在NSCL基于ToF-Bρ技术测量丰中子原子核的质量

王凯龙

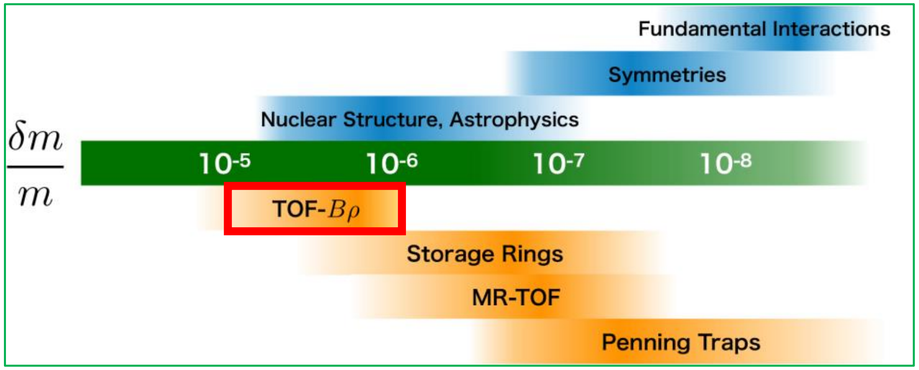
中国科学院近代物理研究所

第一届“粤港澳”核物理论坛，2022.7.2—7.6，广东 珠海

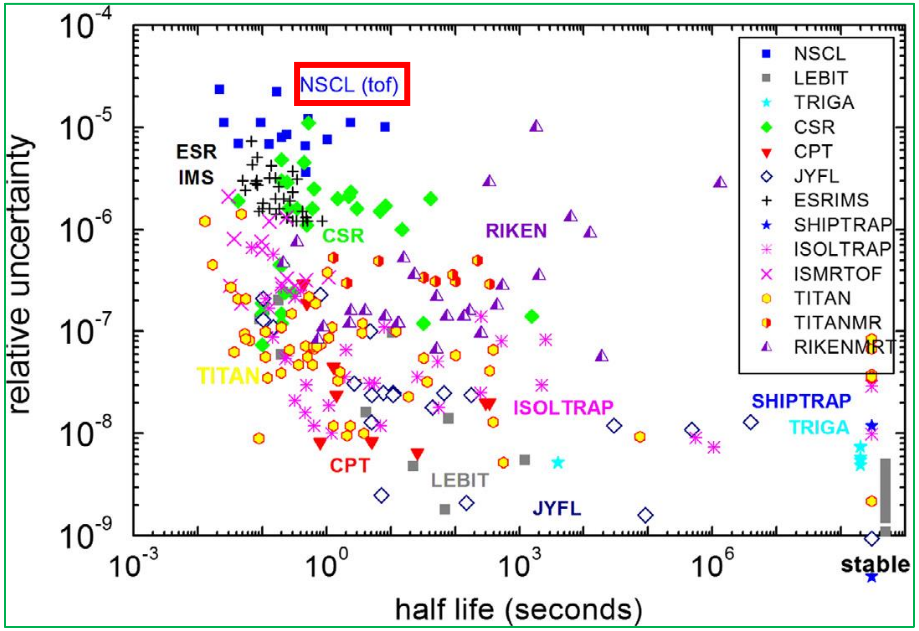
Outline

- ToF-Bρ mass measurement technique
- Tests for the plastic scintillation detectors
- Mass measurement around ^{112}Mo
- Summary

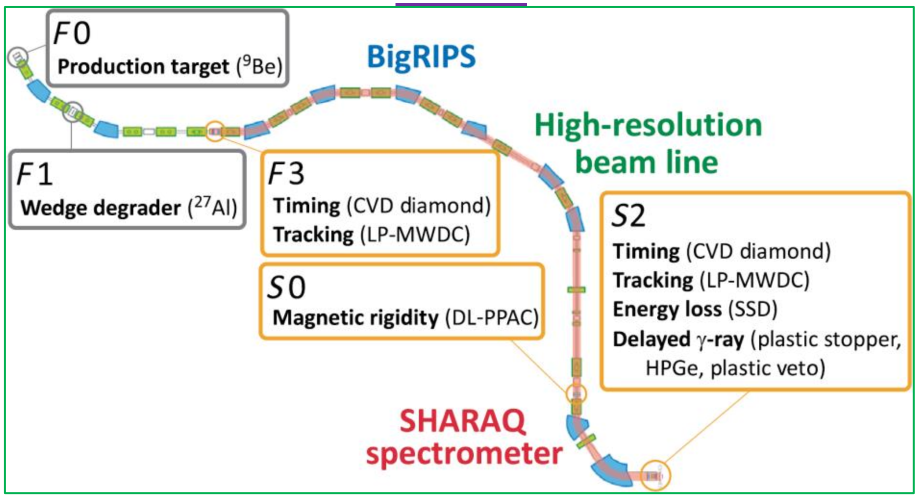
Mass measurement techniques



T. Yamaguchi et al., PPNP 120, 103882 (2021)

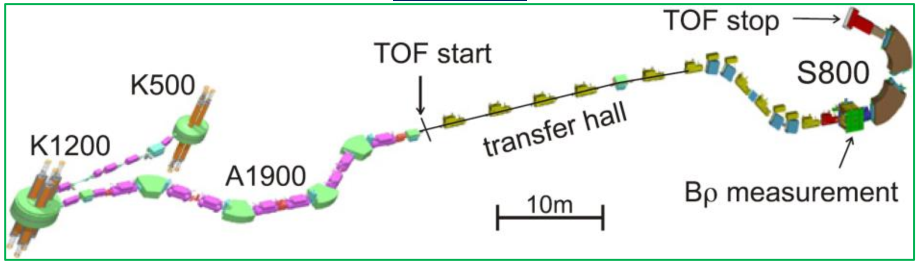


RIKEN



S. Michimasa et al., PRL 121, 022506 (2018)

NSCL



M. Matos et al., NIMA 696, 171 (2012)

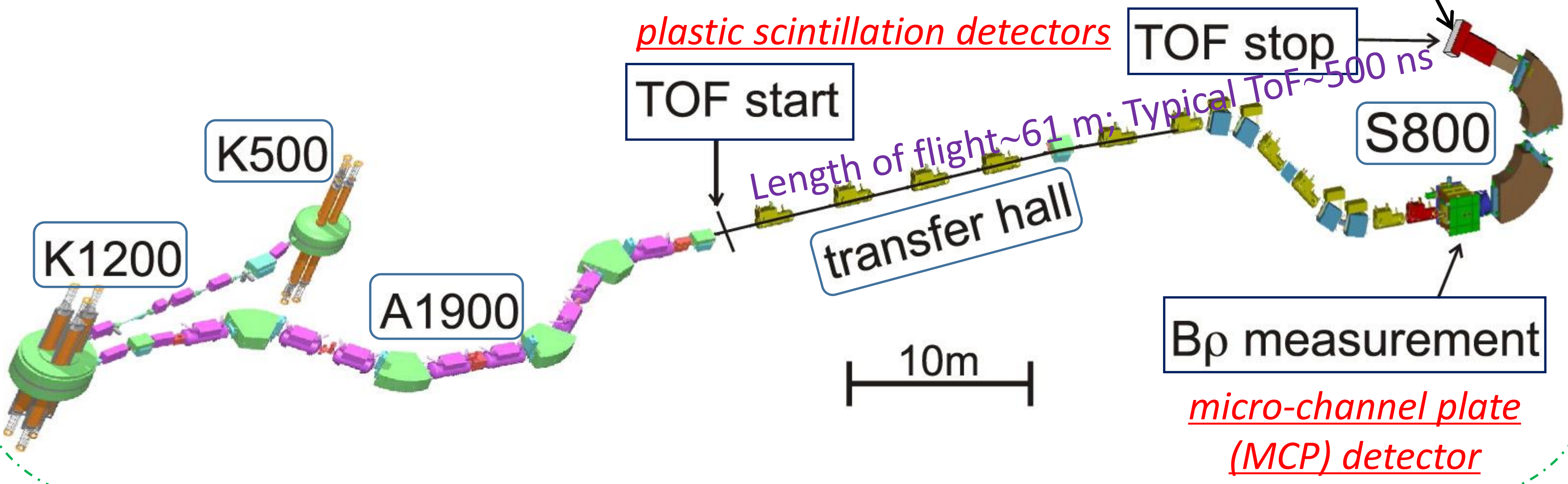
ToF-Bρ technique at NSCL

Ancillary Detectors:

2 CRDC detectors (measure position in ToF stop)

Silicon or Ionization chamber detectors (measure energy of fragments)

Hodoscope (CsI(Na), measure gamma rays emitted from isomers)

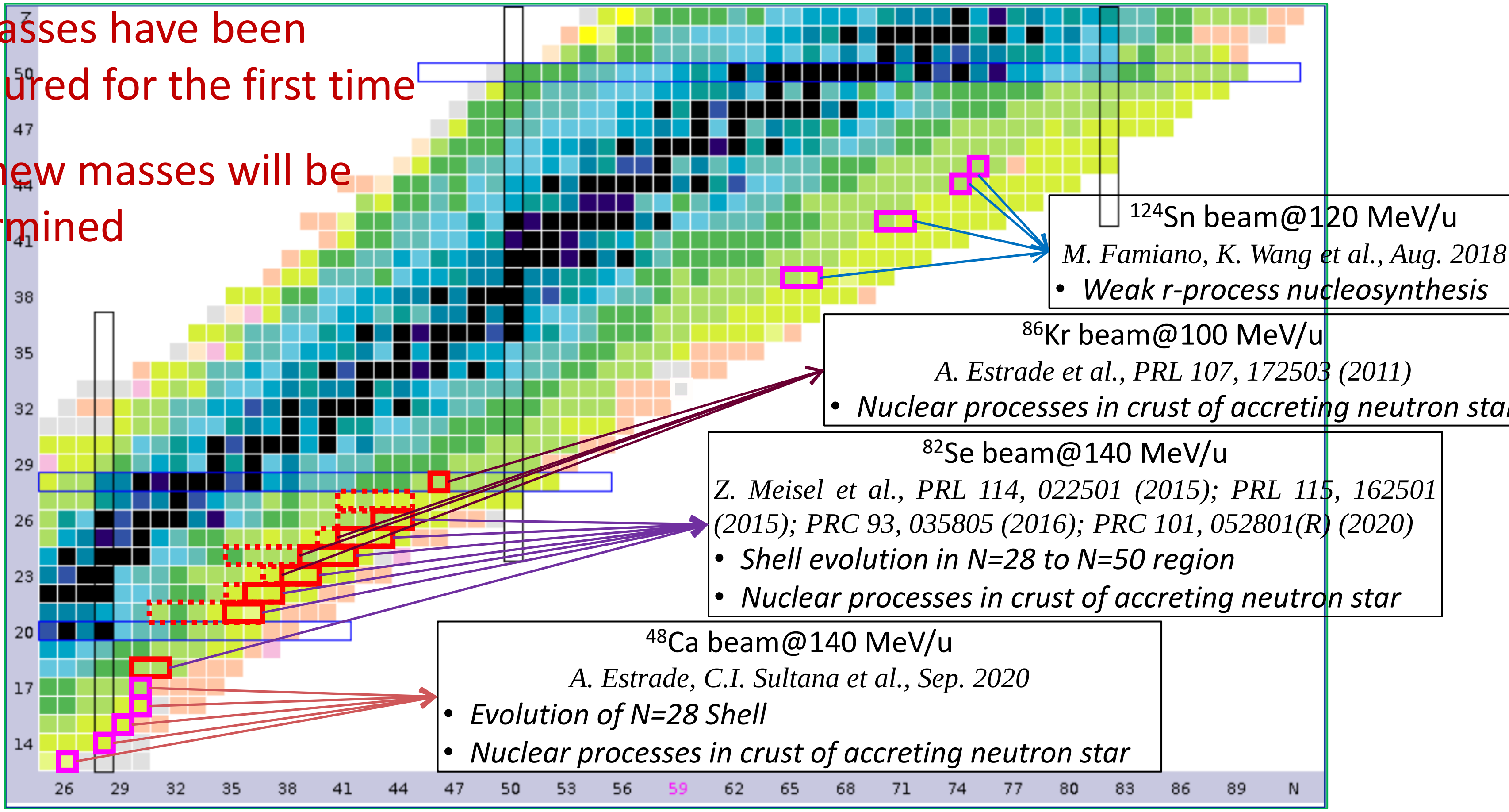


$$m = qB\rho \cdot \sqrt{\left(\frac{T}{L}\right)^2 - \frac{1}{c^2}}$$

Applicable to the very short-lived nuclei with very low yields

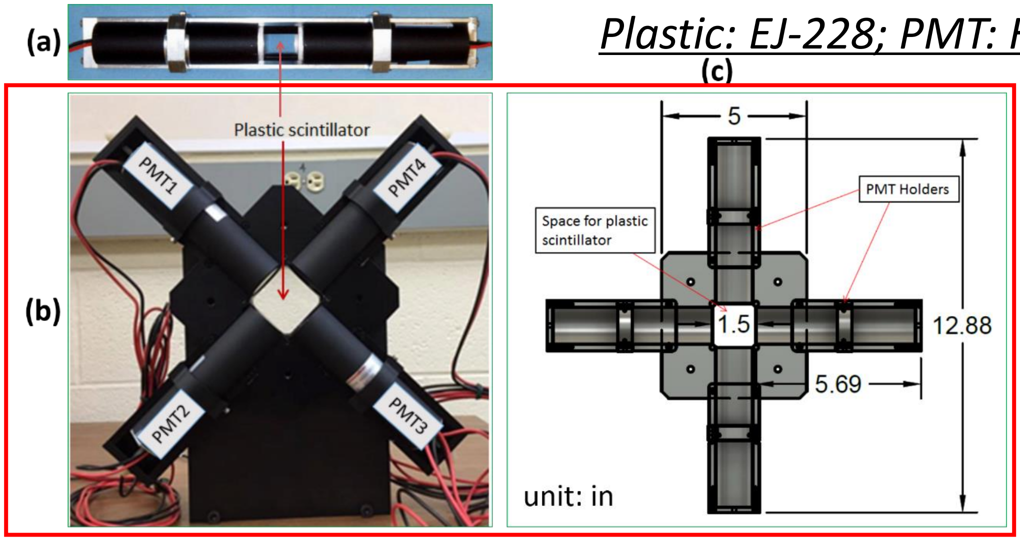
Conducted experiments

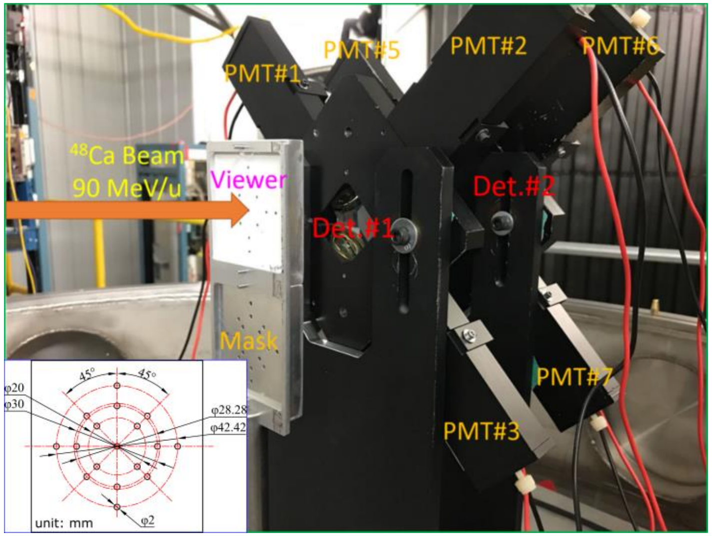
- 17 masses have been measured for the first time
- ~10 new masses will be determined

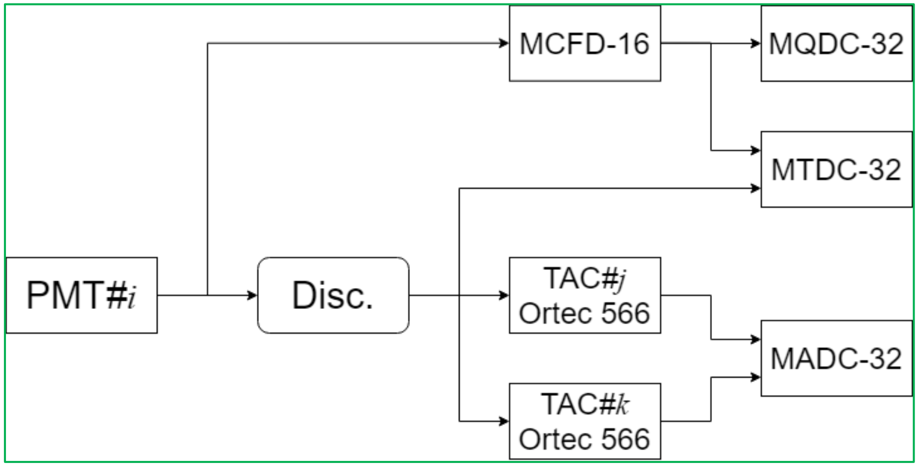


Test plastic scintillation detectors

Plastic: EJ-228; PMT: H6533





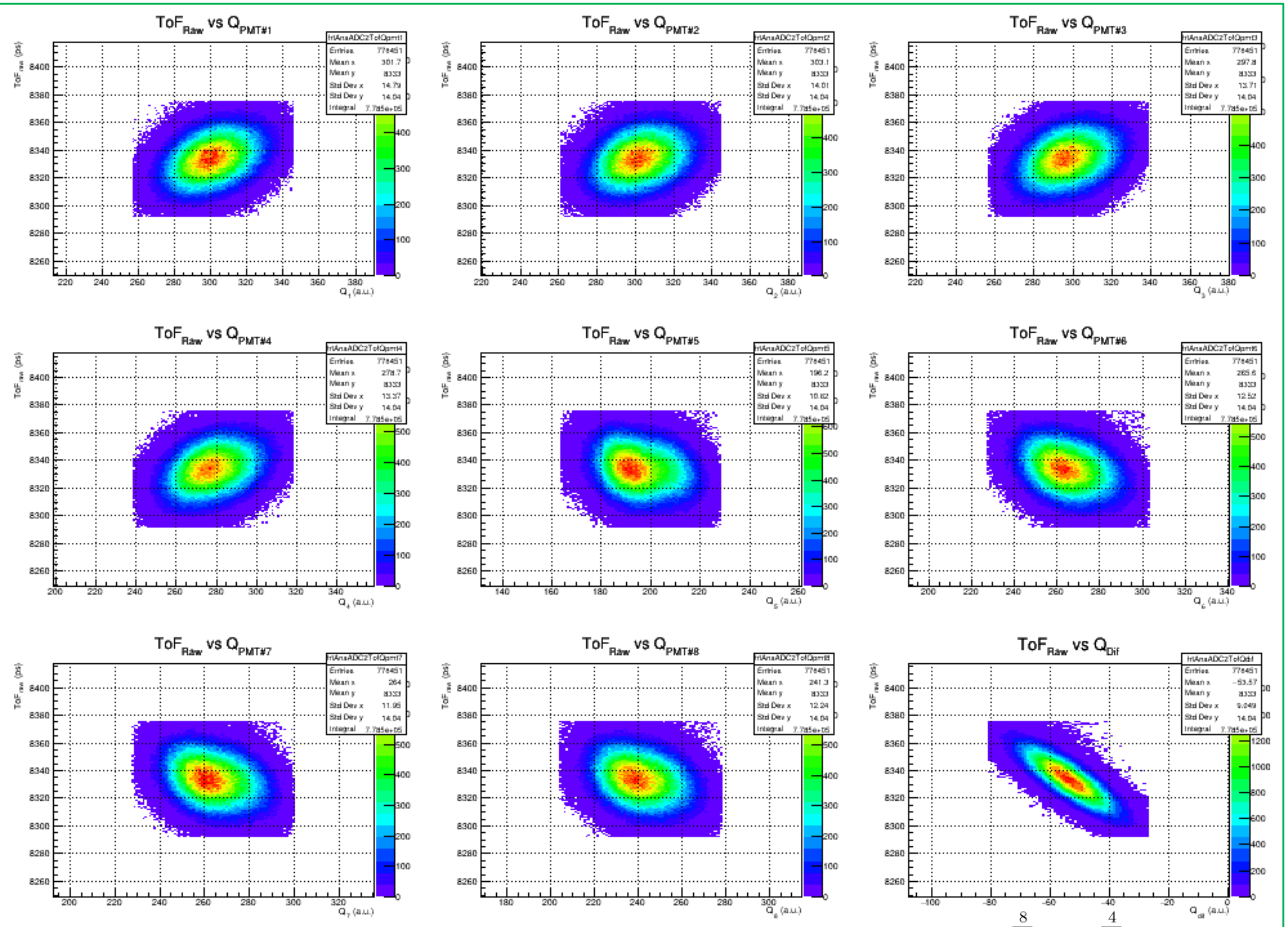


$$ToF = \frac{\sum_{i=5}^{8} T_i}{4} - \frac{\sum_{i=1}^{4} T_i}{4}$$

- Investigate the ToF resolutions with different electronics and beam conditions
  - Time-walk correction
- Explore the positioning capability of this detector

K. Wang, A. Estrade et al., NIMA, 974, 164199 (2020)

Time-walk correction



$$\Delta Q = \frac{\sum_{i=5}^{8} Q_i}{4} - \frac{\sum_{i=1}^{4} Q_i}{4}$$

$$ToF_{\text{corr}}^{(j)} = ToF_{\text{raw}}^{(j)} + \Delta_{ToF}^{(j)}$$

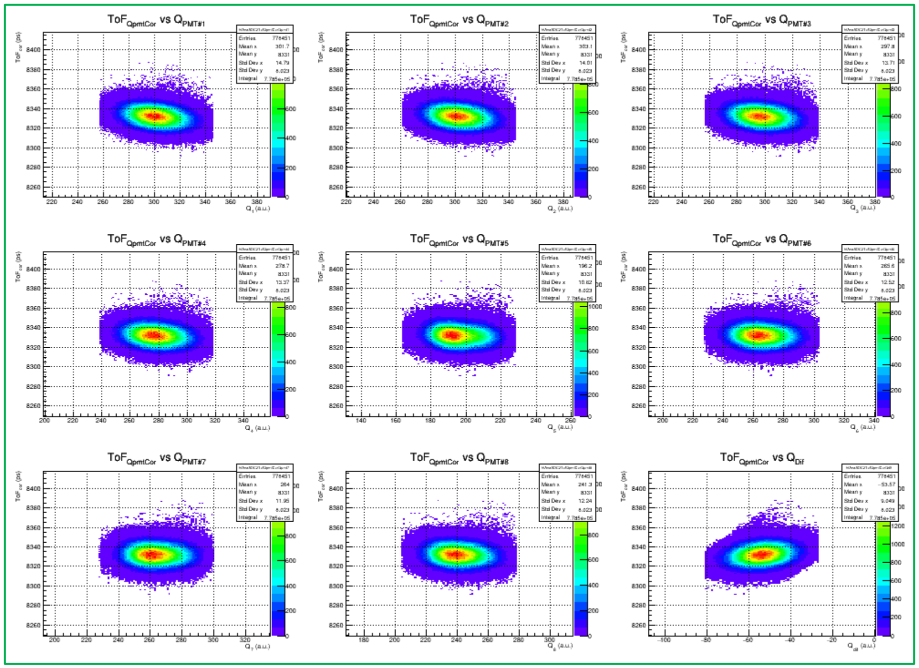
$$\Delta_{ToF}^{(j)} = ToF_{\text{pivot}} - f_{ToF_{raw}}(\mathbf{Q}^{(j)})$$

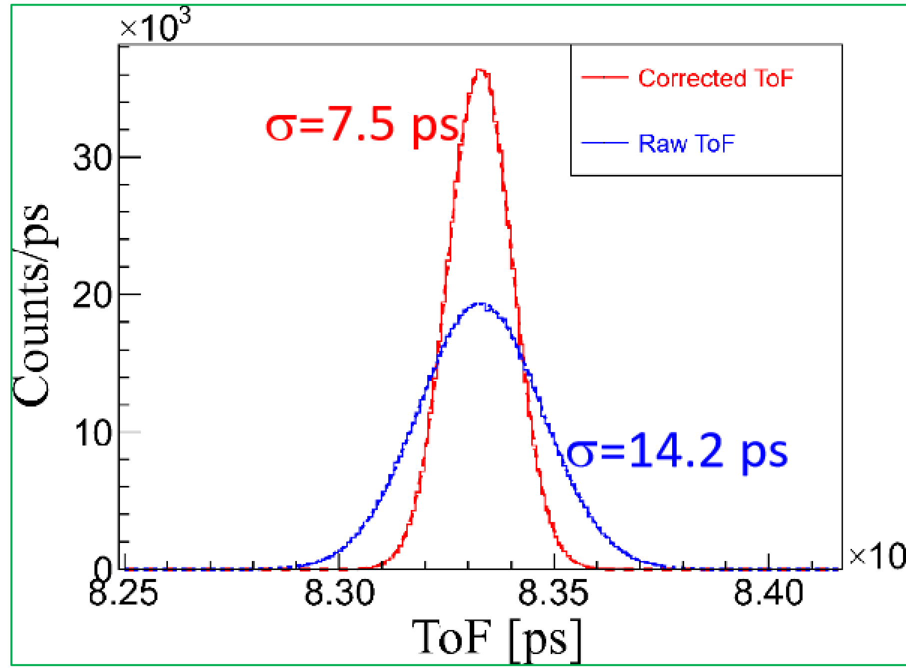
$$f_{ToF_{raw}}(\mathbf{Q}^{(j)}) = c_0 + \sum_{i=1}^{8} c_i \cdot Q_i^{(j)}$$

- $ToF_{corr}^{(j)}$: corrected ToF of j^{th} event
- $ToF_{raw}^{(j)}$: raw ToF of j^{th} event
- $\Delta_{ToF}^{(j)}$: correction value of j^{th} event
- $f_{ToF_{raw}}$, c_i: fitting ToF_{raw} as a linear function of all PMT amplitudes **Q** with parameters c_i
- Q_i^j: amplitude of i^{th} PMT of j^{th} event
- ToF_{pivot}: pivot ToF, constant for all events

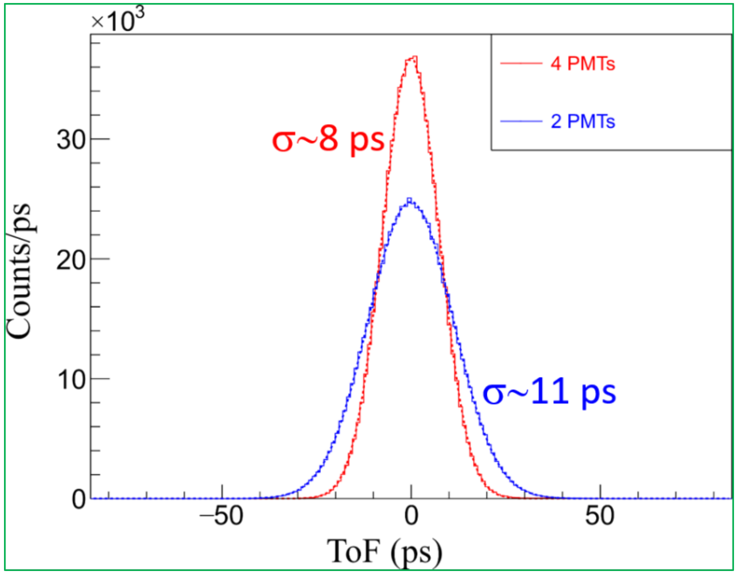
$$ToF_{\text{pivot}} = f_{ToF}(\overline{\mathbf{Q}}) = c_0 + \sum_{i=1}^{8} c_i \cdot \overline{Q_i}$$

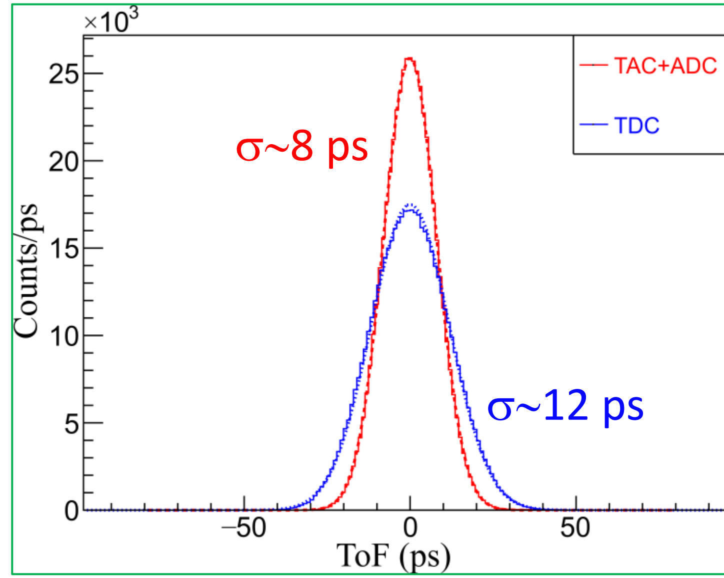
After time-walk correction

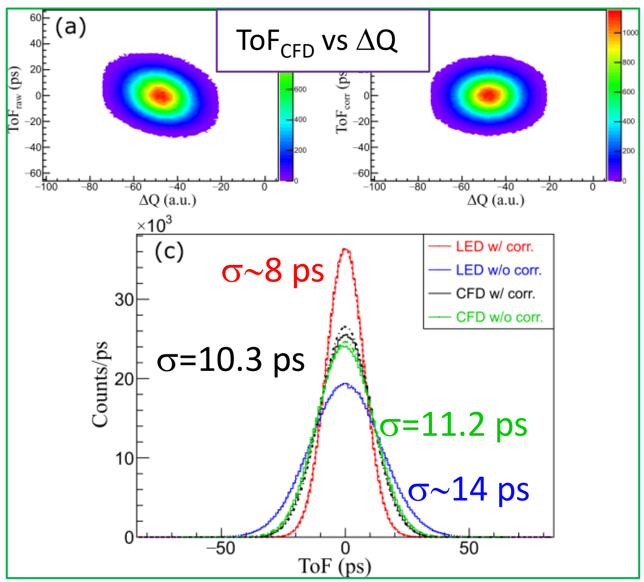




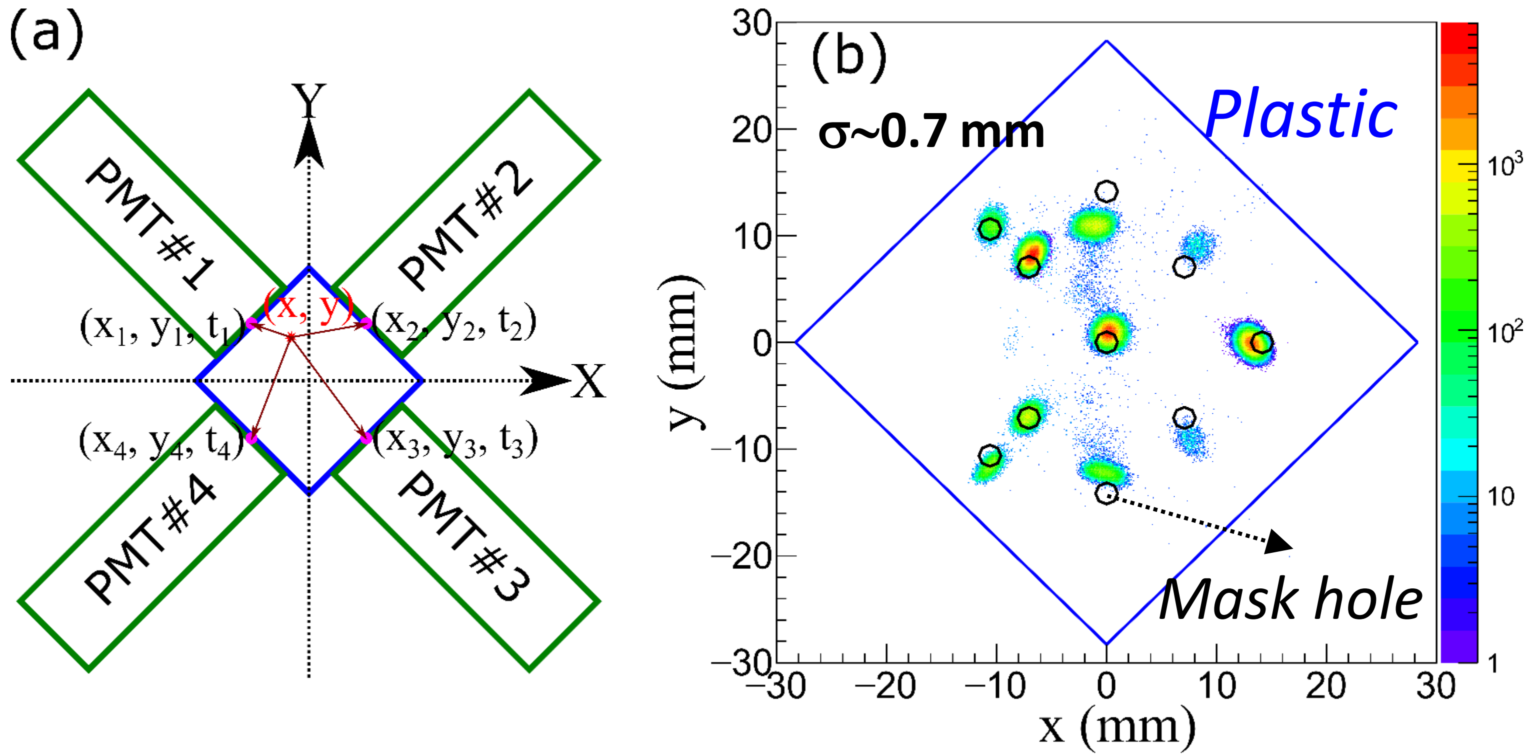
Comparison of ToF resolutions







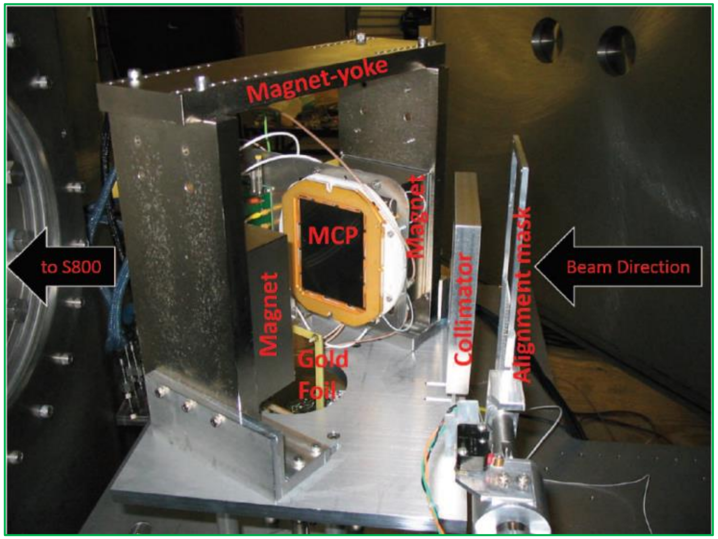
Positioning capability



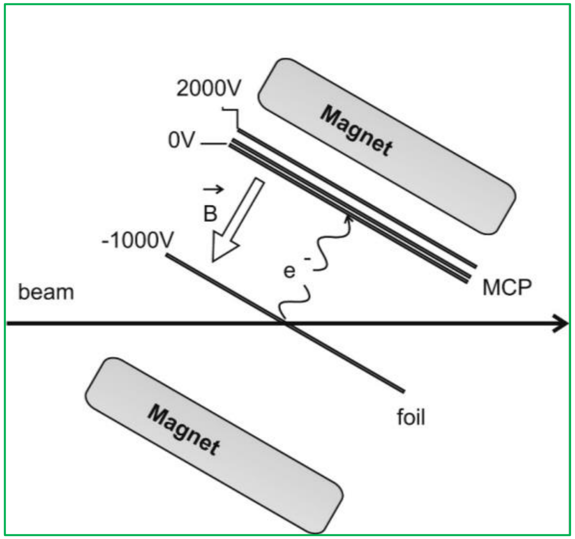
Calibrate positions using a mask

$$x_{\rm raw} = t_1 - t_2 + t_4 - t_3$$
$$y_{\rm raw} = t_4 - t_1 + t_3 - t_2$$

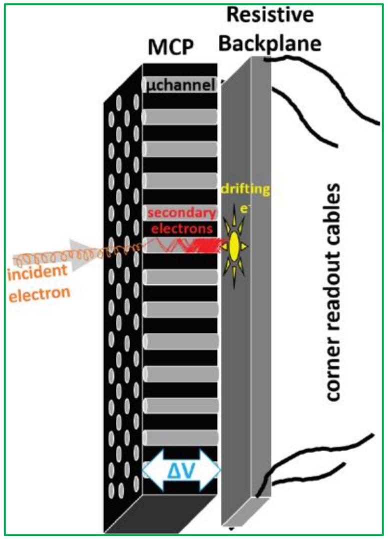
$$x_{\rm cal} = a_0 + a_1 x_{\rm raw} + a_2 y_{\rm raw} + a_3 x_{\rm raw}^2 + a_4 x_{\rm raw} y_{\rm raw} + a_5 y_{\rm raw}^2$$
$$y_{\rm cal} = b_0 + b_1 x_{\rm raw} + b_2 y_{\rm raw} + b_3 x_{\rm raw}^2 + b_4 x_{\rm raw} y_{\rm raw} + b_5 y_{\rm raw}^2$$



Z. Meisel, PhD thesis (2015)

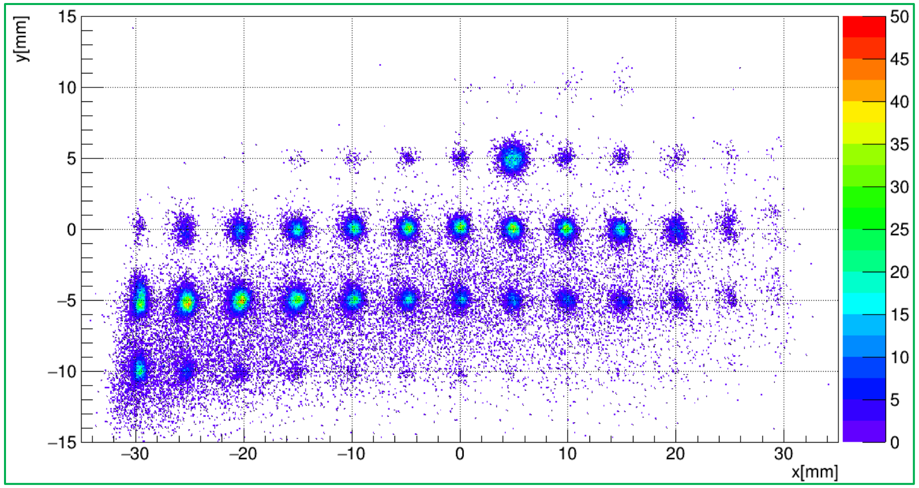


M. Matos et al., NIMA 696, 171 (2012)

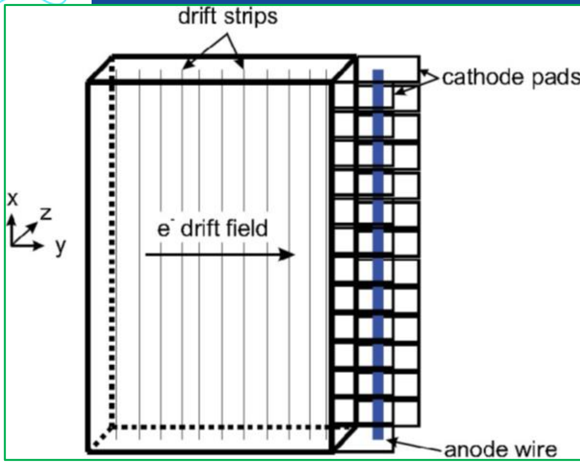


Z. Meisel, PhD thesis (2015)

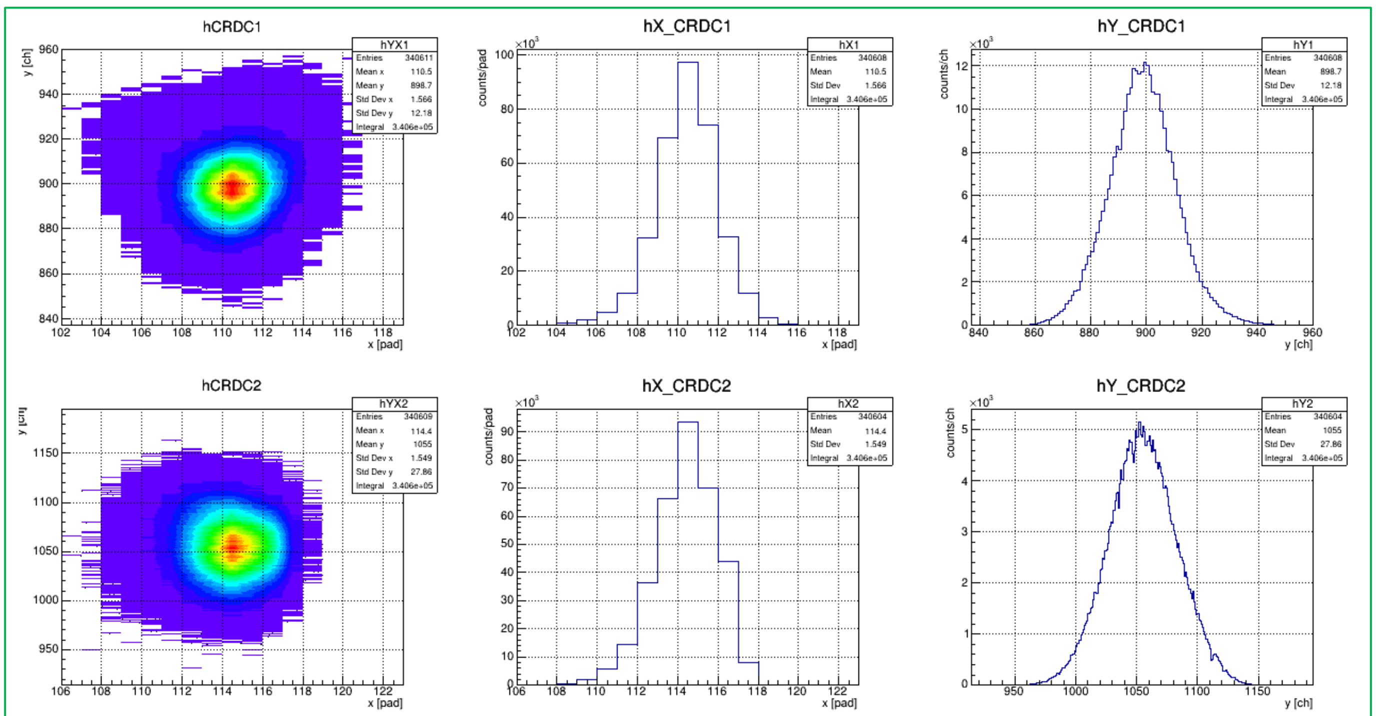
- Beam position in foil can be derived from the difference between the charges in four corners of the backplane
- With the 1st order approximation, $B\rho = B\rho_0(1+\Delta P/P) \cong B\rho_0(1+x/D)$, x as the dispersive direction, D is the dispersion function (107 mm/%)
- Position resolution $\sigma_x \sim 0.7$ mm giving $\sigma_{B\rho}/B\rho \sim 6\times10^{-5}$



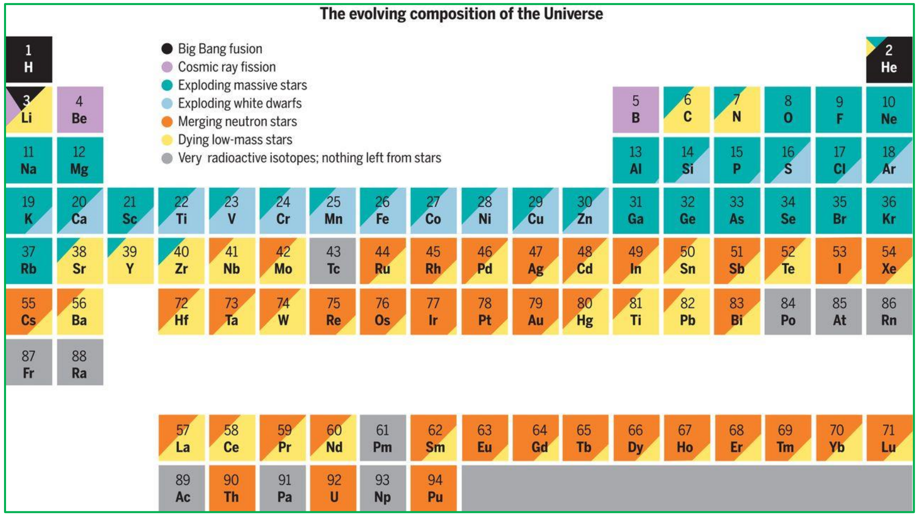
CRDC(Cathode Readout Drift Chamber) detectors



- **Y** (non-dispersive direction): drift time of electrons to anode wire
- **X** (dispersive direction): charge (induced by electrons on anode) distribution on 256 cathode pads: $X = \frac{\sum_{i=1}^{256} i \cdot E_i}{\sum_{i=1}^{256} E_i}$

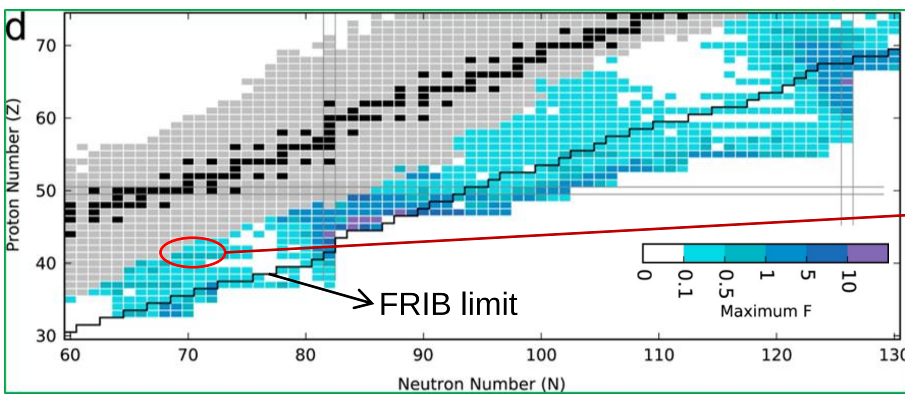


Mass measurement around ^{112}Mo



J. Johnson, Science 363, 474 (2019)

- Elements from Iron to Uranium are mainly made by neutron-capture processes
  - slow neutron-capture process (s-process): Dying low-mass stars
  - rapid neutron-capture process (r-process): Merging neutron stars



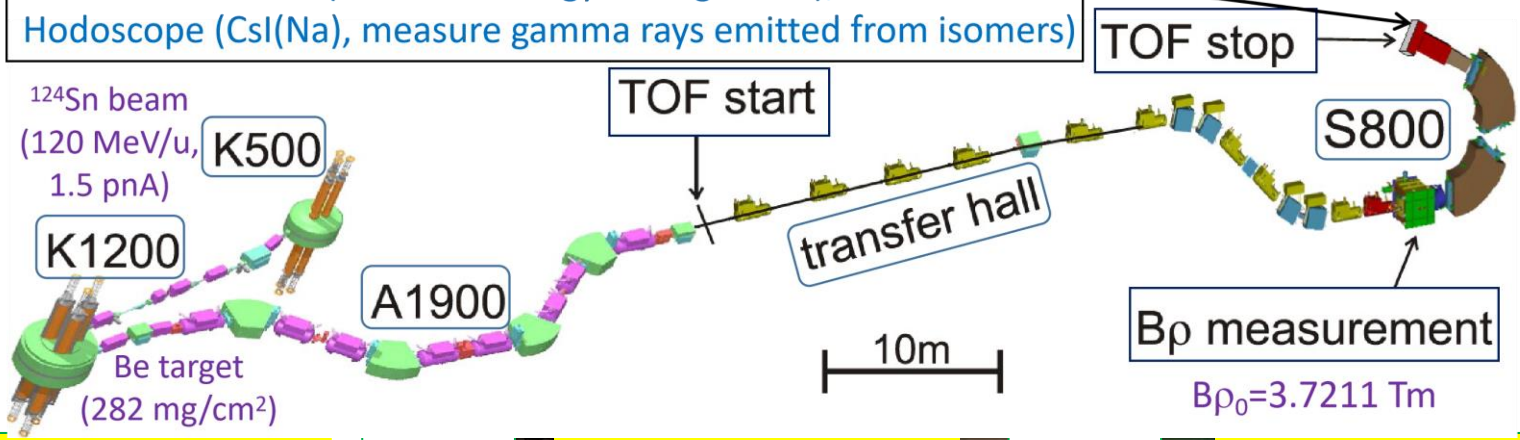
M. Mumpower et al., PPNP 86, 86 (2016)

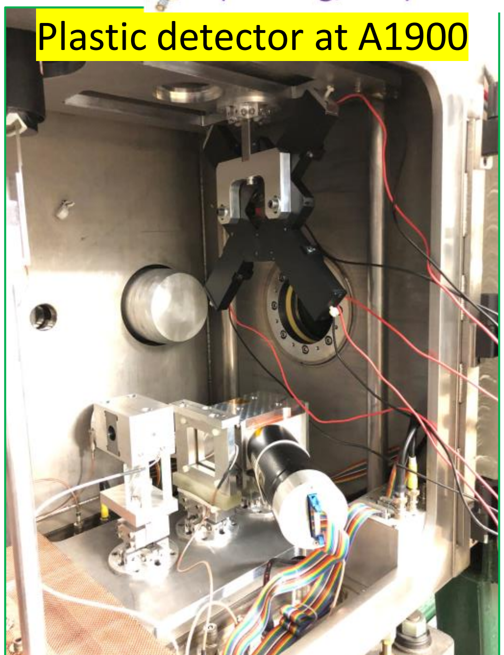
Measuring the masses of nuclei from Zr to Ru around N=70 can offer the better predictive masses of nuclei in r-process path

Experimental setup

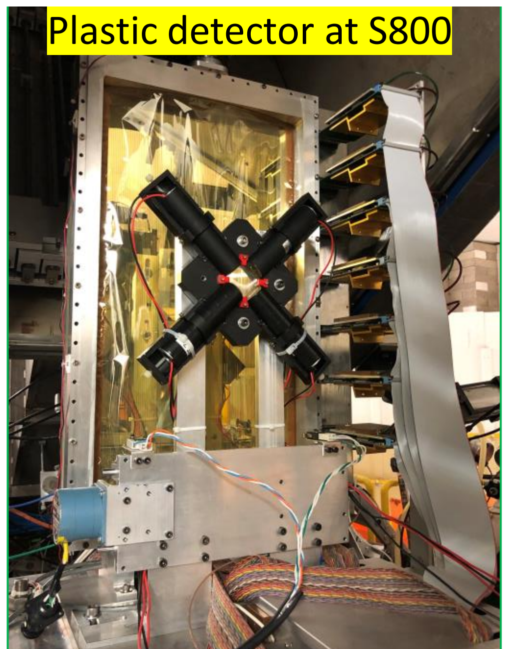
2 CRDC detectors (measure position);
5 silicon detectors (measure energy of fragments);
Hodoscope (CsI(Na), measure gamma rays emitted from isomers)

Aug. 2018

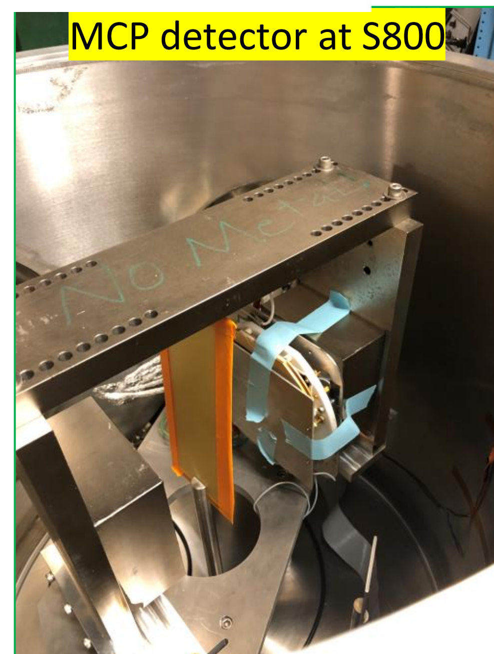




Plastic detector at A1900



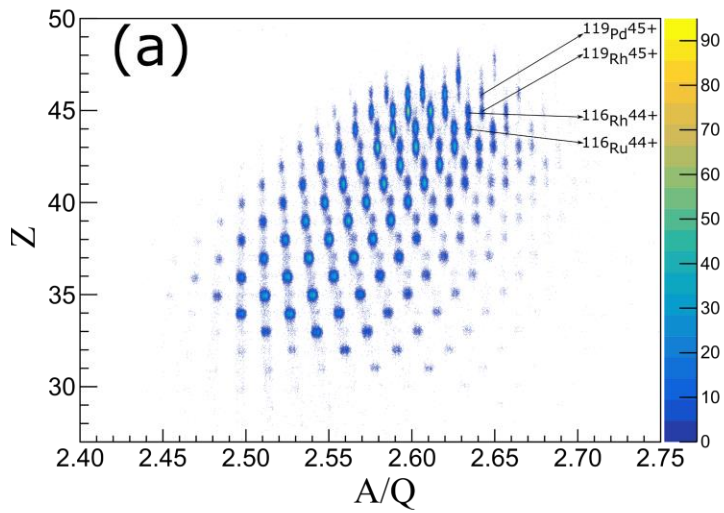
Plastic detector at S800



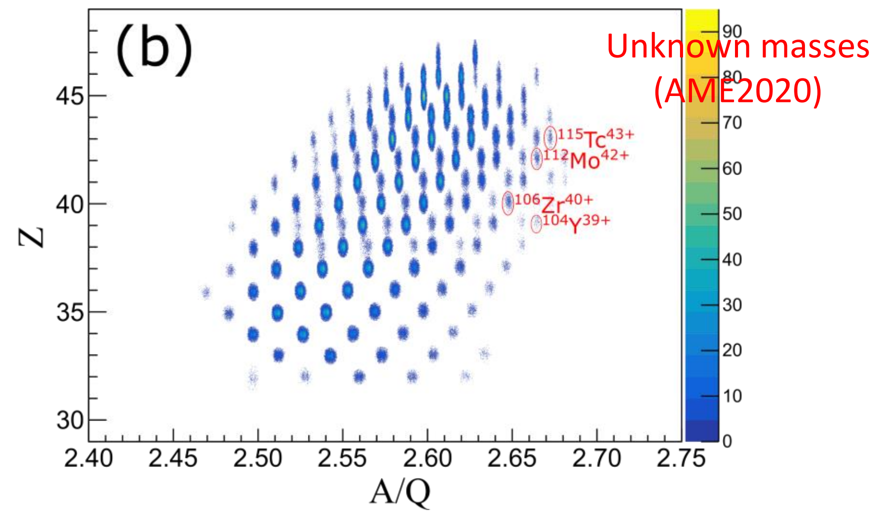
MCP detector at S800

Z-A/Q PID plots

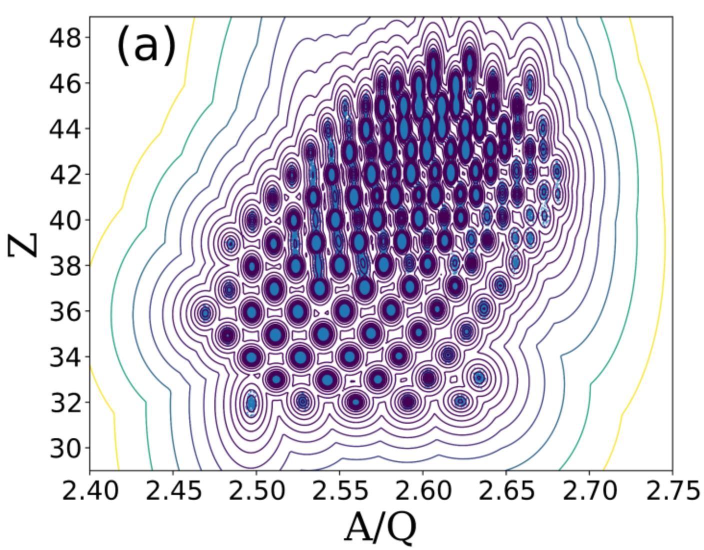
Original PID

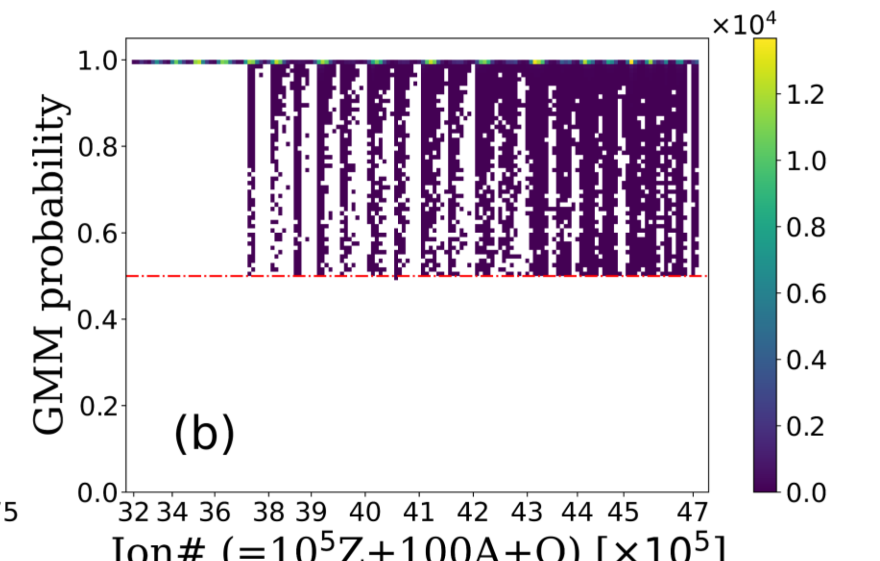


PID using GMM



Gaussian-mixture model for clustering





Mass fit: event-by-event

$$\frac{m}{q} = p_0 + \sum_{i=1}^{8} p_i \cdot x_i + \sum_{i,j=1}^{8} p_{ij} \cdot x_i x_j + \sum_{i,j,k=1}^{8} p_{ijk} \cdot x_i x_j x_k$$

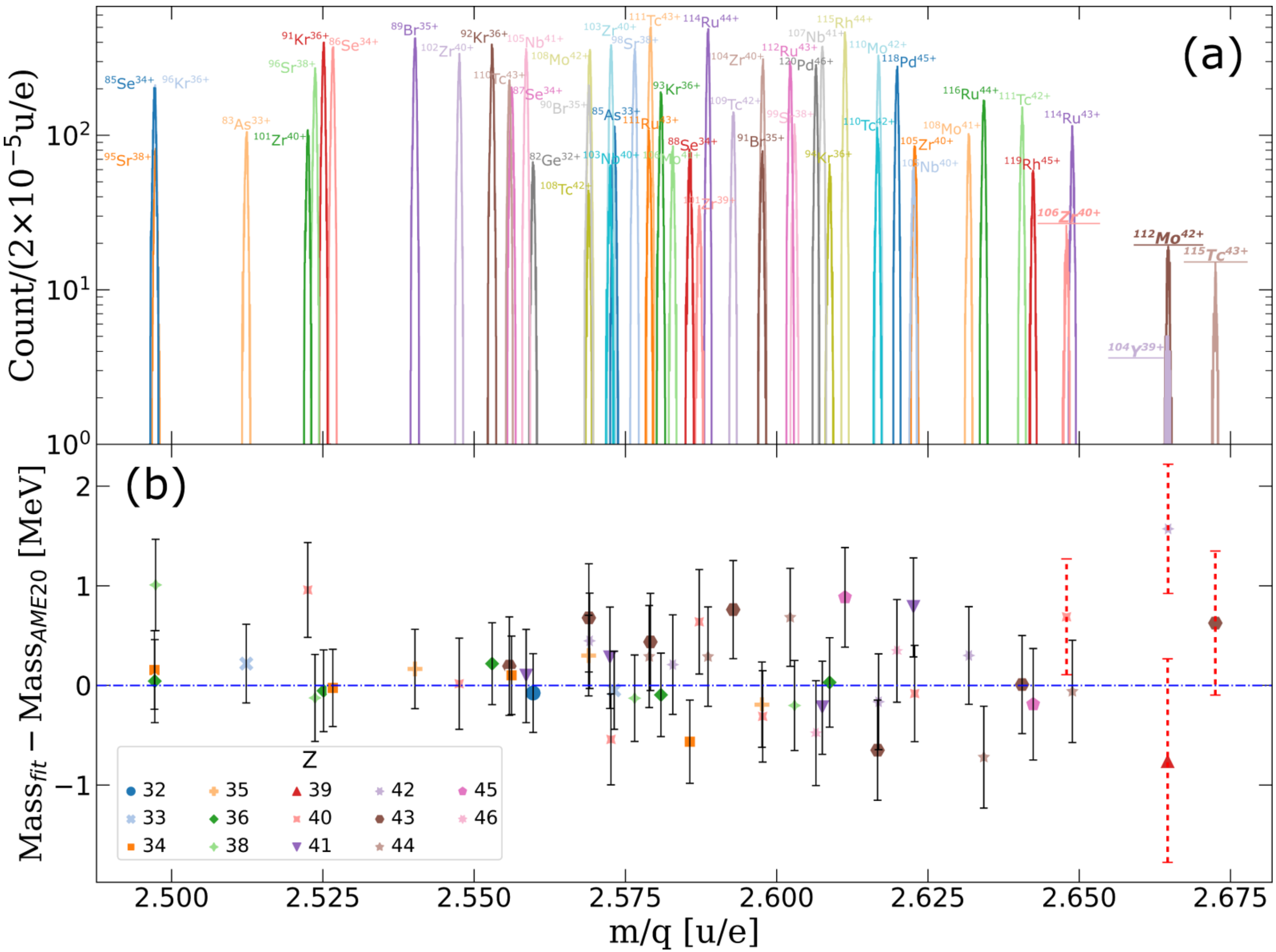
$$x_1 = ToF_{\mathrm{raw}},\ x_2 = Z,\ x_3 = X_{\mathrm{MCP}},\ x_4 = Y_{\mathrm{MCP}},\ x_5 = X_{\mathrm{CRDC1}},$$
$$x_6 = Y_{\mathrm{CRDC1}},\ x_7 = X_{\mathrm{CRDC2}},\ x_8 = Y_{\mathrm{CRDC2}}$$

- 48 reference ions were selected from AME2020 with uncertainty of 2—25 keV without high-energy (>100 keV) isomers
- 300,000 events were used in the fit to obtain 165 parameters p_i
- M/Q for one kind of ion will be the weighted average of all the fitted m/q belonging to this ion
- **Statistical error**: the resolution of m/q distribution for each ion~9.0×10^{-5}, then the error is obtained as **~3.5 keV/e** (**~140 keV** for mass uncertainty)
- **Literal error**: σ^{lit} taken from AME2020
- **Systematic error**: using leave-one-out cross-validation with the event-by-event fit on the reference ions to achieve

$$1-\sqrt{2/N} < \frac{1}{N}\sum_{j=1}^{N} \frac{\left(M/Q_j^{\mathrm{CV}} - M/Q_j^{\mathrm{lit}}\right)^2}{\left(\sigma_j^{\mathrm{statCV}}\right)^2 + \left(\sigma_j^{\mathrm{lit}}\right)^2 + \left(\sigma^{\mathrm{syst}}\right)^2} < 1+\sqrt{2/N}$$

where N=48. Then $\boldsymbol{\sigma^{\mathrm{syst}}}$ **= 10 keV/e**.

Results



Summary

- Plastic scintillation detectors with traditional electronics were tested using nuclear beam at NSCL.
- Conducted the first experiment of ToF-Bρ mass measurement at the NSCL for the r-process and measured 4 new masses.

A. Estrade, M. Barber, T. Chapman, D. McClain, N. Nepal, S. Samaranayake, C.I. Sultana, G. Zimba

K.L. Wang

M. Famiano, K. Bhatt, B. Famiano, J. Jenkins, L. Klan

Z. Meisel

A. Rogers, J. Dopfer, M. Giles

S. George

H. Schatz, T. Baumann, D. Bazin, T. Ginter, S. Jin, S. Liddick, J. Pereira, N. Rijal, O. Tarasov

Thanks for your attention!