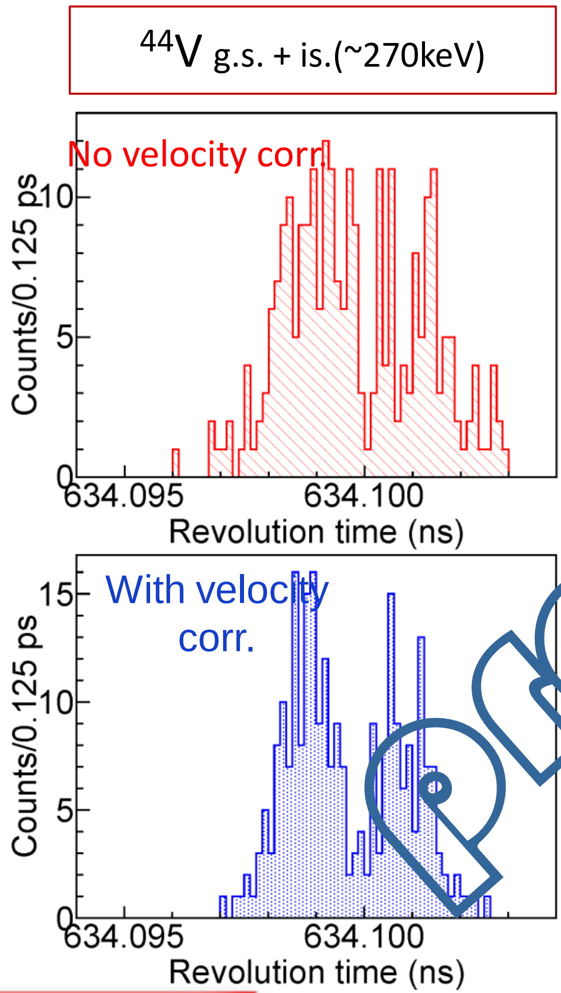
Double-TOF IMS at CSRe

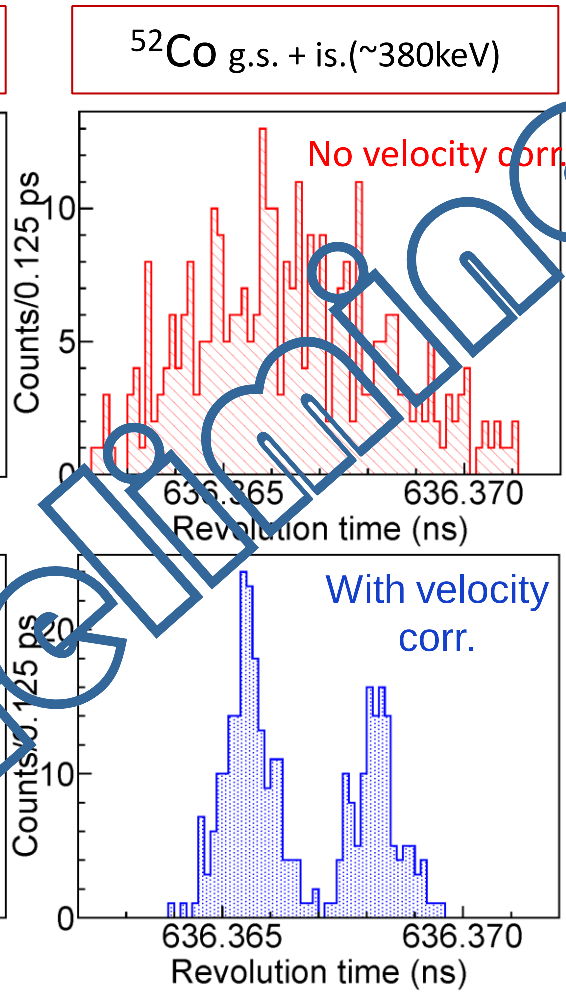
Orbital correction

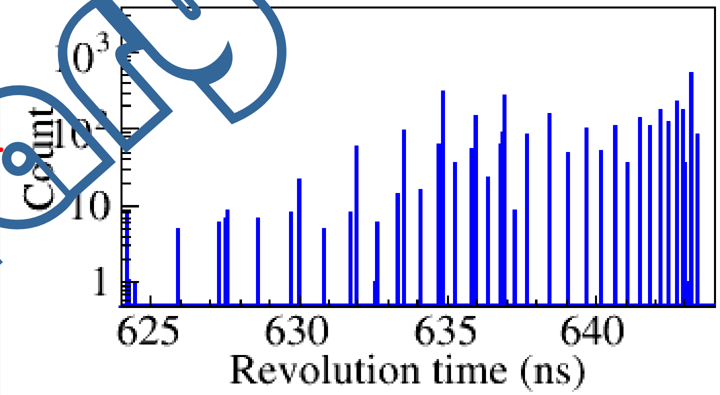
$$T_0 = T_i - \Delta T_i$$

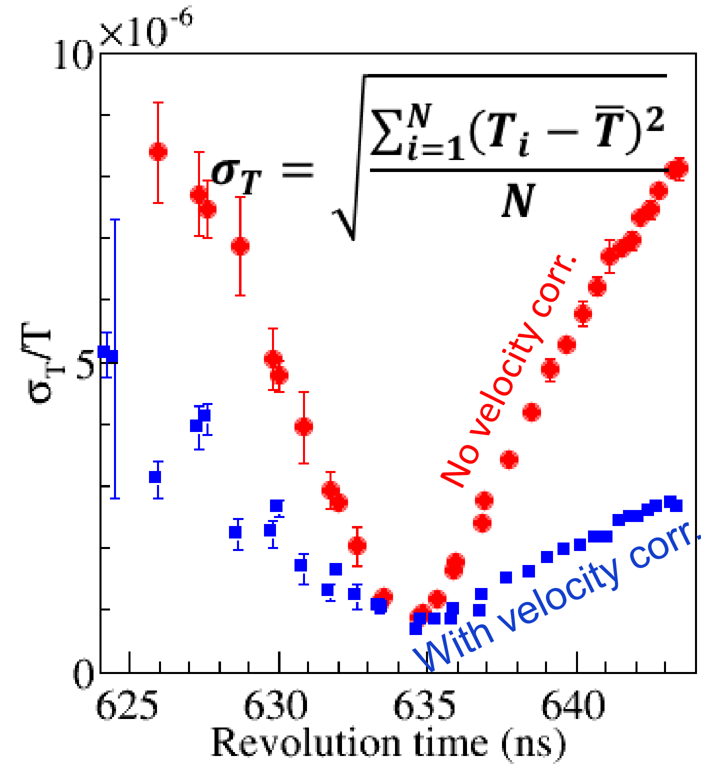


Double-TOF IMS at CSRe









Setting

2017.12.24 21:00~12.26 7:00,34 hours, $^{58}Ni^{19+}(428.05MeV/u, 7\times 10^7 pps)+$ 15mm Be, $B\rho_{RIBLL2-CSRe} = 5.4713\ Tm, \gamma_t = 1.36.$

Institute of Modern Physics, CAS

十二五装置HIAF总体规划

Thank you！

Thank you!