Reaction Experiments with Exotic Beams

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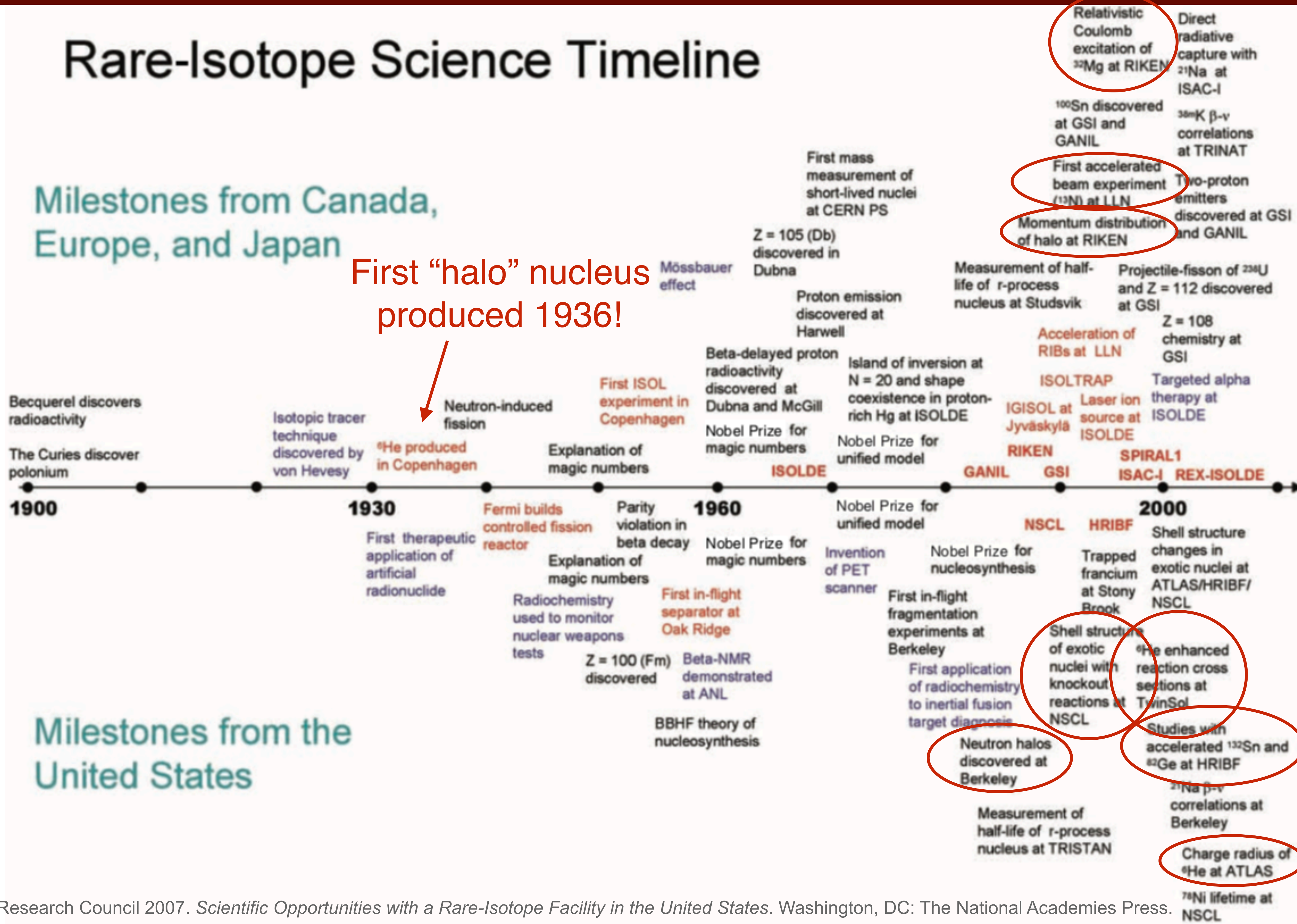
Exotic Beams Summer School 2019
Oak Ridge, TN

Outline of these lectures

- few basics of reaction experiments
- different reaction types
- production of exotic beams for reaction experiments
- some experimental considerations
- example reaction experiments with exotic beams

Some Reaction Milestones (NAS report 2007)



National Research Council 2007. *Scientific Opportunities with a Rare-Isotope Facility in the United States*. Washington, DC: The National Academies Press.

Example: $^{13}N(p,\gamma)^{14}O$: one reaction, many methods!

VOLUME 67, NUMBER 7 PHYSICAL REVIEW LETTERS 12 AUGUST 1991

Determination of the $^{13}N(p,\gamma)\,^{14}O$ Reaction Cross Section Using a ^{13}N Radioactive Ion Beam

PHYSICAL REVIEW C VOLUME 48, NUMBER 6 DECEMBER 1993

Investigation of the $^{13}N(p,\gamma)^{14}O$ reaction using ^{13}N radioactive ion beams

Volume 264, number 3,4 PHYSICS LETTERS B 1 August 1991

1: Direct measurement with intense ^{13}N beam

Determination of the astrophysical $^{13}N(p,\gamma)^{14}O$ cross section through the Coulomb dissociation method

2: Coulomb dissociation of ^{14}O beam

PHYSICAL REVIEW C **69**, 055807 (2004)

Determination of the direct capture contribution for $^{13}N(p,\gamma)^{14}O$ from the $^{14}O \rightarrow {}^{13}N+p$ asymptotic normalization coefficient

3: Heavy ion proton transfer using $^{14}N(^{13}N,^{14}O)^{13}C$

ELSEVIER Physics Letters B 650 (2007) 129–134 www.elsevier.com/locate/physletb

Single-particle resonance levels in ^{14}O examined by $^{13}N+p$ elastic resonance scattering

4: Thick target resonance scattering of ^{13}N

PHYSICAL REVIEW C **74**, 035801 (2006)

$^{13}N(d,n)^{14}O$ reaction and the astrophysical $^{13}N(p,\gamma)^{14}O$ reaction rate

5: Transfer reaction $^{13}N(d,n)^{14}O$ in inverse kinematics

Physics motivation: ^{13}N(p,γ)^{14}O in stellar environment

J. Phys. G: Nucl. Part. Phys. **38** (2011) 024001 M Huyse and R Raabe

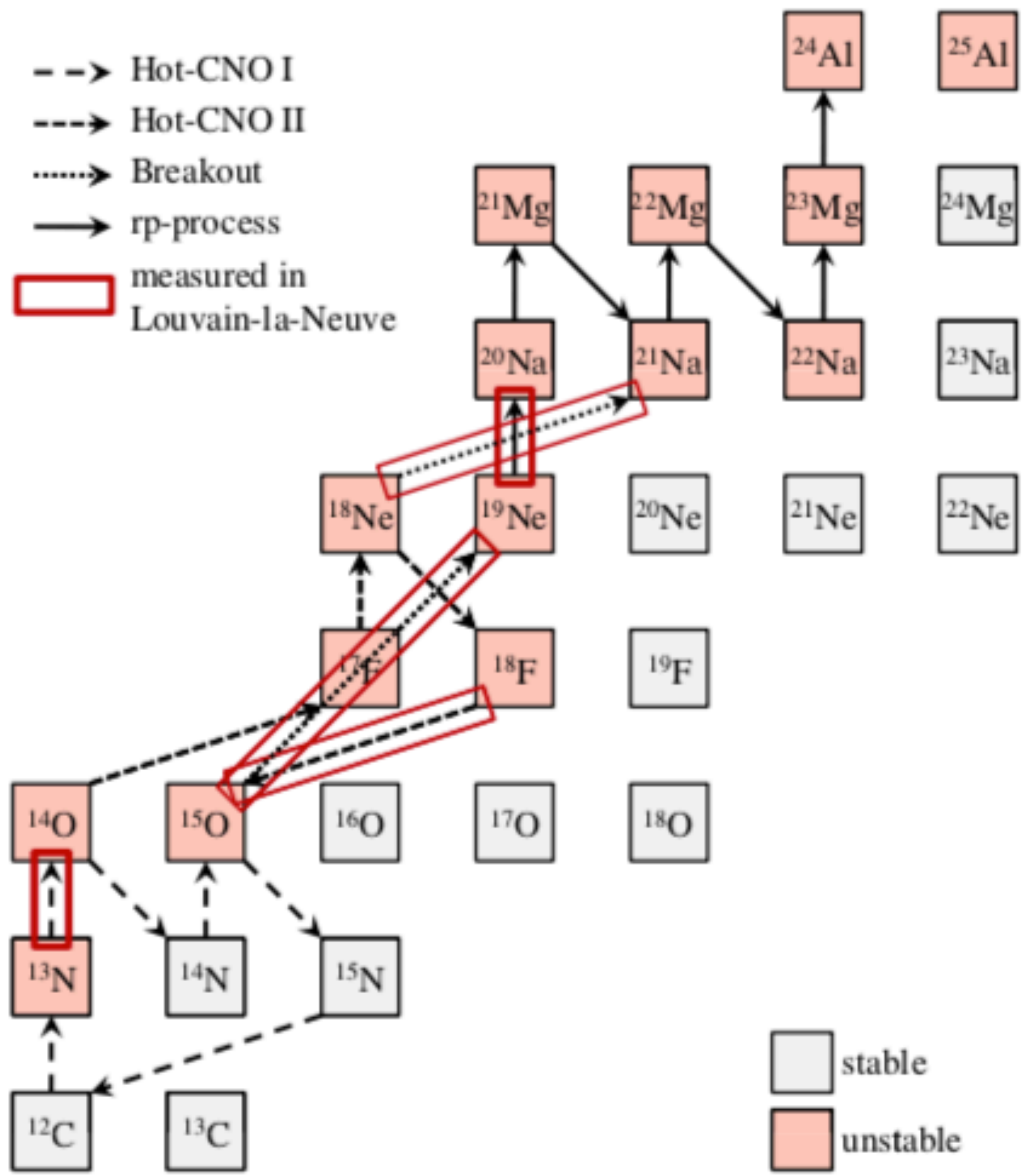


Figure 2. Portion of the chart of nuclei, with indication of the paths of the hot-CNO cycle (Hot-CNO I) and very-hot-CNO cycle (Hot-CNO II), with the possible escape routes. The reactions studied in Louvain-la-Neuve are highlighted.

1: Not only direct measurement of $^{13}N(p,\gamma)^{14}O$

VOLUME 67, NUMBER 7 PHYSICAL REVIEW LETTERS 12 AUGUST 1991

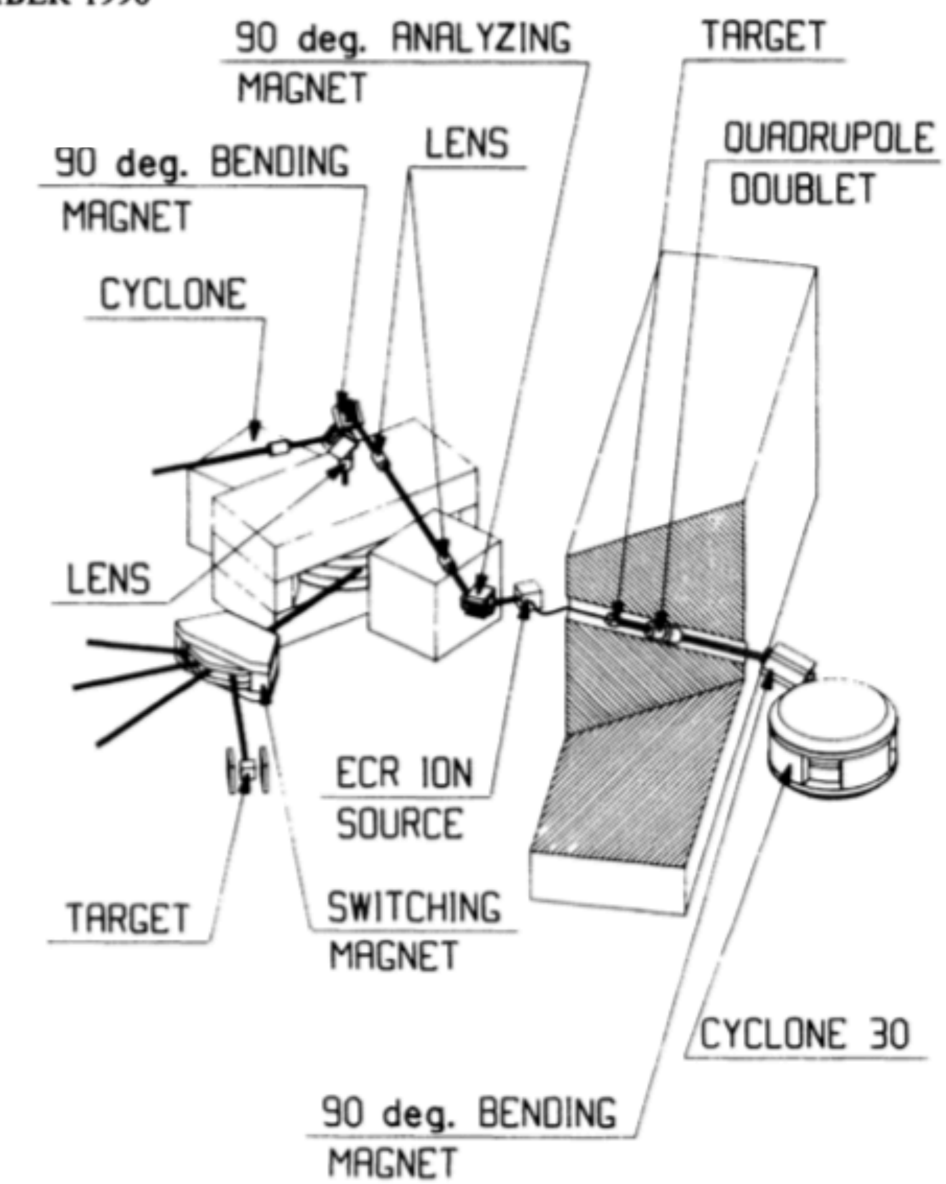
Determination of the $^{13}N(p,\gamma)\,^{14}O$ Reaction Cross Section Using a ^{13}N Radioactive Ion Beam

PID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 42, NUMBER 3 SEPTEMBER 1990

Production of intense radioactive ion beams using two accelerators

An intense beam (1.5×10^8 particles/sec) of radioactive $^{13}N^{1+}$ ions (half-life: $T_{1/2}=10$ min) has been produced and accelerated to 0.65 MeV/nucleon, by coupling two cyclotrons with an electron cyclotron resonance ion source. This is the first time a short-lived radioactive ion beam has been produced by this method, at such an energy and with such a high intensity, a result which opens up a wide field in many applications. The first experiment along these lines will be the measurement of the cross section for the nuclear reaction $^1H(^{13}N,\gamma)^{14}O$ which is the crucial reaction for the operation of the so-called hot CNO cycle in nuclear astrophysics.

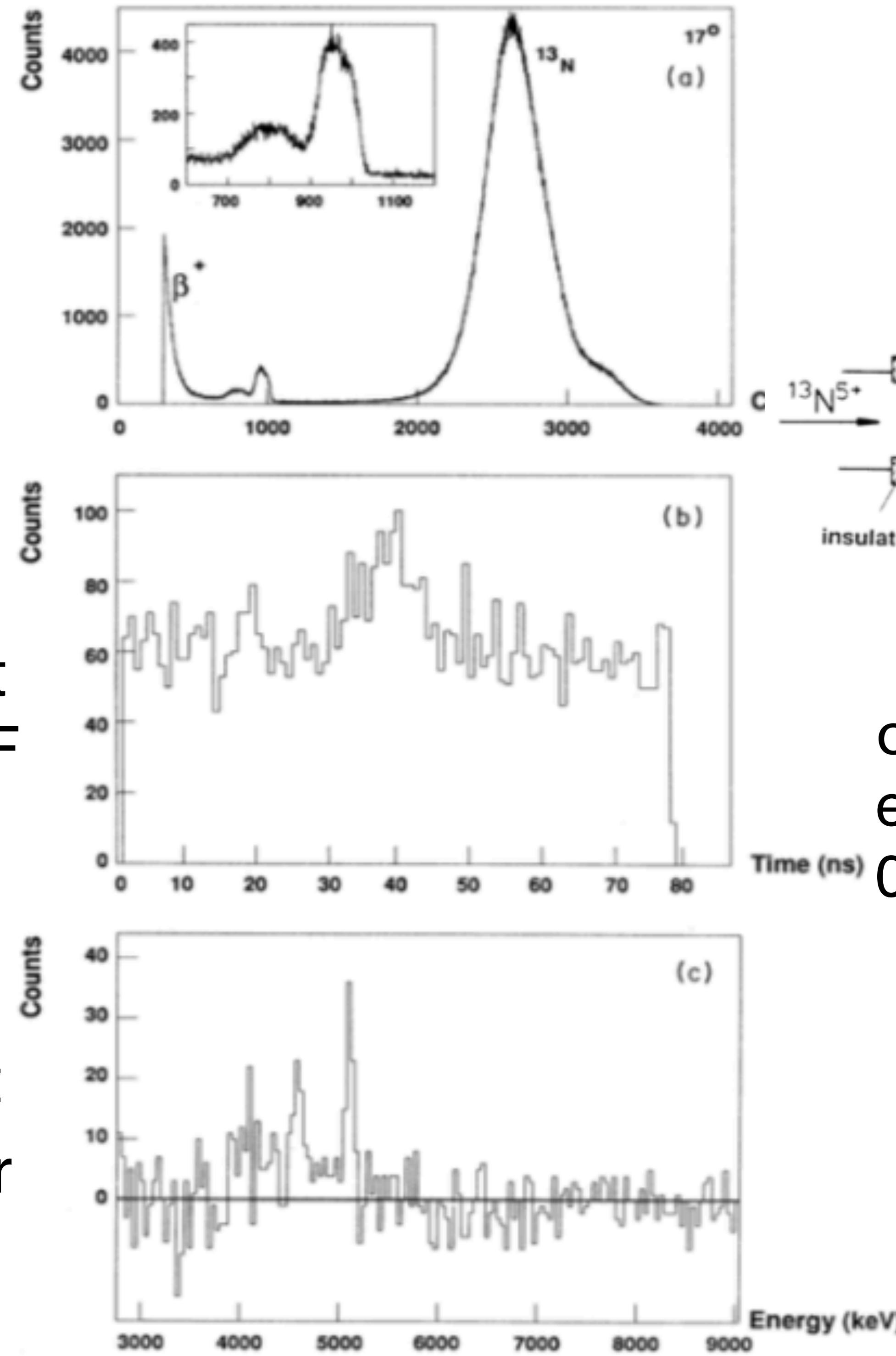


1: Direct measurement of $^{13}N(p,\gamma)^{14}O$

Si detector monitor 17° to beam

Time difference between Ge-det and cyclotron RF

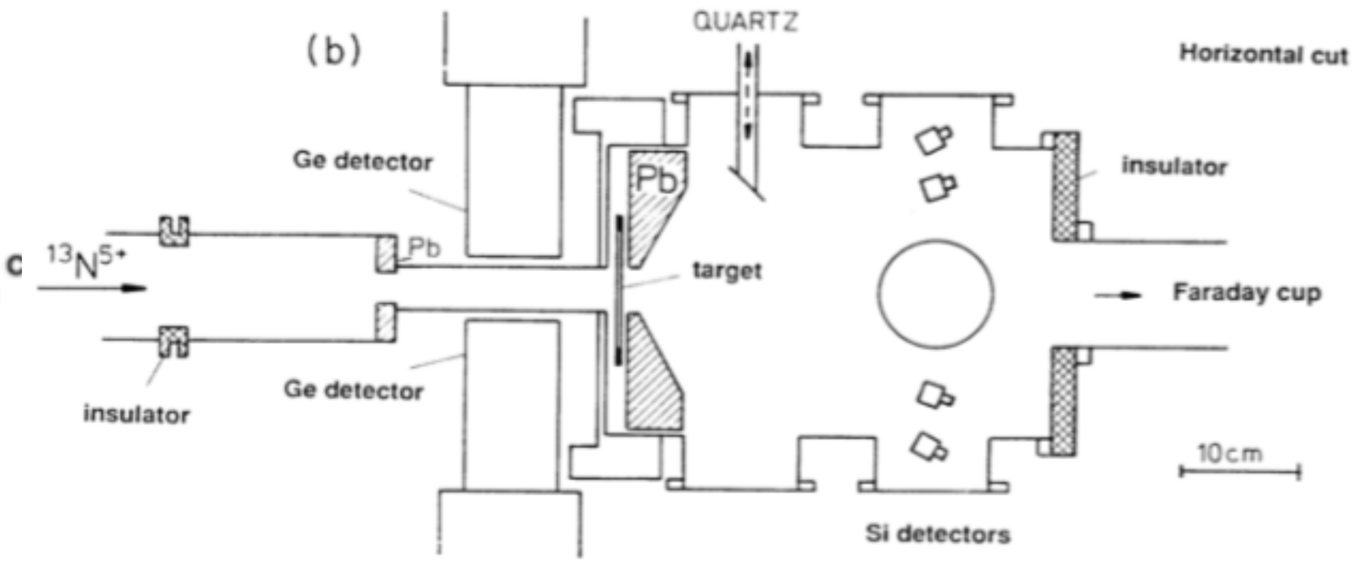
γ-measurement with Ge detector 129° to beam



$5.173 : {}^{14}O(1^-_1 \rightarrow g.s.)$

^{13}N: $2 \cdot 10^8$ pps, impurities < $1 \cdot 10^{-4}$

Target: $(CH_2)_n$, 180(18) ug/cm^2



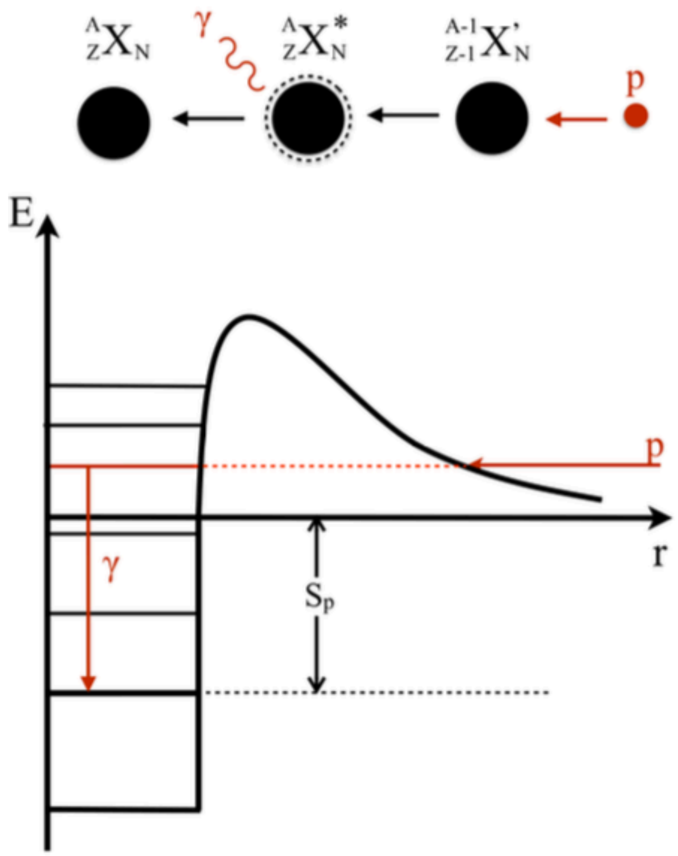
σ = 106 ± 22(stat) ± 20(syst) μb

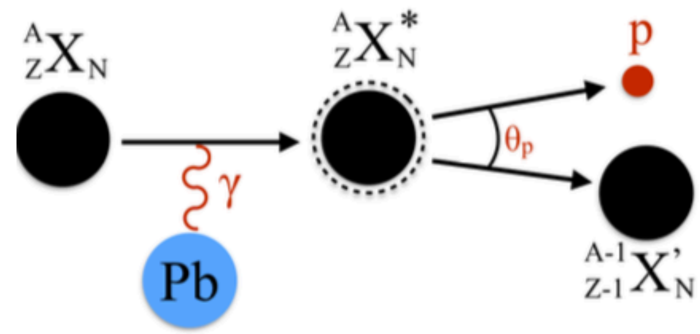
energy averaged over 5.8-8.2 MeV (lab), 0.414-0.586 MeV (cms)

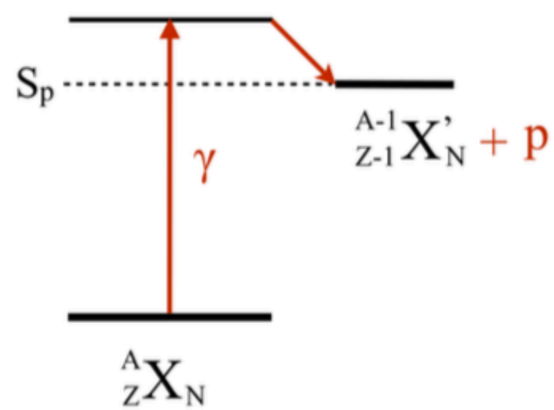
Γ_γ (eV)	Reference
3.8(1.2)	Present
2.44	5
1.9	6
1.2	7
1–10	8
4.1	9
2.7(1.3)	10
≤ 7.6(3.8)	11
$1.4(7)\sigma_{n_0}/\sigma_{n_1}$	12

PRL67, 808 (1991), PRC48, 3088 (1993)

2: Coulomb dissociation







From relativistic kinematics
Invariant mass:

$$M = \sqrt{(m_p c^2)^2 + (m_C c^2)^2 + 2W_p W_C \left(1 - \frac{v_p v_C}{c^2} cos\theta_{pC}\right)}$$

$$W_i = m_i c^2 + E_i$$

Relative angle between p and core

Relative energy of p and core

$$E_{rel} = M - (M_c + M_p) \approx E_p(\theta_p^{max})^2$$

Detailed balance theorem:

$$\sigma(\mathrm{b+c \rightarrow a+\gamma}) = \frac{(2j_a+1)2}{(2j_b+1)(2j_c+1)} \frac{k_\gamma^2}{k^2} \sigma(\mathrm{a+\gamma \rightarrow b+c})$$

Double differential cross section for Eλ:

$$\frac{d^2\sigma}{d\Omega \, dE_\gamma} = \left(\frac{Z_T e}{\hbar v}\right)^2 a^{-2\lambda+2} \frac{df_{E\lambda}(\theta, \xi)}{d\Omega} B(E\lambda, I_i \rightarrow I_f)\rho_f(E_\gamma)$$

Baur et al. NPA458, 188 (1986)

Max opening angles for given relative energy

$$\sin \Delta\theta_b^{max} \simeq \sqrt{(m_c/m_b)E_{bc}/E_0^{lab}}$$

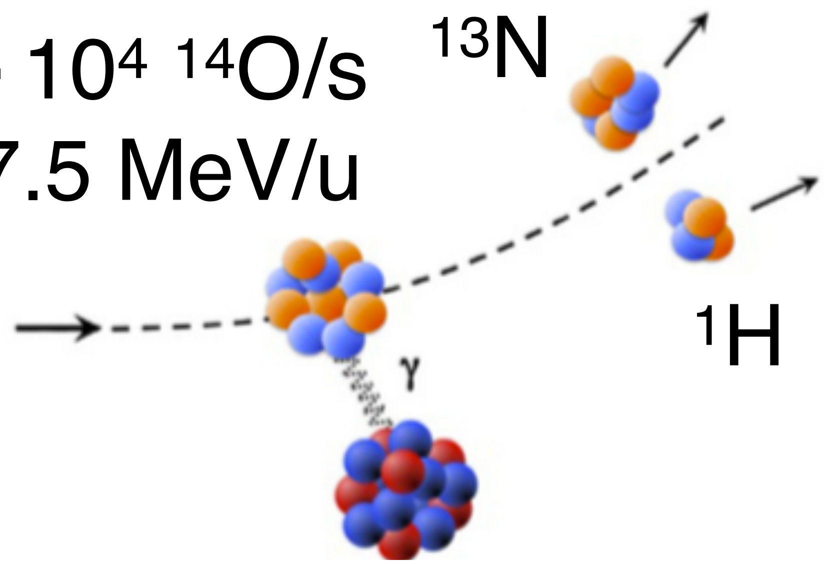
$$\sin \Delta\theta_c^{max} \simeq \sqrt{(m_b/m_c)E_{bc}/E_0^{lab}}$$

4. Conditions of experimental investigations

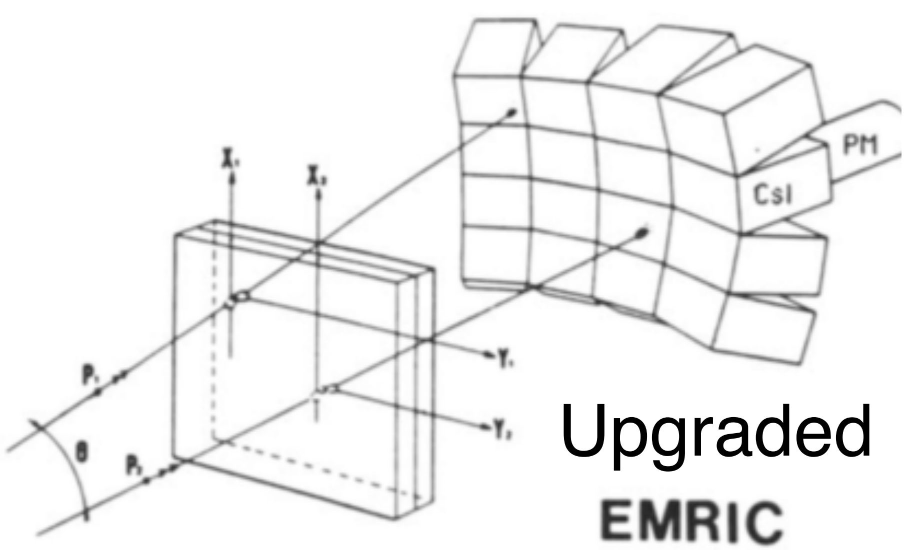
2: Coulomb dissociation of ^{14}O

Motobayashi et al. PLB264, 259 (1991)

$3 \cdot 10^4$ ^{14}O/s
87.5 MeV/u

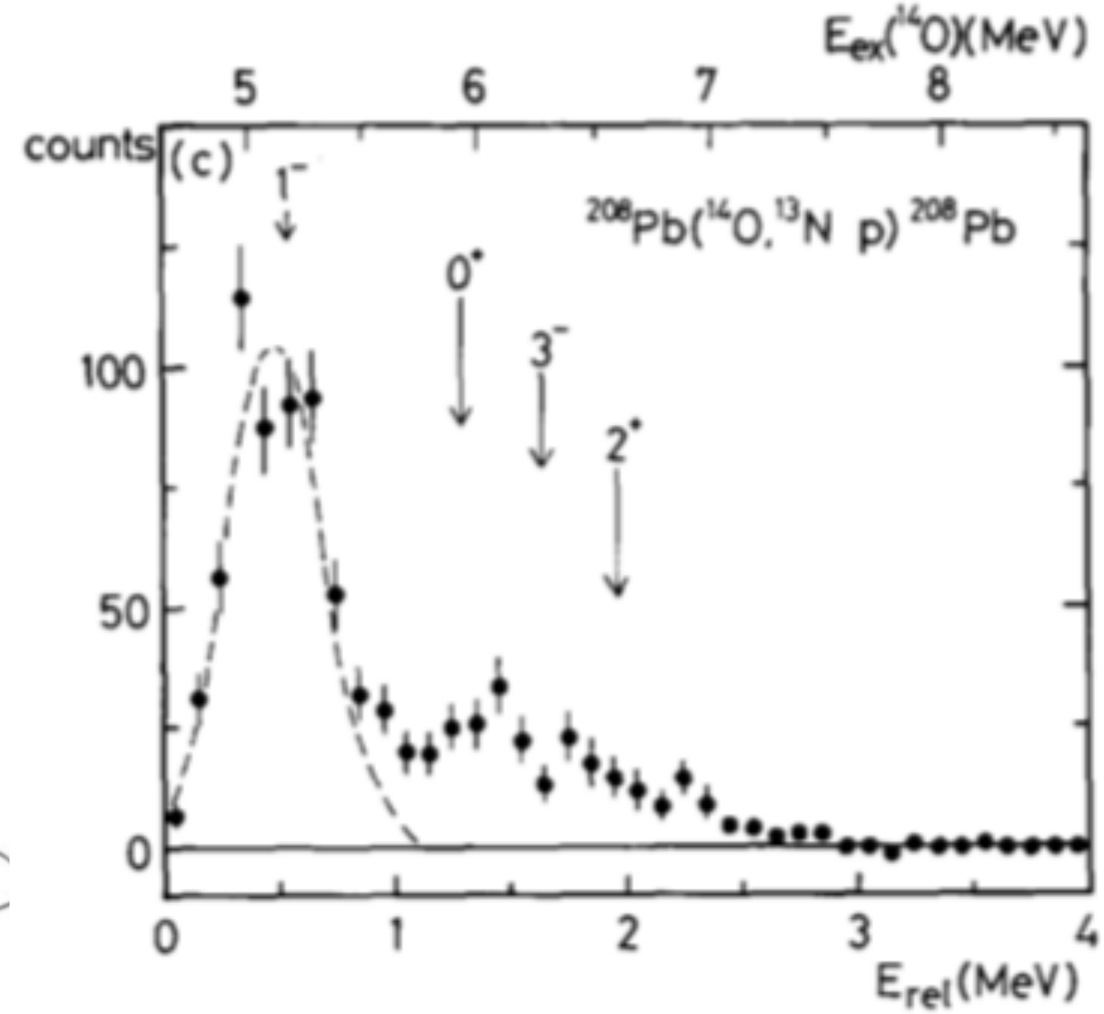


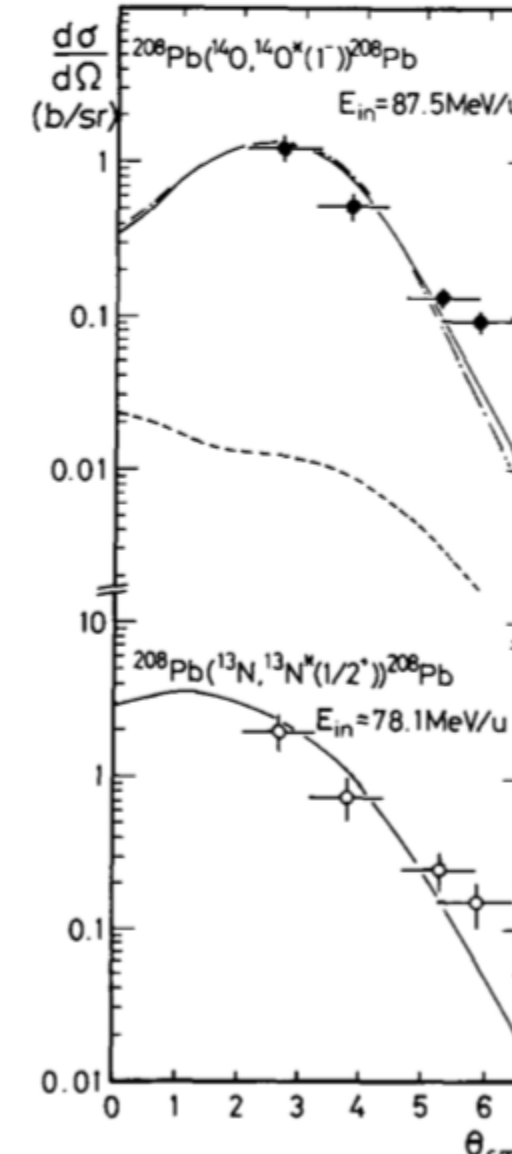
^{208}Pb, 350 mg/cm^2



Upgraded

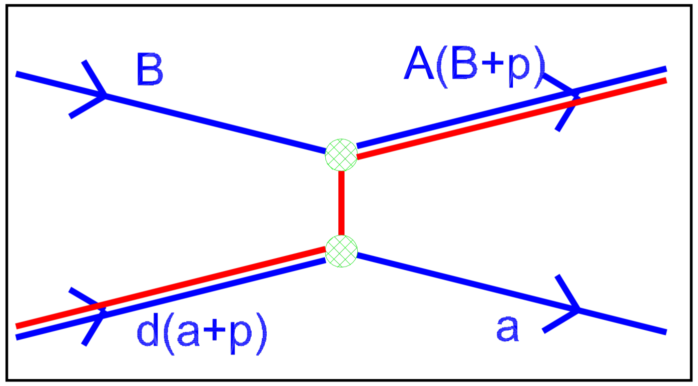
5x5 Si-CsI dE-E telescope
+ plastic hodoscopes





Coupled channel analysis with OMP from
^{17}O+^{208}Pb at 84 MeV/u …
… → Γ_γ = 3.1 ± 0.6 eV

3: Asymptotic Normalization Coefficient (ANC)



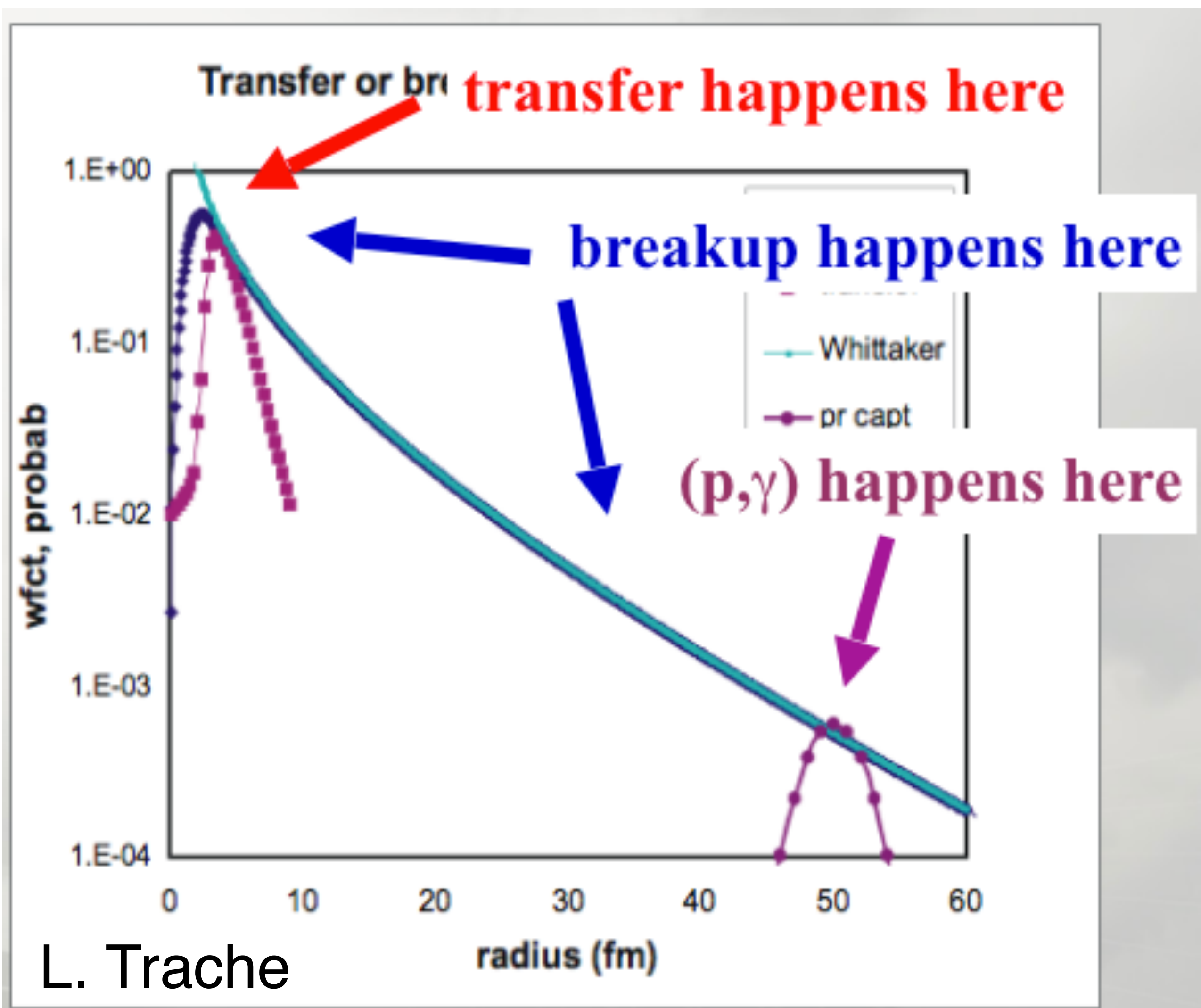
Radial overlap function $I^a_{bxl_aj_a}(r_{bx}) = S^{1/2}_{bxl_aj_a}\Phi_{n_al_aj_a}(r_{bx})$

For peripheral process, overlap asymptotic: $I^a_{bxl_aj_a}(r_{bx}) \xrightarrow{r_{bx}>R_N} C^a_{bxl_aj_a}\frac{W_{-\eta_a,l_a+1/2}(2\kappa_{bx}r_{bx})}{r_{bx}}$ ← ANC

Single particle bound state wave function: $\Phi_{n_al_aj_a}(r_{bx}) \xrightarrow{r_{bx}>R_N} b_{bxl_aj_a}\frac{W_{-\eta_a,l_a+1/2}(2\kappa_{bx}r_{bx})}{r_{bx}}$ ← s.p. ANC

$$\frac{d\sigma}{d\Omega} = \sum_{j_aj_B} S_{bxl_aj_a}S_{Axl_Bj_B}\sigma^{DWBA}_{l_aj_al_Bj_B} \quad \& \quad S_{bxl_aj_a} = \frac{(C^a_{bxl_aj_a})^2}{(b_{bxl_aj_a})^2}$$

$$\rightarrow \frac{d\sigma}{d\Omega} = \sum_{j_aj_B}(C^a_{bxl_aj_a})^2(C^B_{Axl_Bj_B})^2\frac{\sigma^{DWBA}_{l_aj_al_Bj_B}}{(b_{bxl_aj_a})^2(b_{Axl_Bj_B})^2}$$



This is measured for the reaction of interest

These needed from other measurements

$$\sigma_{exp} = (C^{^{14}O}_{p_{1/2}})^2\left[\left(\frac{C^{^{14}N}_{p_{1/2}}}{b^{^{14}O}_{p_{1/2}}b^{^{14}N}_{p_{1/2}}}\right)^2\sigma^{DW}_{p_{1/2},p_{1/2}} + \left(\frac{C^{^{14}N}_{p_{3/2}}}{b^{^{14}O}_{p_{1/2}}b^{^{14}N}_{p_{3/2}}}\right)^2\sigma^{DW}_{p_{1/2},p_{3/2}}\right]$$

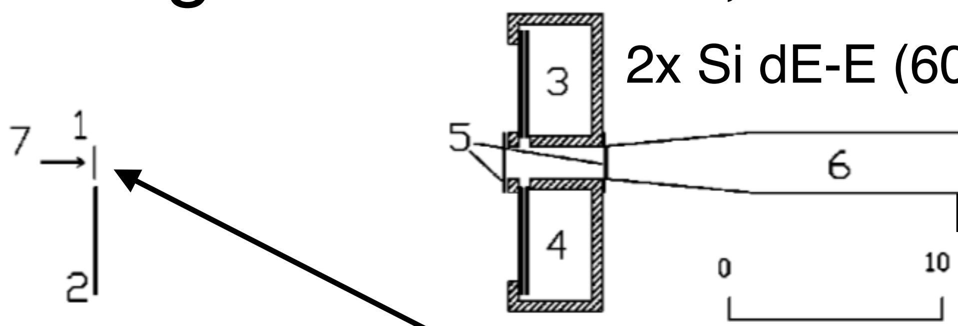
These from single particle model

These from from reaction code

Recent review Tribble et al. Rep. Prog. Phys. 77, 106901 (2014)

3: Proton transfer using $^{14}N(^{13}N,^{14}O)^{13}C$

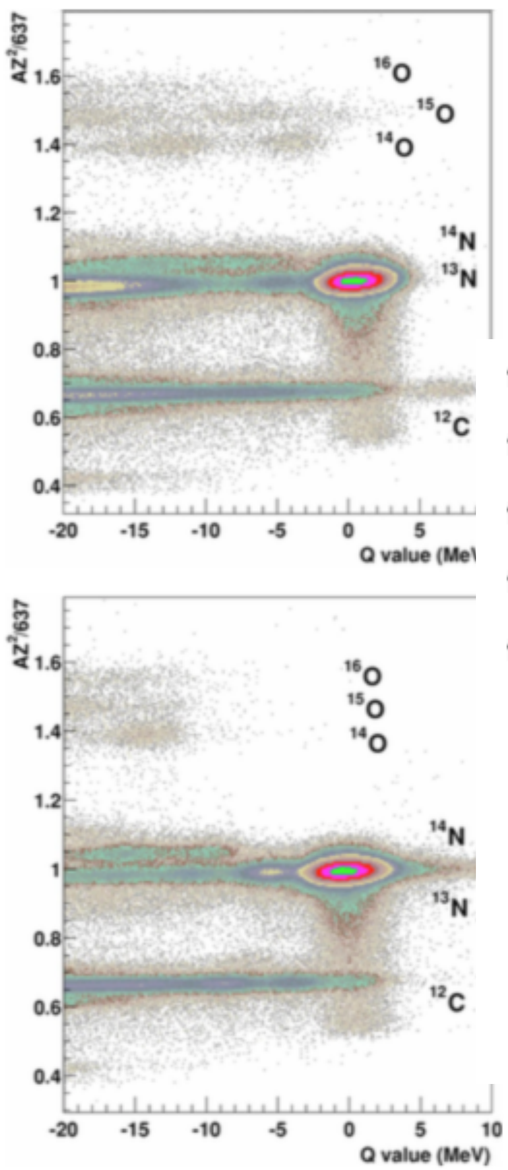
Tang et al. PRC69, 055807 (2004)

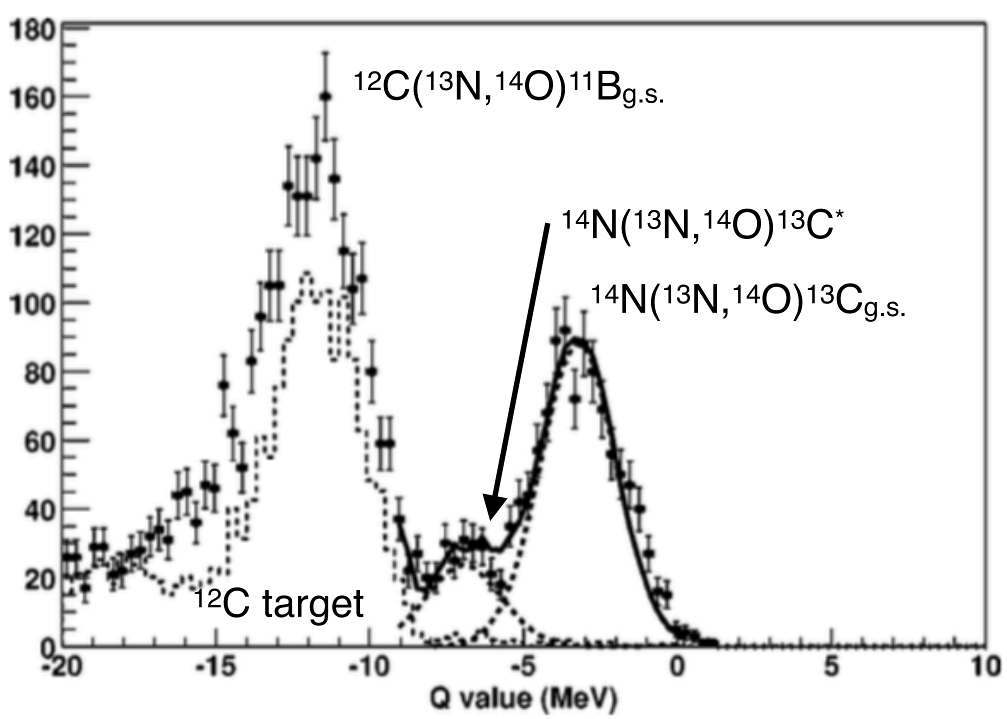


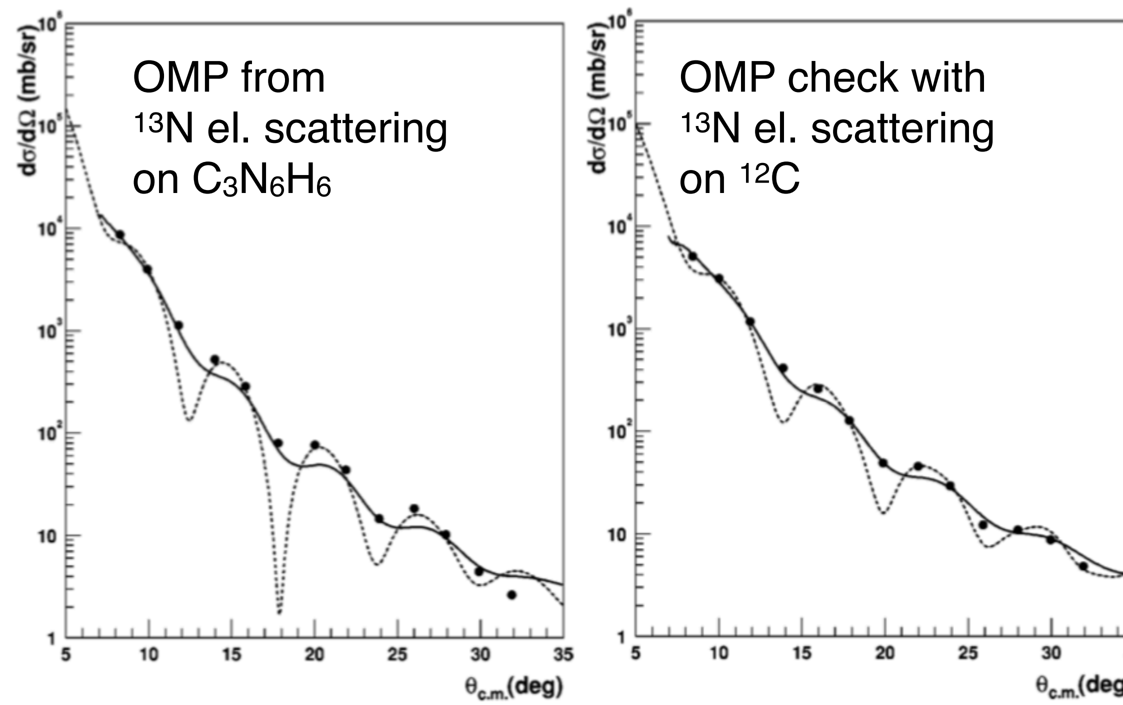
2x Si dE-E (60 µm, PSD) - 500µm

Plastic+PMT beam monitor

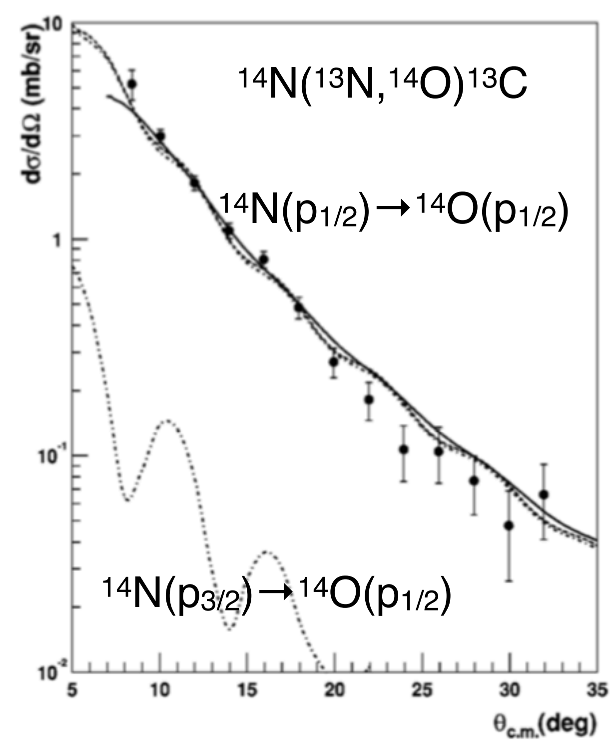
Target: 1.5 mg/cm² $C_3N_6H_6$ on
20 µg/cm² C and 20 µg/cm² collodion
Beam: 600kHz ^{13}N at 11.8 MeV/u, >99% p

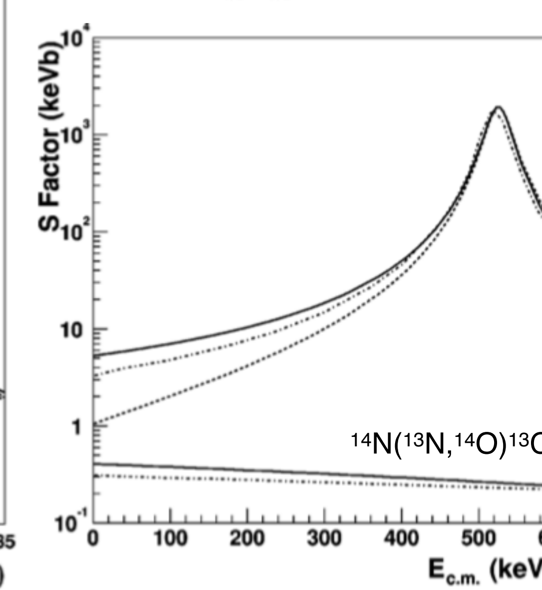






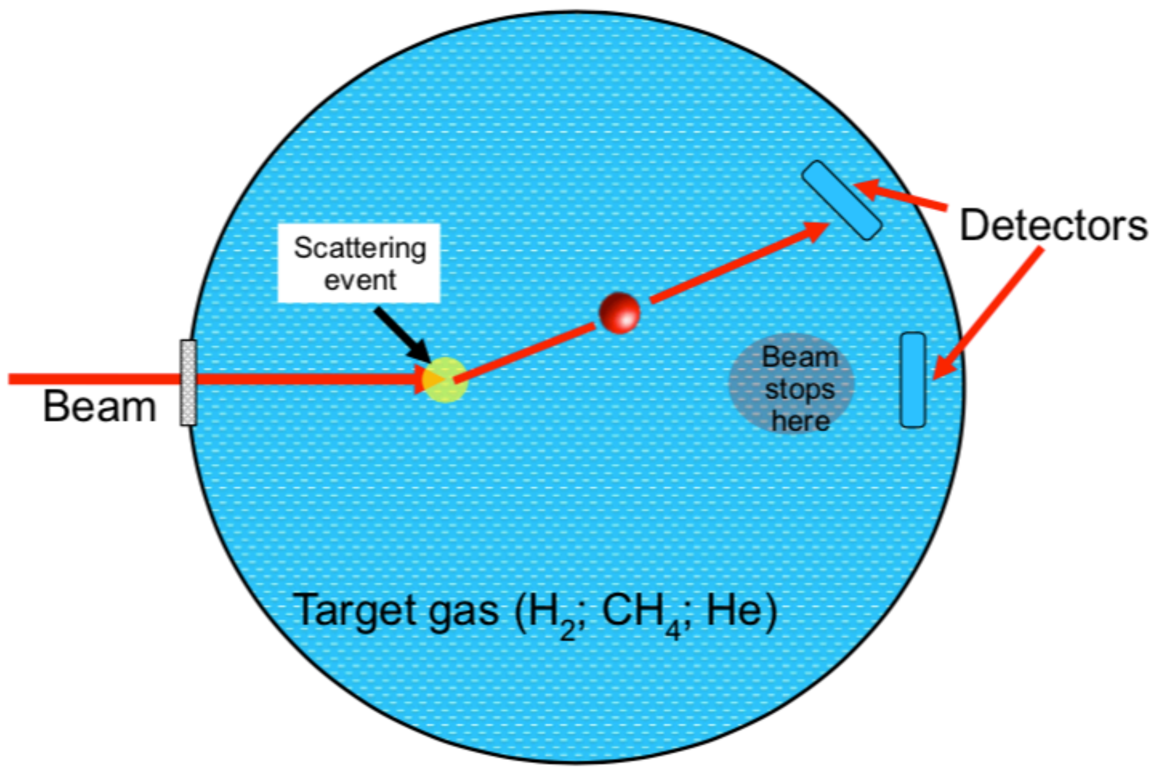
$$\sigma_{\exp} = (C^{^{14}O}_{p_{1/2}})^2 \left[\left(\frac{C^{^{14}N}_{p_{1/2}}}{b^{^{14}O}_{p_{1/2}} b^{^{14}N}_{p_{1/2}}} \right)^2 \sigma^{DW}_{p_{1/2}p_{1/2}} + \left(\frac{C^{^{14}N}_{p_{3/2}}}{b^{^{14}O}_{p_{1/2}} b^{^{14}N}_{p_{3/2}}} \right)^2 \sigma^{DW}_{p_{1/2}p_{3/2}} \right],$$

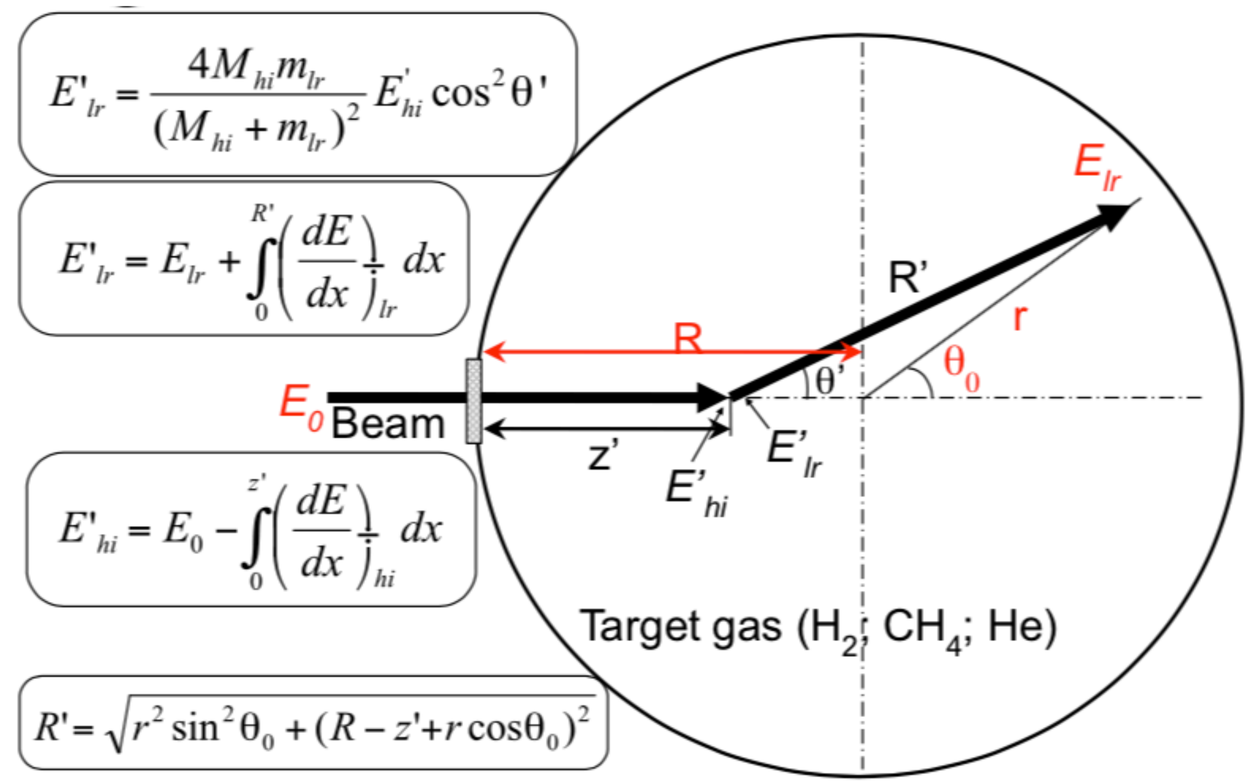




Direct capture and total S-factor ~ 30% larger than before

4: Thick Target Inverse Kinematics (TTIK)





G. Rogachev / EBSS2013

Typical excitation function measurement:

Measure cross section, change energy, measure cross section, change energy, …

Thick Target Inverse Kinematics (TTIK):

Scattering on thick target (gas or solid) so that the beam stops within the target, but elastically scattered (180°) target nuclei go further away and are measured with detectors

→ Measure whole excitation function from E_{beam} downwards in one measurement!

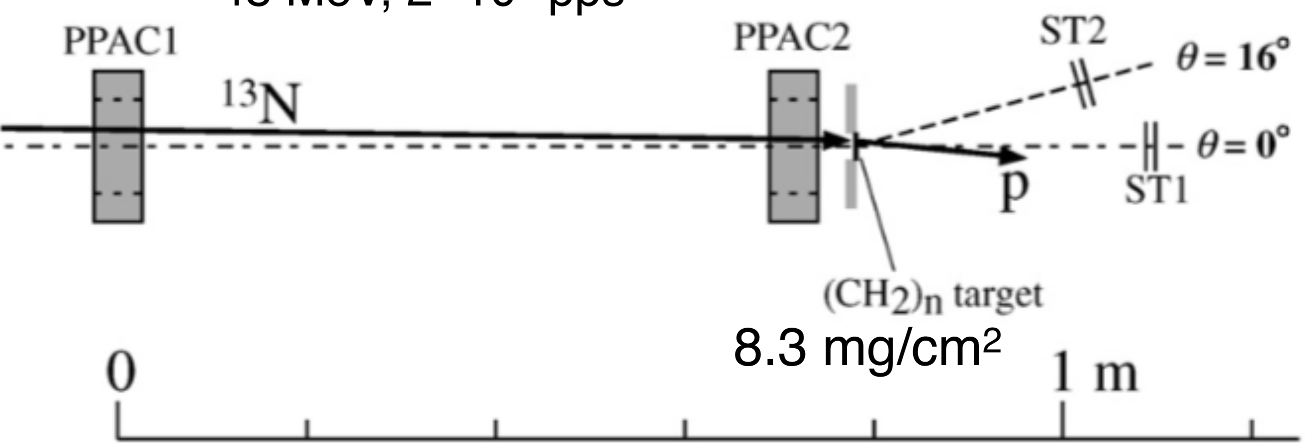
Original idea: K.P. Artemov et al., Sov. J. Nucl. Phys. 52, 408 (1990)

4: Resonant elastic scattering ^{13}N+p

Teranishi et al. PLB650, 129 (2007)

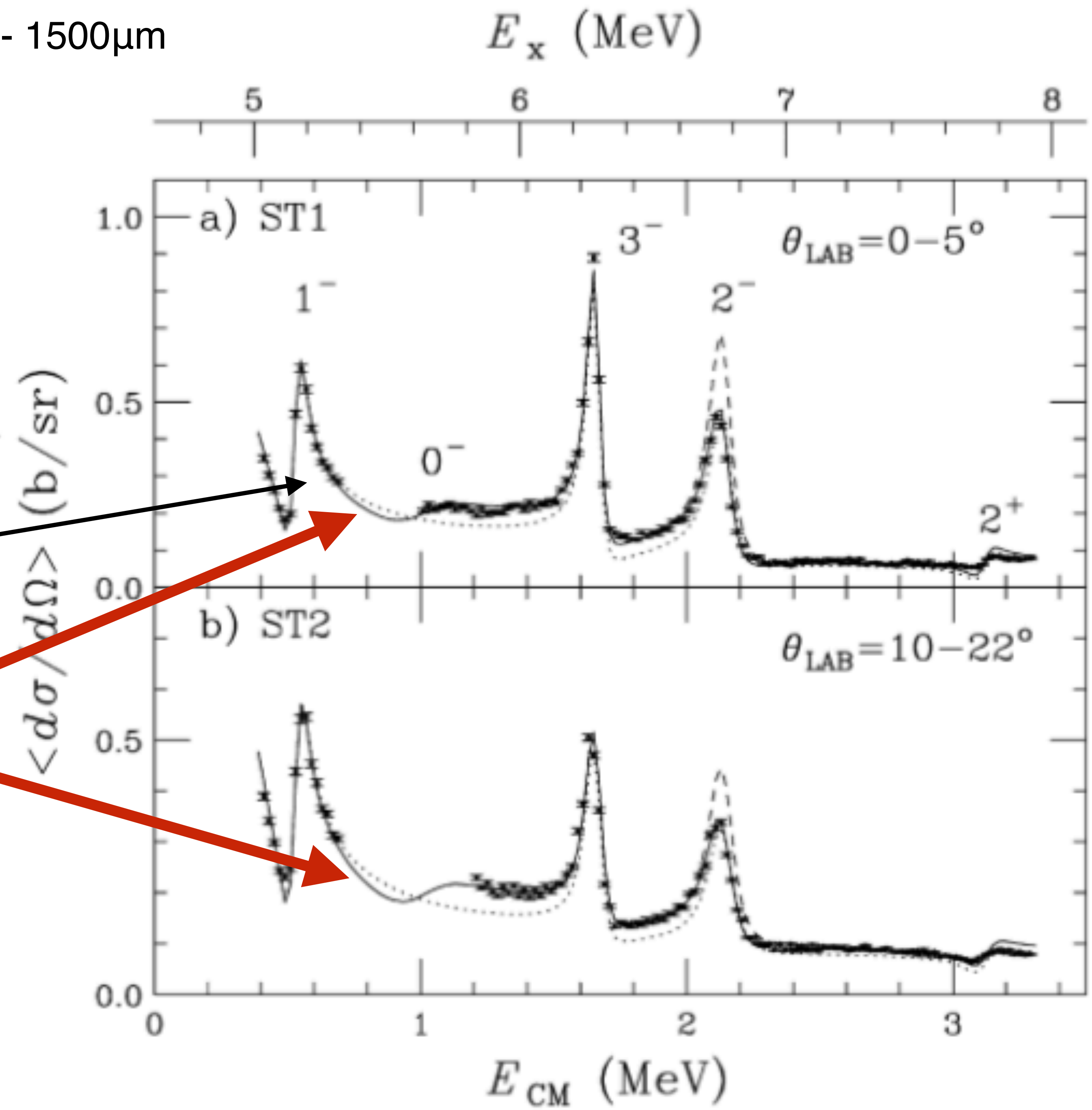
2x Si dE-E (75 µm DSSD) - 1500µm

48 MeV, $2 \cdot 10^5$ pps

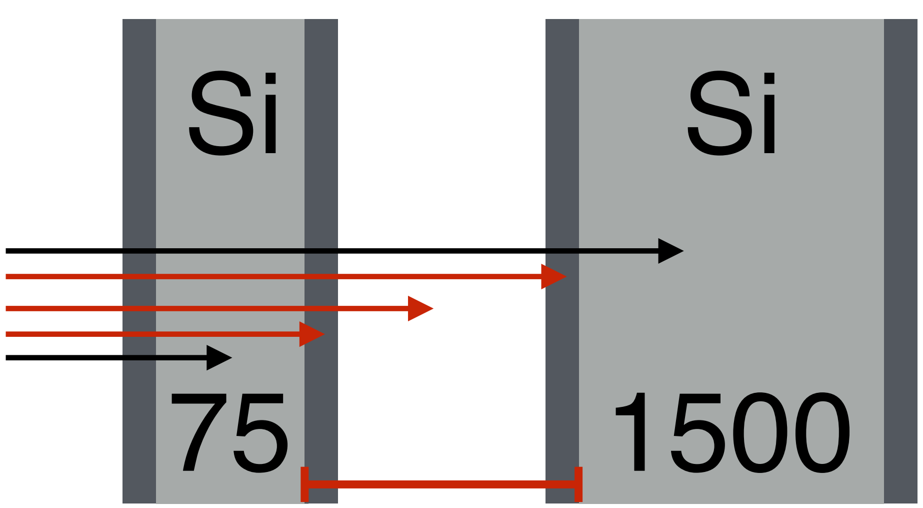


8.3 mg/cm^2

E_x = 5.159(10) MeV favors $E_x \sim$ 5.155 MeV than the group of $E_x \sim$ 5.175 MeV



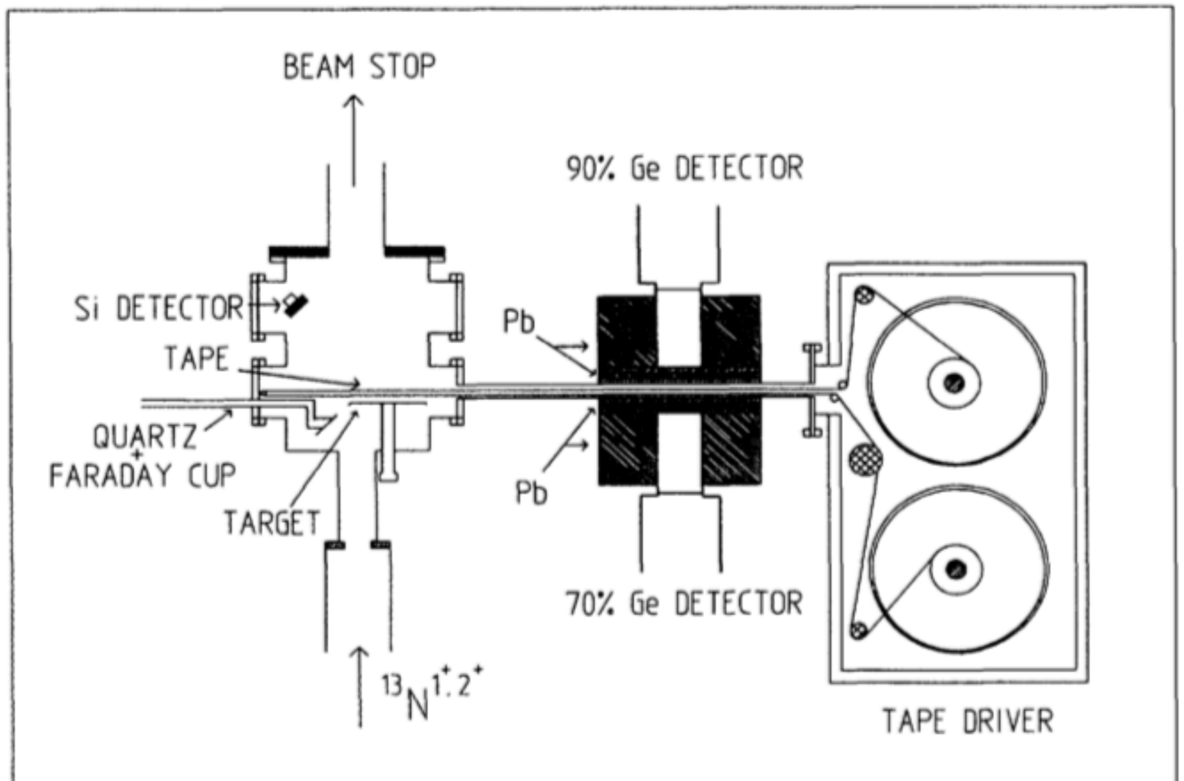
Why this gap?



Full energy of these not detected!

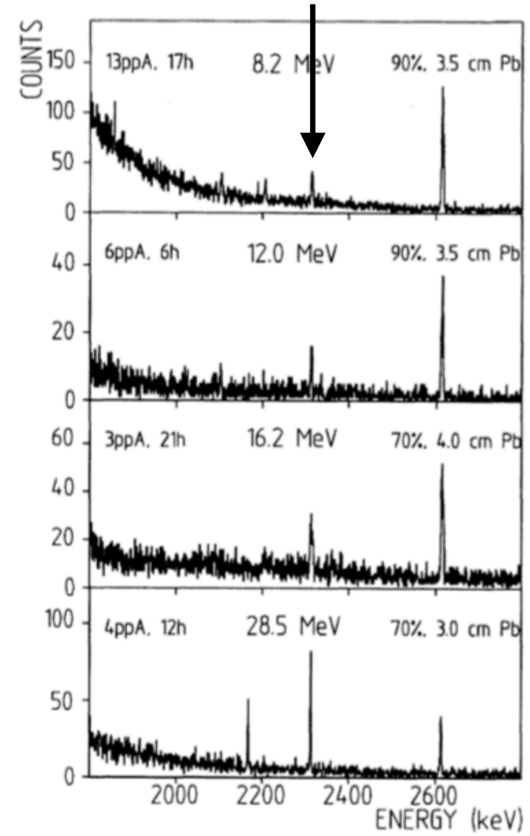
5: $^{13}N(d,n)^{14}O$ in inverse kinematics

Decrock et al. PRC48, 2057 (1993)



Various $(CD_2)_n$ targets and ^{13}N energies

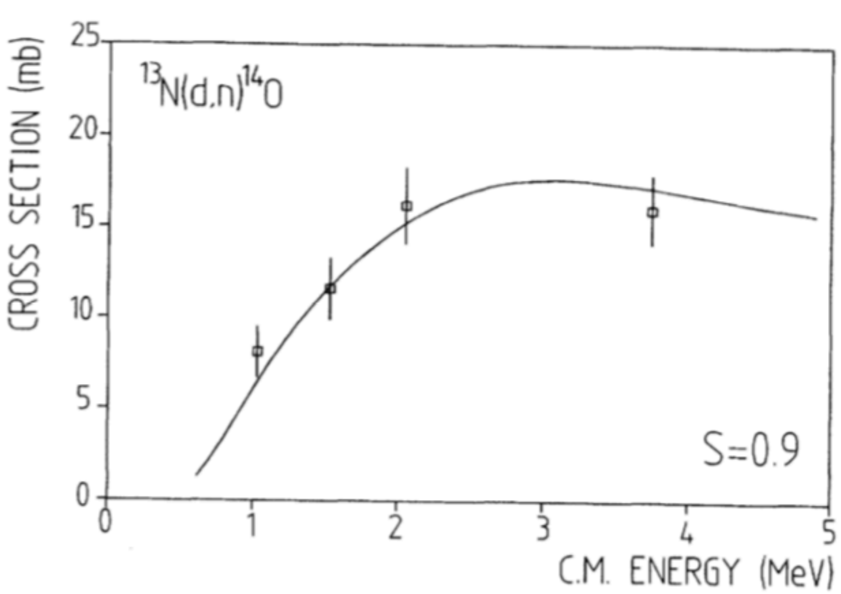
$^{14}O(\beta^+)^{14}N \rightarrow$ 2.3 MeV γ (b.r. 99.39%)

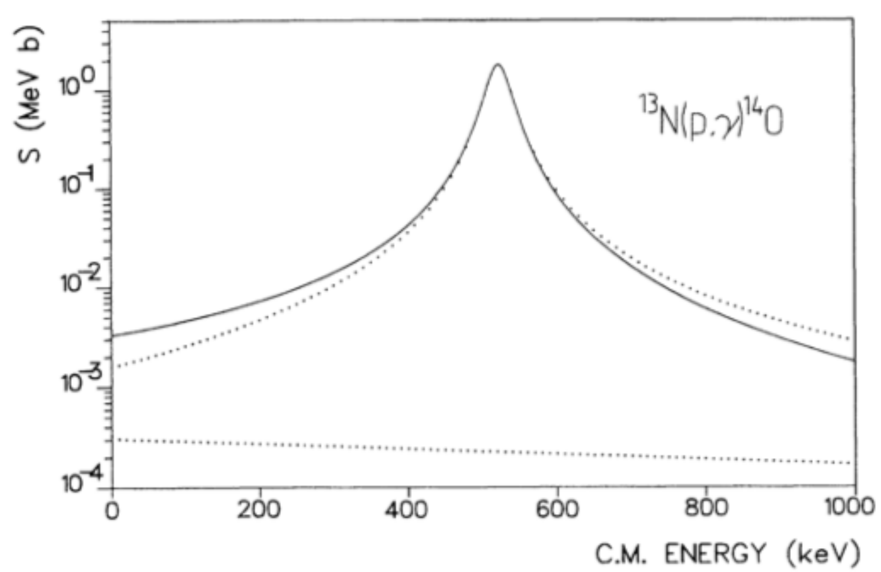


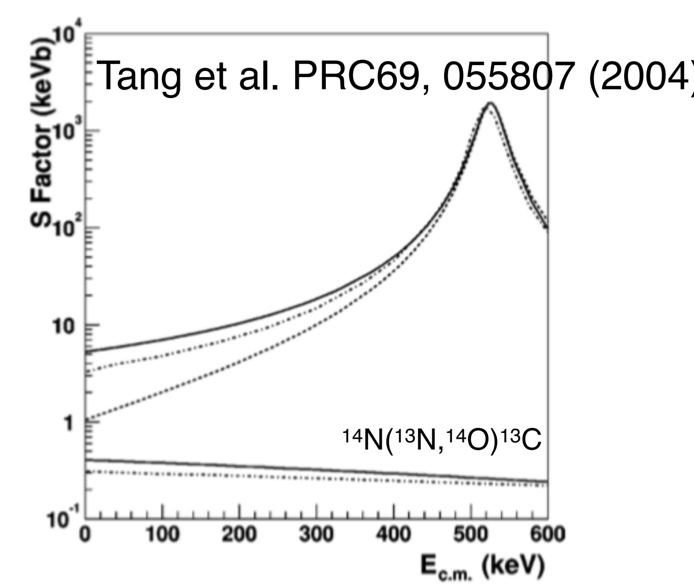
Two ways to determine σ:

$$\sigma = Y/(\eta \Delta X)$$

$$\sigma = \frac{I_\gamma}{I_{deuteron}} \left[\frac{d\sigma}{d\omega}\right]_{lab} d\omega$$



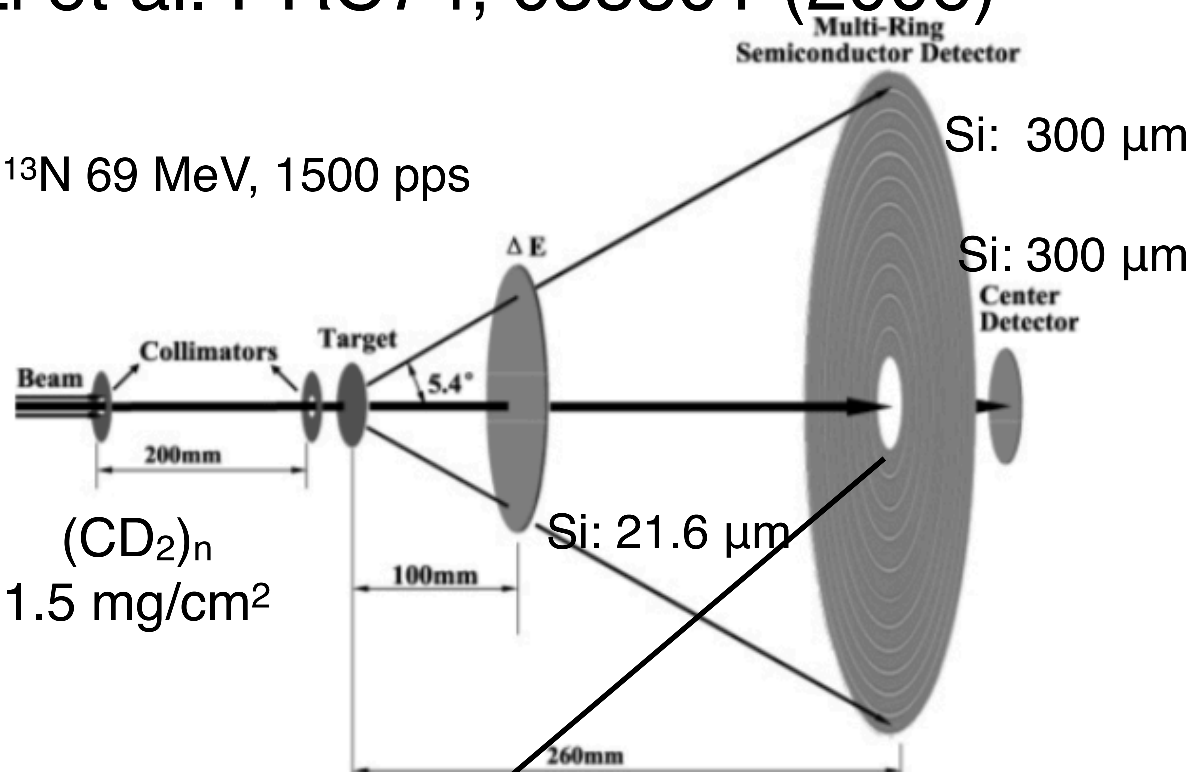


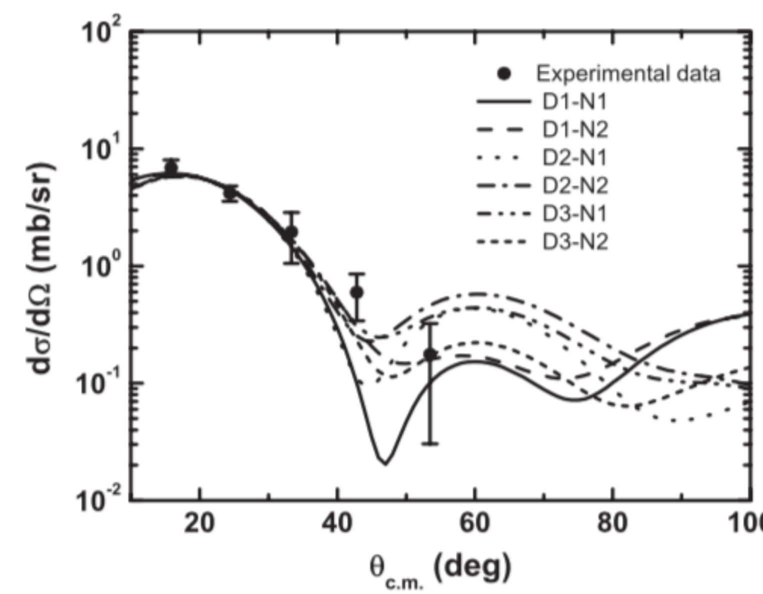


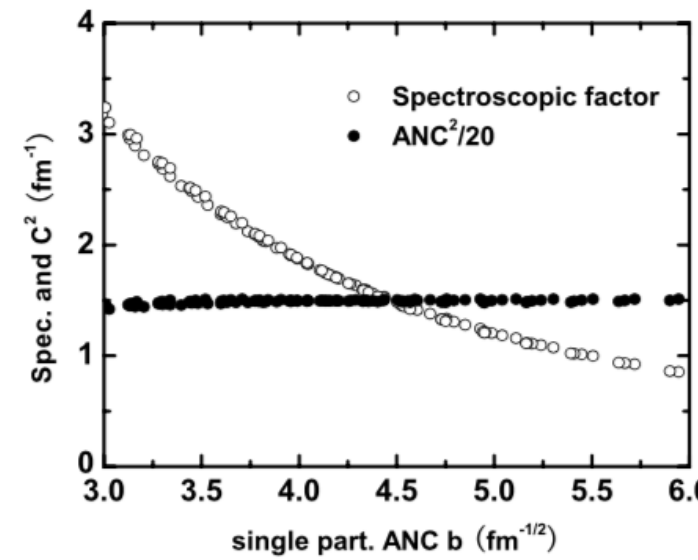
Discrepancy for direct capture S-factor ~ 30%

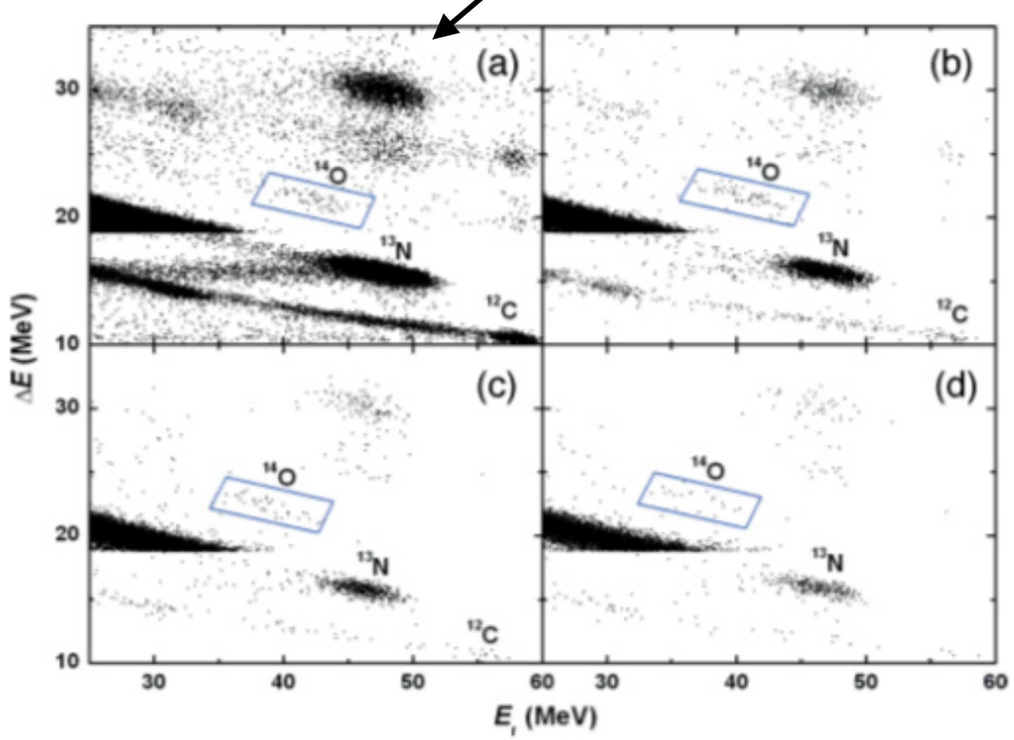
5: $^{13}N(d,n)^{14}O$ in inverse kinematics

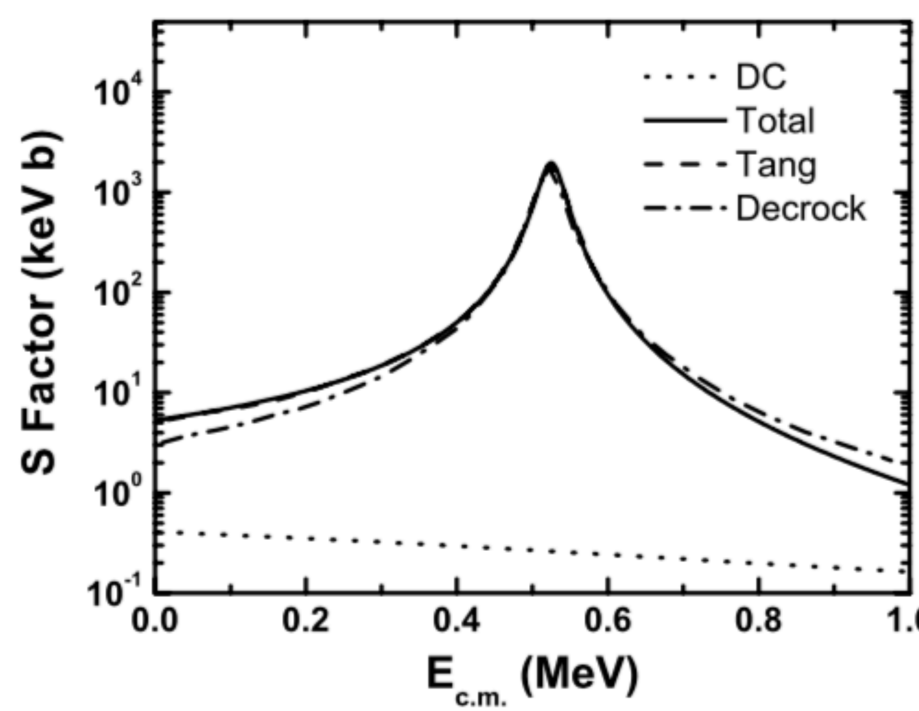
Li et al. PRC74, 035801 (2006)







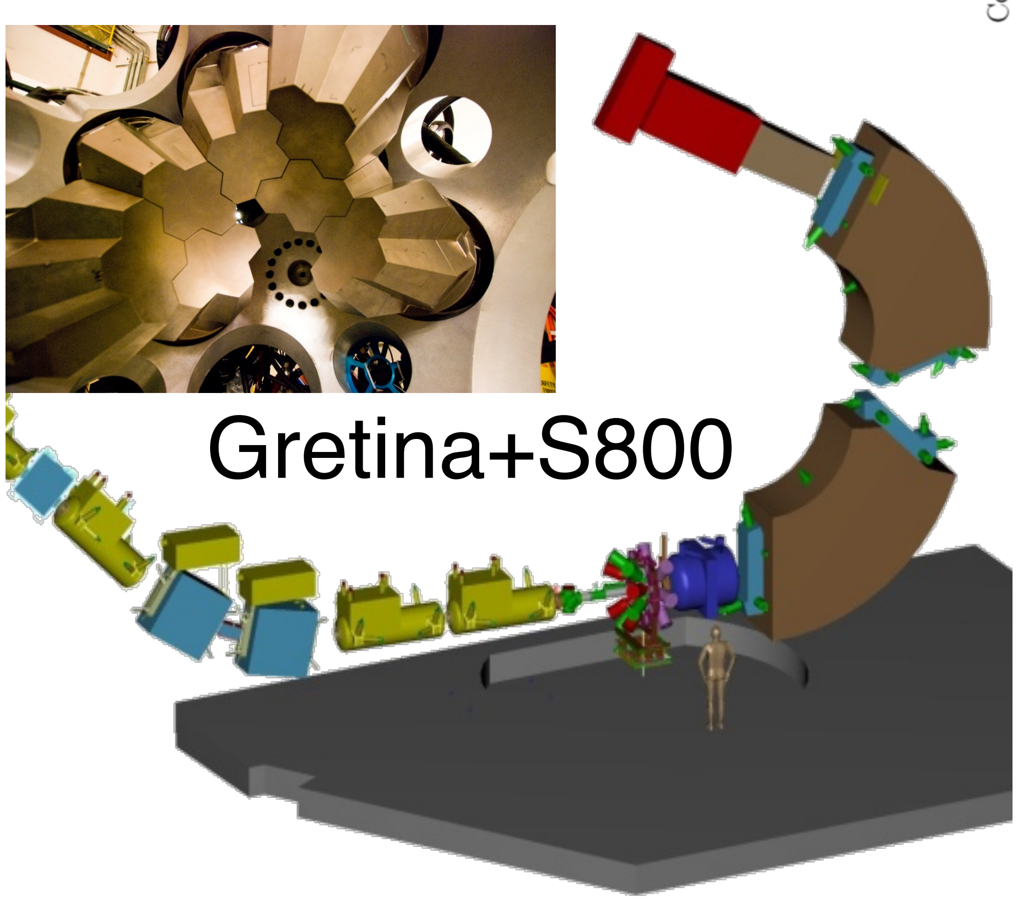


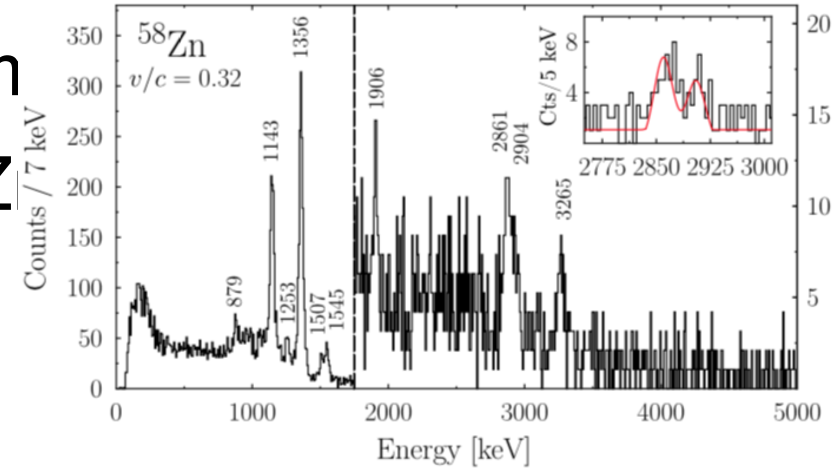


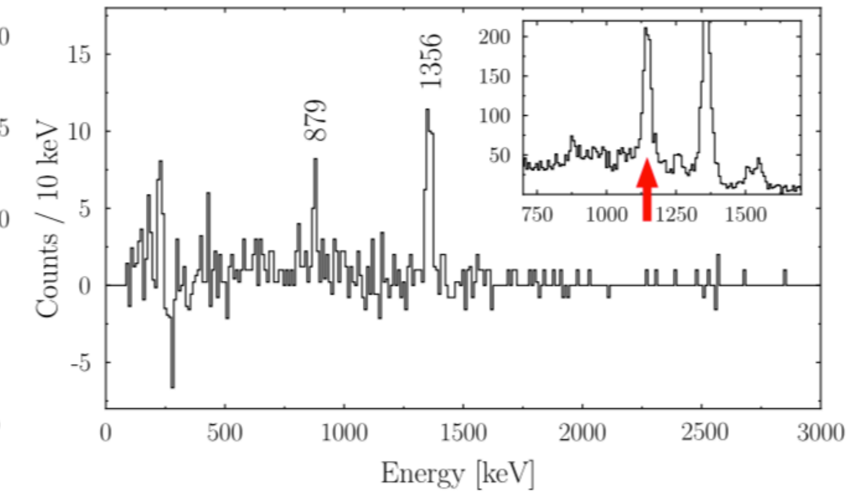
A more modern (d,n) measurement: d(^{57}Cu,^{58}Zn)n

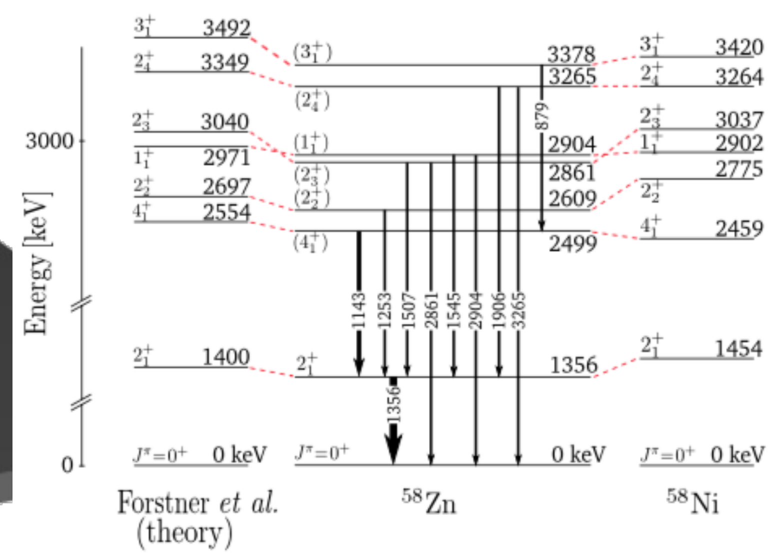
^{57}Cu(d,nγ)^{58}Zn in inverse kinen

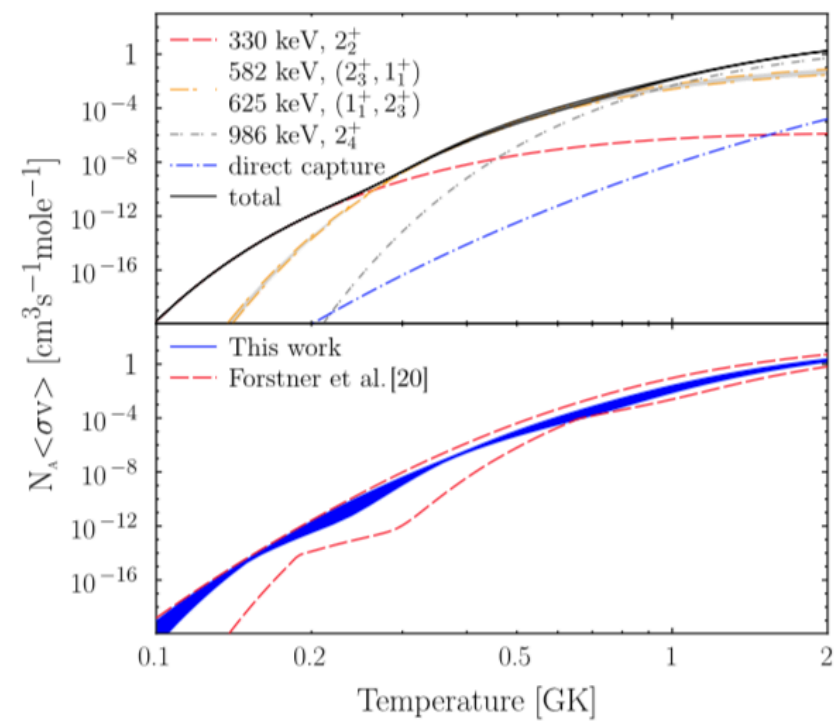
surrogate for ^{57}Cu(p,γ)^{58}Z











75 MeV/u ^{57}Cu, $3 \cdot 10^4$ pps, 20% purity

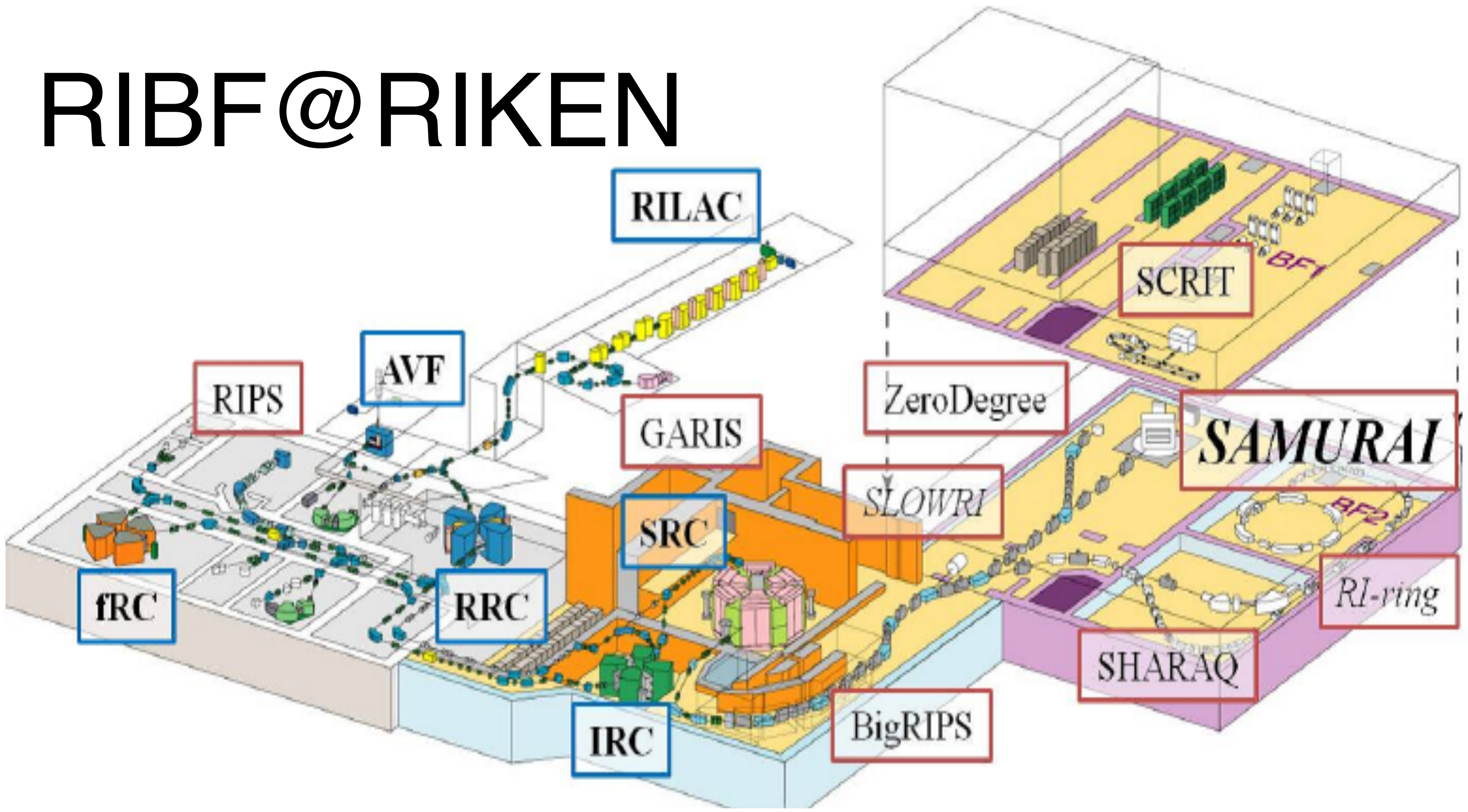
225 mg/cm^2 CD_2 target

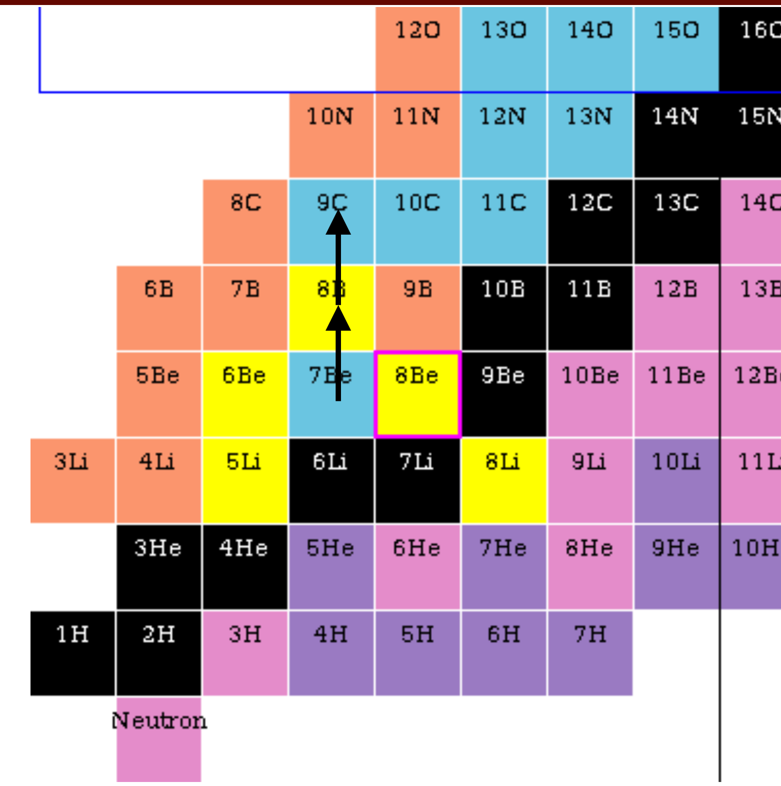
^{58}Zn in S800 + γ coincidence

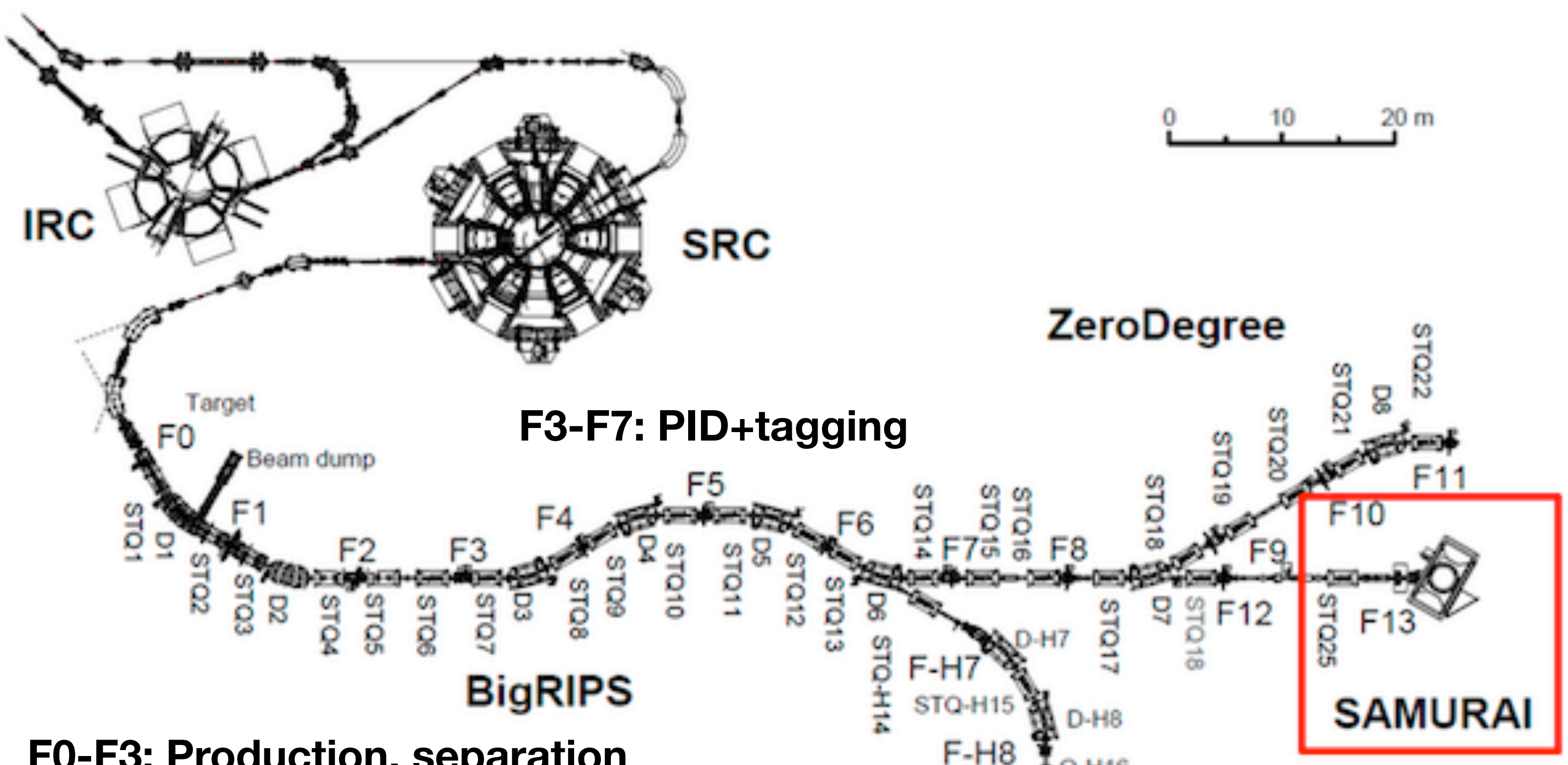
Langer et al. PRL 113, 032502 (2014)

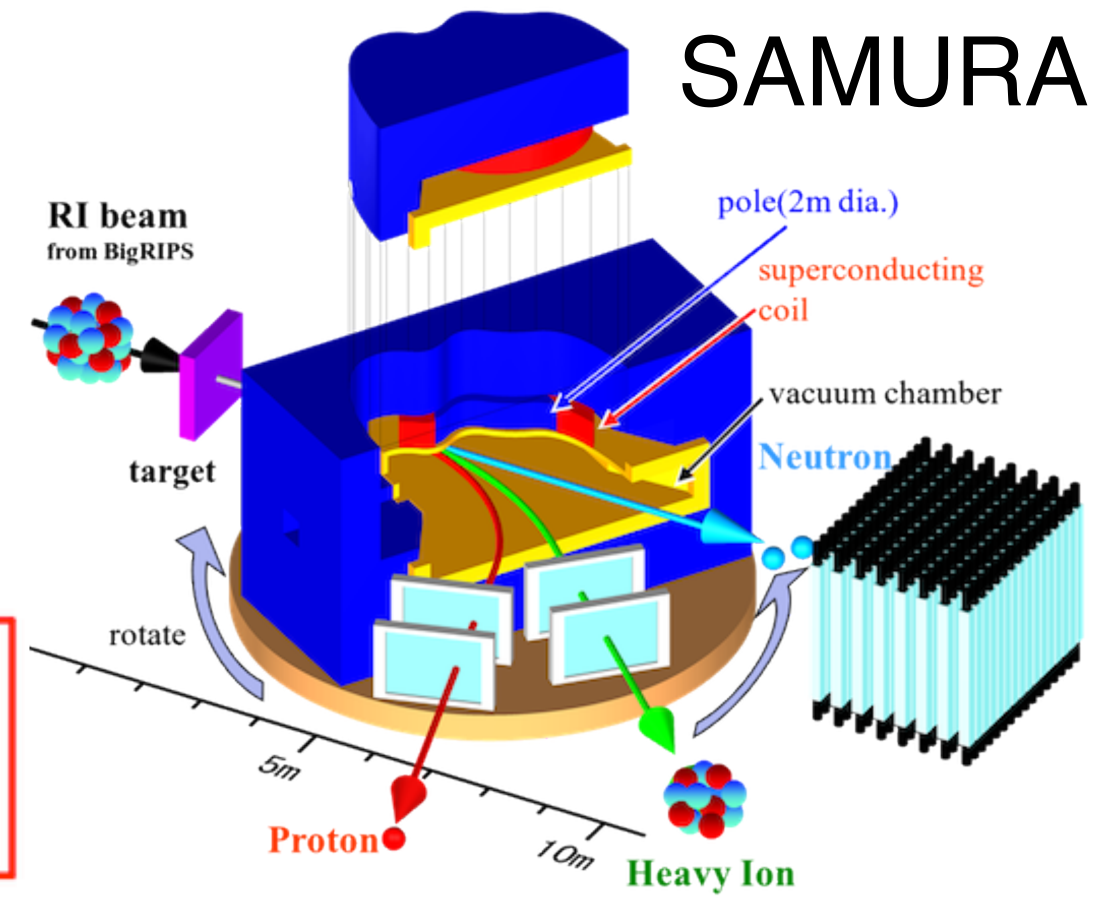
A more modern Coulomb breakup experiment

RIBF@RIKEN

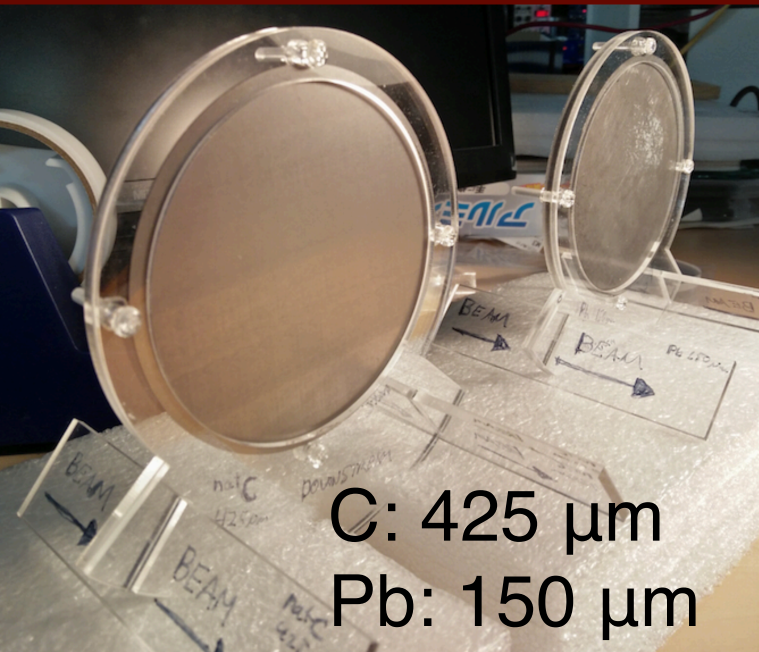


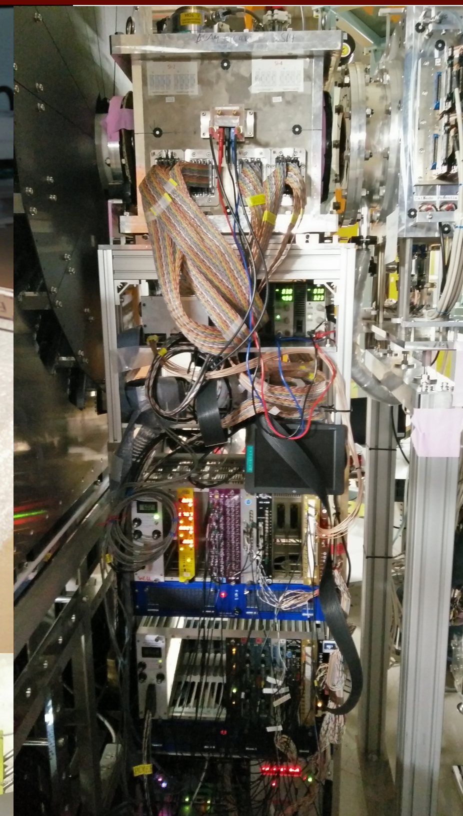


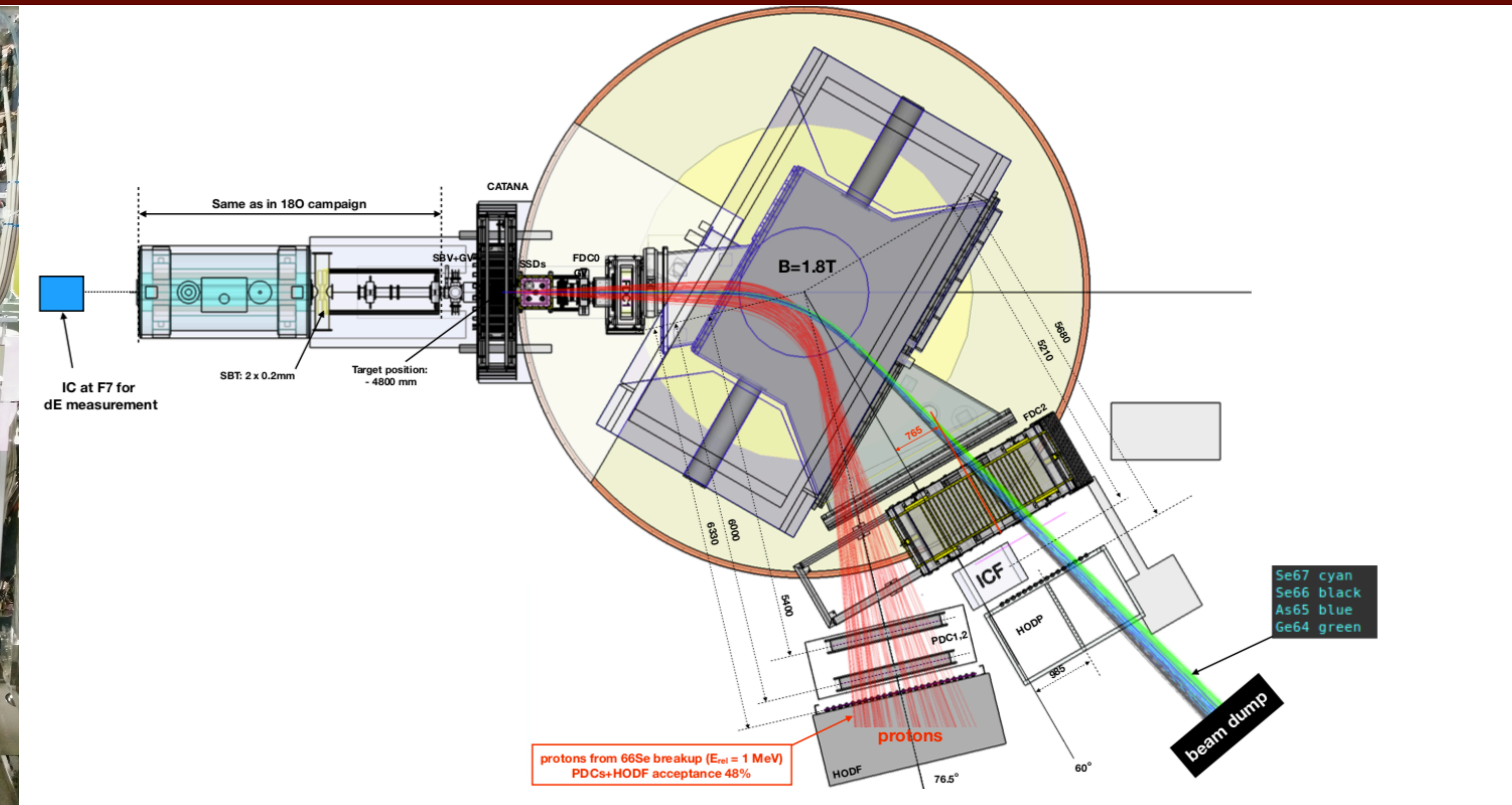


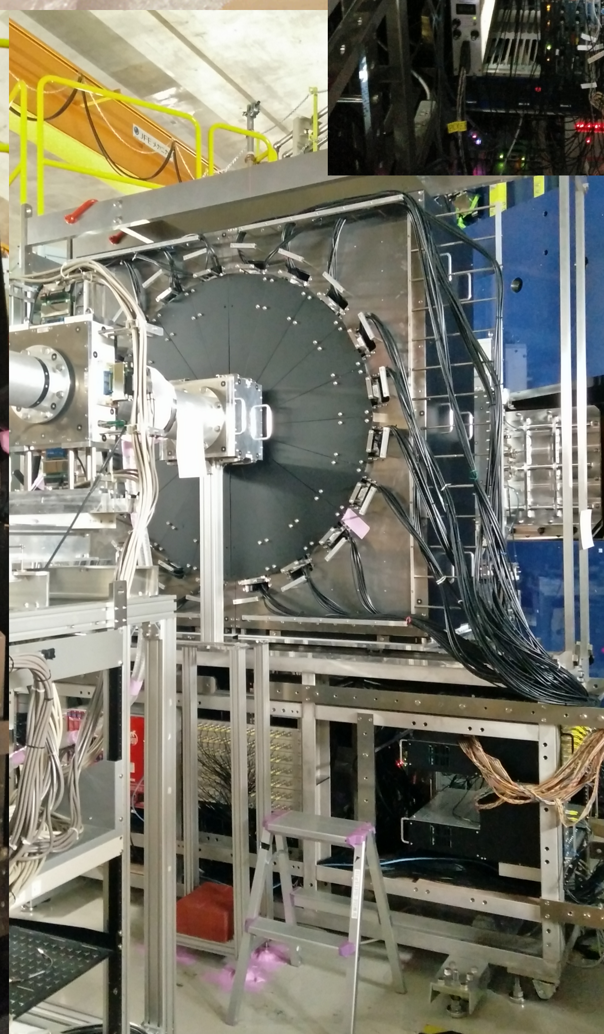


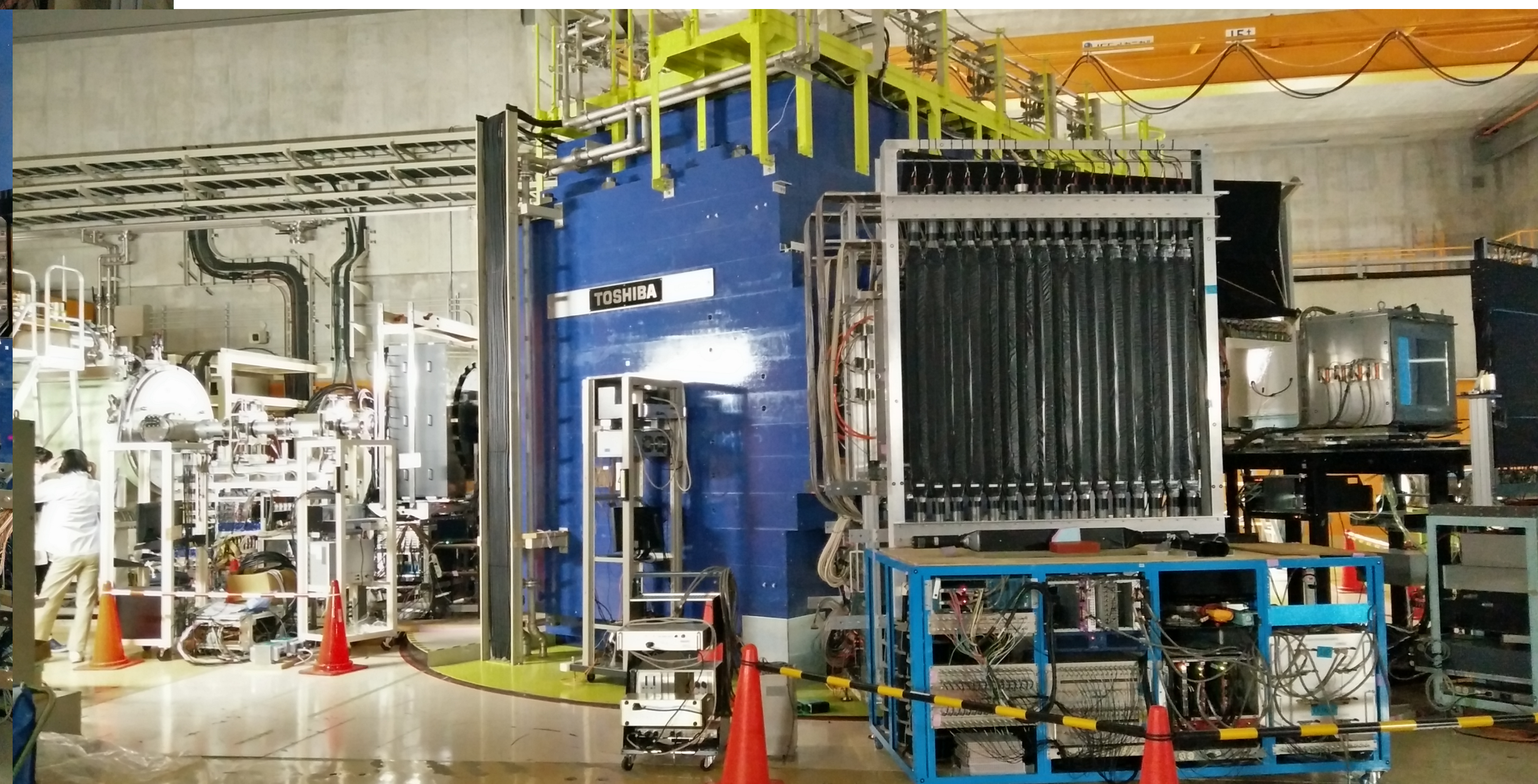
A more modern Coulomb and Nuclear breakup setup





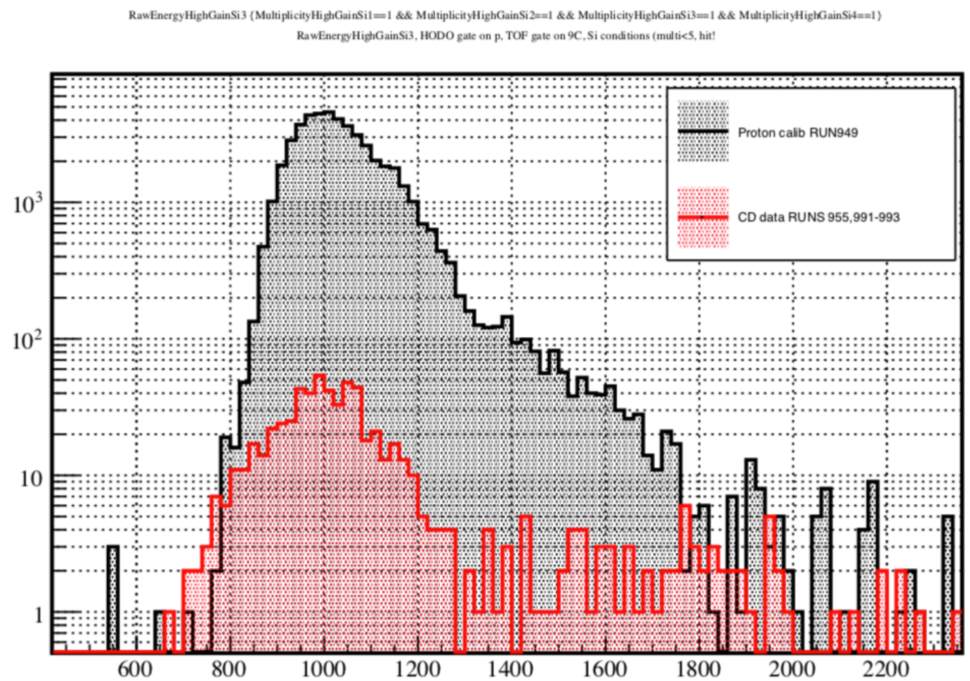


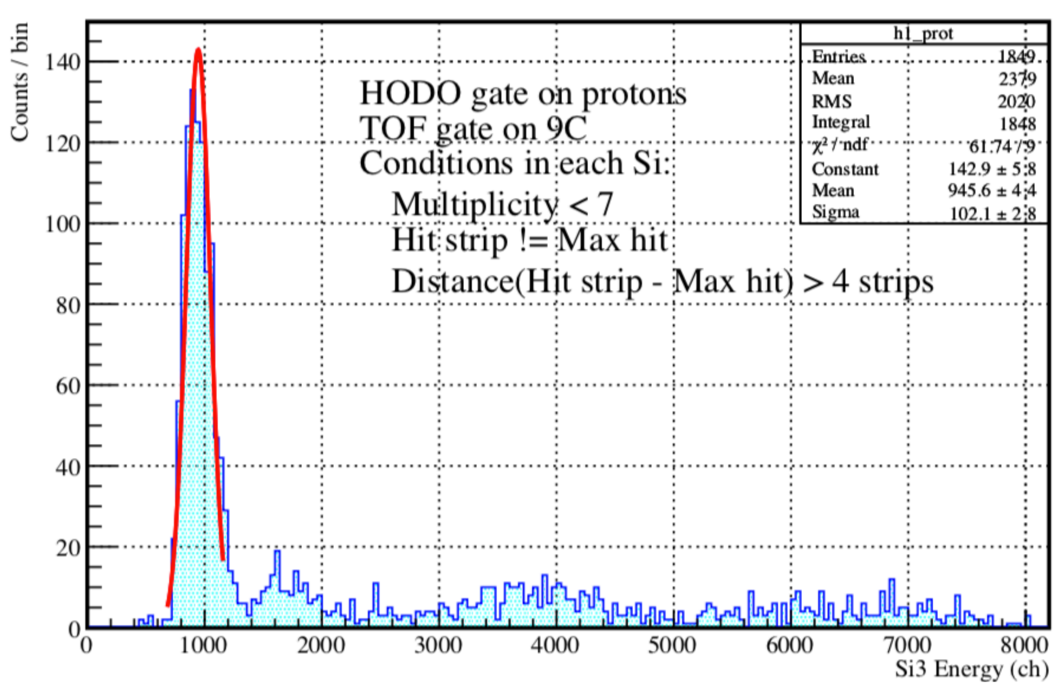




Example of $^{9}C+^{208}Pb$ data (2h online monitor)

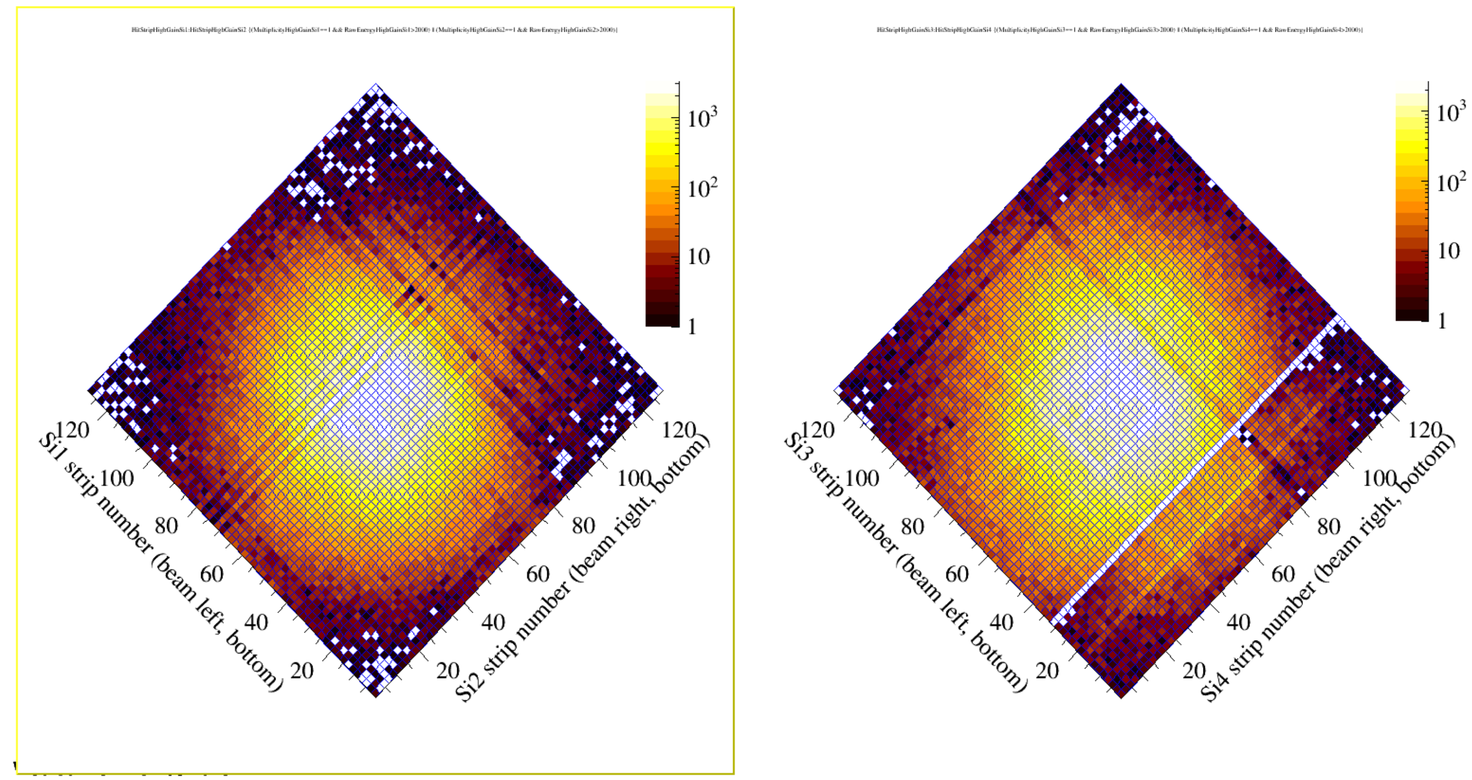
Proton calibration @150 AMeV



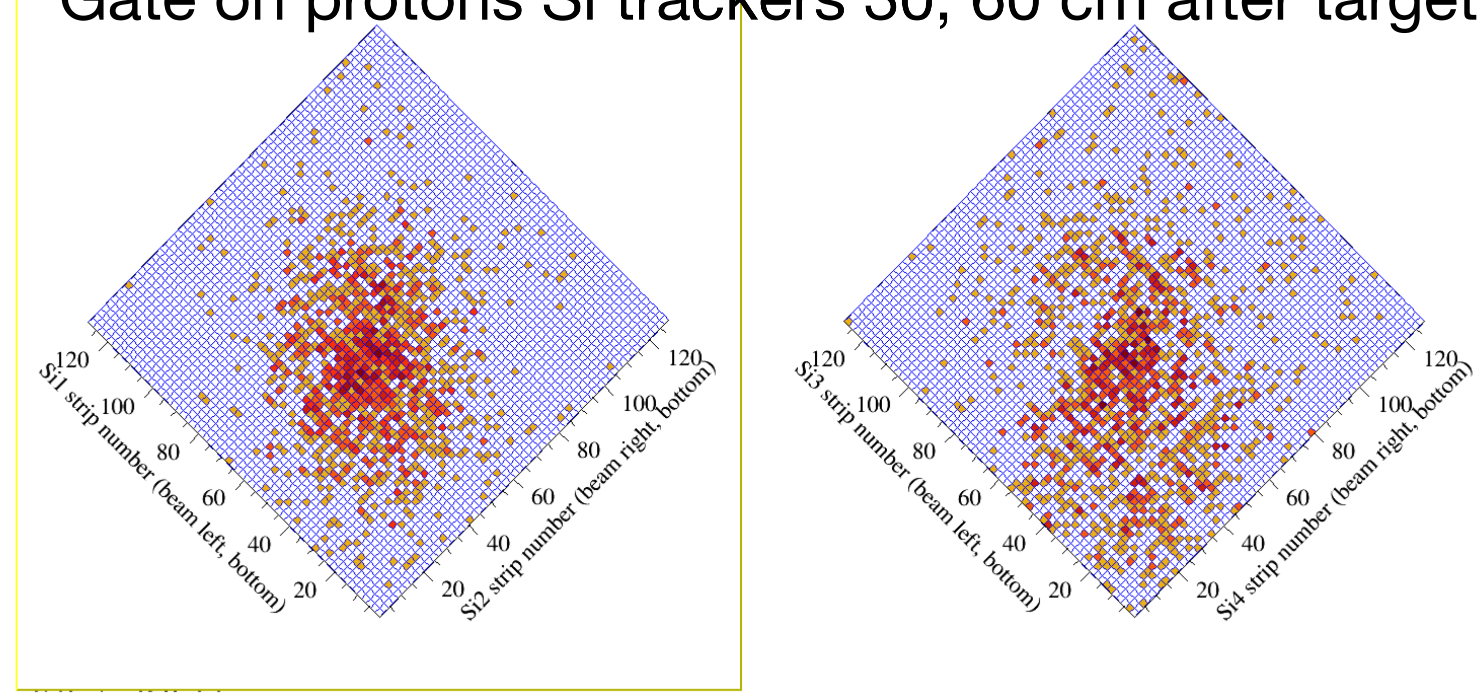


Work in progress part of
A. Chilug PhD Thesis, IFIN-HH, Romania

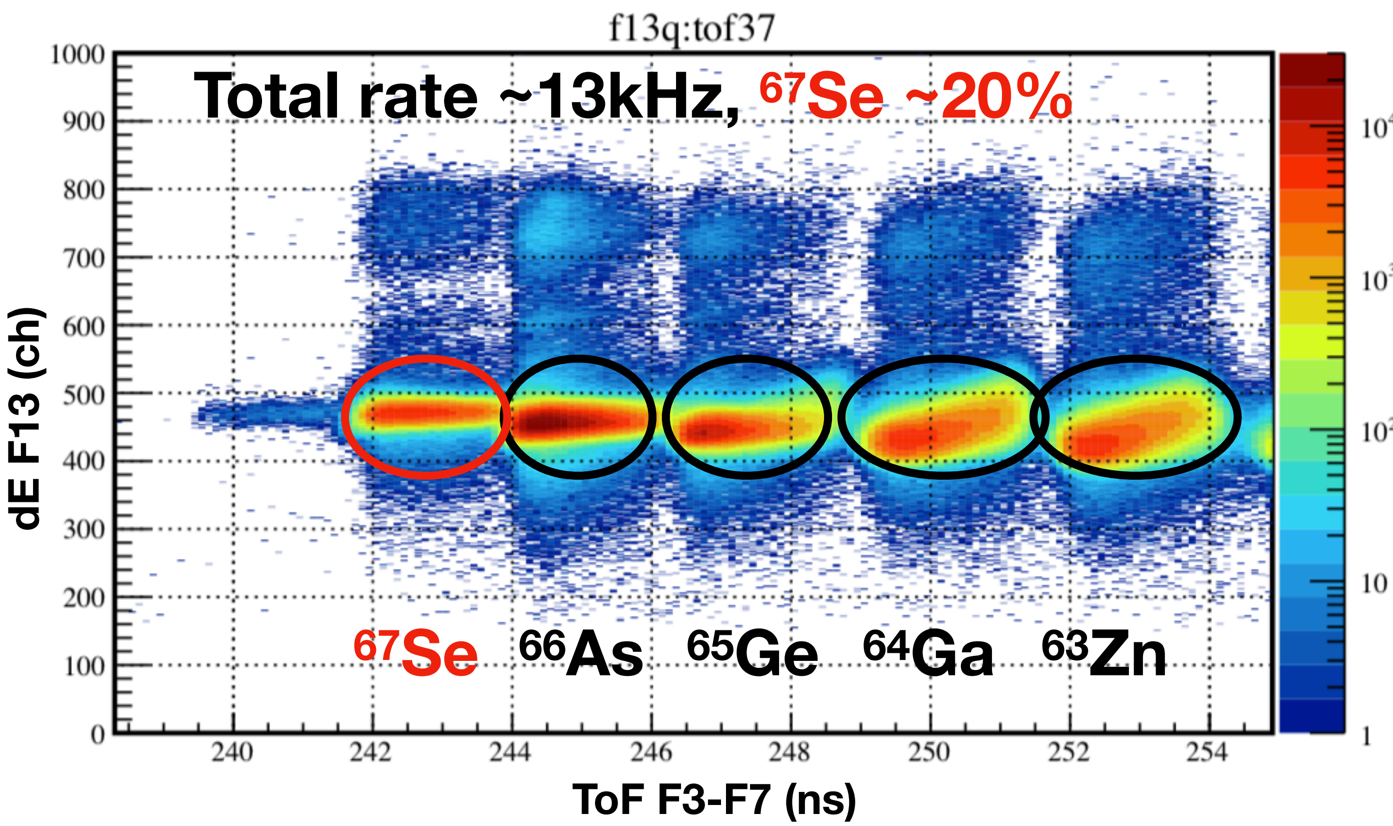
^{9}C beam spot in Si trackers 30, 60 cm after target



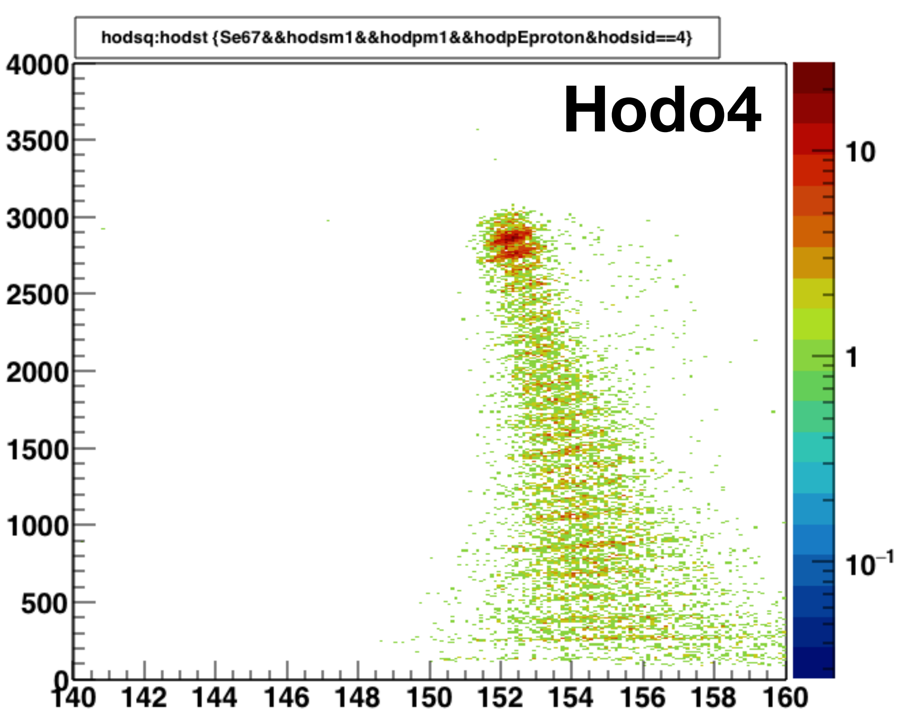
Gate on protons Si trackers 30, 60 cm after target

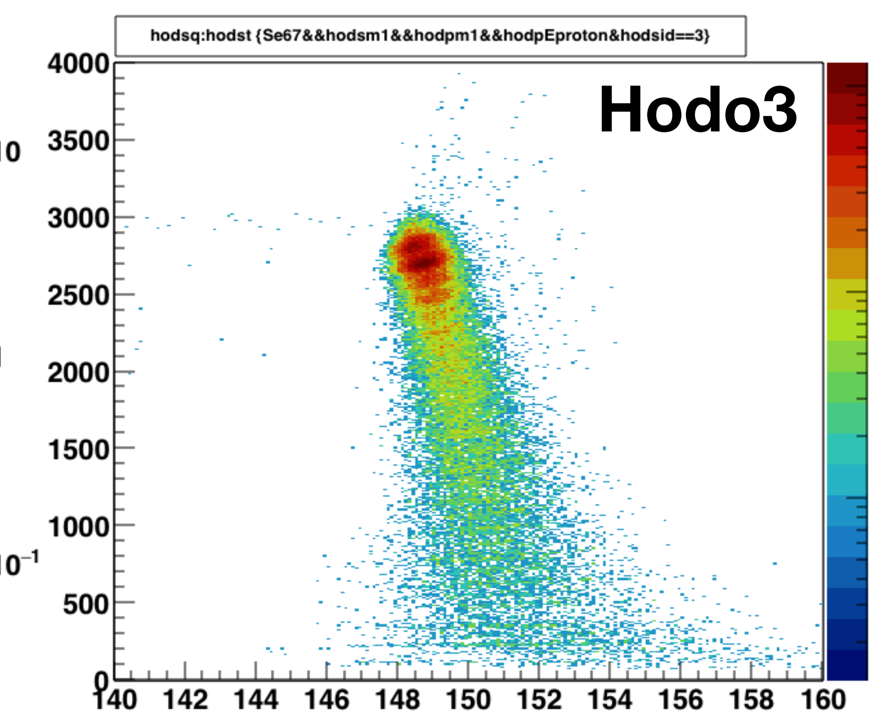


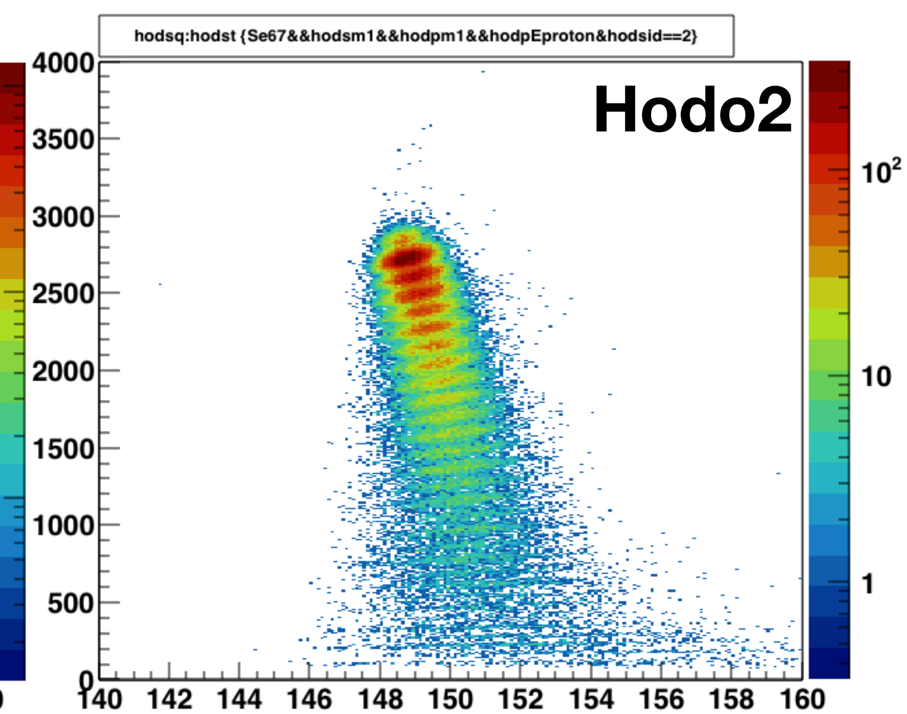
More new isotopes to come?



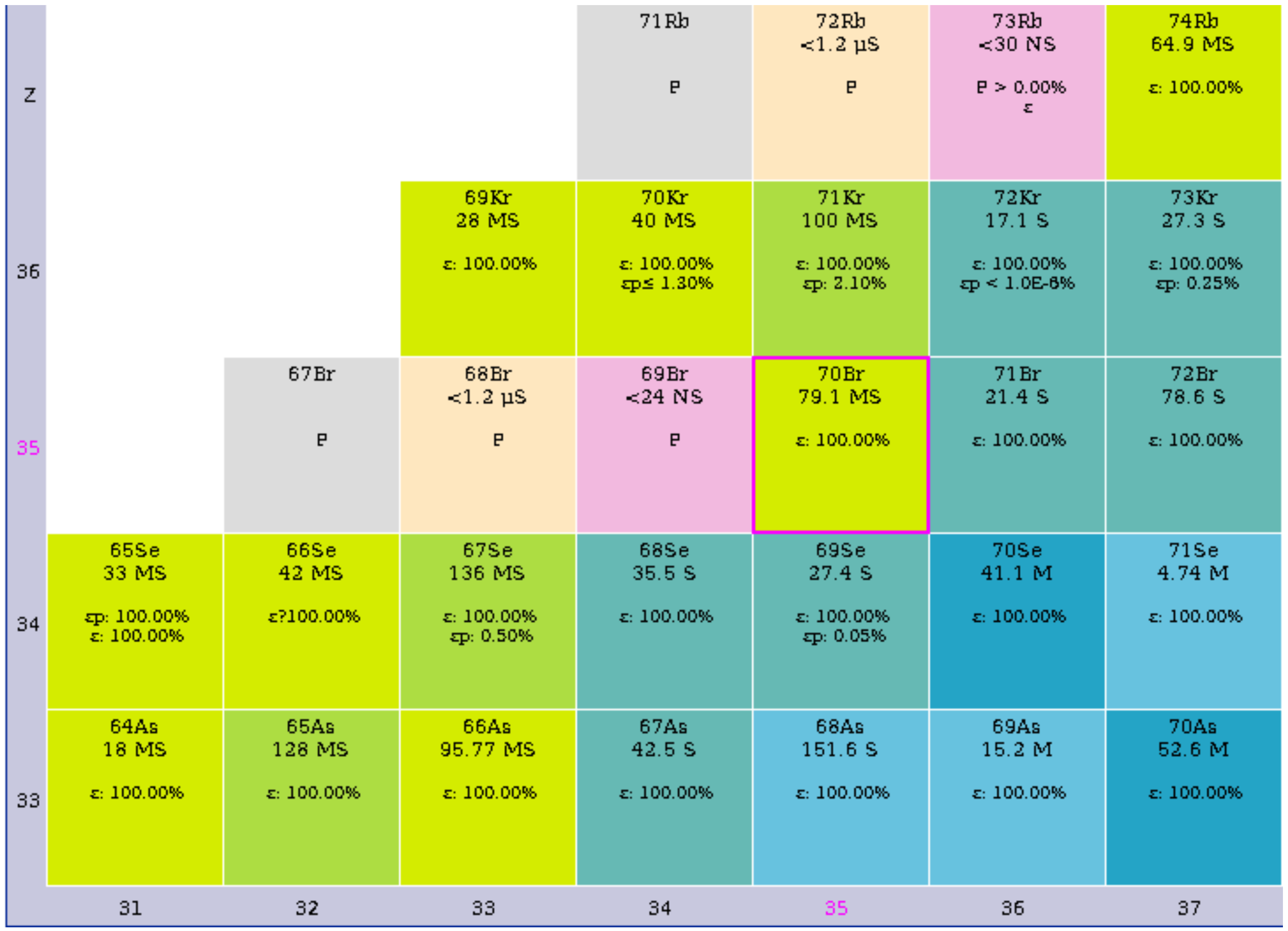
Z \ N	29	30	31	32	33	34	35	36	N
Z (34)		64Se >180 NS ε: 100.00%	65Se 33 MS ε: 100.00% εp: 100.00%	66Se 42 MS ε?100.00%	67Se 136 MS ε: 100.00% εp: 0.50%	68Se 35.5 S ε: 100.00%	69Se 27.4 S ε: 100.00% εp: 0.05%	70Se 41.1 M ε: 100.00%	71Se 4.74 M ε: 100.00%
33	62As P	63As <43 NS P	64As 18 MS ε: 100.00%	65As 128 MS ε: 100.00%	66As 95.77 MS ε: 100.00%	67As 42.5 S ε: 100.00%	68As 151.6 S ε: 100.00%	69As 15.2 M ε: 100.00%	70As 52.6 M ε: 100.00%
32	61Ge 44 MS ε: 100.00% εp > 62.00%	62Ge 129 MS ε: 100.00% εp	63Ge 150 MS ε: 100.00%	64Ge 63.7 S ε: 100.00%	65Ge 30.9 S ε: 100.00% εp: 0.01%	66Ge 2.26 H ε: 100.00%	67Ge 18.9 M ε: 100.00%	68Ge 270.93 D ε: 100.00%	69Ge 39.05 H ε: 100.00%
31	60Ga 70 MS ε: 100.00% εp: 1.60%	61Ga 167 MS ε: 100.00% εp < 0.25%	62Ga 116.121 MS ε: 100.00% εp	63Ga 32.4 S ε: 100.00%	64Ga 2.627 M ε: 100.00%	65Ga 15.2 M ε: 100.00%	66Ga 9.49 H ε: 100.00%	67Ga 3.2617 D ε: 100.00%	68Ga 67.71 M ε: 100.00%
30	59Zn 182.0 MS ε: 100.00% εp: 0.10%	60Zn 2.38 M ε: 100.00%	61Zn 89.1 S ε: 100.00%	62Zn 9.186 H ε: 100.00%	63Zn 38.47 M ε: 100.00%	64Zn ≥7.0E20 Y 49.17% 2ε	65Zn 243.93 D ε: 100.00%	66Zn STABLE 27.73%	67Zn STABLE 4.04%



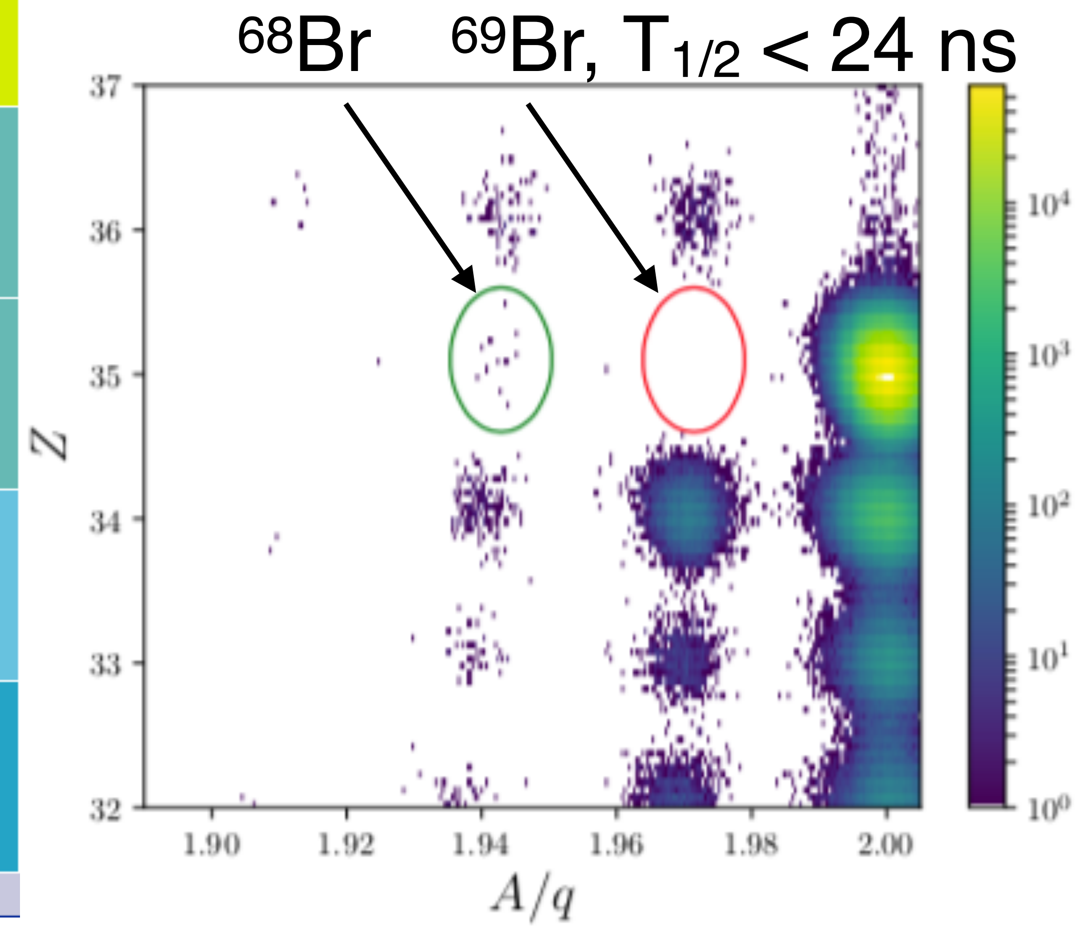




Making new isotopes with exotic beams



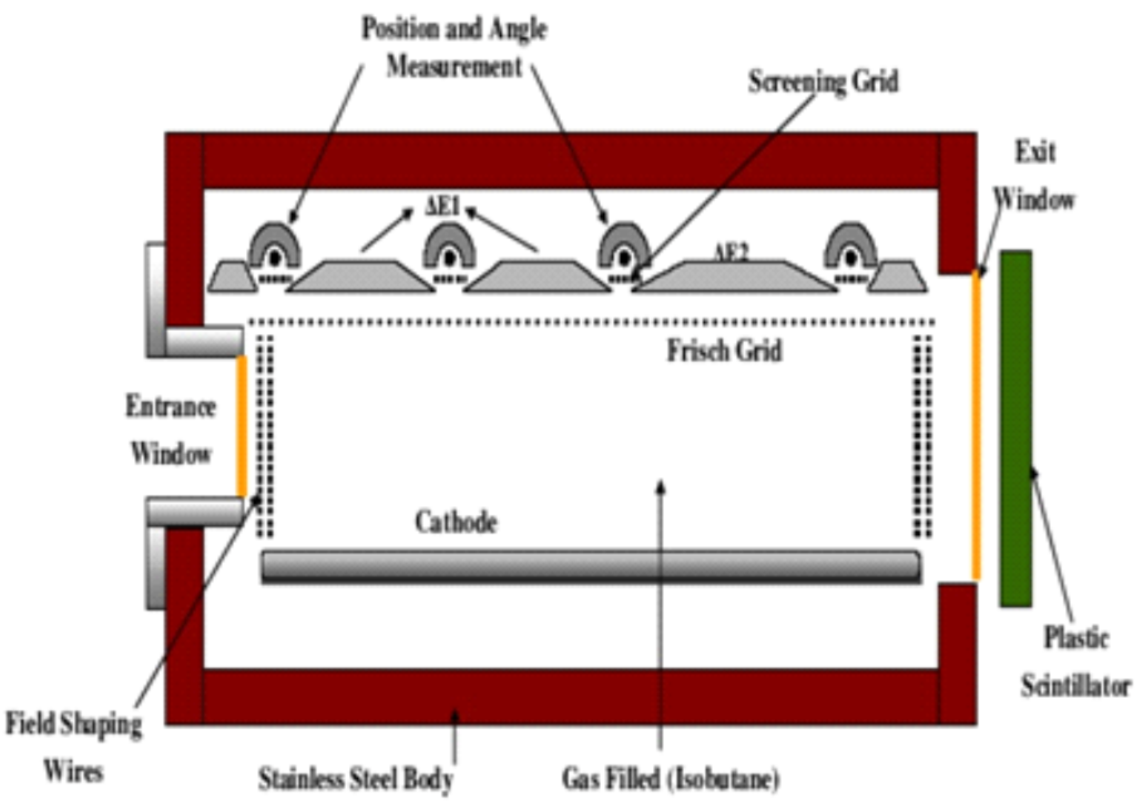
Wimmer et al. arXiv:1906.04067v1

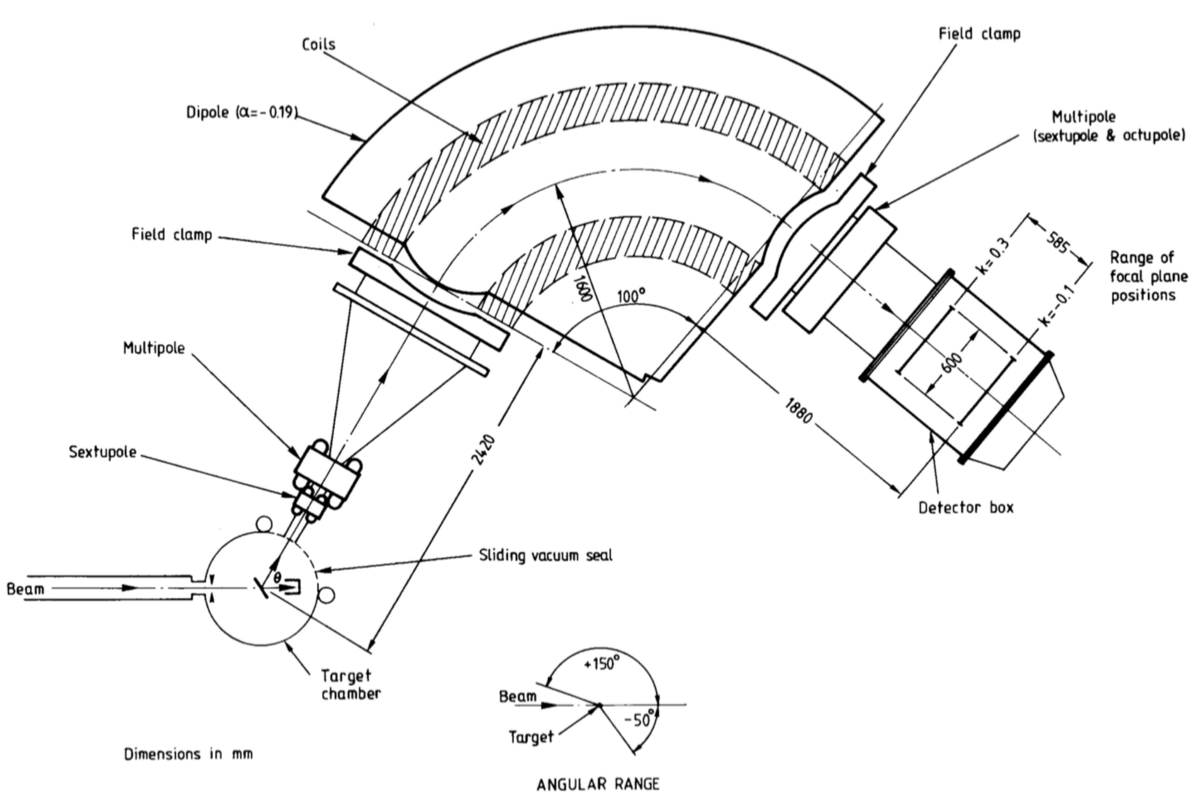


beam	reaction	events in ROI	background	corrected yield	σ^{-xpyn}(ave.) (mb)	expected yield	$\langle\tau\rangle$ (ns)
^{70}Br	-2n	12	0.15(2)	14.7(50)(18)	0.57(21)	1740(710)	51(6)
^{70}Kr	-1p1n	140	113(3)	33(16)(4)	82(12)	2240(500)	57(7)
^{71}Kr	-1p2n	20	9.0(3)	13.7(60)(12)	5.7(12)	2690(720)	46(6)
^{72}Kr	-1p3n	12	3.8(2)	10(4)(2)	0.32(8)	1130(340)	51(6)

^{70,71,72}Kr and ^{70}Br at 170 AMeV on a 703 mg/cm^2 ^{9}Be target. Knockout and few nucleon removal reactions. Separation and PID with ZeroDegreeSpectrometer at RIBF.

Less exotic transfer reaction for developing exotic instruments

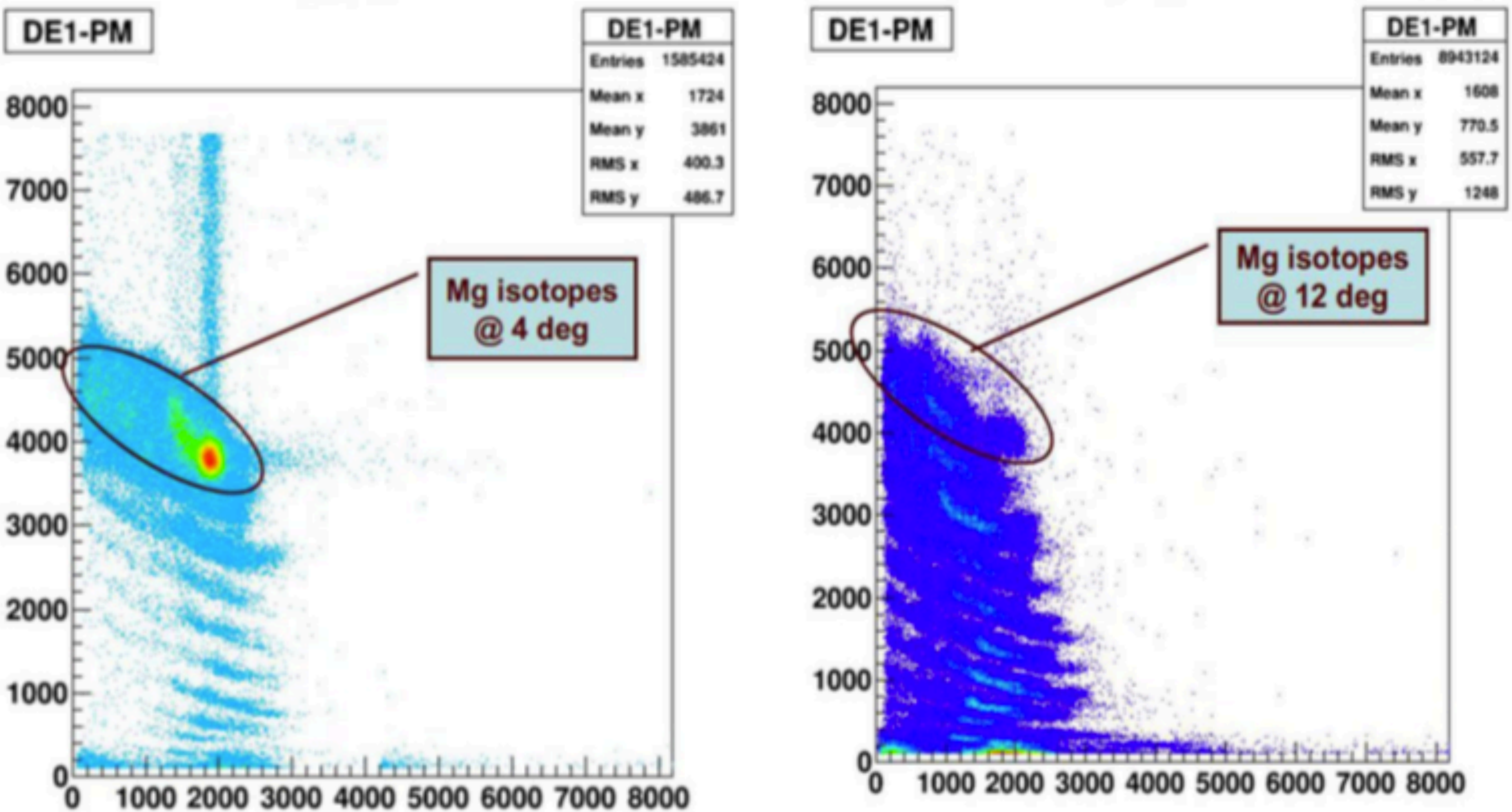




- MDM spectrometer (originally from Daresbury)

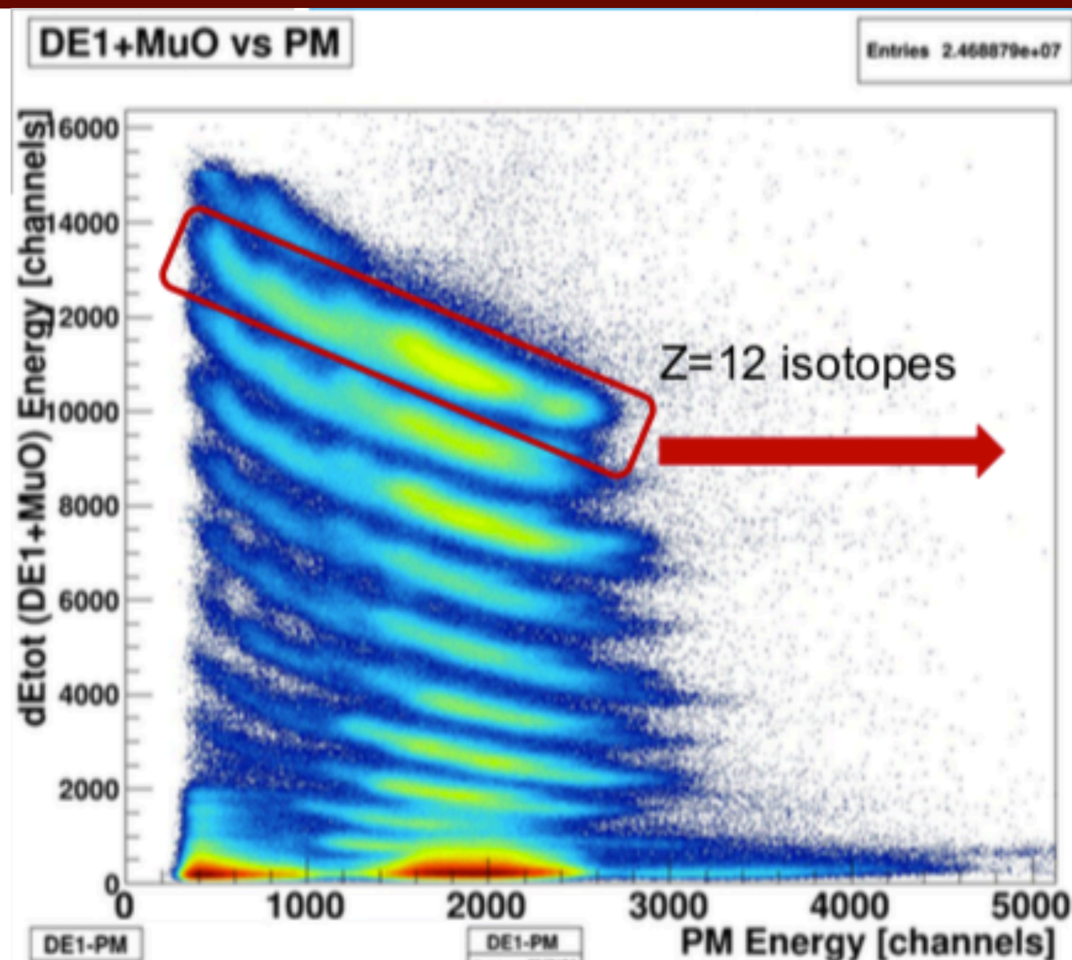
- “Oxford” detector:
  - 4 x resistive wire for position
  - anode plates for dE
  - plastic scintillator for E_{res}
  - iC_4H_{10} ~20 … 150 torr

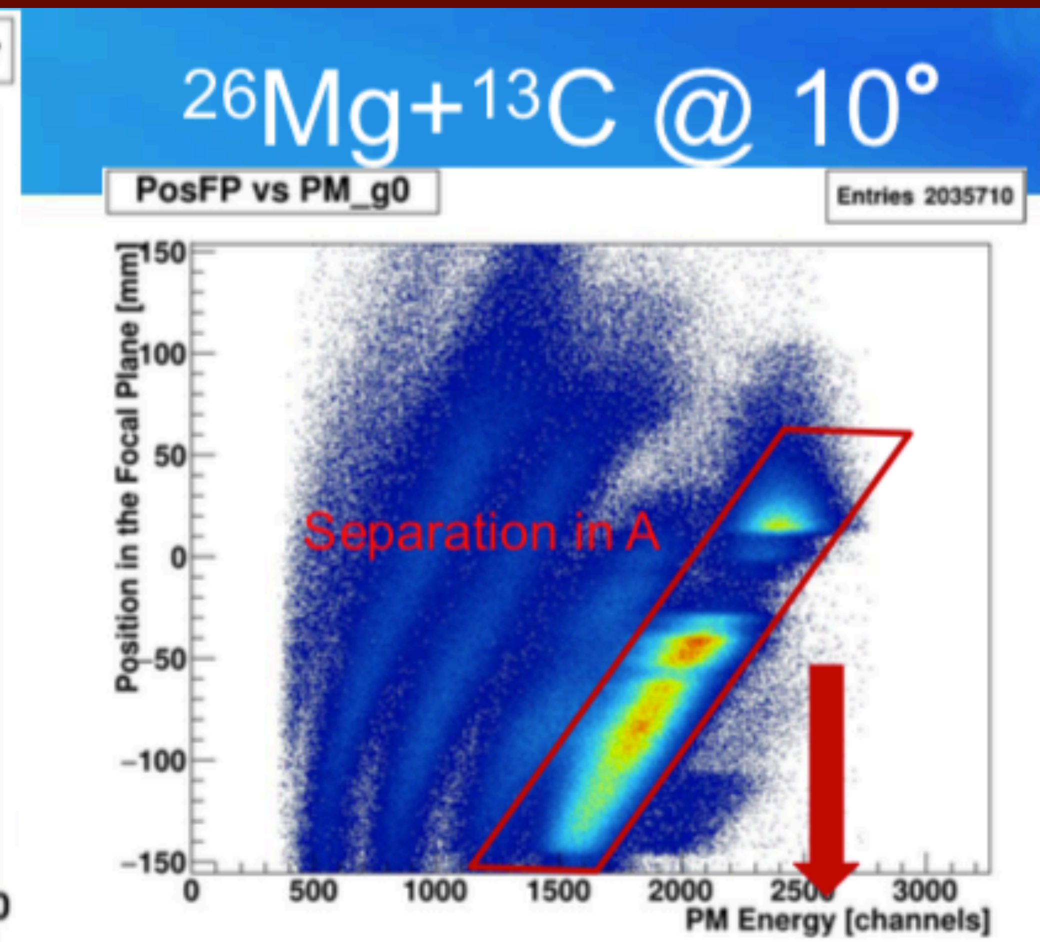
$^{26}Mg + ^{13}C$ transfer, circa 2009

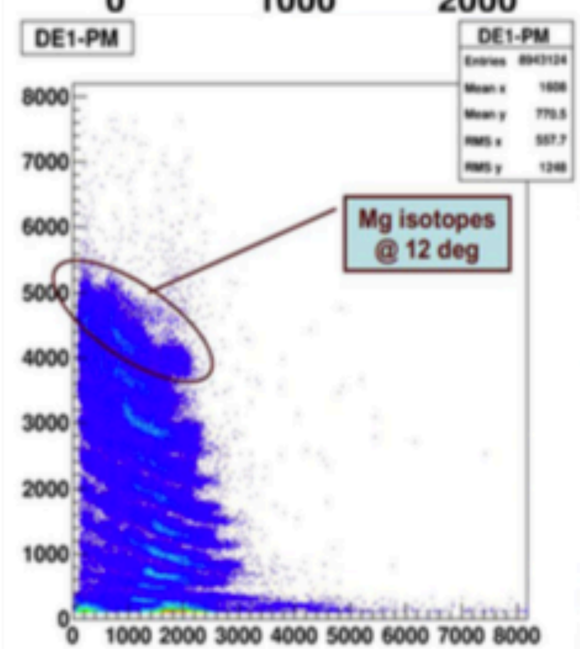


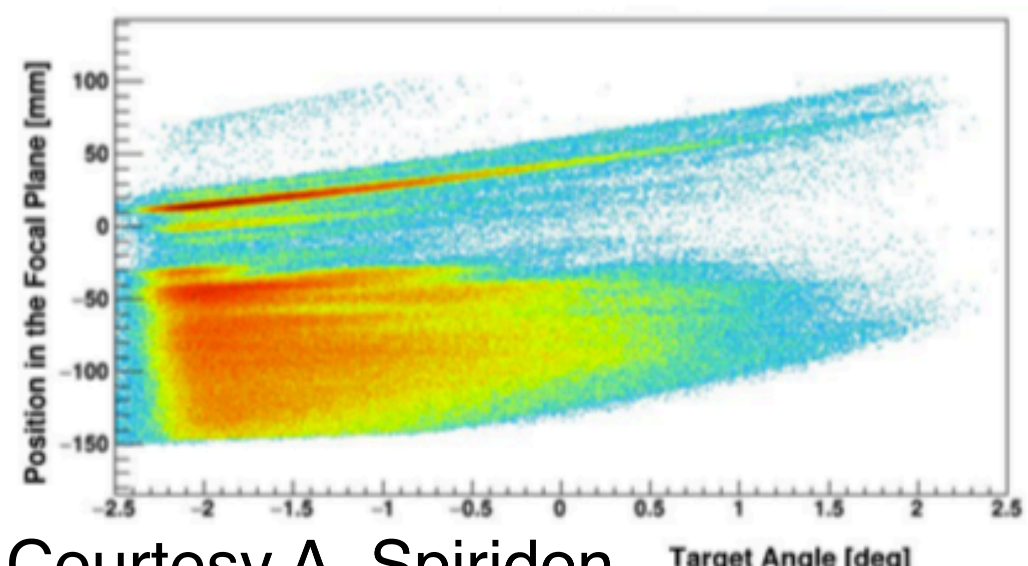
Courtesy A. Spiridon

$^{13}C(^{26}Mg,^{27}Mg)^{12}C$ @ 12 MeV/u, 2016





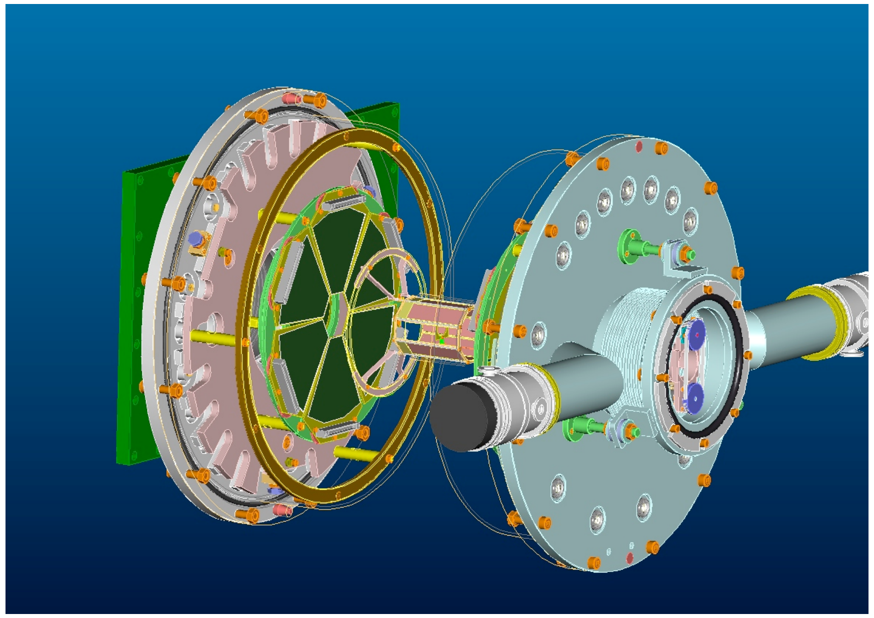


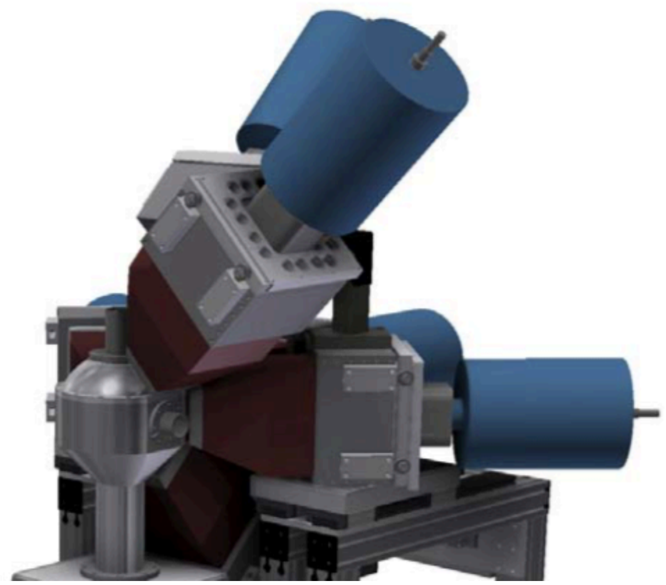


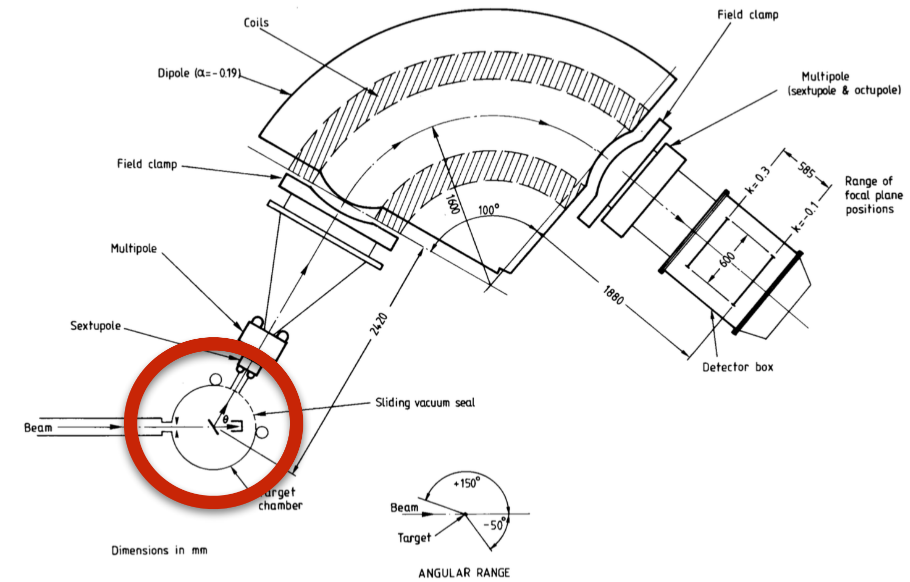
Courtesy A. Spiridon

What did change? Changed dE from ion chamber to Micromegas!

Equipment from 40 decades: TIARA for TEXAS (T4T), TIARA+Hyperion+MDM





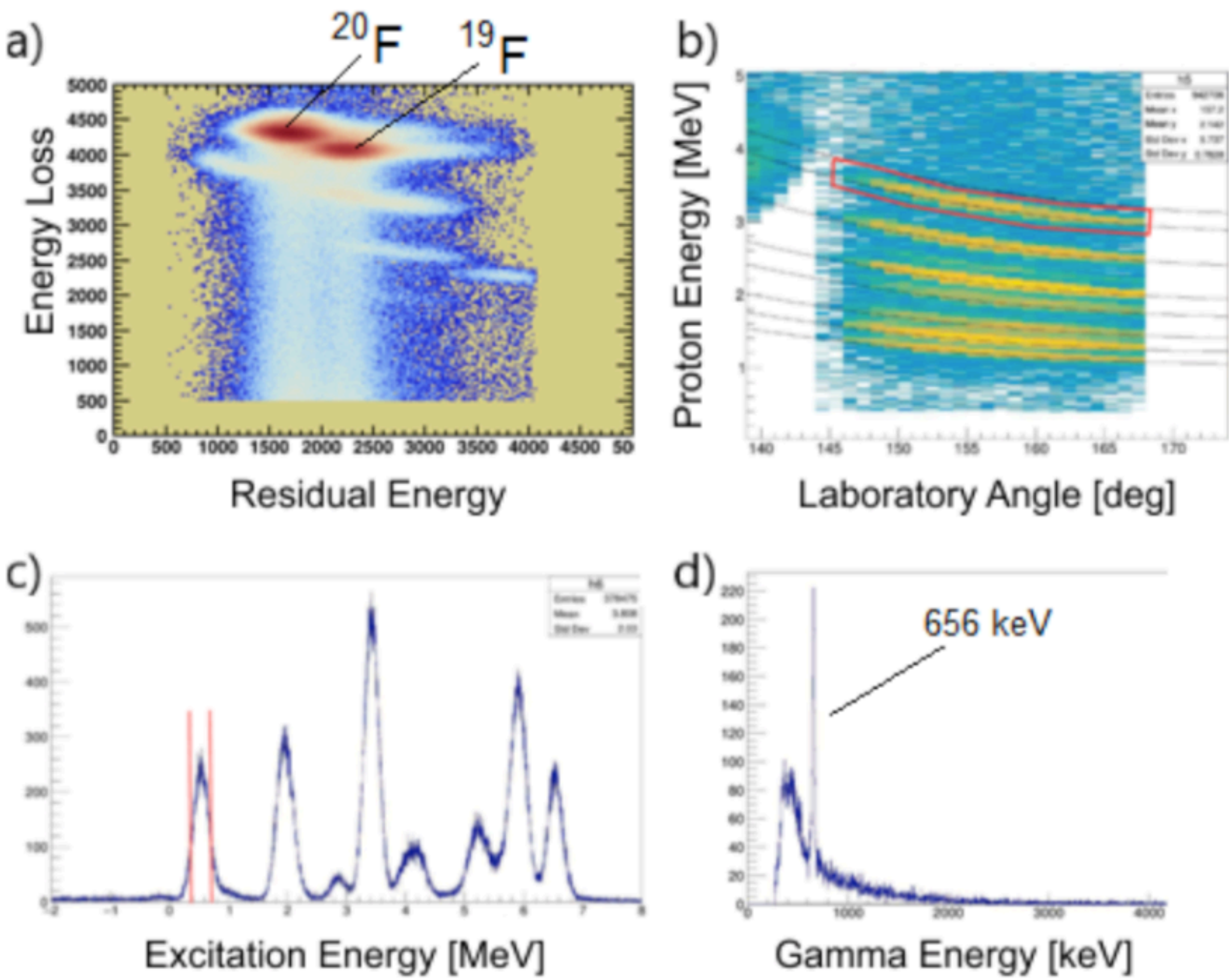


- Transfer reactions, e.g. (d,p), (^{6}Li,d) in inverse kinematics
- Si barrel + backward (forward) Si array from Surrey
- 4 x HPGe “clover” from LLNL Hyperion array
- MDM as 0 degree spectrometer
- Oxford FP detector with Micromegas

Stable beam commissioning with:
d(^{19}F,^{20}F)p, d(^{23}Na,^{24}Na)p, d(^{25}Mg,^{26}Mg)p, ^{6}Li(^{22}Ne,^{25,26}Mg)d

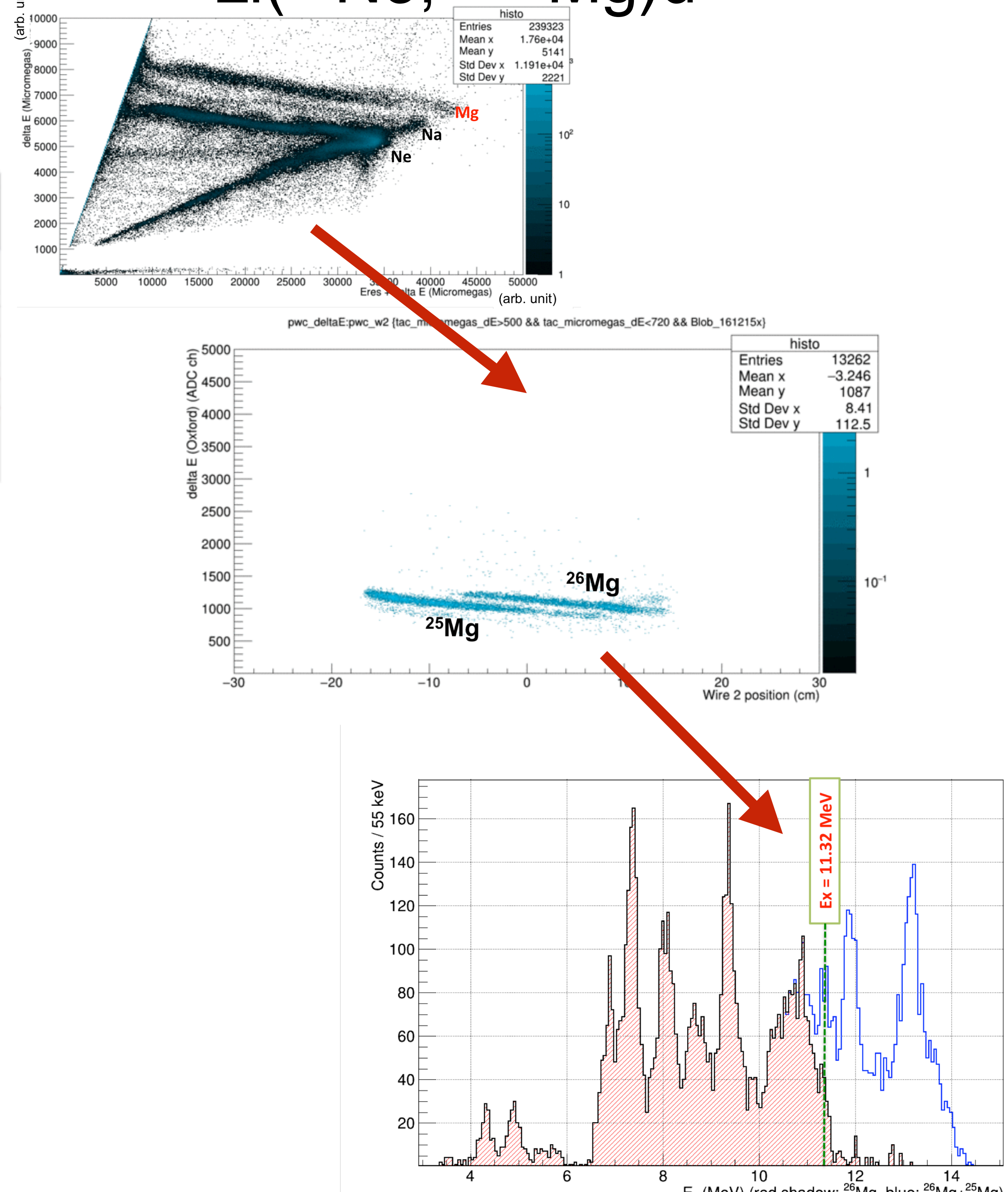
Examples from commissioning runs

d(^{19}F,^{20}F)p



G. Christian et al. CI annual report 2016-7, I-37

^{6}Li(^{22}Ne,^{25,26}Mg)d



S. Ota et al. CI annual report 2017-8, I-4

Summary

- few basics of reaction experiments

- different reaction types

- production of exotic beams for reaction experiments

- some experimental considerations

- example reaction experiments with exotic beams

Thank y'all!

Some references and literature

Books:
C.A. Bertulani and P. Danielewicz, *Introduction to Nuclear Reactions,* IOP Publishing (2004).
I.J. Thompson and F. Nunes, *Nuclear Reactions for Astrophysics,* Cambridge University Press (2009).
K.S. Krane, *Introductory Nuclear Physics,* John Wiley & Sons (1988).
C. Iliadis, *Nuclear Physics of Stars*, Wiley (2007).

Euroschool on Exotic Beams Lecture Notes (Vol. I - V),
Lecture Notes in Physics (LNP) 651,700,764,879,948, Springer
https://www.euroschoolonexoticbeams.be/site/pages/lecture_notes (<— has also slides from past editions)

Previous Exotic Beam Summer School editions pages (slide availability varies year by year):
https://fribusers.org/gatherings/schools.html

Recent review articles:
K Wimmer, J. Phys. G. 45, 033002 (2018).
Tribble et al., Rep. Prog. Phys. 77**,** 106901 (2014).
P.G. Hansen and J.A. Tostevin, Annu. Rev. Nucl. Part. Sci., 53, 219 (2003).