NuSTAR meeting 2015, GSI

Applications of Isochronous Mass Spectrometry (IMS) at HIRFL-CSR

OUTLINE

- Introduction to Isochronous Mass Spectrometry
- Experimental results and techniques
- Summary

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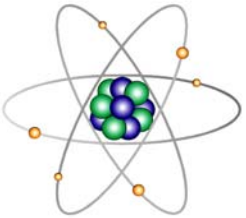
04/03/2015

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

GSI

Max-Planck-Institut
für Kernphysik



Interaction

$$M(Z,N) \neq \sum_{i=1}^{A} m_i$$

Mass Excess

Nuclear mass

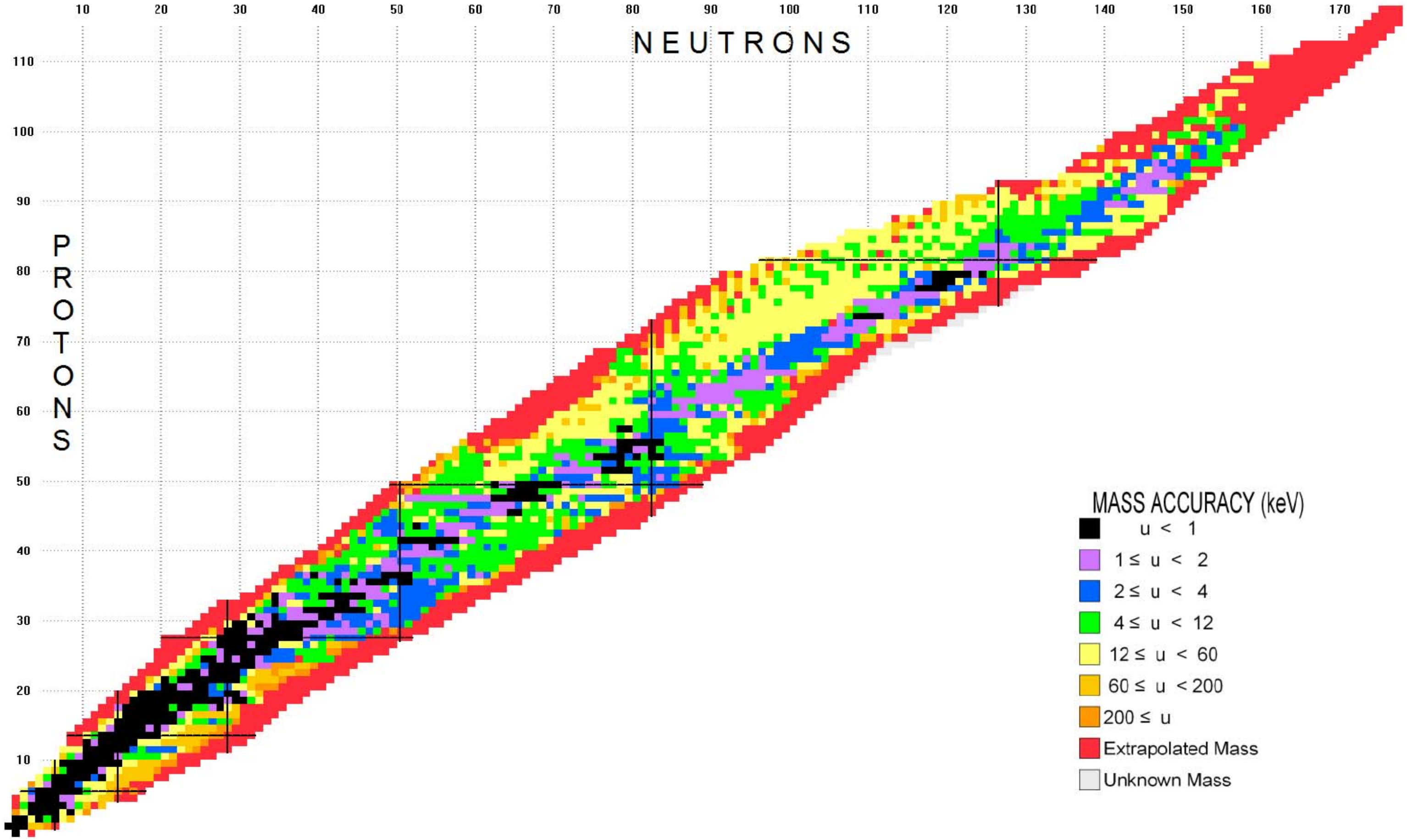
Field of application	Mass uncertainty
Chemistry: identification of molecules	10^{-5}–10^{-6}
Nuclear physics: shells, sub-shells, pairing	10^{-6}
Nuclear fine structure: deformation, halos	10^{-7}–10^{-8}
Astrophysics: r, rp-process, waiting points	10^{-7}
Nuclear models and formulas: IMME	10^{-7}–10^{-8}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

K. Blaum et al., Phys. Rep. 425, 1 (2006)1

Short life, low production cross-section

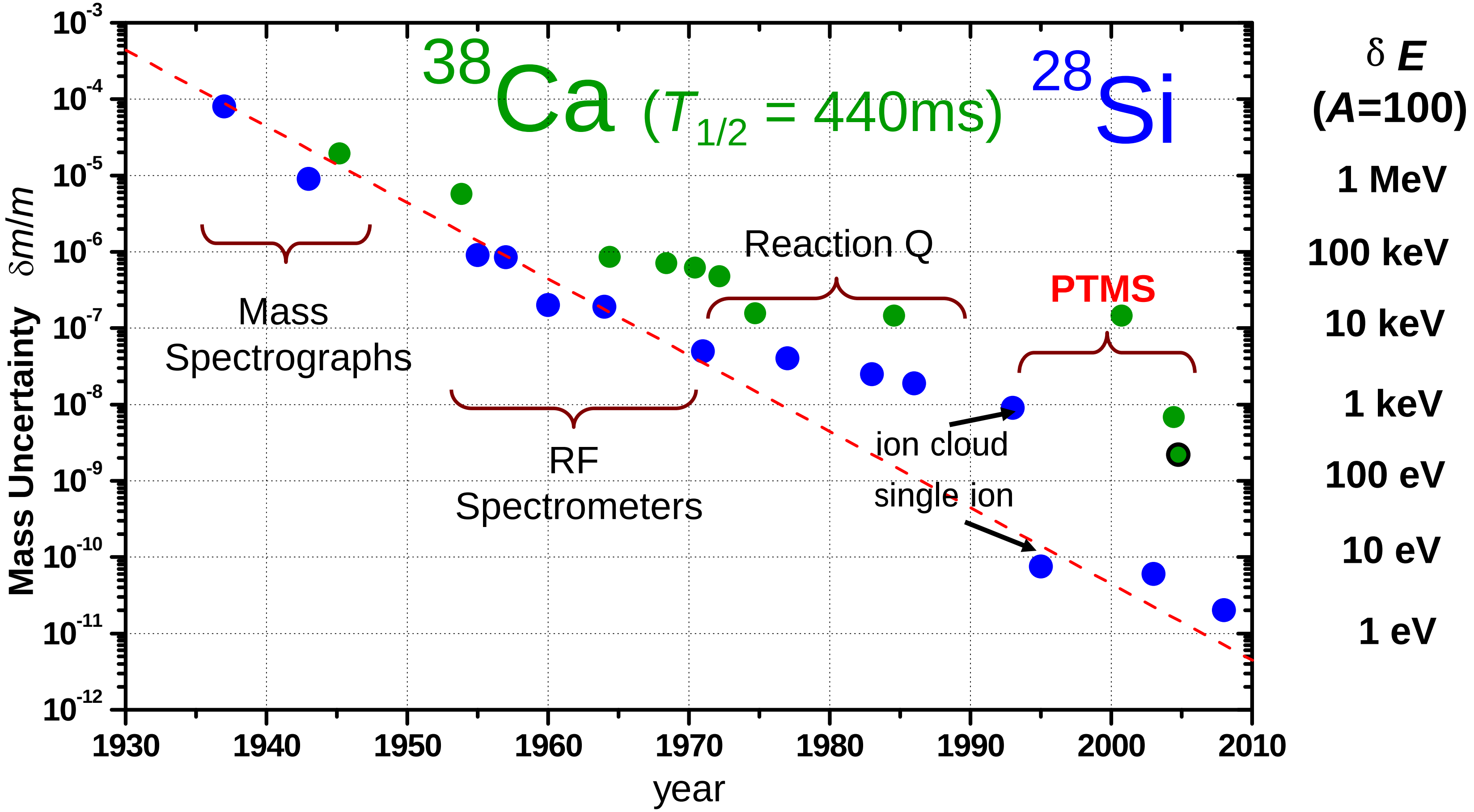
Many masses of nuclides still are unknown

Chart of the nuclides displaying the accuracy ’u’ of masses



G. Audi et al.,Chin. Phys. C36 (2012)1157

Picture obtained from Klaus Blaum's talk



- Penning Trap
- **MR TOF**
- **Time-of-flight-Brho Mass measurement**
- **Schottky mass spectrometry**
- **Isochronous mass spectrometry**

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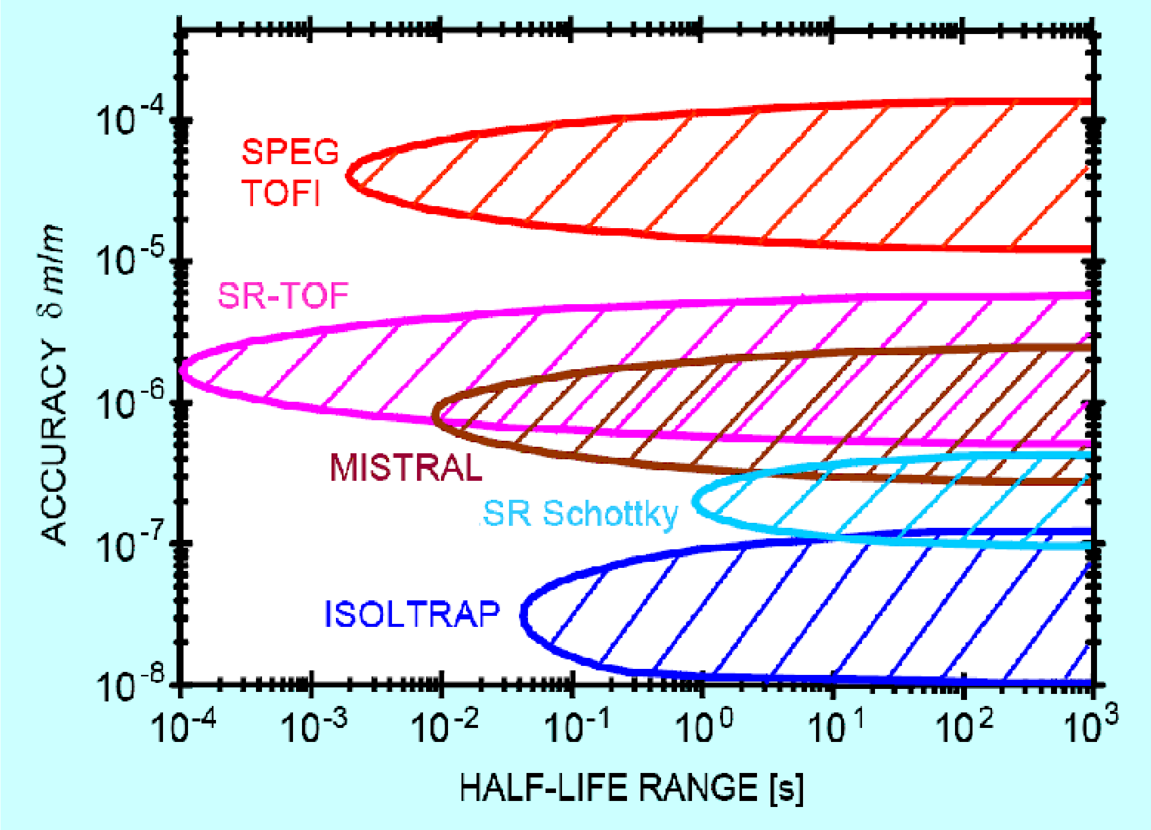


Picture obtained from M.Saidur Rahaman'thesis

Nuclear Instruments and Methods in Physics Research A258 (1987) 289–296
North-Holland, Amsterdam

Proposeed by H. Wollnik about 30 years ago.

Section I. Mass spectrometers / separators

MASS SEPARATORS

H. WOLLNIK

II. Physikalisches Institut, Universität Giessen, D-6300 Giessen, FRG

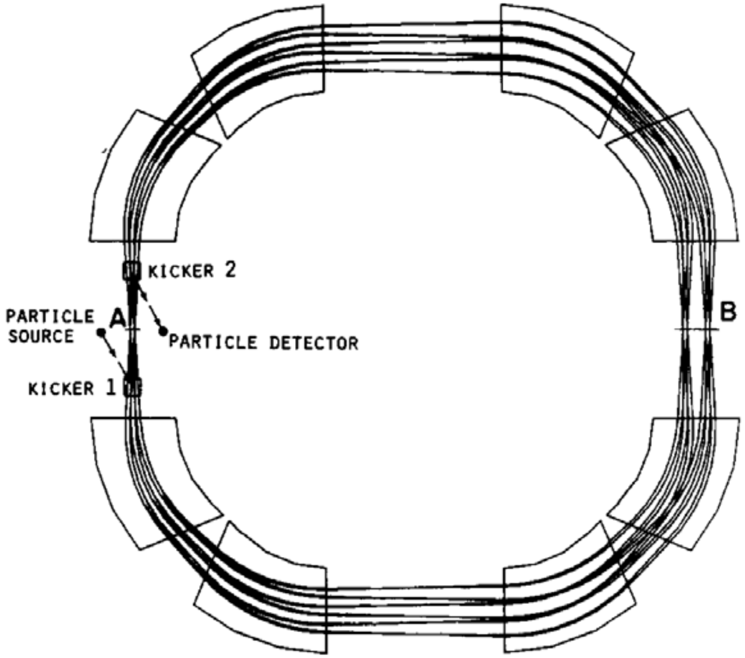


Fig. 8. An isochronous time-of-flight mass spectrometer which achieves a lateral totally achromatic and an energy independent longitudinal focus after 180° of bend. Particles which start simultaneously at the target thus arrive at the same time after a deflection of $n\pi$ with $n = 1, 2, 3$ … independent of the ion energy-to-charge ratio as well as of the position from which and the angle at which the ion under consideration left the target so that the ion flight time depends exclusively on the ion's mass to charge ratio. If introduced by the indicated first "kicker", ions can be ejected from the ring by the second "kicker" after one or several turns. Introducing ac-driven electrostatic deflectors at the points A and B or both one can use such a ring also as a high resolving mass separator since charged particles can then pass only at times when the electrostatic fields go through zero. If one ac cycle becomes very short as compared to the flight time of the ions between points A and B, the achievable mass resolving power can be very high.

Mass resolving power~1.5×10^5

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 446 (2000) 569–580

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

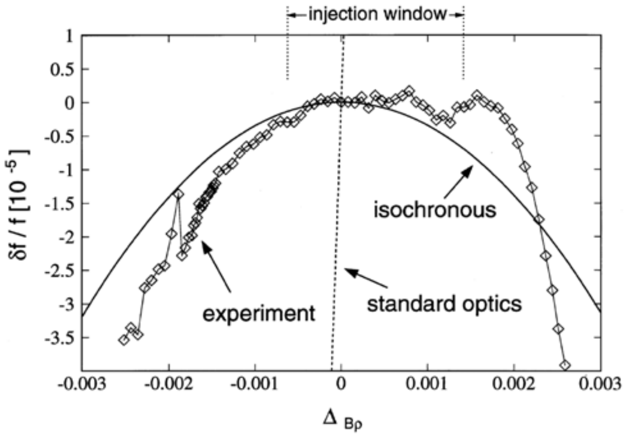
www.elsevier.nl/locate/nima

First isochronous mass spectrometry at the experimental storage ring ESR

M. Hausmann[a,b,*,1], F. Attallah[a], K. Beckert[a], F. Bosch[a], A. Dolinskiy[c],
H. Eickhoff[a], M. Falch[d], B. Franczak[a], B. Franzke[a],
O. Klepper[a], H.-J. Kluge[a], C. Kozhuharov[a], K.E.G.
F. Nolden[a], Yu.N. Novikov[f], T. Radon[a], H. Scha
J. Stadlmann[b], M. Steck[a], T. Winkler[a],

[a]Gesellschaft für Schwerionenforschung GSI, Planckstr. 1, D-642
[b]II. Physikalisches Institut, Justus-Liebig-Universität, Heinrich-Buff-Ring
[c]Institute for Nuclear Research, Kiev, Ukrai
[d]Sektion Physik, Ludwig-Maximilians-Universität, Am Coulombwall 1,
[e]Institut für Physik, Johannes Gutenberg-Universität, Staudingerweg
[f]St. Petersburg Nuclear Physics Institute, Gatchina 18

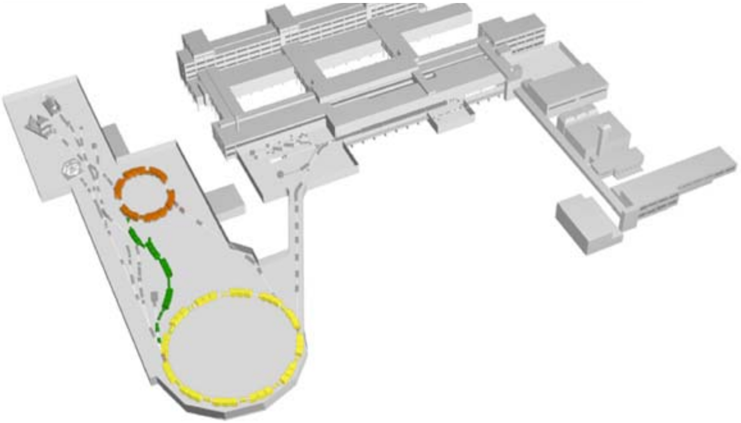
Received 28 September 1999; accepted 29 Octo



$\Delta v/v \sim 10^{-3}$

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

$\gamma \sim \gamma_t$

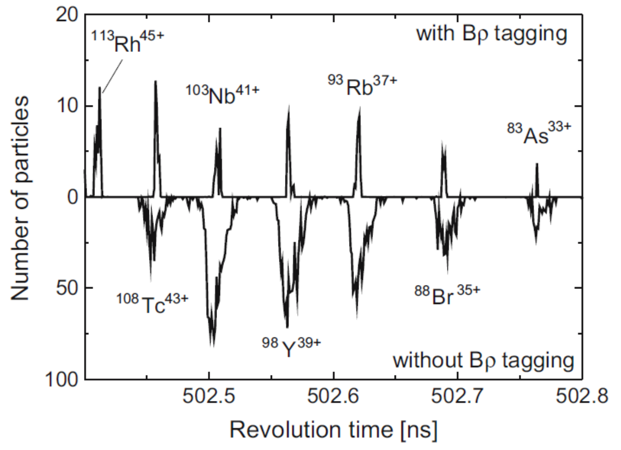


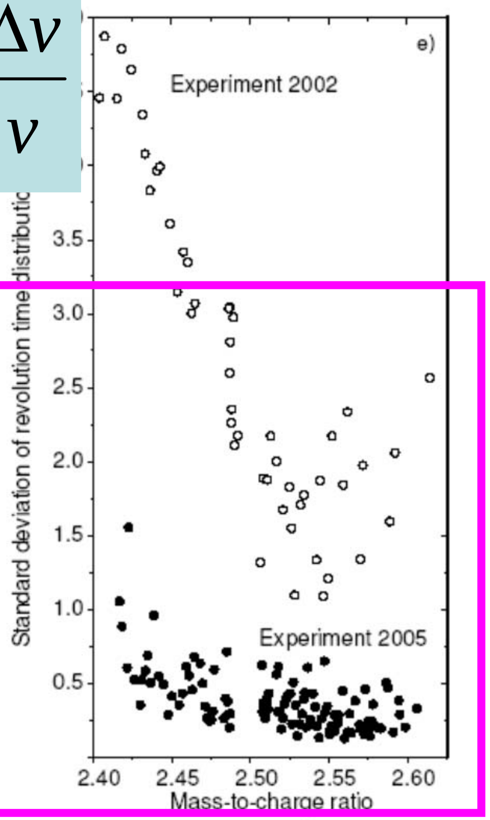
Hyperfine Interact (2006) 173:49–54
DOI 10.1007/s10751-007-9541-4

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

A new experimental approach for isochronous mass measurements of short-lived exotic nuclei with the FRS-ESR facility

H. Geissel · R. Knöbel · Yu. A. Litvinov · B. Sur
K. Beckert · P. Beller · F. Bosch · D. Boutin ·
C. Brandau · L. Chen · B. Fabian · M. Hausman
C. Kozhuharov · J. Kurcewicz · S. A. Litvinov ·
M. Mazzocco · F. Montes · G. Münzenberg ·
A. Musumarra · C. Nociforo · F. Nolden · W. R.
C. Scheidenberger · M. Steck · H. Weick · M. W

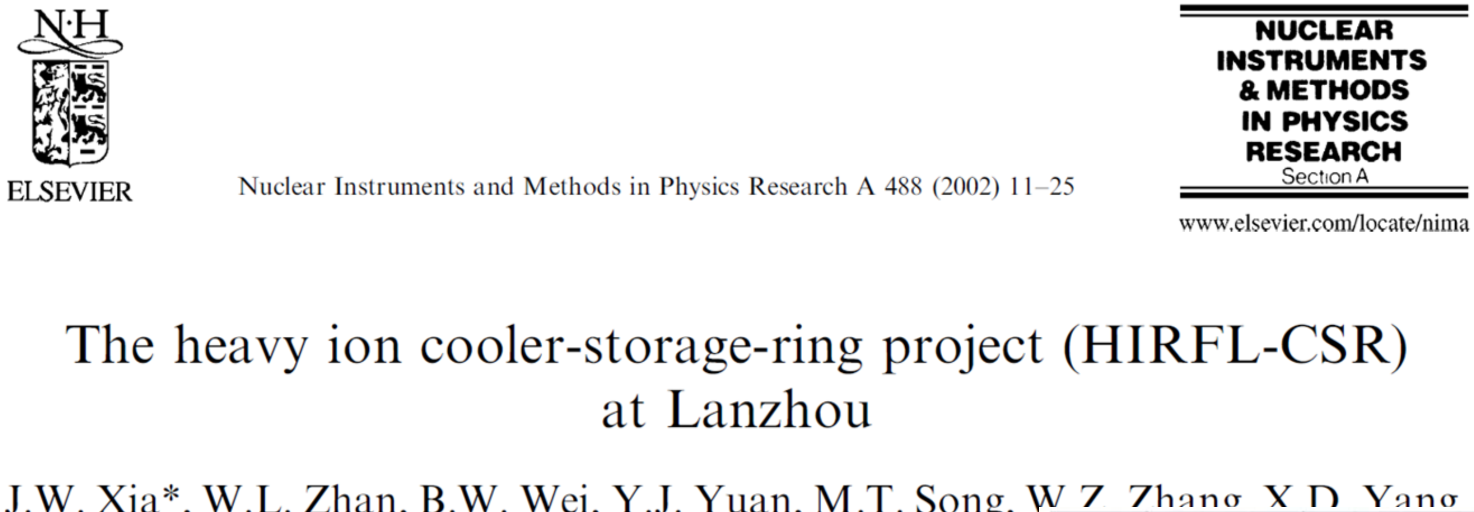




Abstract Projectile fragments separated in flight with the FRS have been injected into the storage ring ESR. Operating the ESR in the isochronous mode has enabled high-reso ady in our pilot experime d accurate results for a restricted isotope range in the neighborhood of a selected isotope characterized by the best isochronous condition. In the present experiment this restriction has been overcome by precise external magnetic rigidity determination ($1.5 \cdot 10^{-4}$) at the dispersive midplane of the FRS. In this way the mass resolving power for neutron-rich fission fragments covering a large mass-over-charge ratio in one spectrum has

Mass resolving power ~ 200 000 (FWHM)

*I*nstitute of *M*odern *P*hysics (IMP)



Nuclear Instruments and Methods in Physics Research A 488 (2002) 11–25

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

www.elsevier.com/locate/nima

The heavy ion cooler-storage-ring project (HIRFL-CSR) at Lanzhou

J.W. Xia*, W.L. Zhan, B.W. Wei, Y.J. Yuan, M.T. Song, W.Z. Zhang, X.D. Yang
P. Yuan, D.Q. Gao, H.W. Zhao, X.T. Yang, G.Q.
J.R. Dang, X.H. Cai, Y.F. Wang, J.Y. Tang, W.M. Qi
L.Z. Mao, Z.Z. Zhou

Institute of Modern Physics (IMP), Chinese Academy of Sciences, P.O. Box 31, Lanzhou

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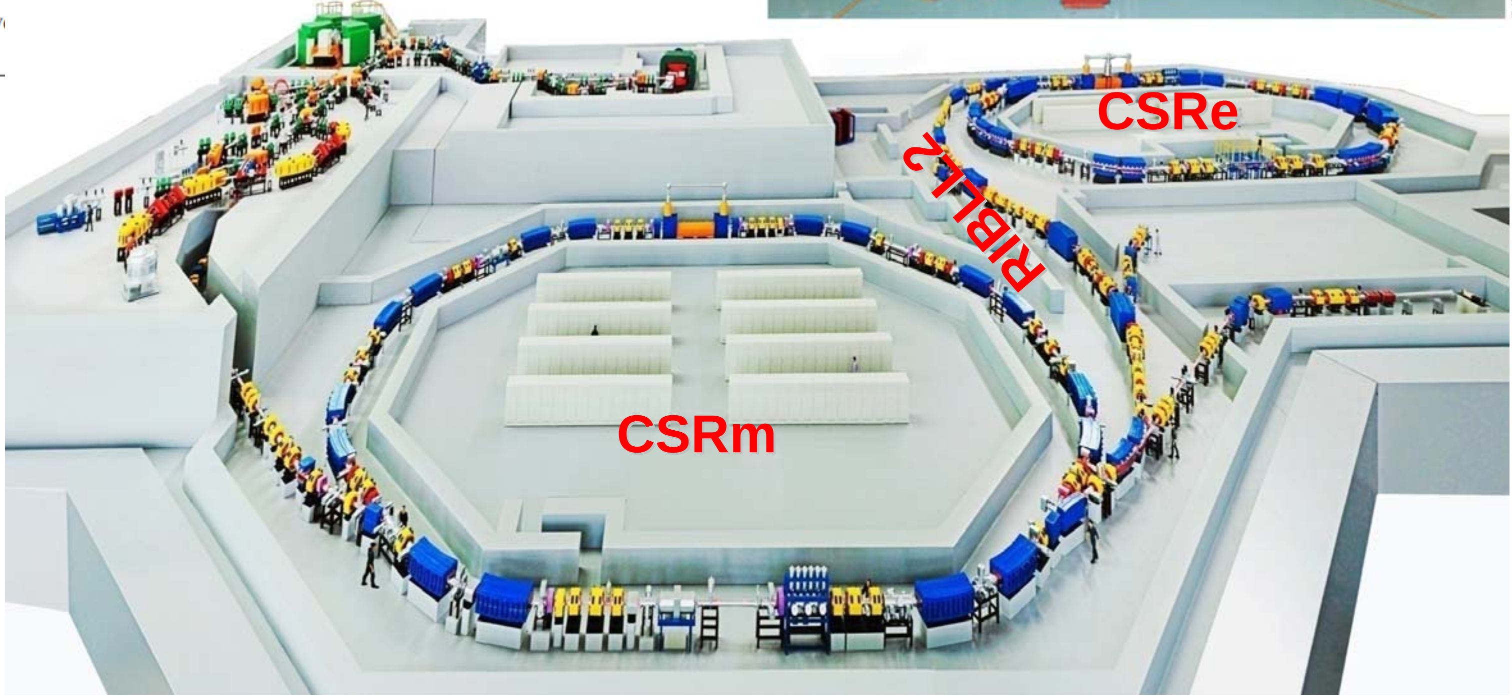
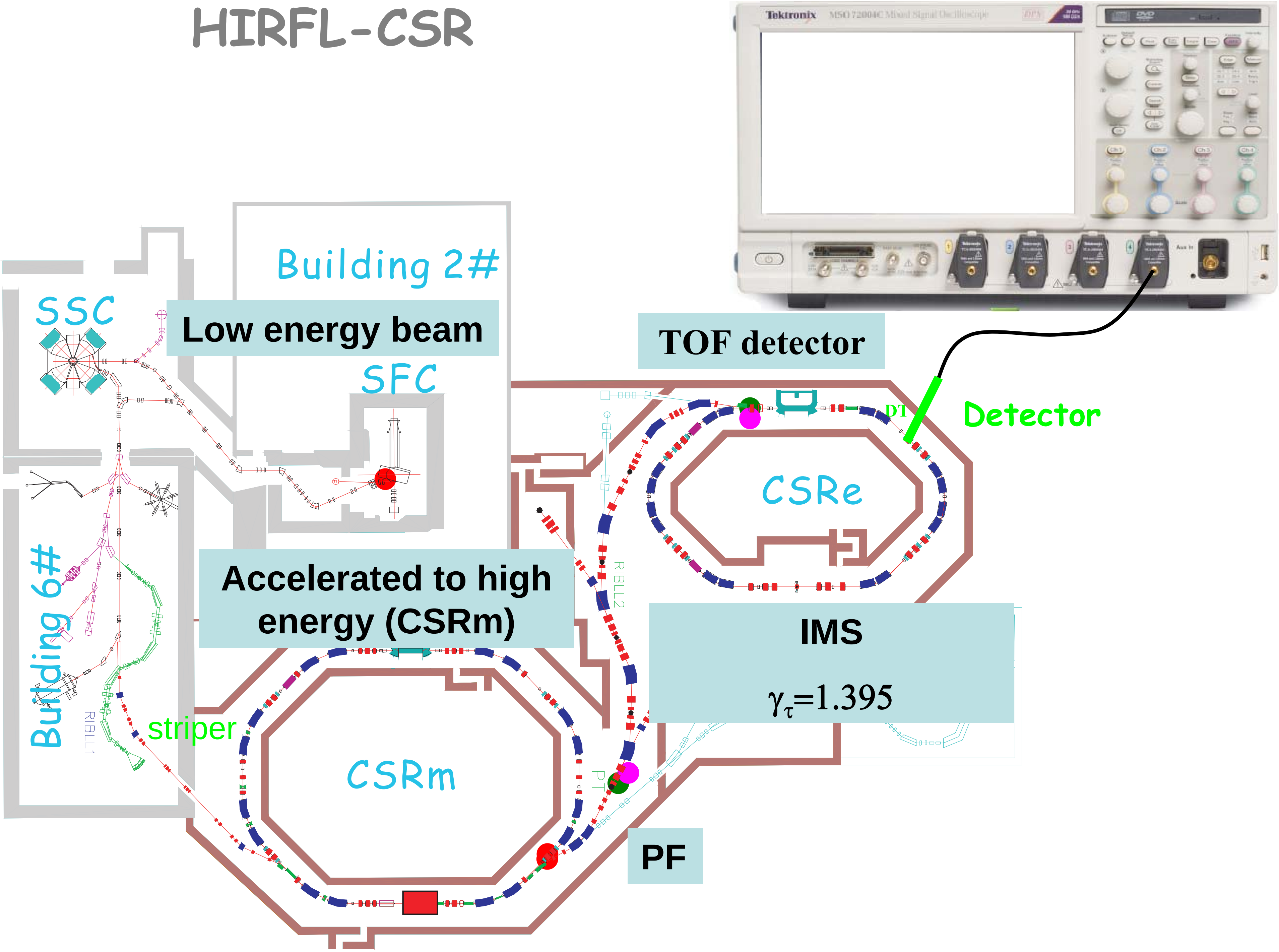


HIRFL-CSR



Low energy beam

TOF detector

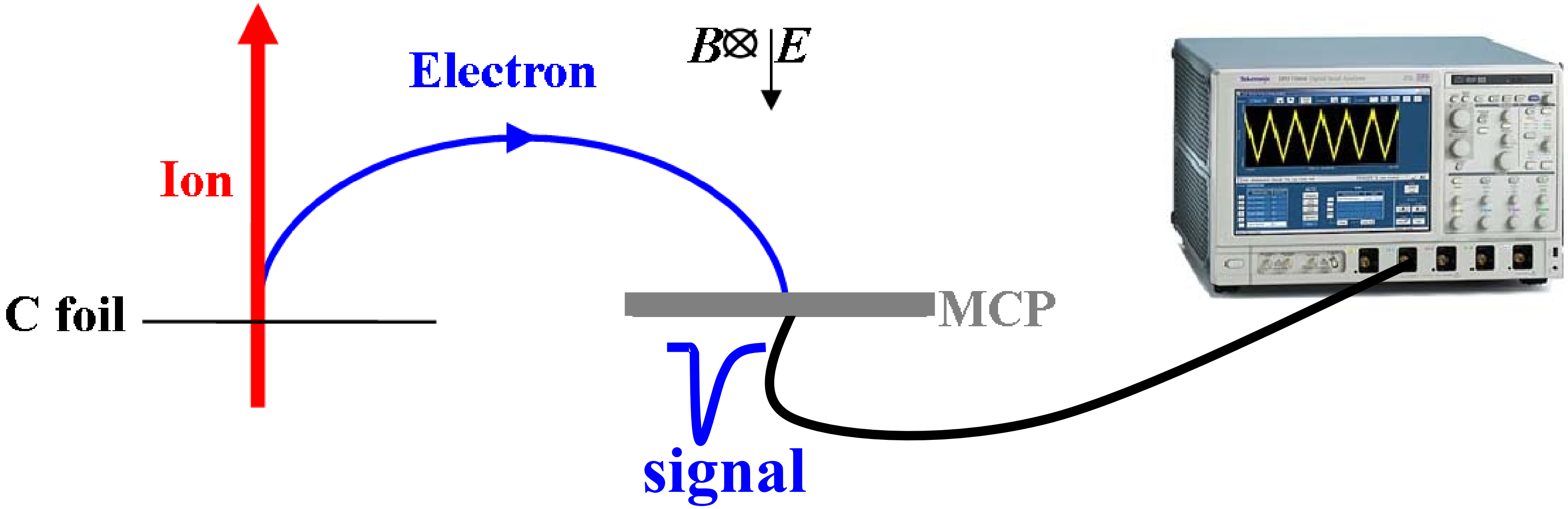
Accelerated to high energy (CSRm)

IMS

$\gamma_{\tau}=1.395$

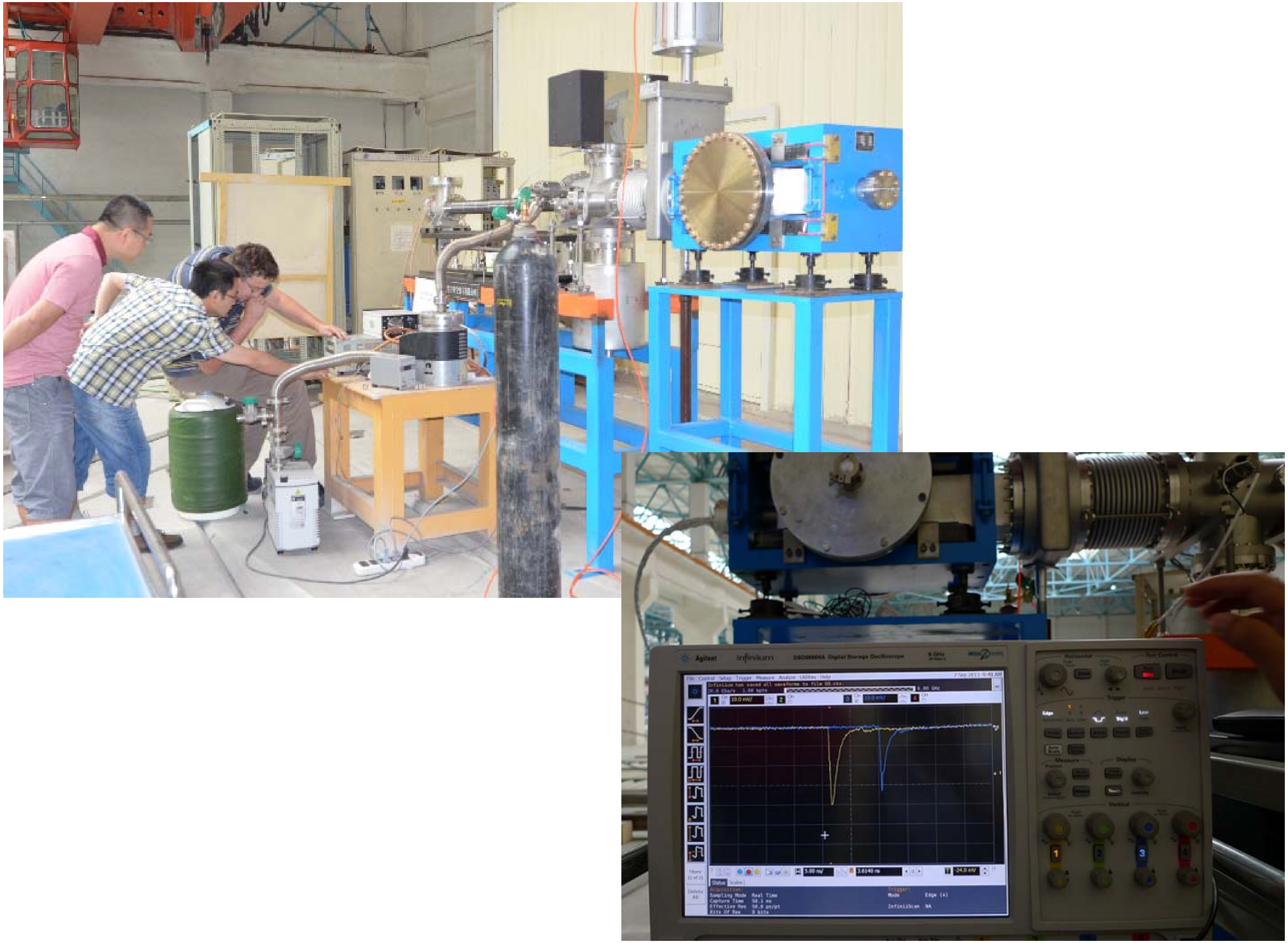
PF

Fast time detector



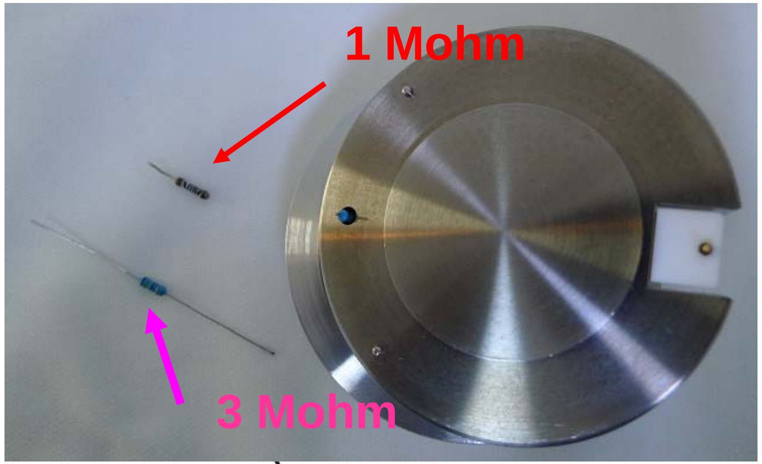
Time resolution ~50ps, Efficency~20%-70%

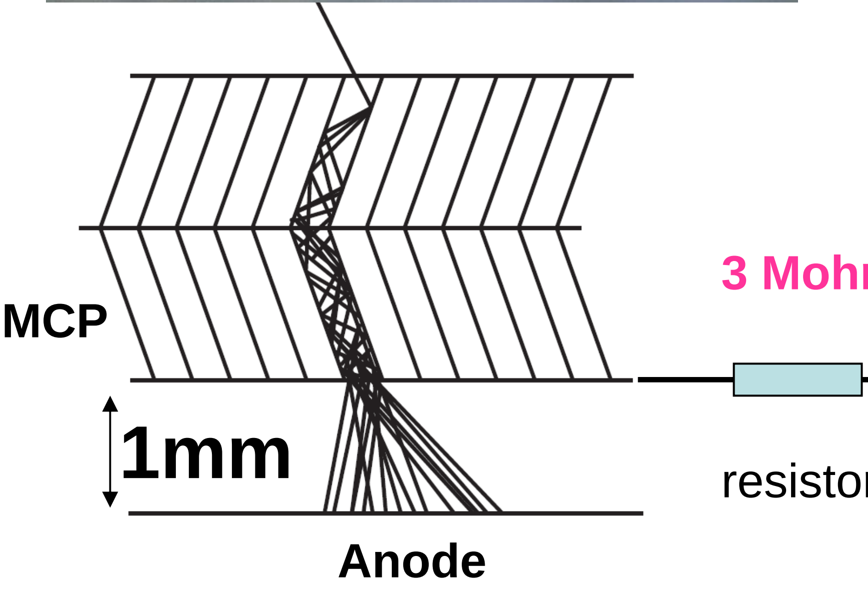
B. Mei, et al., NIM A624,109(2010)


Agilent
Infiniium

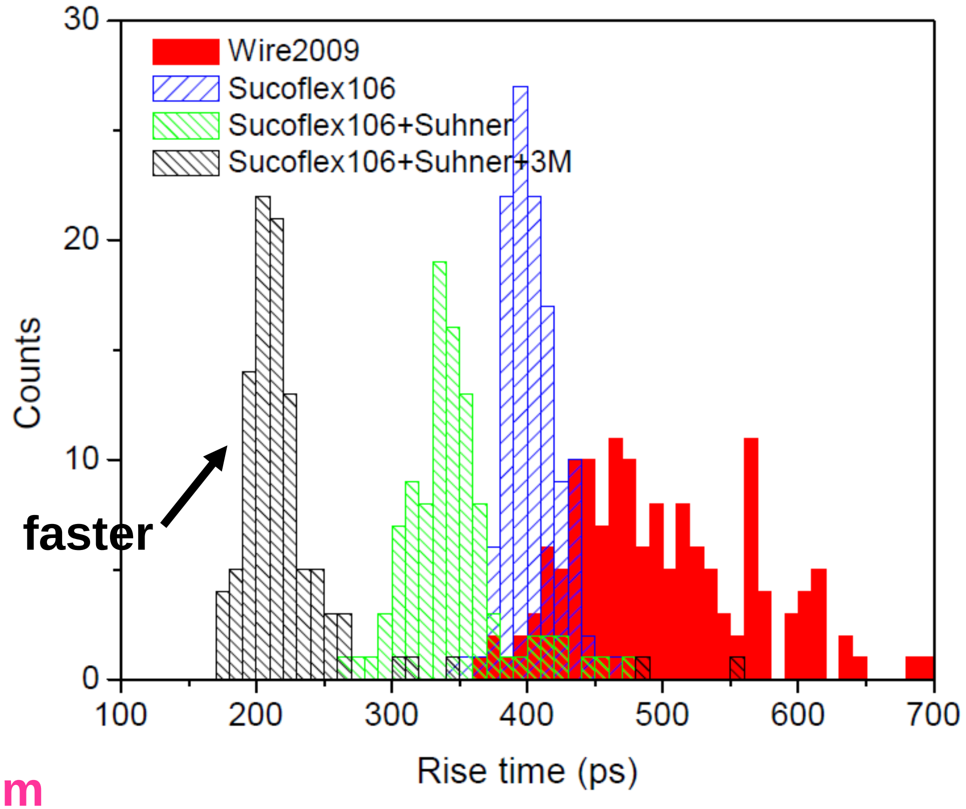
Improve transmission of high frequency signal

Advanced Performance TOF



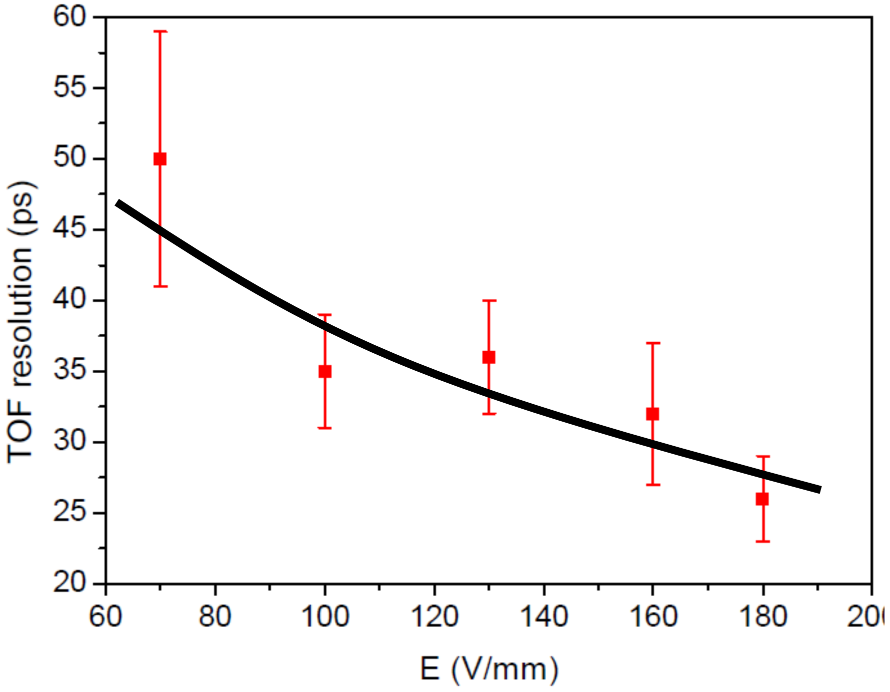


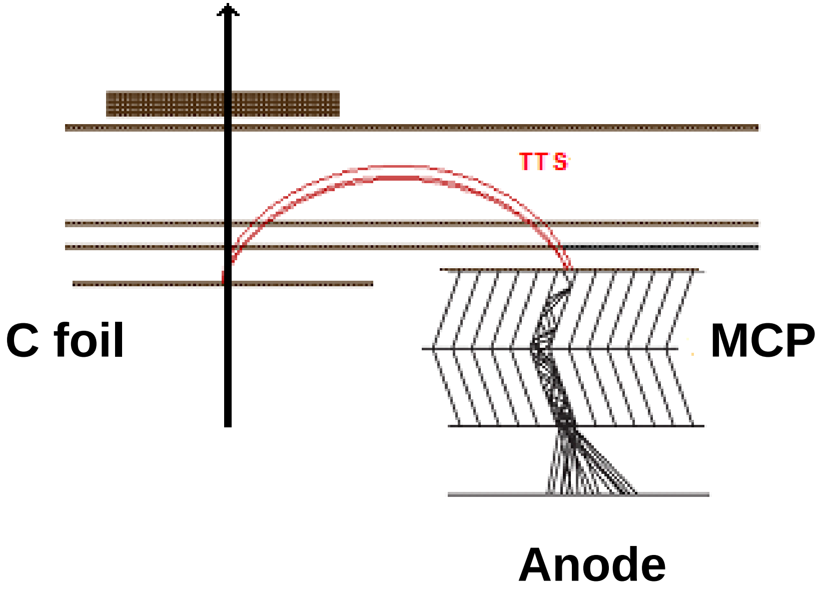
Optimize the structure of MCP



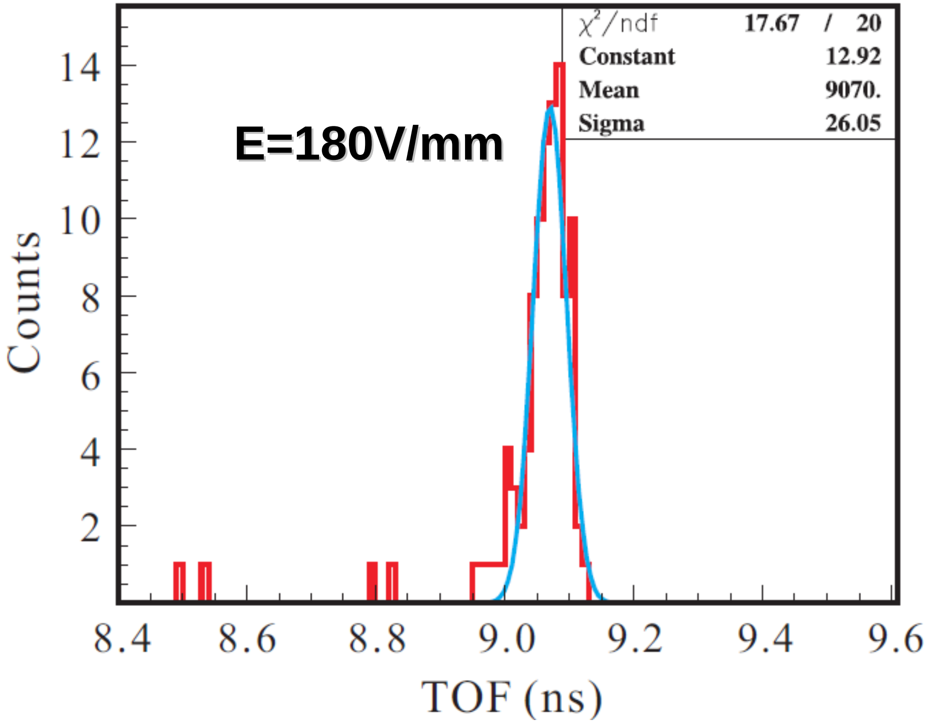
Rising time ~220 ps

W. Zhang, et al., NIMA 756, 1(2014)



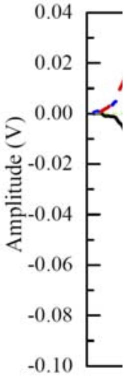


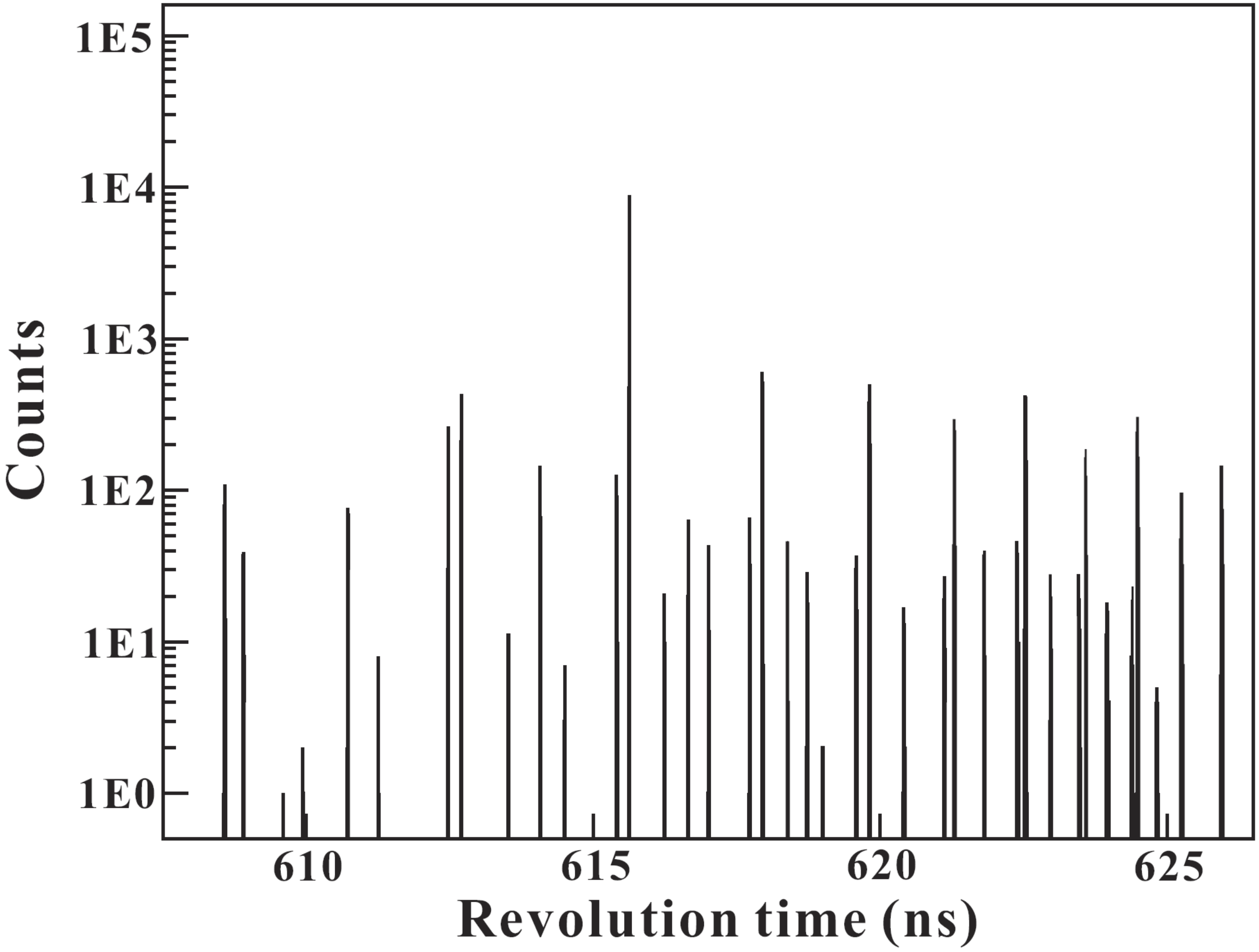
W. Zhang, et al., NIMA 756, 1(2014)



Time resolution is ~ 18 ps

Data analysis

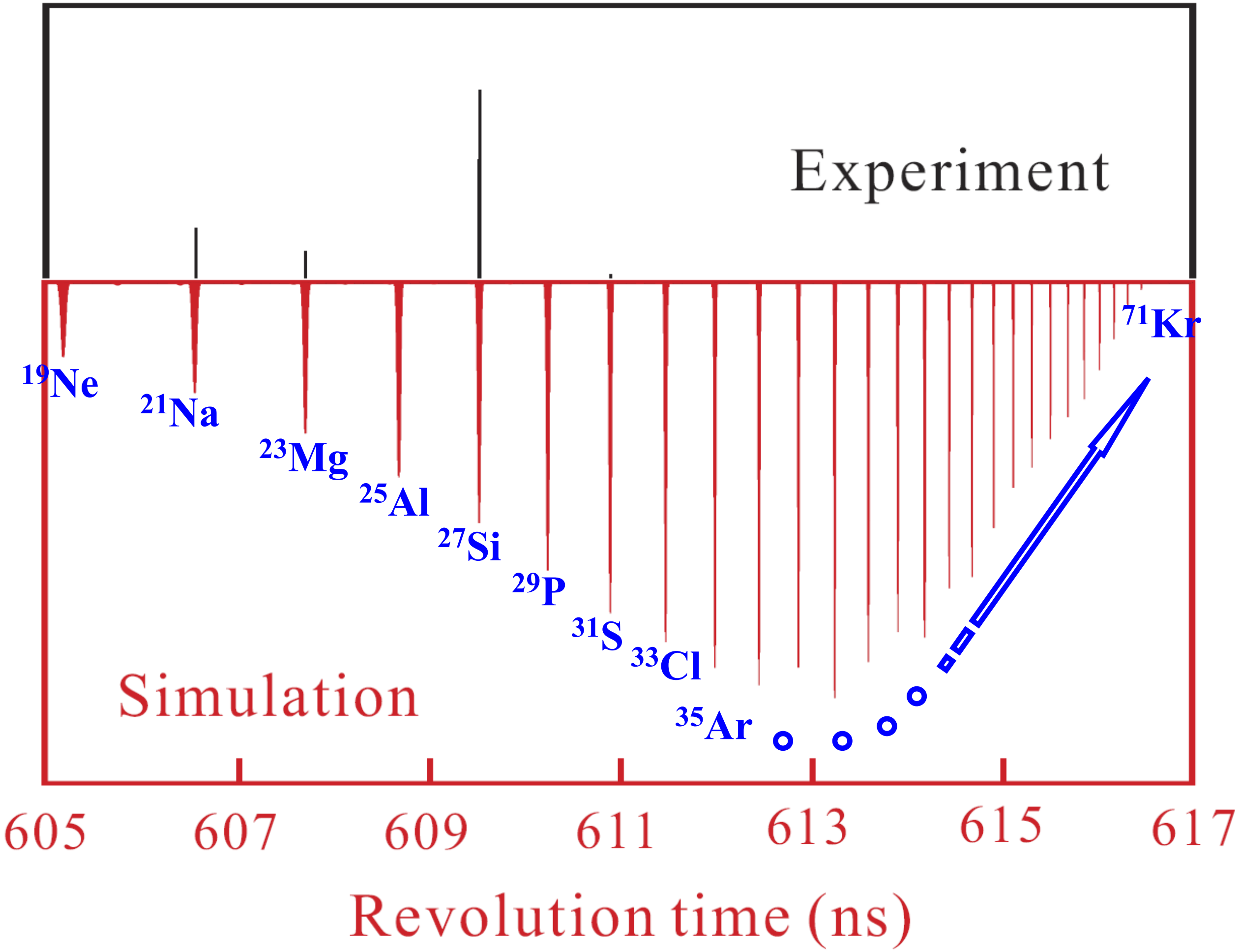


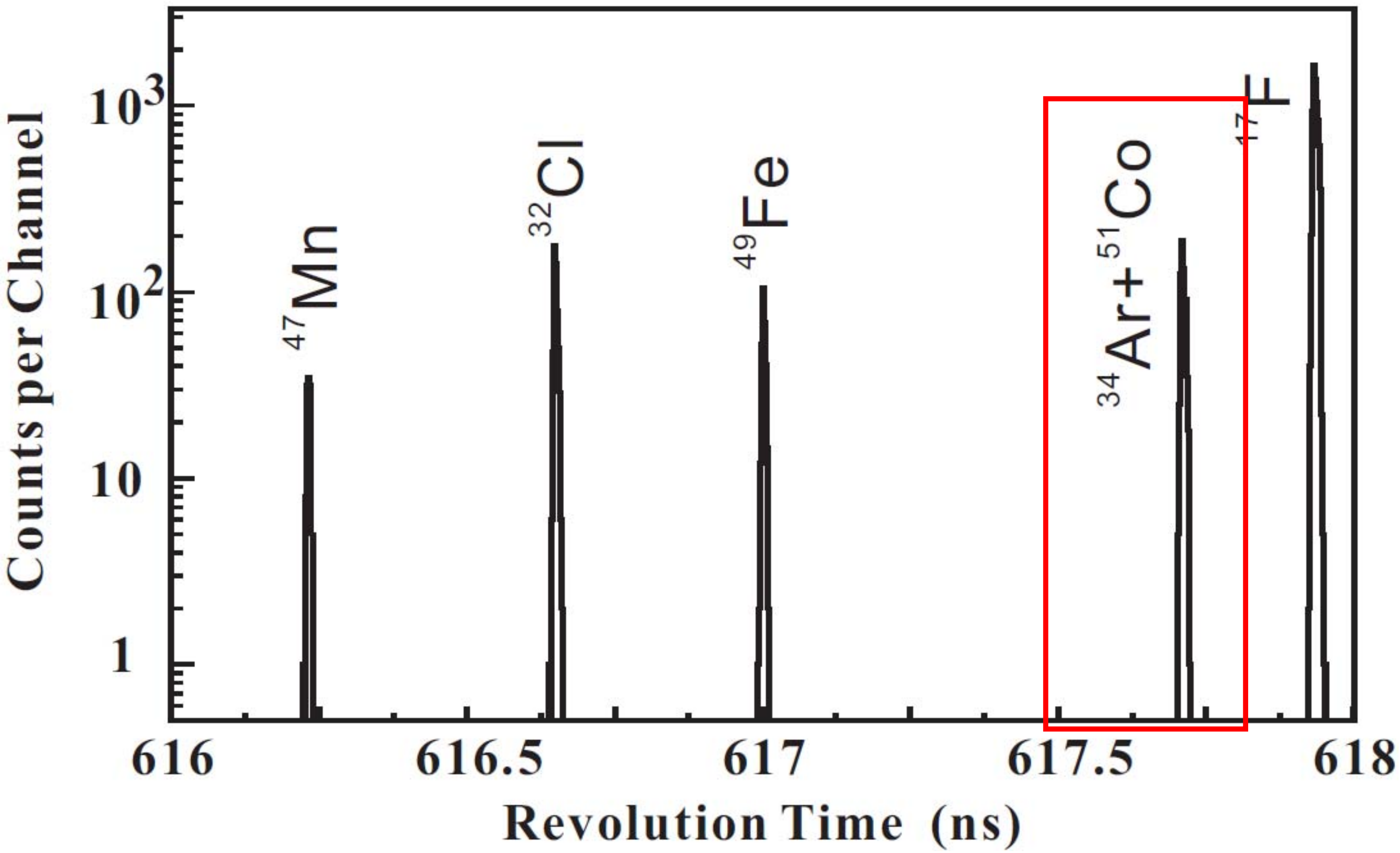


M. Matos, Ph.D. Thesis, JLU Giessen, 2004.

X. L. Tu, et al., NIMA654,213(2011)

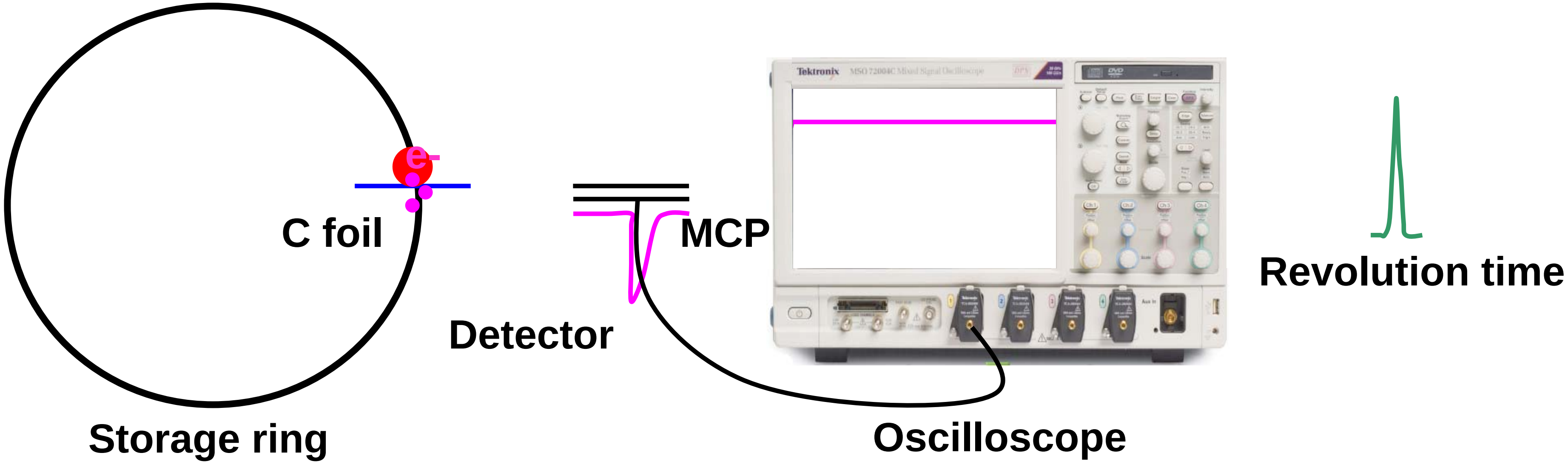
Identification of ions





$^{51}Co^{27+}$and $^{34}Ar^{18+}$ ions have very close mass to charge ratios [$\Delta(m/q)/(m/q)$~5×10^{-6}].

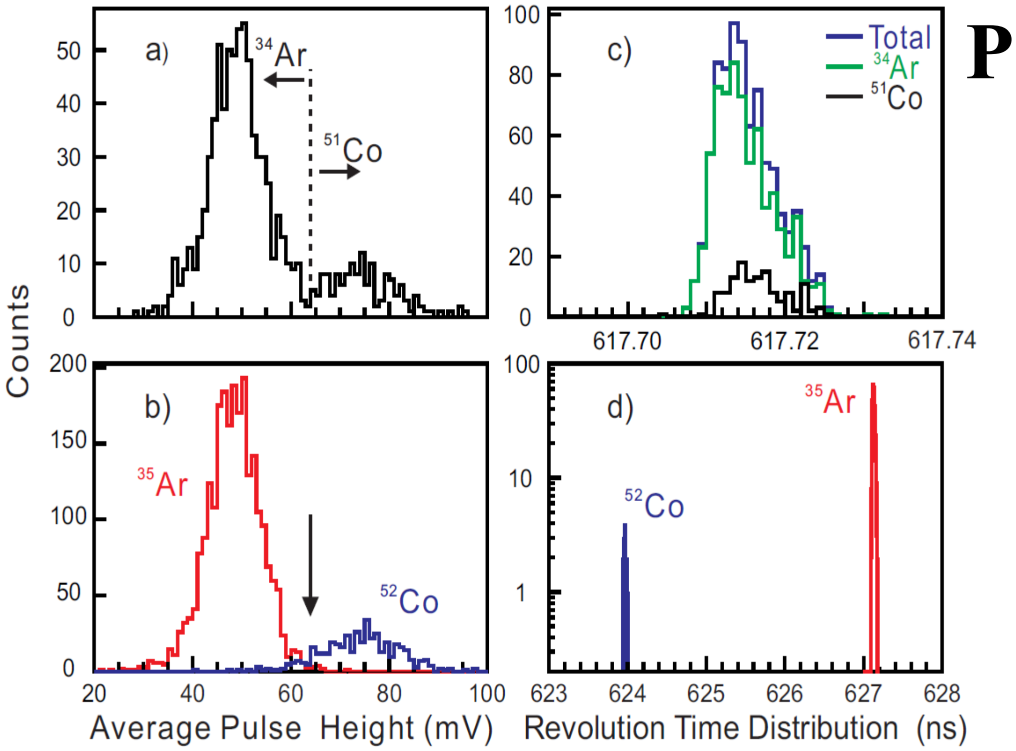
They can not be resolved by their revolution time.



$$\text{Amp} \propto \text{electron number} \propto Q^2$$

higher **more** **bigger**

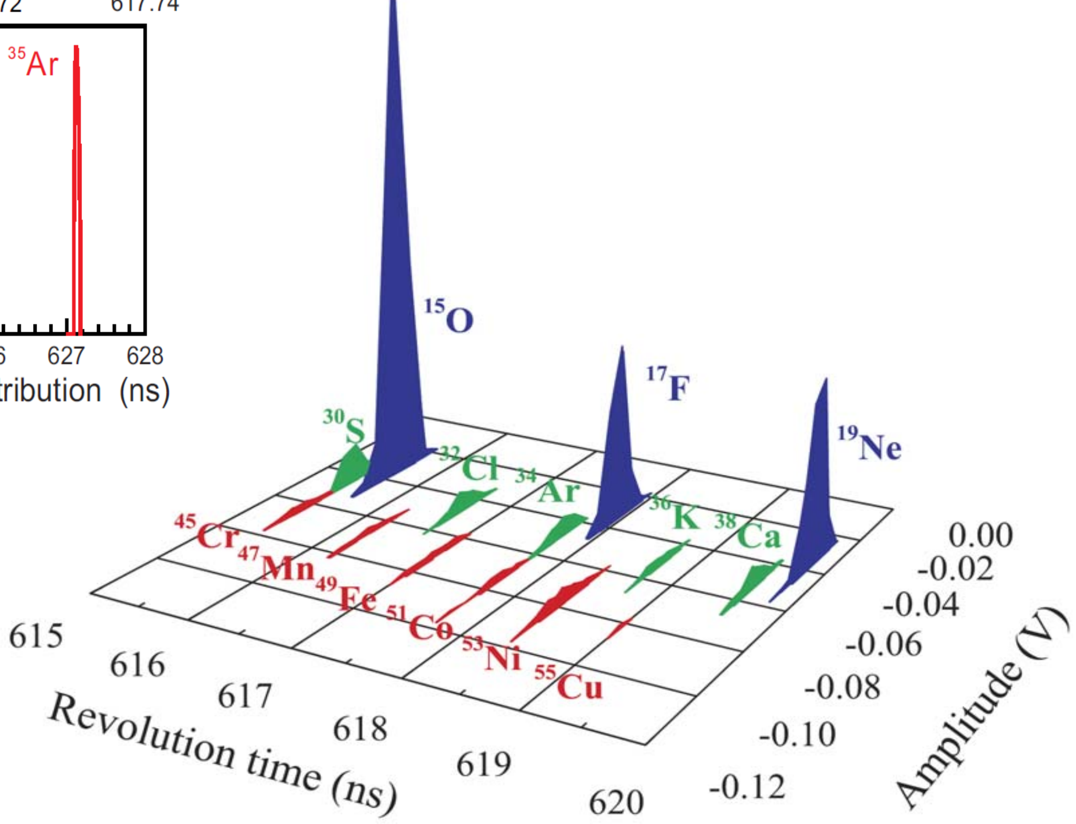
Particle identification



Particle identification with

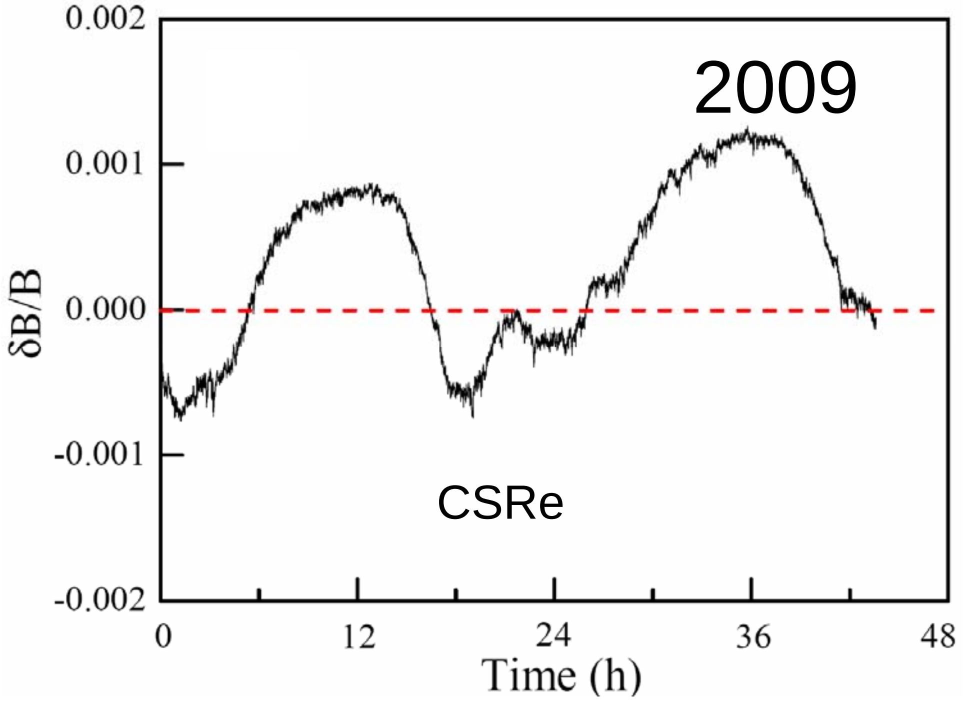
Revolution time ***and***

Average amplitude

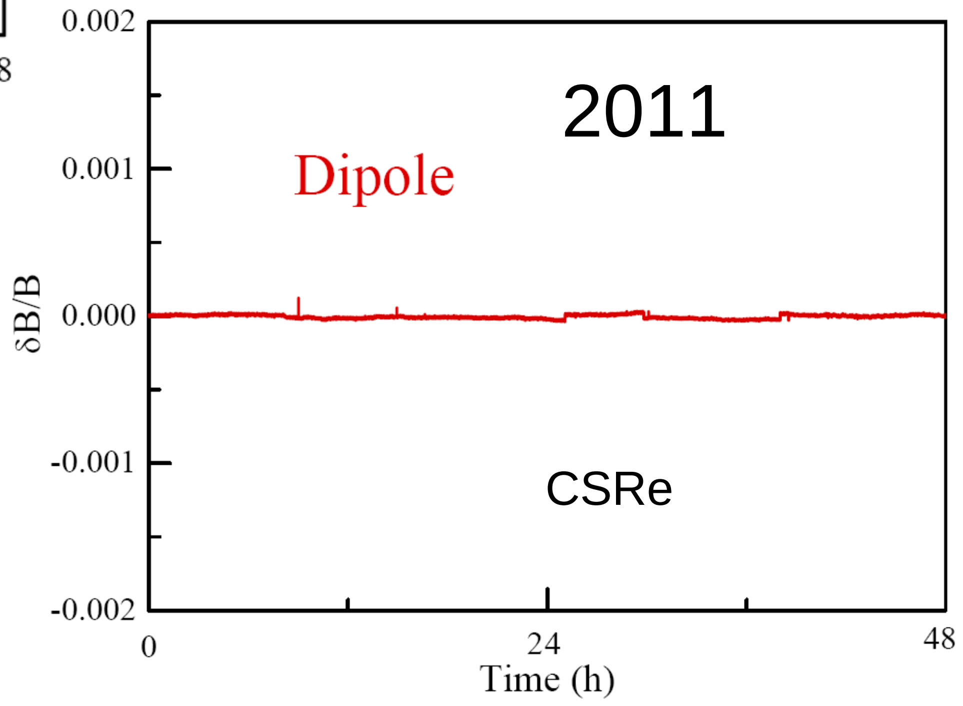


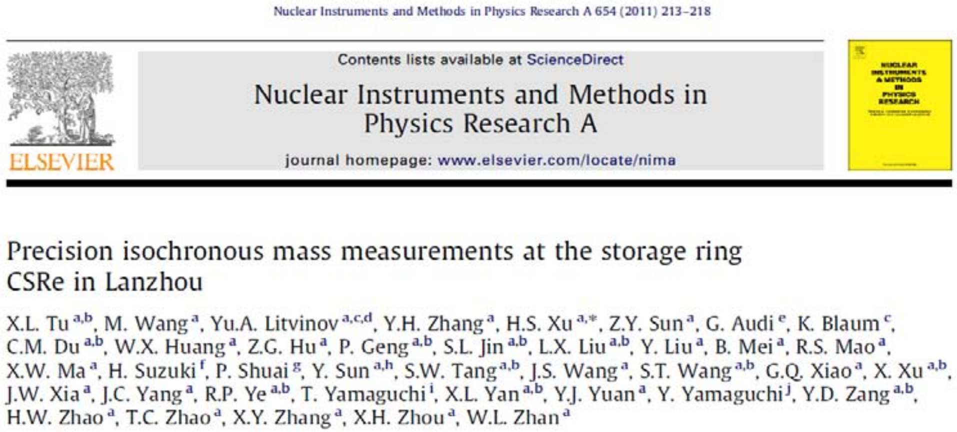
P. Shuai et al., Phys. Lett. B735, 327(2014)

Stability of magnetic field



Improve power supply





Nuclear Instruments and Methods in Physics Research A 654 (2011) 213–218

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Precision isochronous mass measurements at the storage ring CSRe in Lanzhou

X.L. Tu [a,b], M. Wang [a], Yu.A. Litvinov [a,c,d], Y.H. Zhang [a], H.S. Xu [a,*], Z.Y. Sun [a], G. Audi [e], K. Blaum [c], C.M. Du [a,b], W.X. Huang [a], Z.G. Hu [a], P. Geng [a,b], S.L. Jin [a,b], L.X. Liu [a,b], Y. Liu [a], B. Mei [a], R.S. Mao [a], X.W. Ma [a], H. Suzuki [f], P. Shuai [g], Y. Sun [a,h], S.W. Tang [a,b], J.S. Wang [a], S.T. Wang [a,b], G.Q. Xiao [a], X. Xu [a,b], J.W. Xia [a], J.C. Yang [a], R.P. Ye [a,b], T. Yamaguchi [i], X.L. Yan [a,b], Y.J. Yuan [a], Y. Yamaguchi [j], Y.D. Zang [a,b], H.W. Zhao [a], T.C. Zhao [a], X.Y. Zhang [a], X.H. Zhou [a], W.L. Zhan [a]

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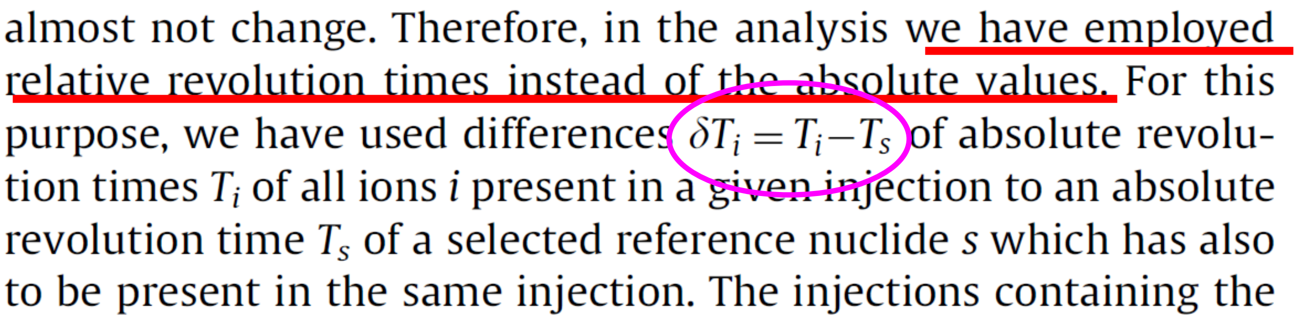
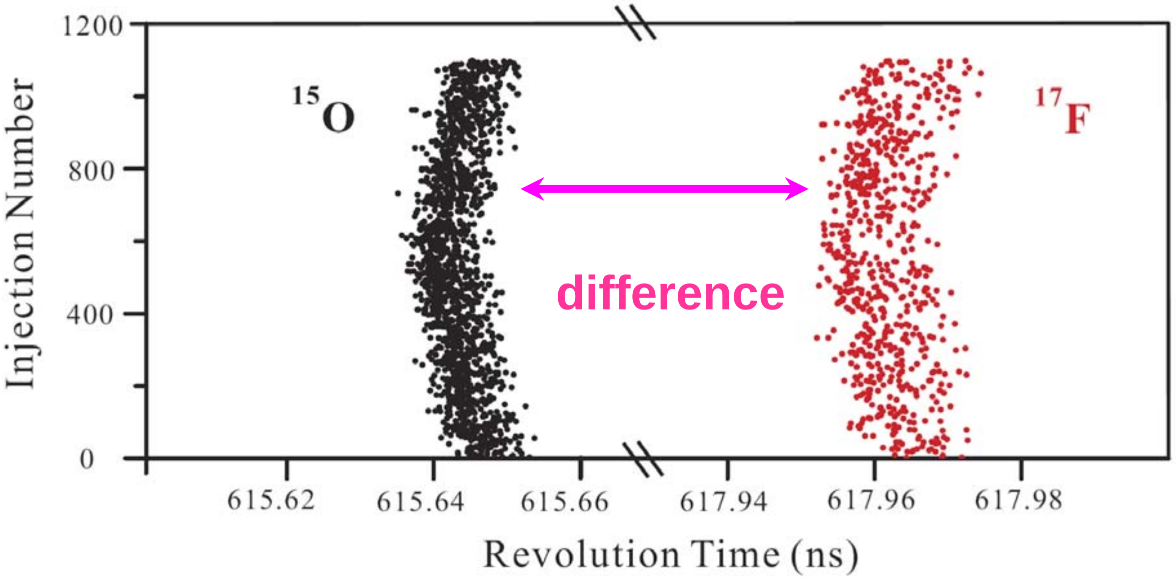
[b] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[c] Max-Planck-Institut für Kernphysik, D-69117 Heidelberg, Germany
[d] GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany
[e] CSNSM-IN2P3-CNRS, Université de Paris Sud, F-91405 Orsay, France
[f] Institute of Physics, University of Tsukuba, Ibaraki 305-8571, Japan
[g] Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China
[h] Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China
[i] Saitama University, Saitama 338-8570, Japan
[j] RIKEN Nishina Center, RIKEN, Saitama 351-0198, Japan



almost not change. Therefore, in the analysis we have employed relative revolution times instead of the absolute values. For this purpose, we have used differences $\delta T_i = T_i - T_s$ of absolute revolution times T_i of all ions i present in a given injection to an absolute revolution time T_s of a selected reference nuclide s which has also to be present in the same injection. The injections containing the



difference

Chinese Science Bulletin

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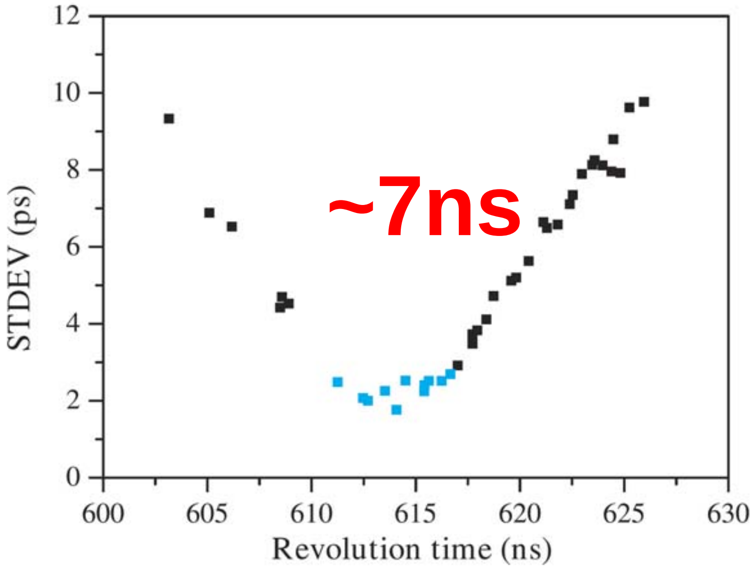
Springer

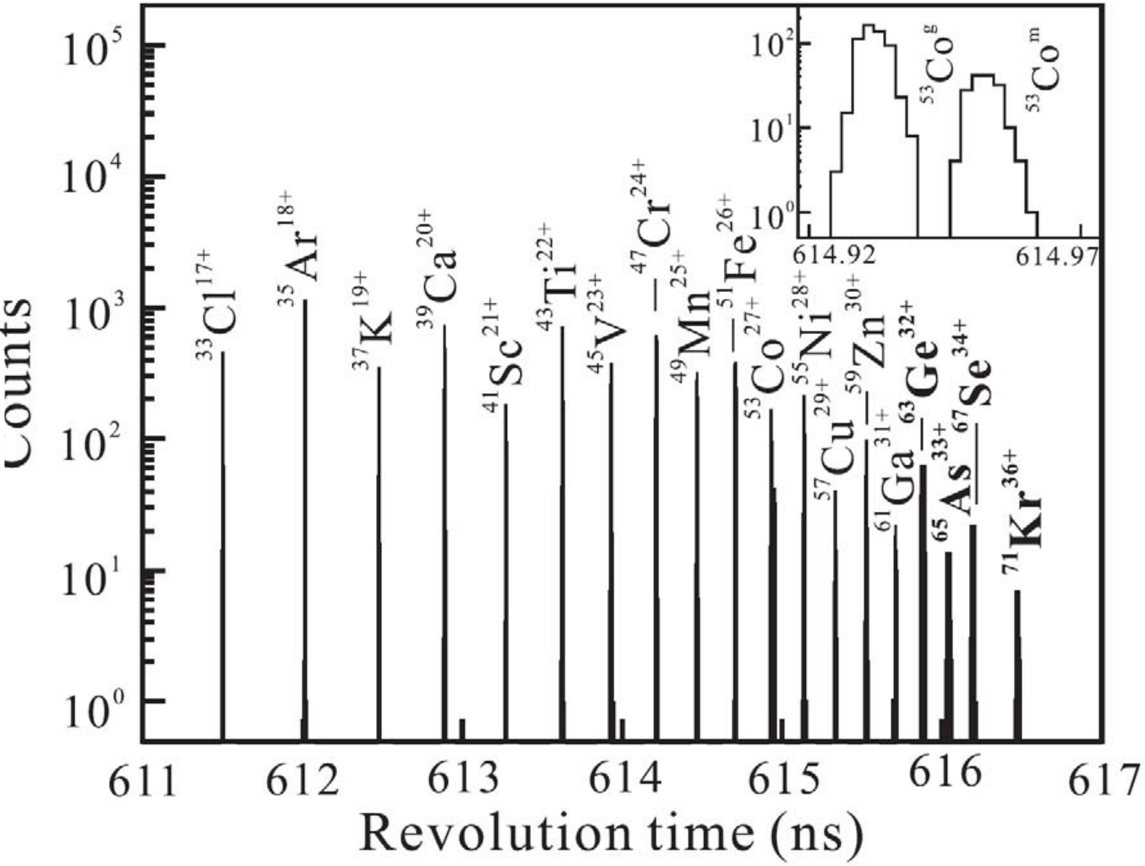
A mass Resolving Power($m/\Delta m$) ~ 1.7×10^5

First mass measurement of short-lived nuclides at HIRFL-CSR

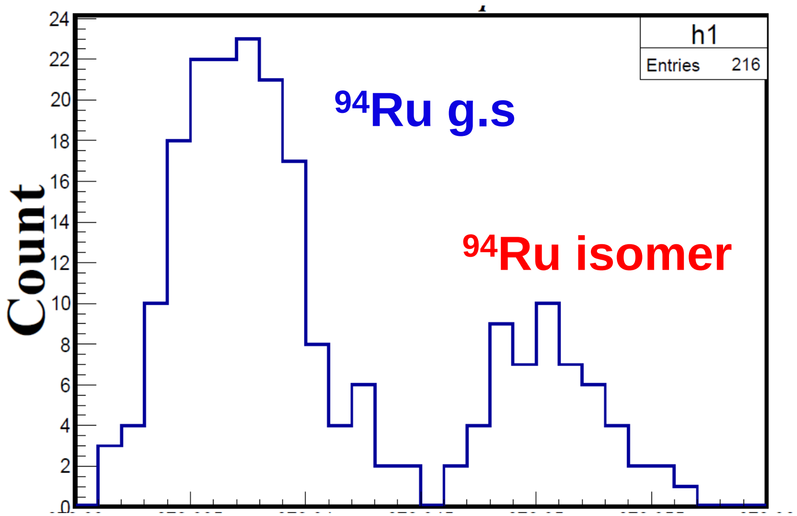
XU HuShan[1†], TU XiaoLin[1,2], YUAN Y
MAO RuiShi[1], HU ZhengGuo[1], MEI B
GENG Peng[1,2], LIU Yong[1], ZHAO Tie
MAO LiJun[1], ZHANG YuHu[1], ZHOU X
ZHAO HongWei[1] & ZHAN WenLong[1]



~7ns



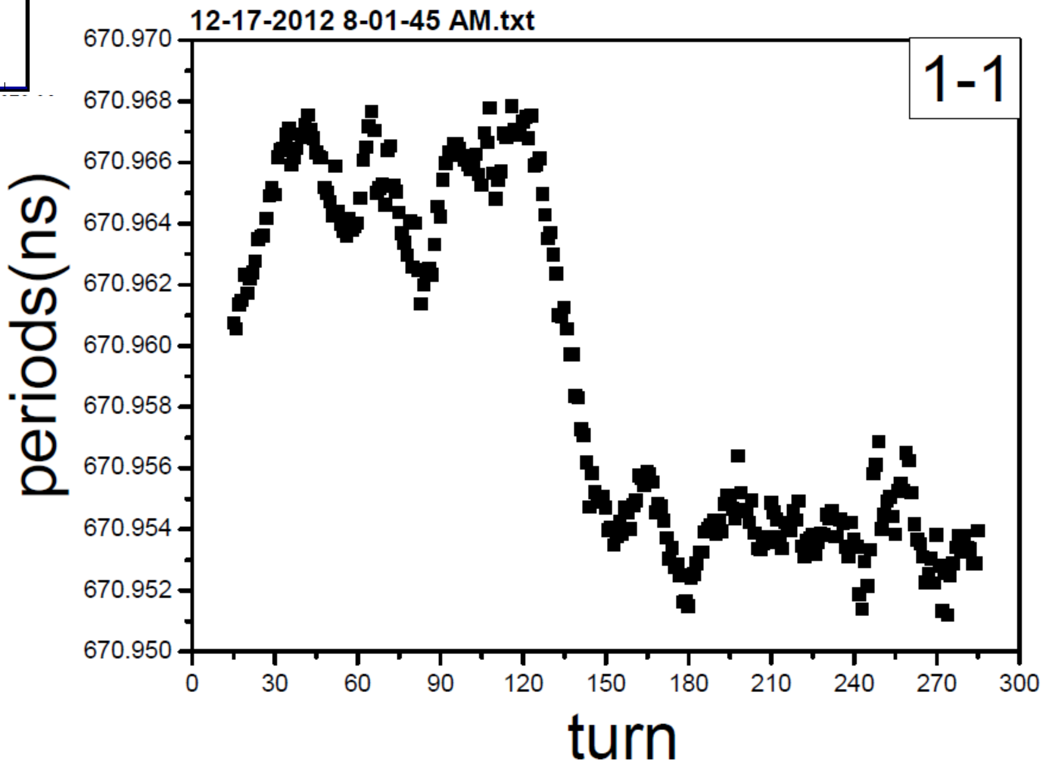
In-ring decay of the ^{94}Ru isomer

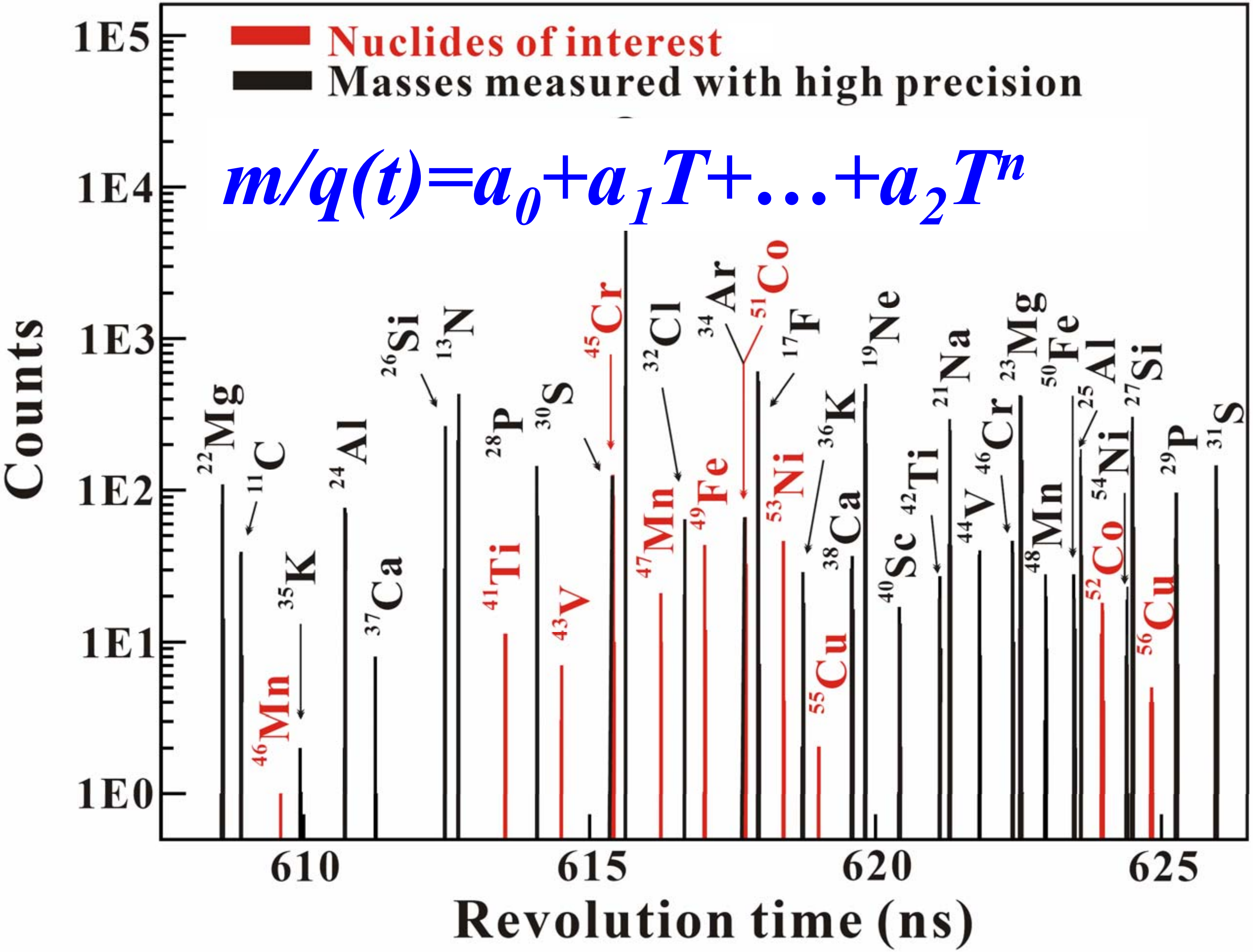


$T_{1/2} = 71(4)\ \mu s$

Ex=2645 KeV

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





$$m/q(t)=a_0+a_1T+\ldots+a_2T^n$$

Mass measurements at HIRFL-CSR

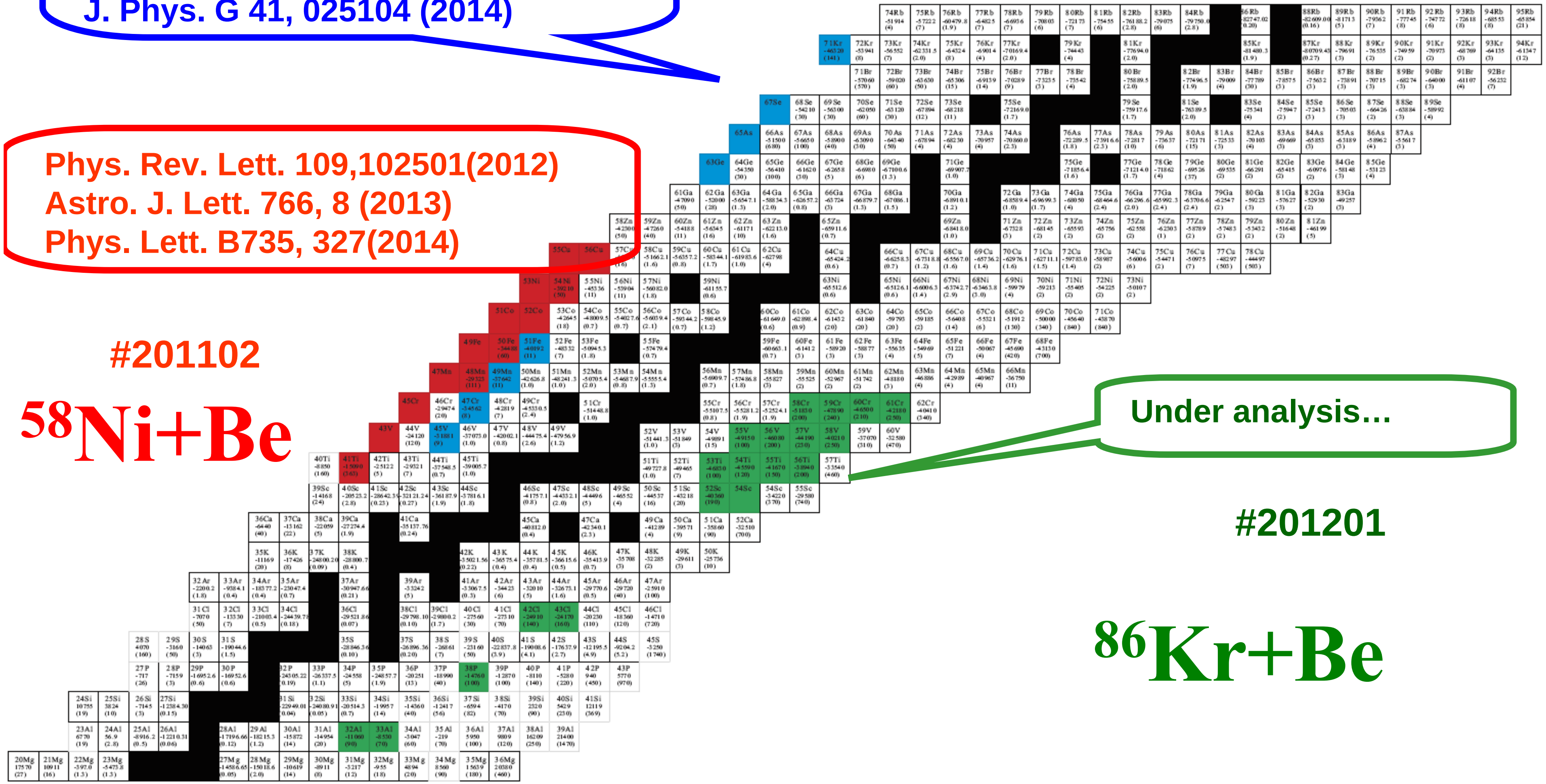
#200910

Since 2007

Nucl. Instr. Meth. A624, 109 (2010)
Nucl. Instr. Meth. A654, 213 (2011)
Phys. Rev. Lett. 106, 112501 (2011)
J. Phys. G 41, 025104 (2014)

^{78}Kr+Be

Phys. Rev. Lett. 109,102501(2012)
Astro. J. Lett. 766, 8 (2013)
Phys. Lett. B735, 327(2014)



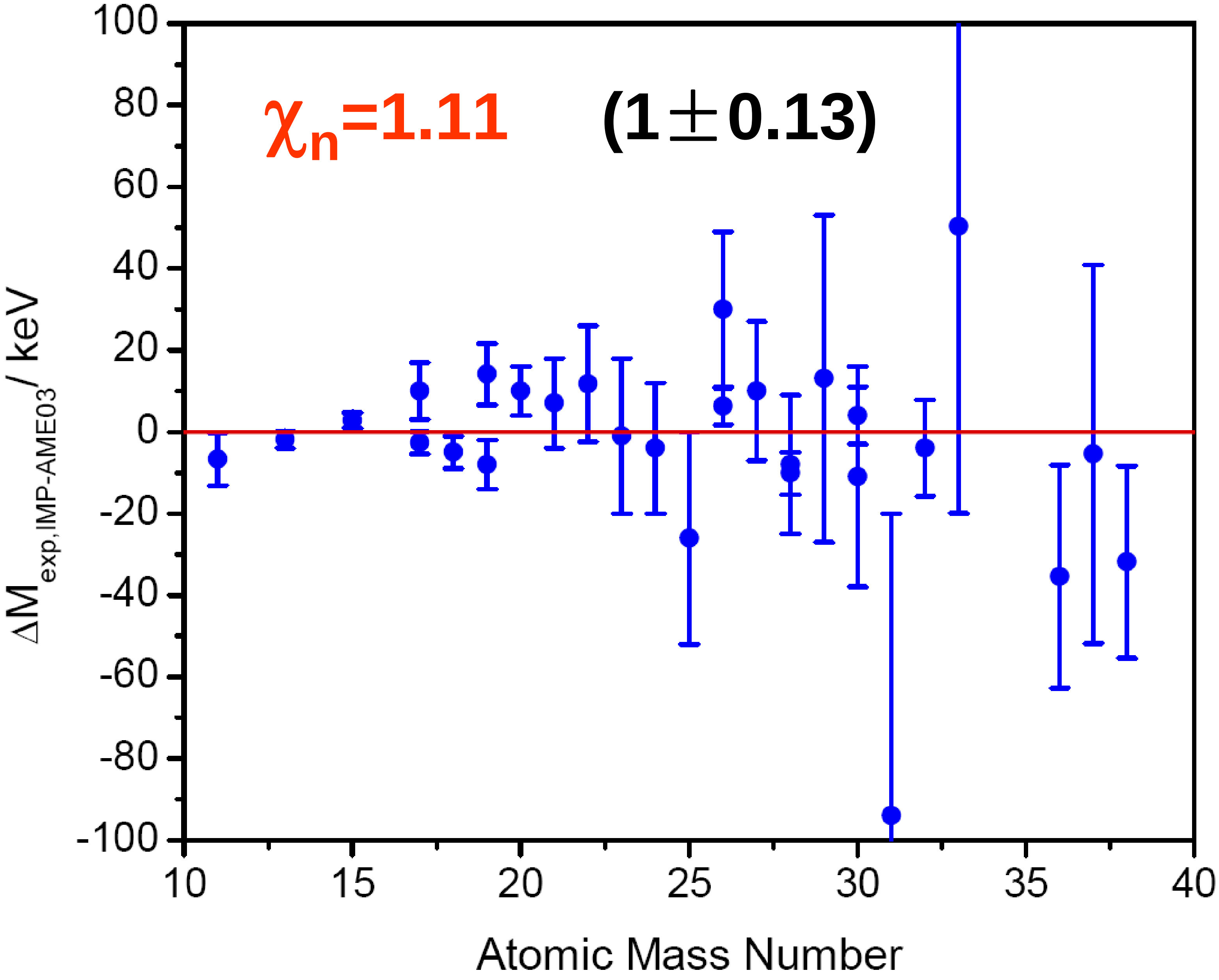
#201102

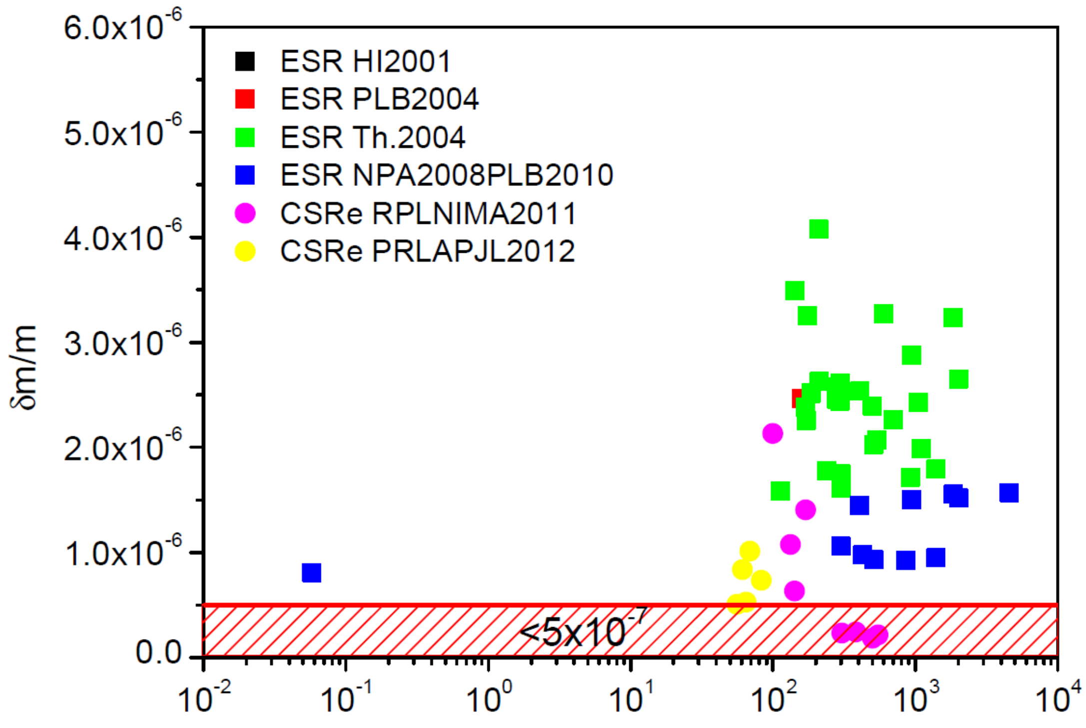
^{58}Ni+Be

Under analysis…

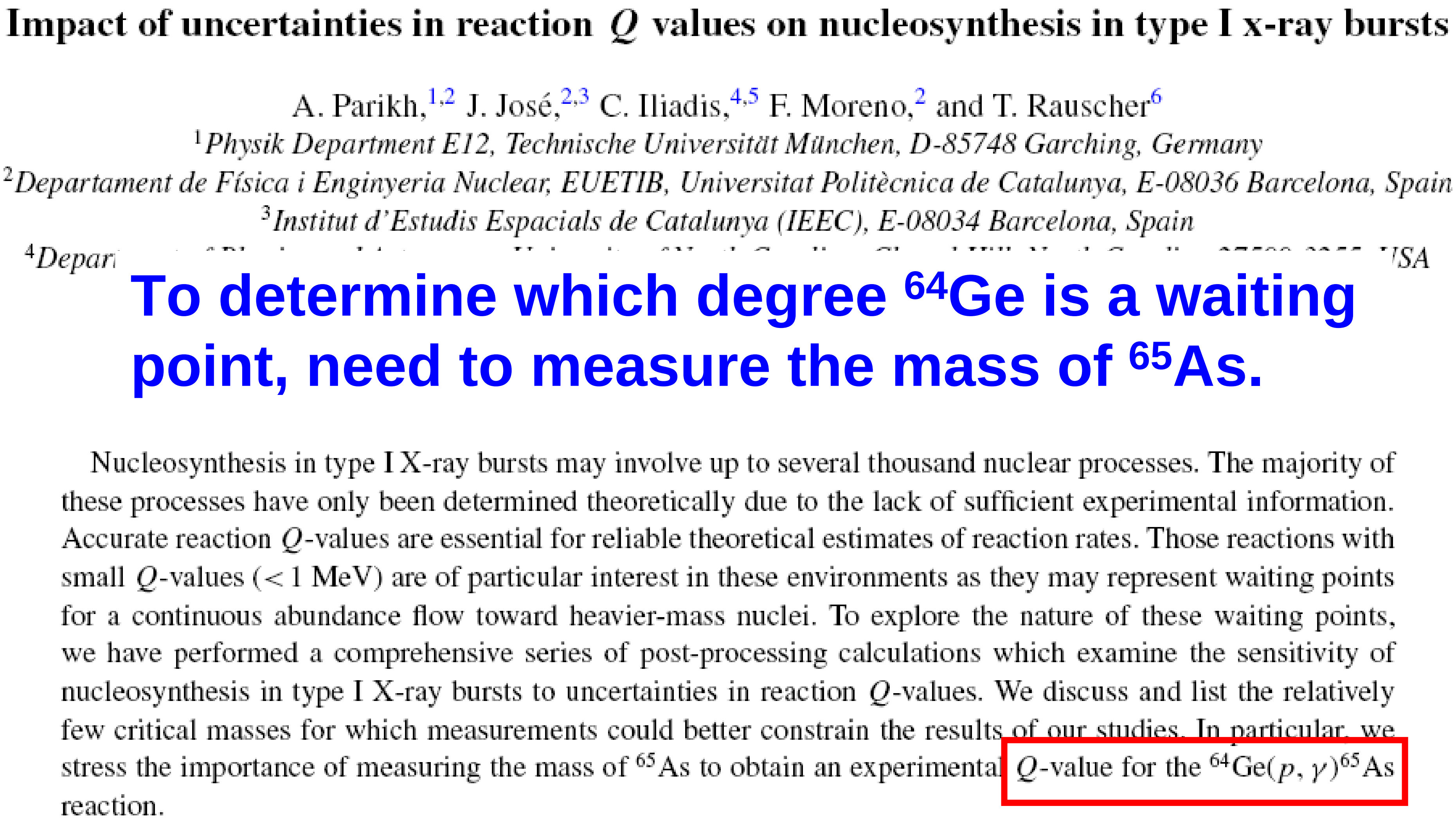
#201201

^{86}Kr+Be


χ_n=1.11
(1±0.13)
$\Delta M_{exp,IMP-AME03}$/ keV
100
80
60
40
20
0
-20
-40
-60
-80
-100
10
15
20
25
30
35
40
Atomic Mass Number



Field of application	**Mass 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, rp-process, waiting points	10^{-7}
Nuclear models and formulas: IMME	10^{-7}–10^{-8}
Weak interaction studies: CVC, CKM	10^{-8}
Atomic physics: binding energy, QED	10^{-9}–10^{-11}
Metrology: fundamental constants, CPT	$<10^{-10}$



Impact of uncertainties in reaction Q values on nucleosynthesis in type I x-ray bursts

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[4]Depar

To determine which degree ^{64}Ge is a waiting point, need to measure the mass of ^{65}As.

Nucleosynthesis in type I X-ray bursts may involve up to several thousand nuclear processes. The majority of these processes have only been determined theoretically due to the lack of sufficient experimental information. Accurate reaction Q-values are essential for reliable theoretical estimates of reaction rates. Those reactions with small Q-values (< 1 MeV) are of particular interest in these environments as they may represent waiting points for a continuous abundance flow toward heavier-mass nuclei. To explore the nature of these waiting points, we have performed a comprehensive series of post-processing calculations which examine the sensitivity of nucleosynthesis in type I X-ray bursts to uncertainties in reaction Q-values. We discuss and list the relatively few critical masses for which measurements could better constrain the results of our studies. In particular, we stress the importance of measuring the mass of ^{65}As to obtain an experimental Q-value for the ^{64}Ge$(p,\gamma)^{65}$As reaction.

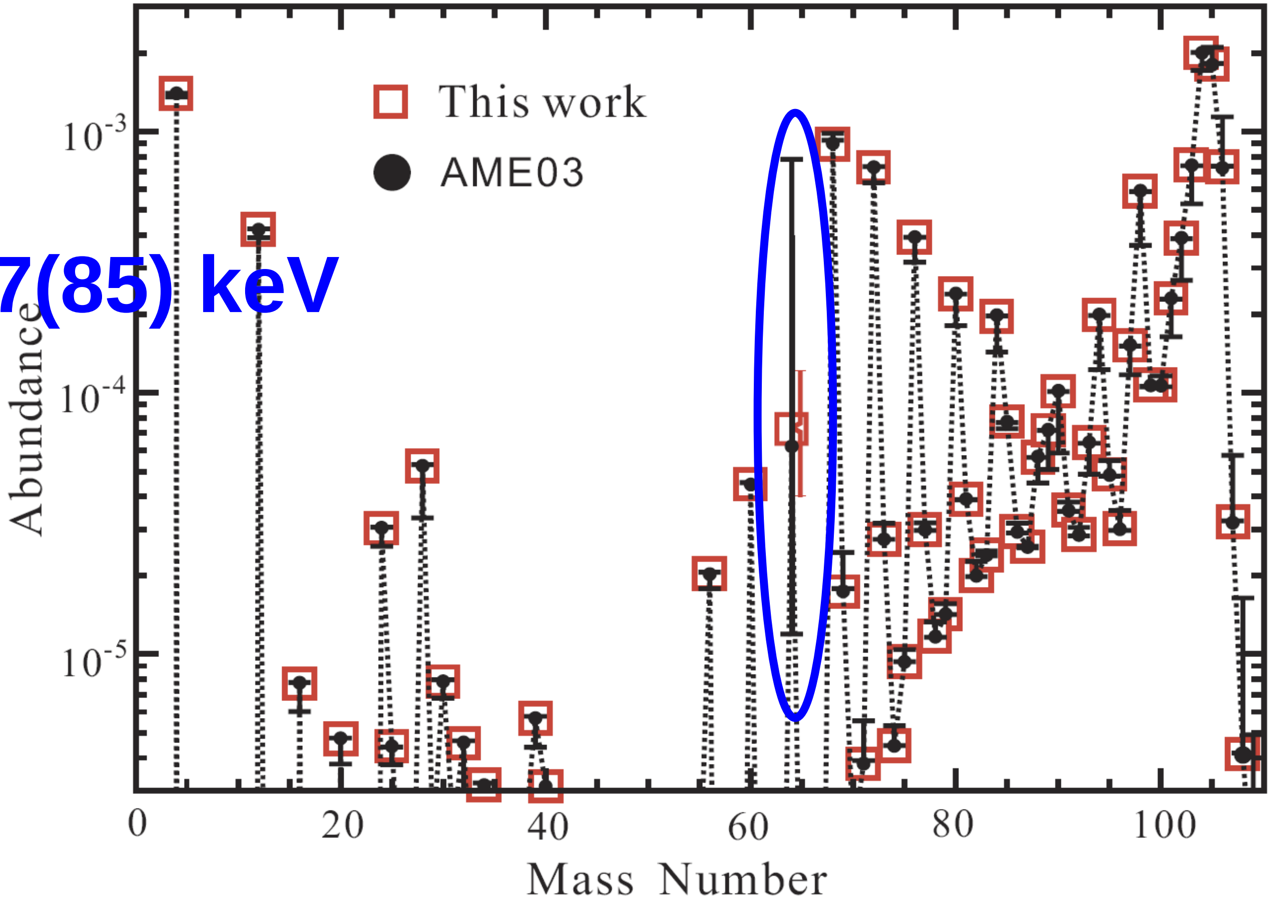
$$\lambda_{i(\gamma,p)j} = \frac{(2J_p+1)G_j}{G_i}\left(\frac{\mu kT}{2\pi\hbar}\right)^{3/2} exp\left(-\frac{Q_{j(p,\gamma)}}{kT}\right).<\sigma\upsilon>_{j(p,\gamma)i}$$

PRC79,045802 (2009)

^{64}Ge is a waiting point ?

^{64}Ge(p, r)^{65}As

ME(^{65}As)=–46937(85) keV
Q=90(85) keV



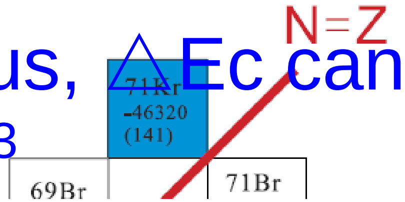
H. Schatz’s calculation

89%–90% of the reaction flow passes through ^{64}Ge via proton capture indicating that **^{64}Ge is not a significant rp-process waiting point**.

X. L. Tu, et al., PRL106,112501(2011)

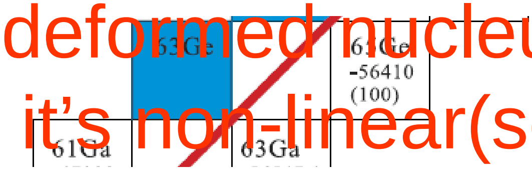
Coulomb displacement energy(CDE), △*Ec*, is the difference of binding energy of mirror nuclei.

$$\Delta Ec = B_{<} - B_{>}$$



For charged spherical nucleus, △Ec can be expressed as a linear function of $Z/A^{1/3}$

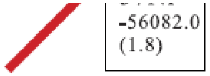
$$\triangle E_c = A + B(Z_{<}/A^{1/3})$$



However, for a deformed nucleus with quadrupole deformation β_2, it’s non-linear(second order polynomial)

$$\triangle E_c(\beta_2) \simeq \triangle E_c(0)[1 - \frac{4}{45}\beta_2^2]$$

D. D. Long, P. Richard, C. F. Moore, and J. D. Fox, Phys. Rev. **149** (1966) 906.



M. S. Antony and V. B. Ndocko Ndongue, Il Nuovo Cimento **93** (1986) 249.

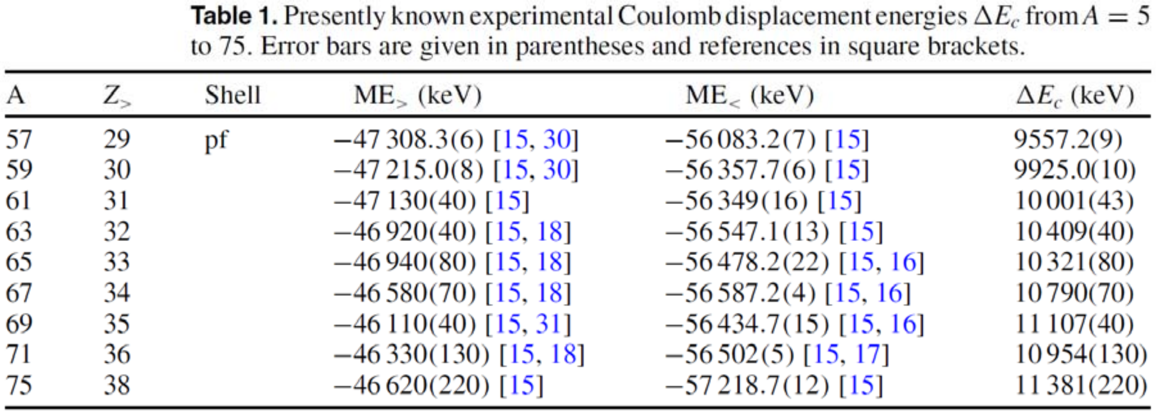
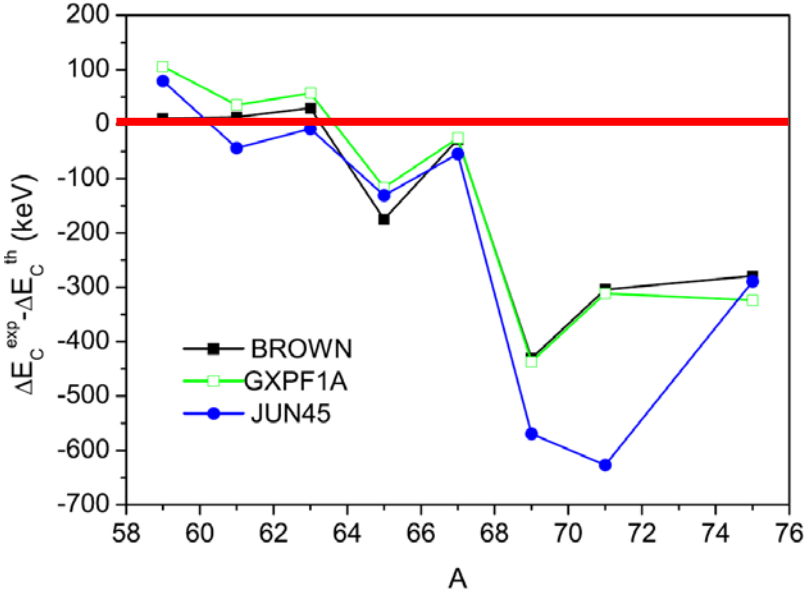


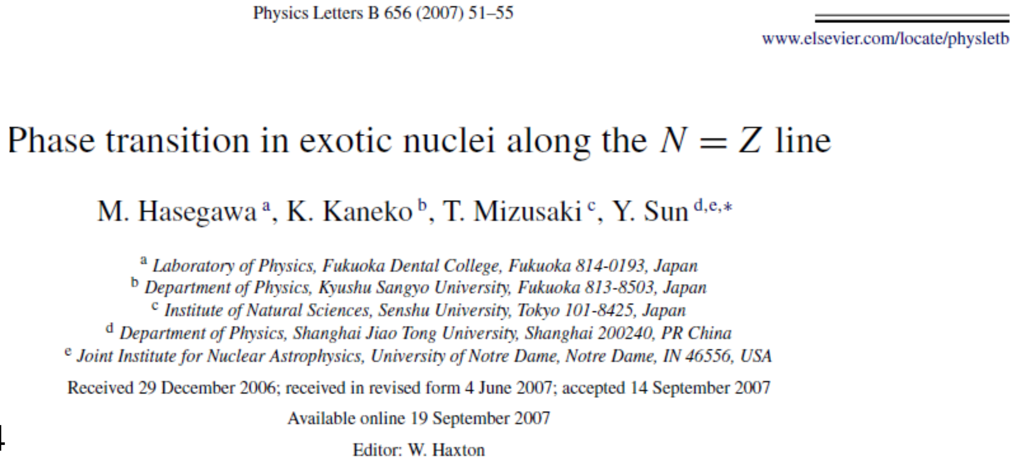
Table 1. Presently known experimental Coulomb displacement energies ΔE_c from $A = 5$ to 75. Error bars are given in parentheses and references in square brackets.

A	$Z_>$	Shell	$ME_>$ (keV)	$ME_<$ (keV)	ΔE_c (keV)
57	29	pf	−47 308.3(6) [15, 30]	−56 083.2(7) [15]	9557.2(9)
59	30		−47 215.0(8) [15, 30]	−56 357.7(6) [15]	9925.0(10)
61	31		−47 130(40) [15]	−56 349(16) [15]	10 001(43)
63	32		−46 920(40) [15, 18]	−56 547.1(13) [15]	10 409(40)
65	33		−46 940(80) [15, 18]	−56 478.2(22) [15, 16]	10 321(80)
67	34		−46 580(70) [15, 18]	−56 587.2(4) [15, 16]	10 790(70)
69	35		−46 110(40) [15, 31]	−56 434.7(15) [15, 16]	11 107(40)
71	36		−46 330(130) [15, 18]	−56 502(5) [15, 17]	10 954(130)
75	38		−46 620(220) [15]	−57 218.7(12) [15]	11 381(220)



X. L. Tu, et al., J. Phys. G **41** (2014) 025104

$$\triangle E_c(\beta_2) \simeq \triangle E_c(0)[1 - \frac{4}{45}\beta_2^2]$$



Physics Letters B 656 (2007) 51–55

www.elsevier.com/locate/physletb

Phase transition in exotic nuclei along the $N = Z$ line

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[c] *Institute of Natural Sciences, Senshu University, Tokyo 101-8425, Japan*
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Available online 19 September 2007
Editor: W. Haxton

This systematic tendency indicates the spherical shape starts to change around A=65

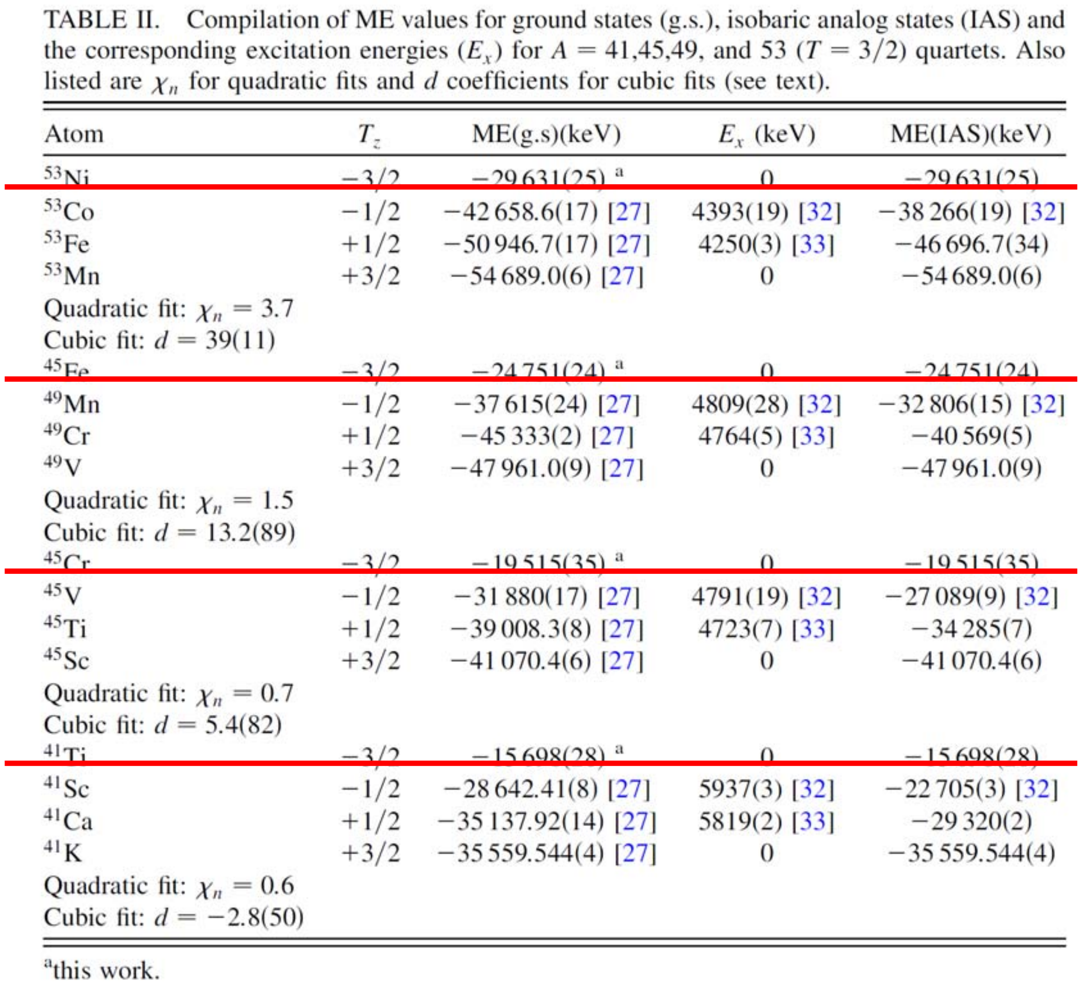
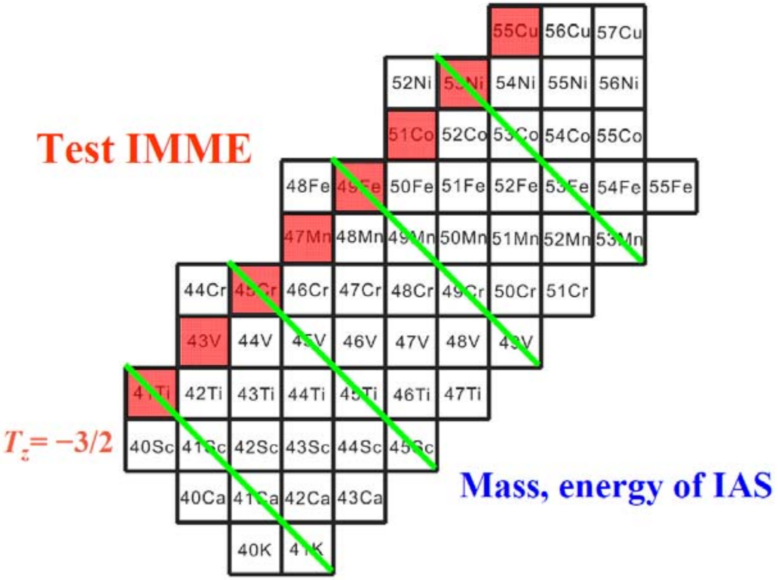


TABLE II. Compilation of ME values for ground states (g.s.), isobaric analog states (IAS) and the corresponding excitation energies (E_x) for $A = 41,45,49$, and 53 ($T = 3/2$) quartets. Also listed are χ_n for quadratic fits and d coefficients for cubic fits (see text).

Atom	T_z	ME(g.s)(keV)	E_x (keV)	ME(IAS)(keV)
^{53}Ni	−3/2	−29 631(25) [a]	0	−29 631(25)
^{53}Co	−1/2	−42 658.6(17) [27]	4393(19) [32]	−38 266(19) [32]
^{53}Fe	+1/2	−50 946.7(17) [27]	4250(3) [33]	−46 696.7(34)
^{53}Mn	+3/2	−54 689.0(6) [27]	0	−54 689.0(6)
Quadratic fit: $\chi_n = 3.7$				
Cubic fit: $d = 39(11)$				
^{45}Fe	−3/2	−24 751(24) [a]	0	−24 751(24)
^{49}Mn	−1/2	−37 615(24) [27]	4809(28) [32]	−32 806(15) [32]
^{49}Cr	+1/2	−45 333(2) [27]	4764(5) [33]	−40 569(5)
^{49}V	+3/2	−47 961.0(9) [27]	0	−47 961.0(9)
Quadratic fit: $\chi_n = 1.5$				
Cubic fit: $d = 13.2(89)$				
^{45}Cr	−3/2	−19 515(35) [a]	0	−19 515(35)
^{45}V	−1/2	−31 880(17) [27]	4791(19) [32]	−27 089(9) [32]
^{45}Ti	+1/2	−39 008.3(8) [27]	4723(7) [33]	−34 285(7)
^{45}Sc	+3/2	−41 070.4(6) [27]	0	−41 070.4(6)
Quadratic fit: $\chi_n = 0.7$				
Cubic fit: $d = 5.4(82)$				
^{41}Ti	−3/2	−15 698(28) [a]	0	−15 698(28)
^{41}Sc	−1/2	−28 642.41(8) [27]	5937(3) [32]	−22 705(3) [32]
^{41}Ca	+1/2	−35 137.92(14) [27]	5819(2) [33]	−29 320(2)
^{41}K	+3/2	−35 559.544(4) [27]	0	−35 559.544(4)
Quadratic fit: $\chi_n = 0.6$				
Cubic fit: $d = -2.8(50)$				

[a] this work.

58Ni+Be



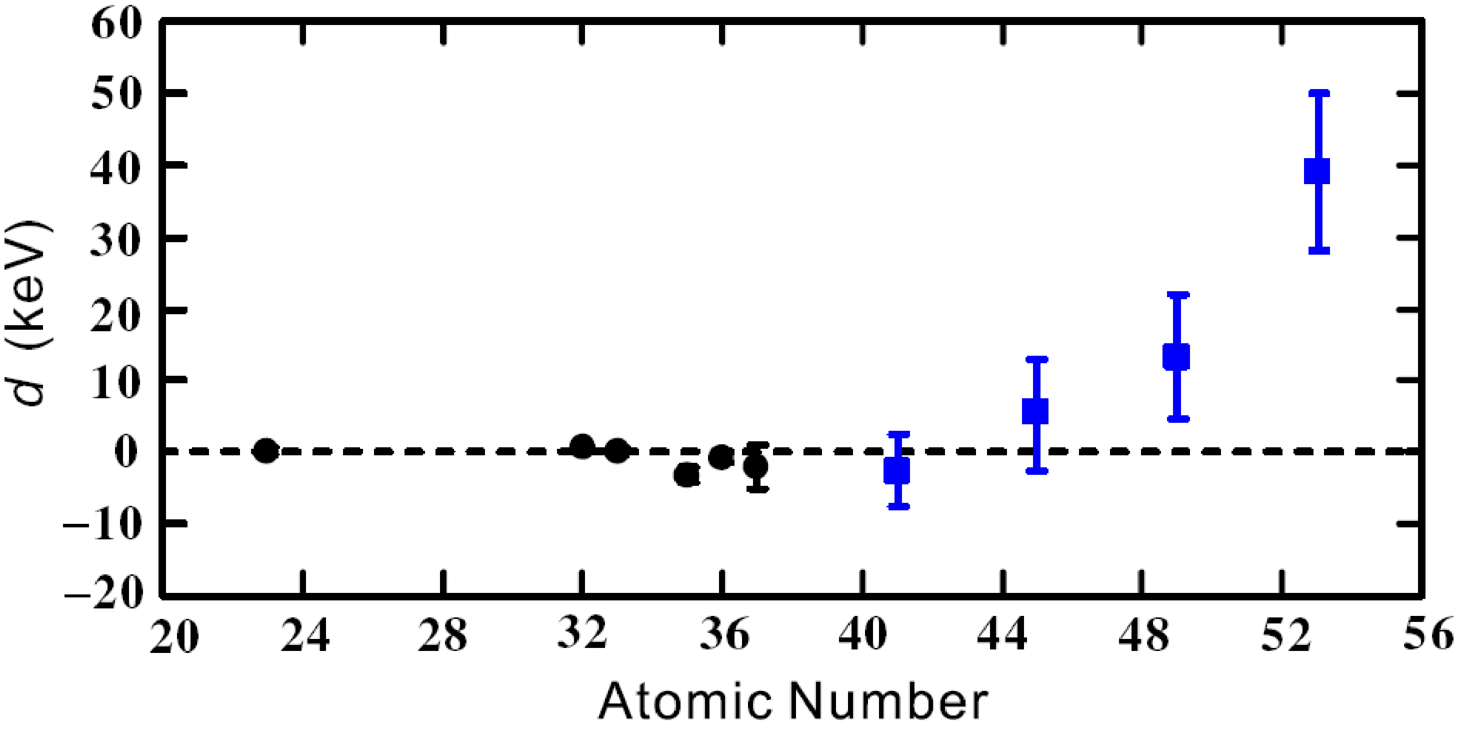
Isobaric Multiplet Mass Equation (IMME)

$$\mathrm{ME}\,(A, T, T_z) = a(A, T) + b(A, T)T_z + c(A, T)T_z^2$$

A correction, $d(A,T)T_z^3$ of IMME is proportional to $Z\alpha$.

Test the IMME in *fp* shell nuclei

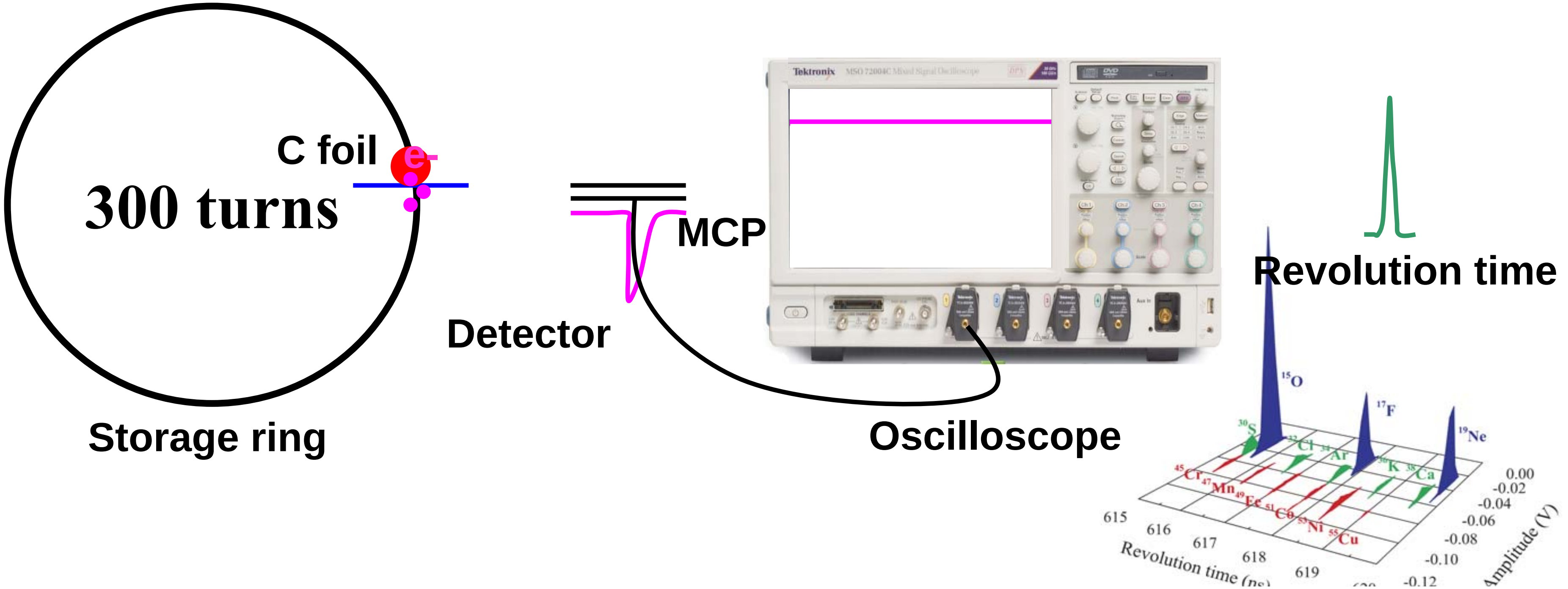
$$M(T,A,T_3) = a(T,A,) + b(T,A)T_3 + c(T,A)T_3^2 + d(T,A)T_3^3$$

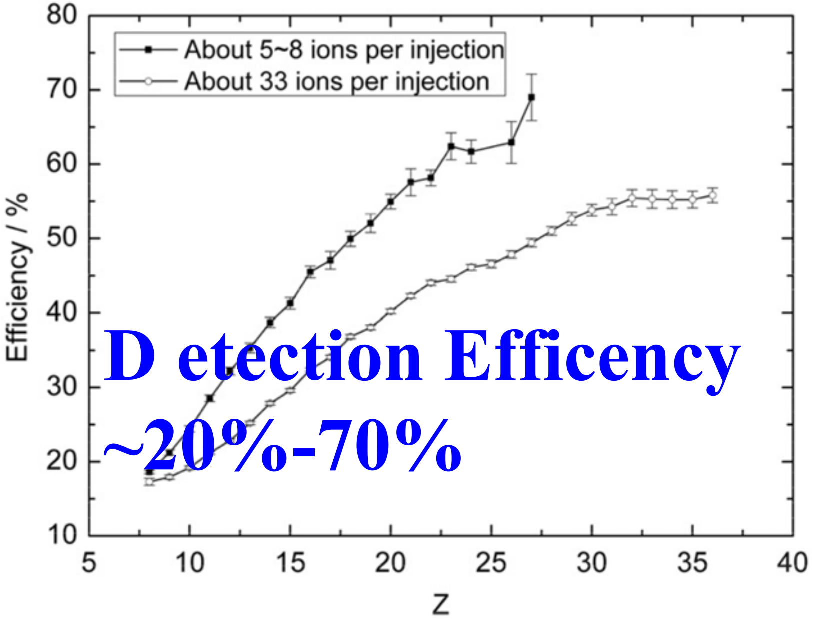


***d* parameters increase gradually up to A=53 for which *d* is 3.5s deviated from zero.**

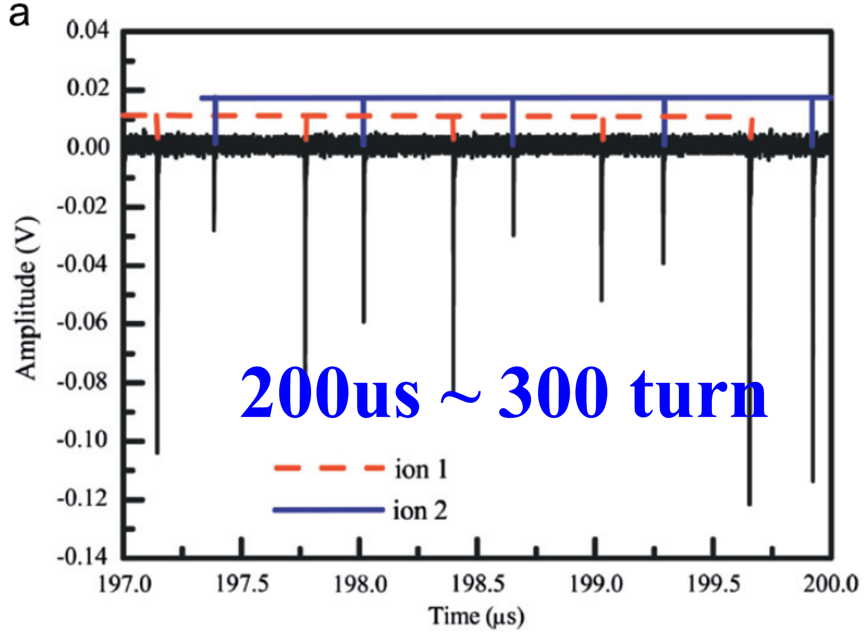
Y. H. Zhang, et al., PRL109, 102501(2012) allowed us for the first time to perform a test of IMME in fp-shell nuclei. We found a breakdown of the quadratic form of IMME for the $A = 53$ ($T = 3/2$) quartet. The disagreement cannot be explained by either the existing or the new theoretical calculations of isospin mixing. If this breakdown can be confirmed by improved experimental data (ground-state masses, energies of the IAS), possible reasons, such as enhanced effects of isospin mixing and/or charge-dependent nuclear forces in the fp-shell, should be investigated.

Y. H. Zhang, et al., PRL109, 102501(2012)



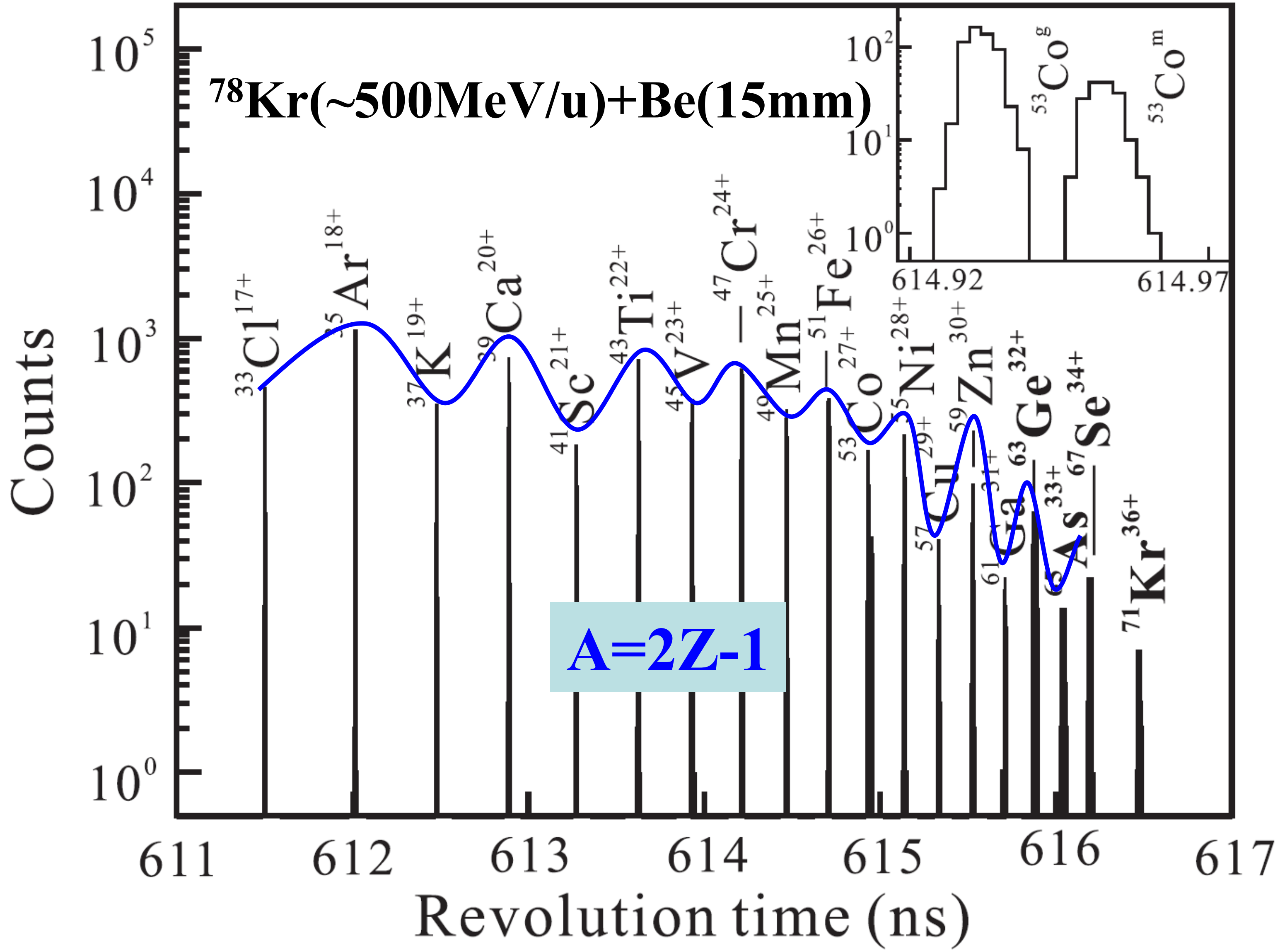


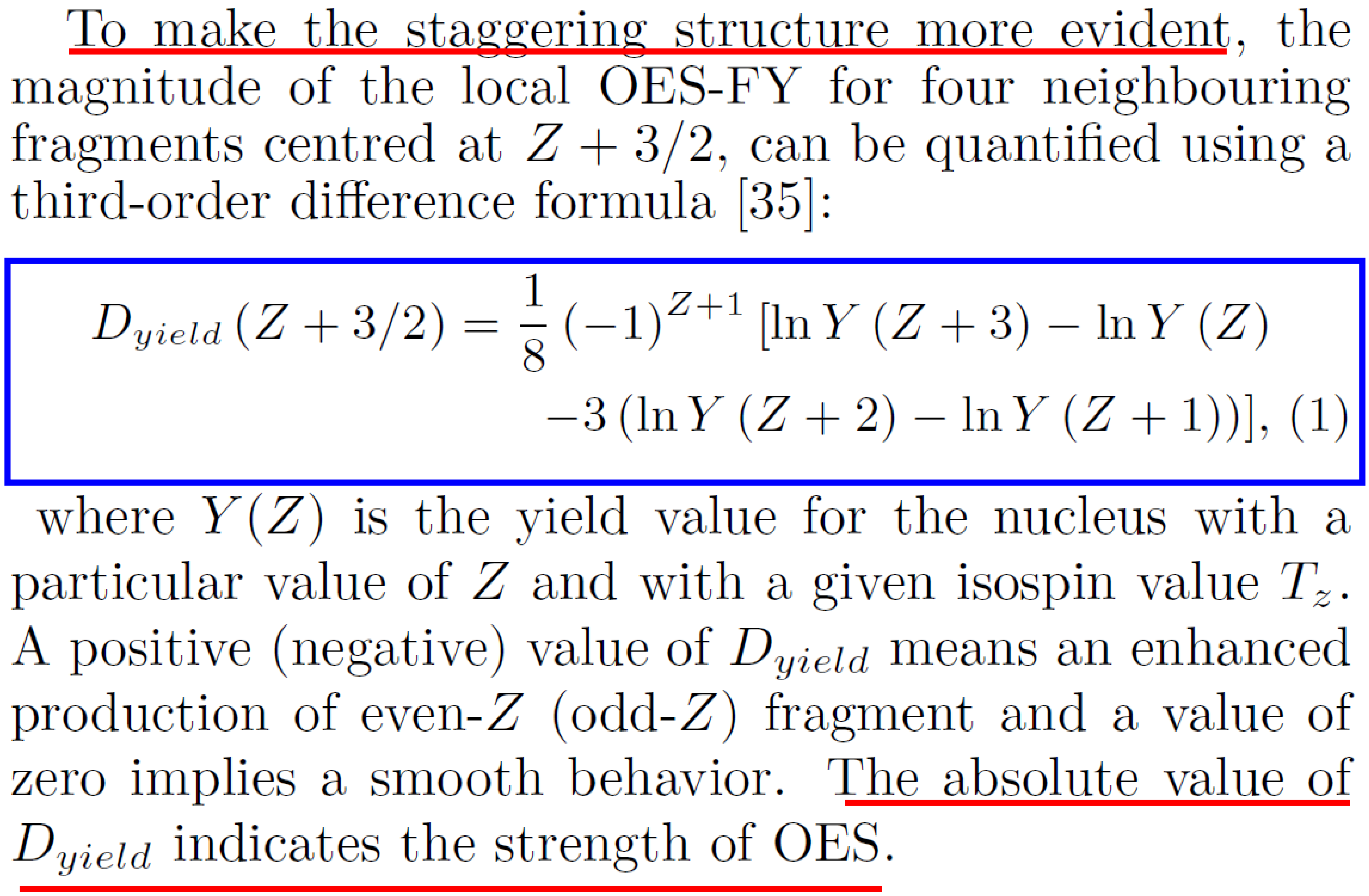
Detection Efficency ~20%-70%



200us ~ 300 turn

Odd-Even Staggering of Yields



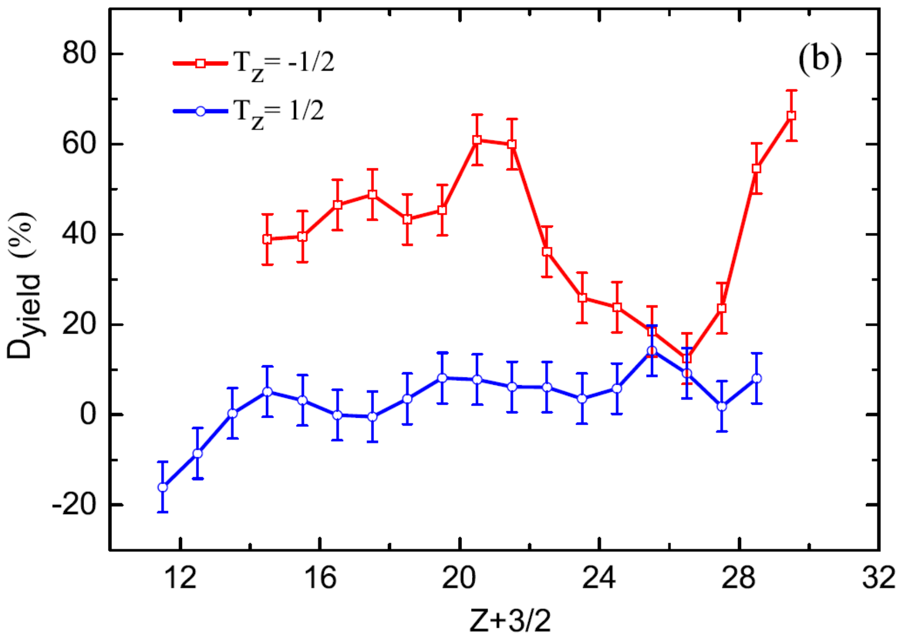


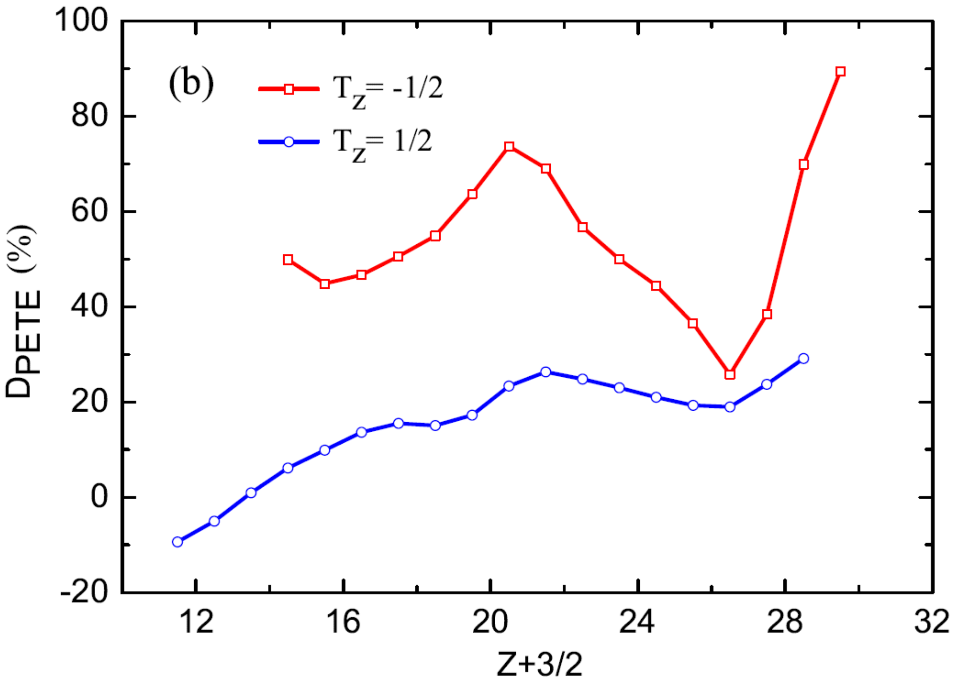
To make the staggering structure more evident, the magnitude of the local OES-FY for four neighbouring fragments centred at $Z+3/2$, can be quantified using a third-order difference formula [35]:

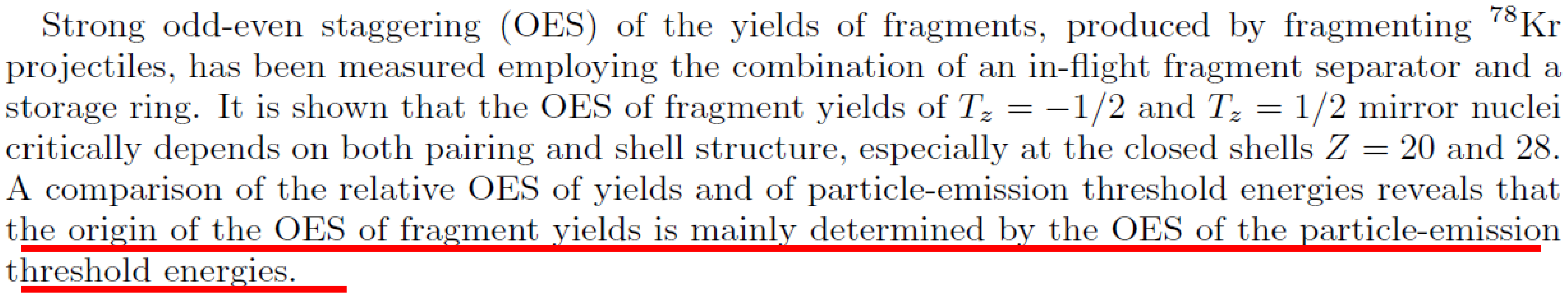
$$D_{yield}\left(Z+3/2\right)=\frac{1}{8}\left(-1\right)^{Z+1}\left[\ln Y\left(Z+3\right)-\ln Y\left(Z\right)\right.$$
$$\left.-3\left(\ln Y\left(Z+2\right)-\ln Y\left(Z+1\right)\right)\right], \quad (1)$$

where $Y(Z)$ is the yield value for the nucleus with a particular value of Z and with a given isospin value T_z. A positive (negative) value of D_{yield} means an enhanced production of even-Z (odd-Z) fragment and a value of zero implies a smooth behavior. The absolute value of D_{yield} indicates the strength of OES.

B. L. Tracy et al., Phys. Rev. C 5, 222 (1972).







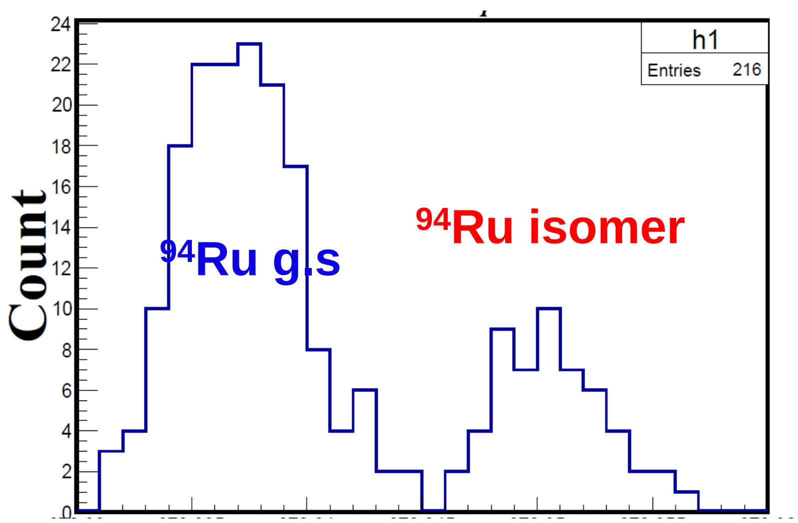
Strong odd-even staggering (OES) of the yields of fragments, produced by fragmenting ^{78}Kr projectiles, has been measured employing the combination of an in-flight fragment separator and a storage ring. It is shown that the OES of fragment yields of $T_z = -1/2$ and $T_z = 1/2$ mirror nuclei critically depends on both pairing and shell structure, especially at the closed shells $Z = 20$ and 28. A comparison of the relative OES of yields and of particle-emission threshold energies reveals that the origin of the OES of fragment yields is mainly determined by the OES of the particle-emission threshold energies.

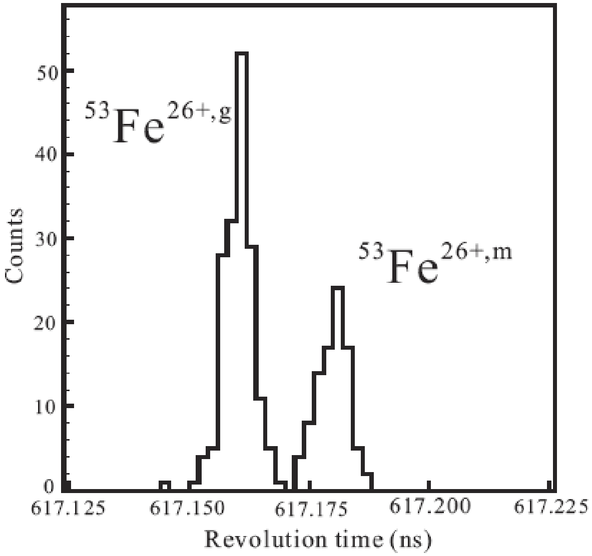
Particle-Emission Threshold Energy (PETE) is the smallest value from either the neutron or the proton separation energy.

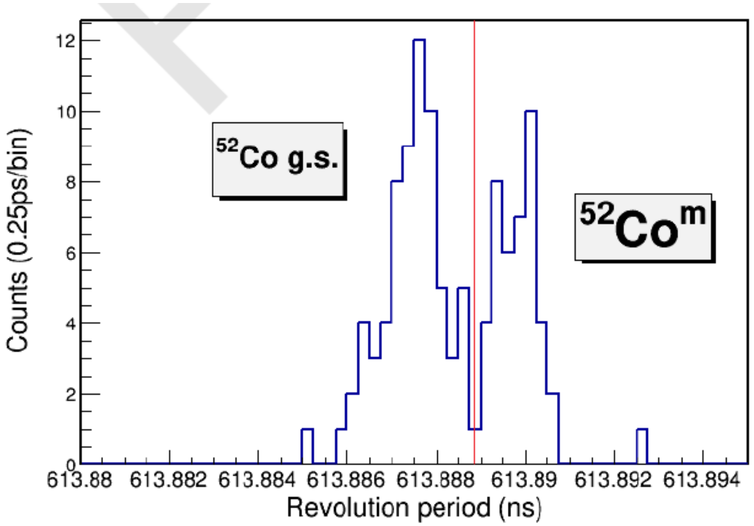
B. Mei, et al., Phys. Rev. C89, 054612(2014)

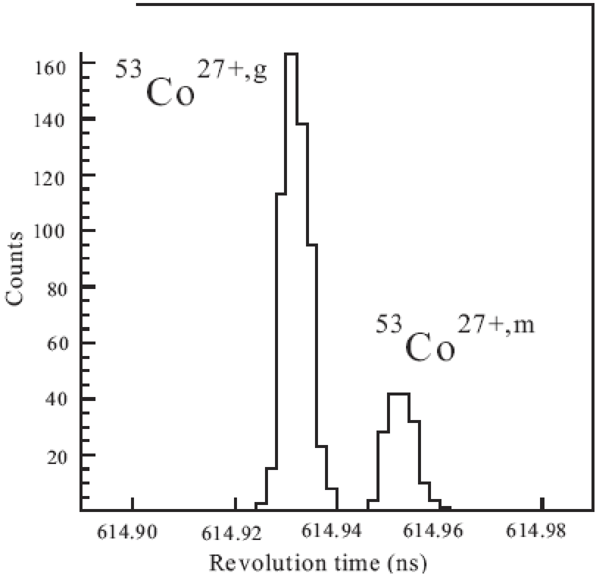
Projectile fragmentation → Isomer

A mass Resolving Power($m/\Delta m$) ~ 1.7×10^5

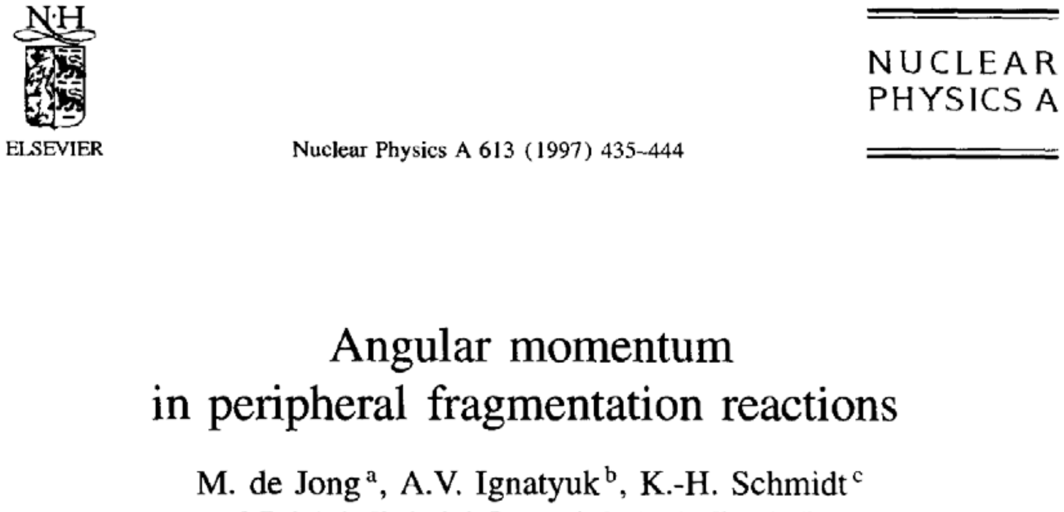








Isomeric Yield ratio



ELSEVIER

Nuclear Physics A 613 (1997) 435–444

NUCLEAR
PHYSICS A

Angular momentum in peripheral fragmentation reactions

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Bondarenko Sq., 249020 Obninsk, Kaluga R
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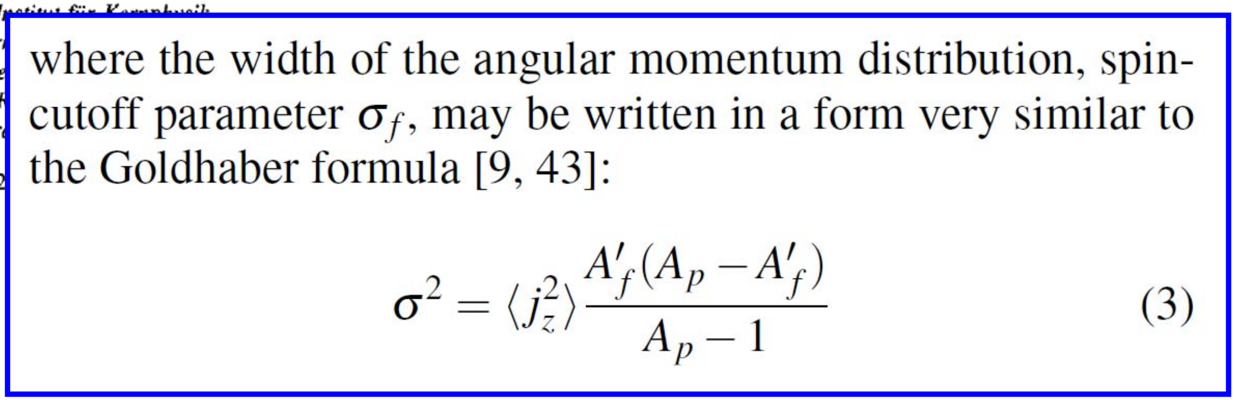
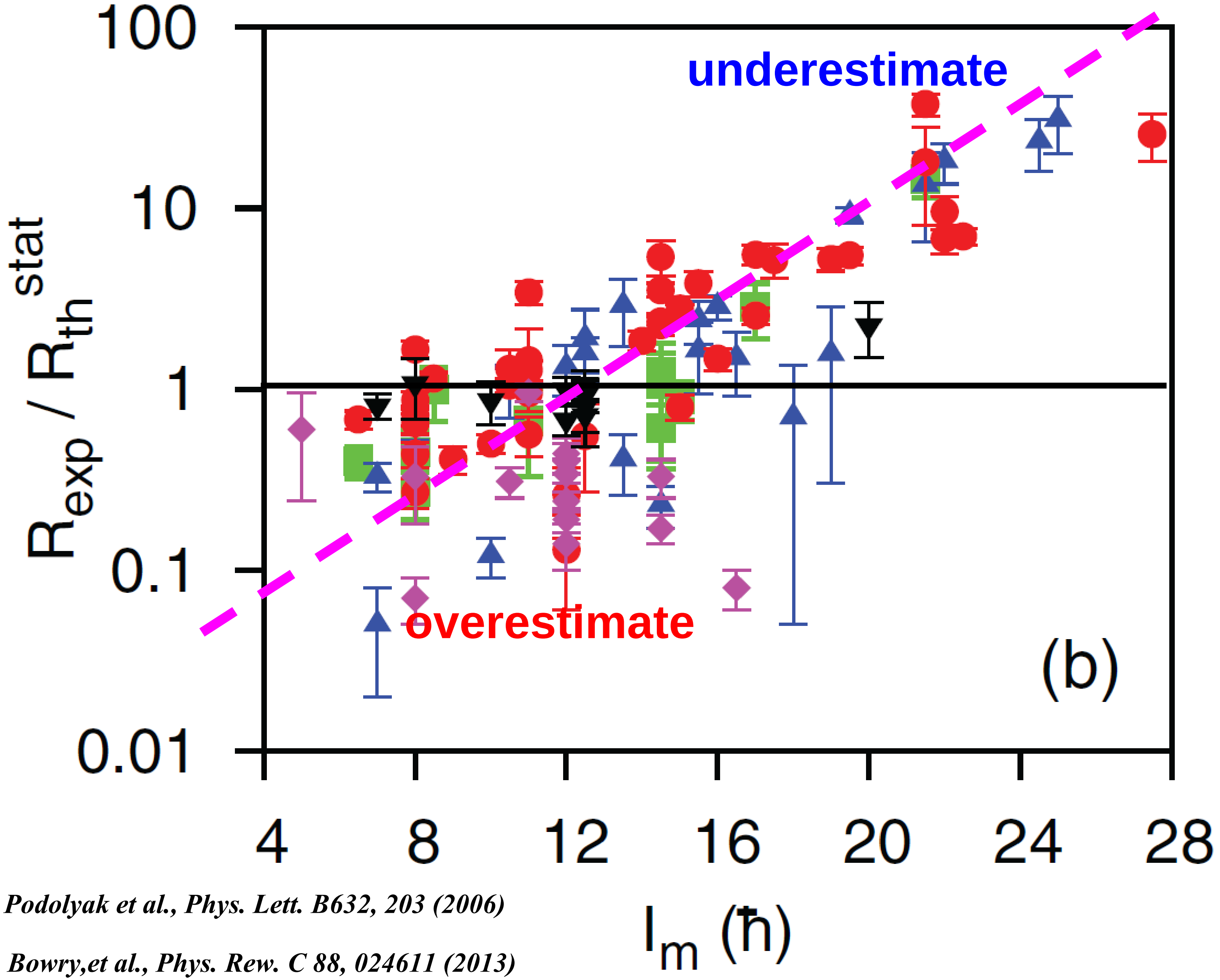
Received 8 August 1996; revised 2



where the width of the angular momentum distribution, spin-cutoff parameter σ_f, may be written in a form very similar to the Goldhaber formula [9, 43]:

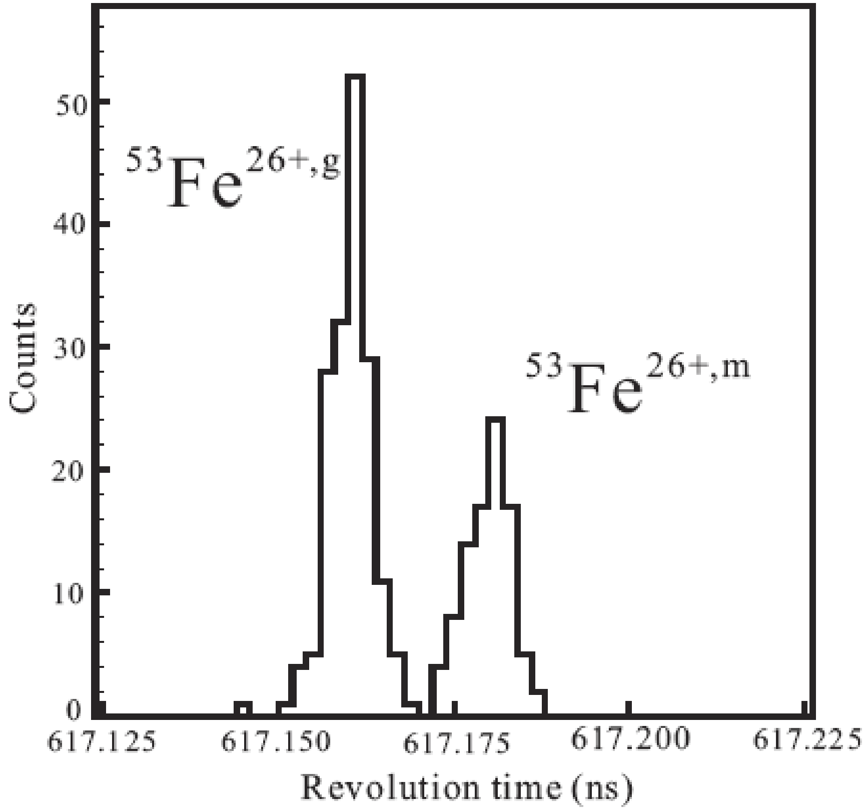
$$\sigma^2 = \langle j_z^2 \rangle \frac{A'_f(A_p - A'_f)}{A_p - 1} \tag{3}$$

$$R_{th} = \int_{J_m}^{\infty} P_J dJ = \exp\left[- \frac{J_m(J_m+1)}{2\sigma_f^2} \right].$$



Z. Podolyak et al., Phys. Lett. B632, 203 (2006)

M. Bowry,et al., Phys. Rew. C 88, 024611 (2013)



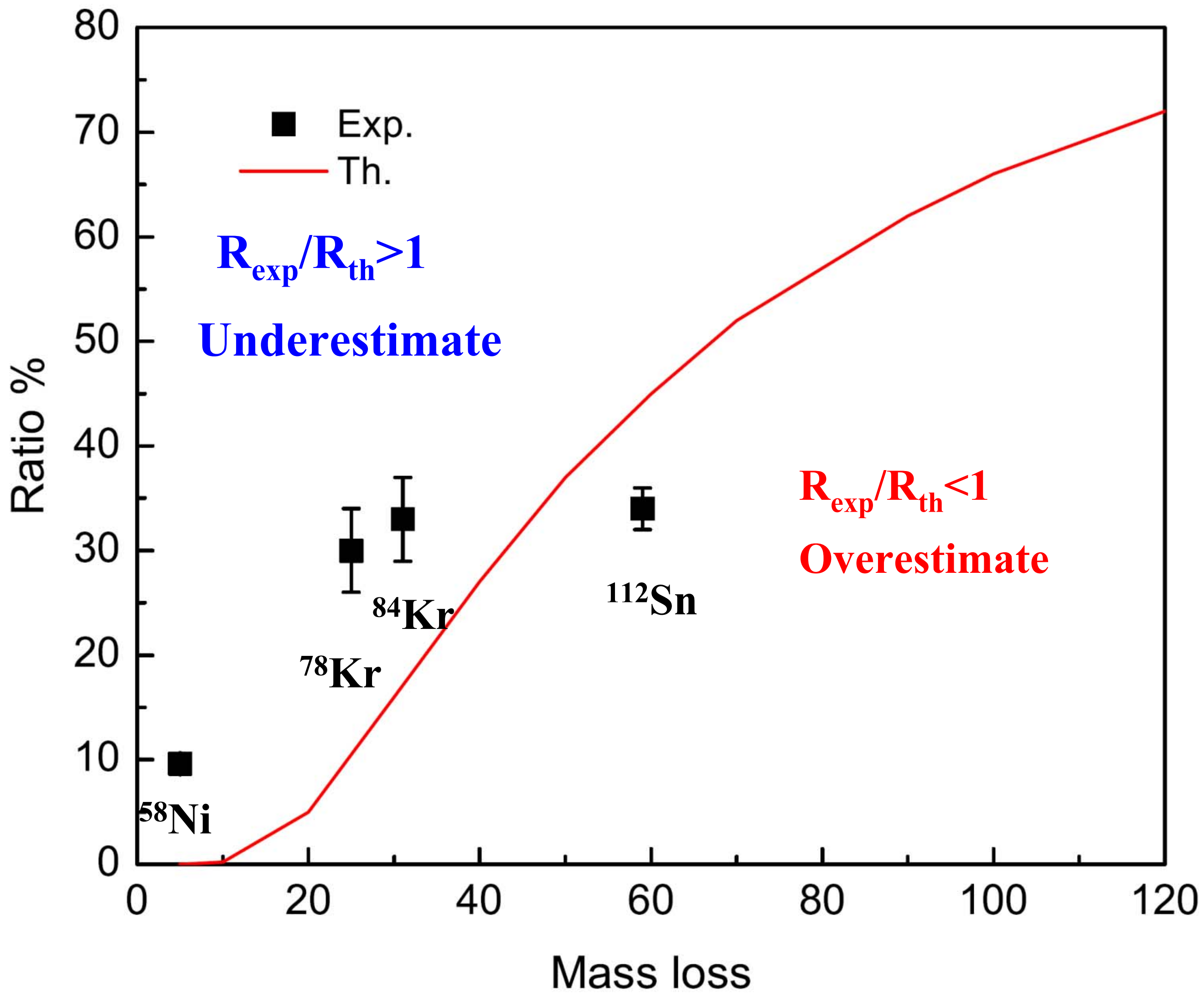
MASS LOSS: A_p-A'_f

$$R_{th}=\int_{J_m}^{\infty} P_J dJ=\exp\left[-\frac{J_m(J_m+1)}{2\sigma_f^2}\right].$$

$$\sigma^2=\langle j_z^2\rangle\frac{A'_f(A_p-A'_f)}{A_p-1}$$

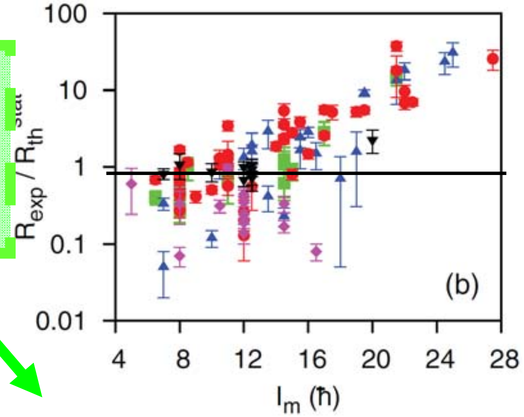
Different projectiles **(58Ni, 78Kr, 84Kr, 112Sn)** have been used to produce the same isomeric state, e.g., the high-spin 19/2 state in 53Fe.

^{53}Fe, isomeric ratios, J=19/2



Small mass loss ~ higher spin ~ underestimate

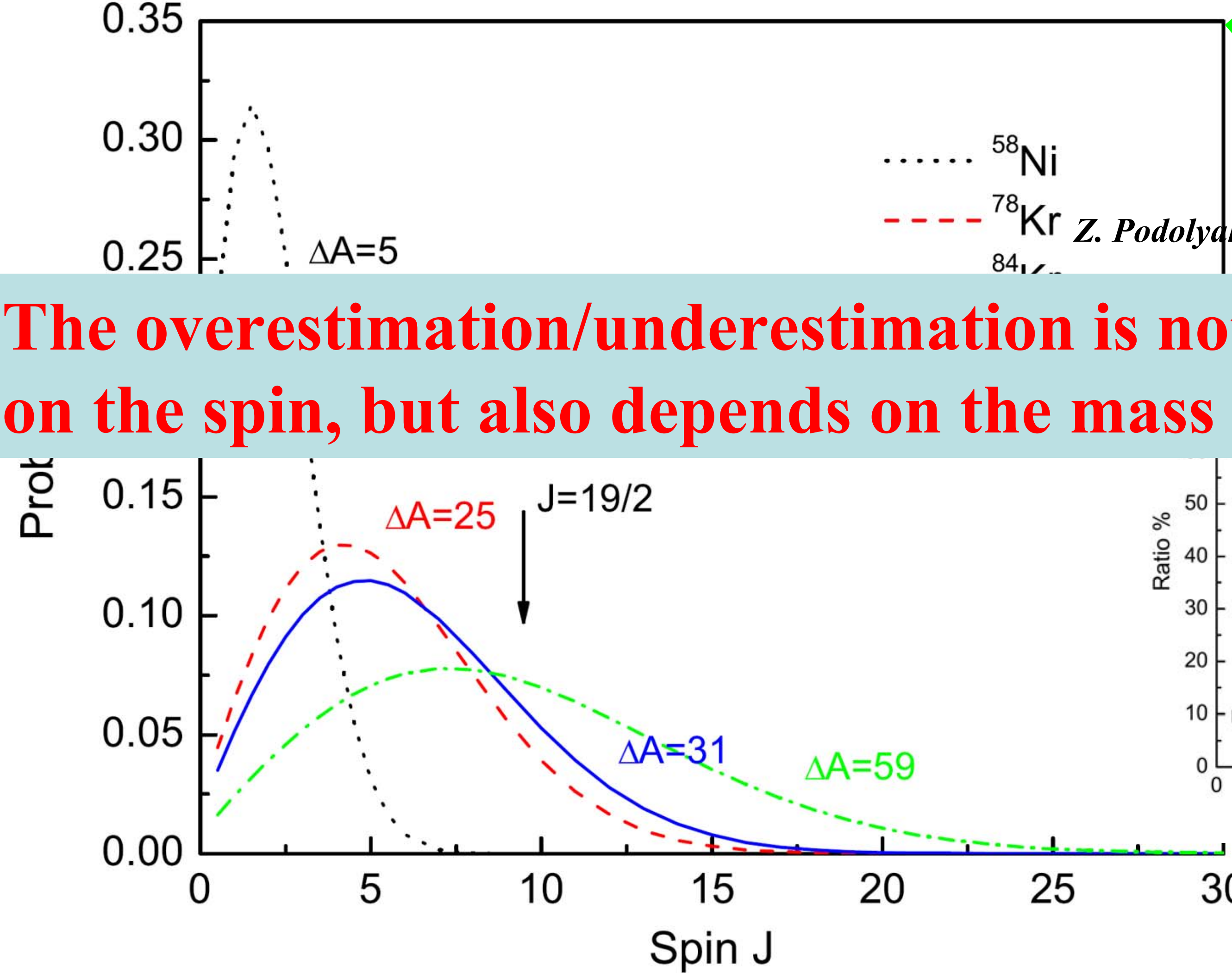
Large mass loss ~ lower spin ~ overestimate

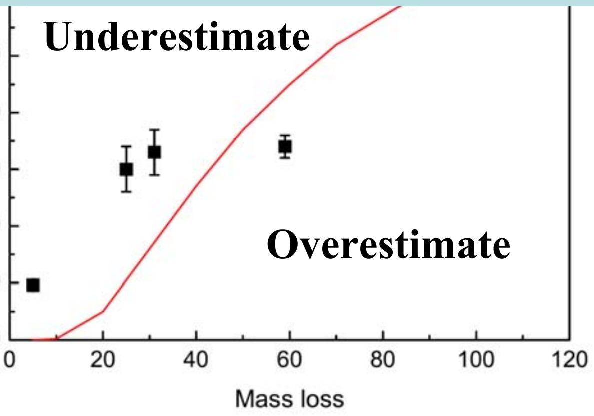


Observed by Z. Podolyak

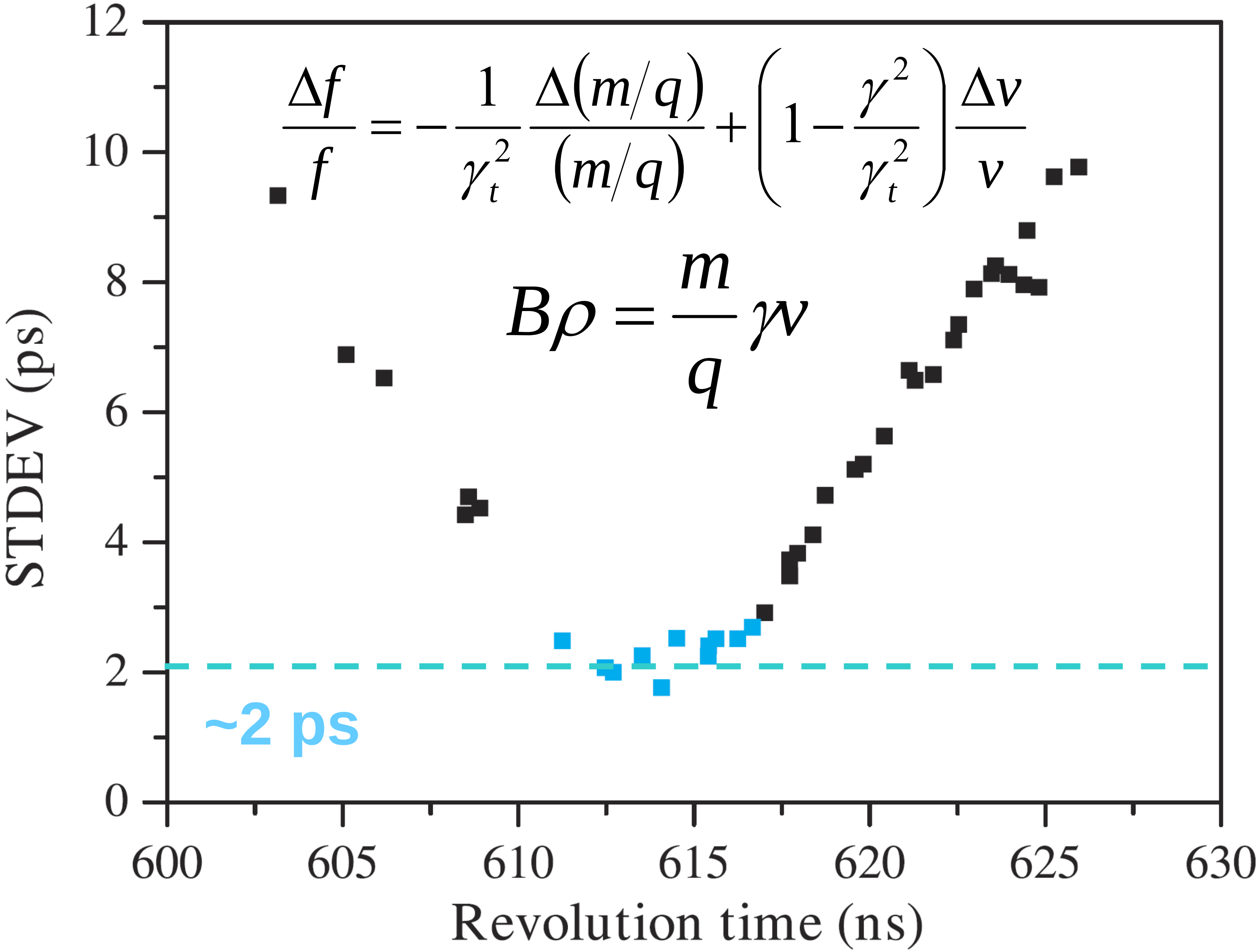
Z. Podolyak et al., Phys. Lett. B632, 203 (2006)

The overestimation/underestimation is not only dependent on the spin, but also depends on the mass loss





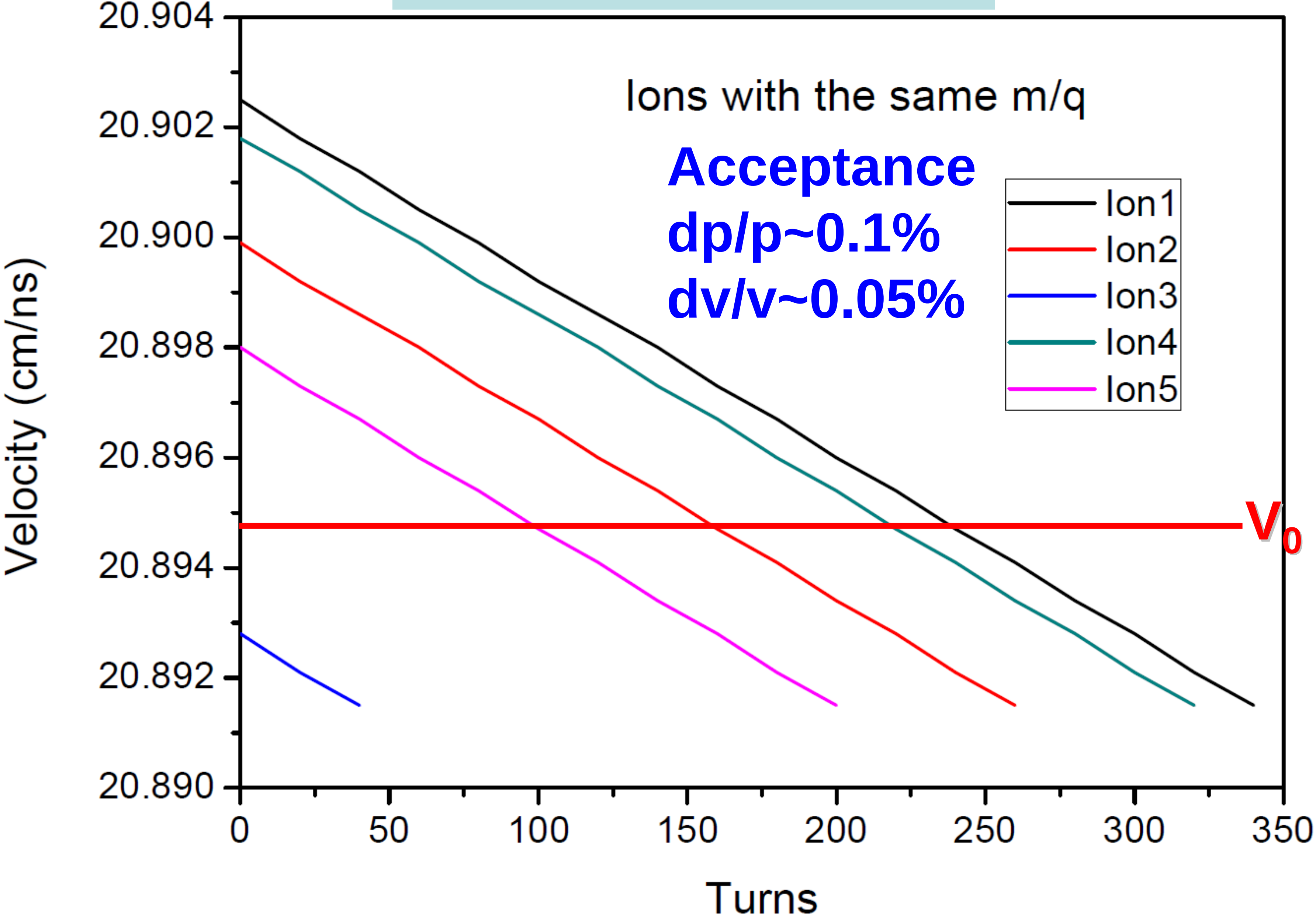
The production probability as a function of spin for 53Fe



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

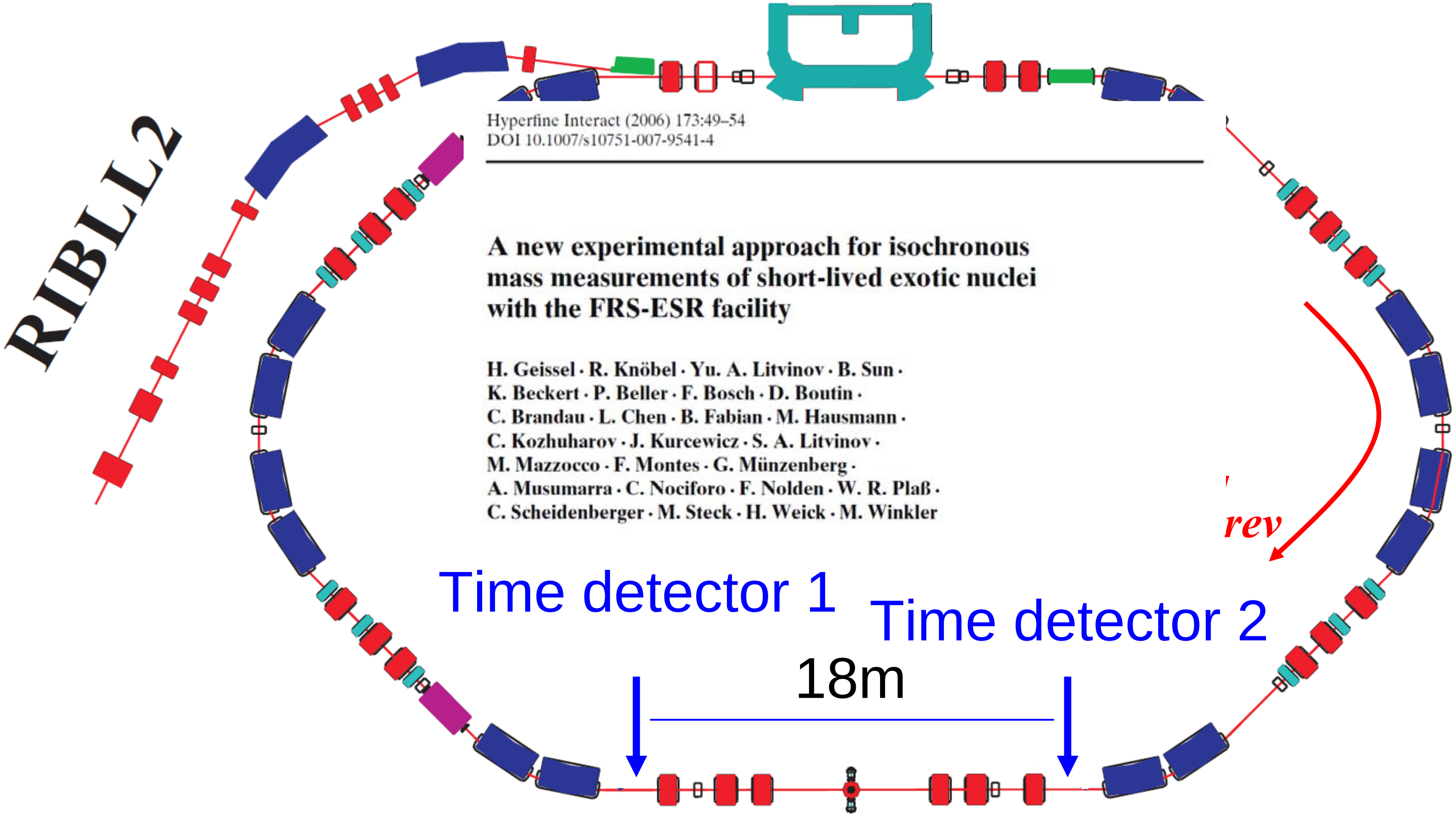
$$B\rho = \frac{m}{q}\gamma v$$

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



Ions with the same m/q

Acceptance
dp/p~0.1%
dv/v~0.05%



Hyperfine Interact (2006) 173:49–54
DOI 10.1007/s10751-007-9541-4

A new experimental approach for isochronous mass measurements of short-lived exotic nuclei with the FRS-ESR facility

H. Geissel · R. Knöbel · Yu. A. Litvinov · B. Sun ·
K. Beckert · P. Beller · F. Bosch · D. Boutin ·
C. Brandau · L. Chen · B. Fabian · M. Hausmann ·
C. Kozhuharov · J. Kurcewicz · S. A. Litvinov ·
M. Mazzocco · F. Montes · G. Münzenberg ·
A. Musumarra · C. Nociforo · F. Nolden · W. R. Plaß ·
C. Scheidenberger · M. Steck · H. Weick · M. Winkler

$$V=L/(T_1-T_2)=L/TOF$$

Summary

1、HIRFL-CSR can be operated as IMS

2、Improvement of technique

- Amplitude-revolution time identification
- High time resolution detector

3、Mass experimental results

- ^{64}Ge is not a significant rp-process waiting point
- Spherical shape starts to change around 65As
- Breakdown of IMME at A=53,T=3/2

4、Reaction mechanism study with IMS

- Odd-Even Staggering of yields
- Isomeric ratios

Thanks for your attention

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