The Fragment Mass Analyzer (FMA) and The Study of Proton Emitters

Darek Seweryniak

filling in for

Cary N. Davids

ATLAS 25th Anniversary Celebration

October 22, 2010

Argonne NATIONAL LABORATORY

... for a brighter future

U.S. Department of Energy

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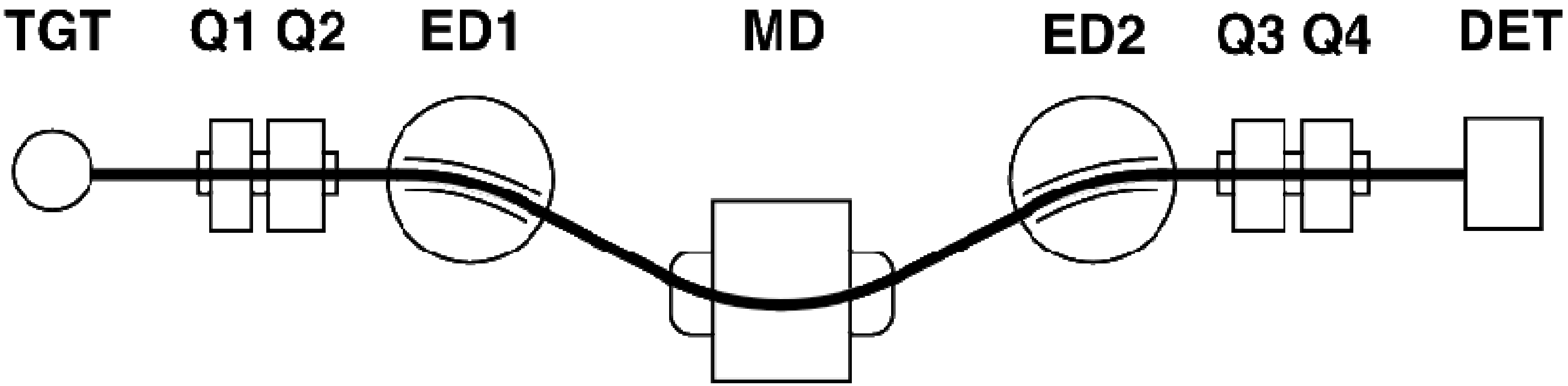
What Can a Recoil Separator Do for Us?

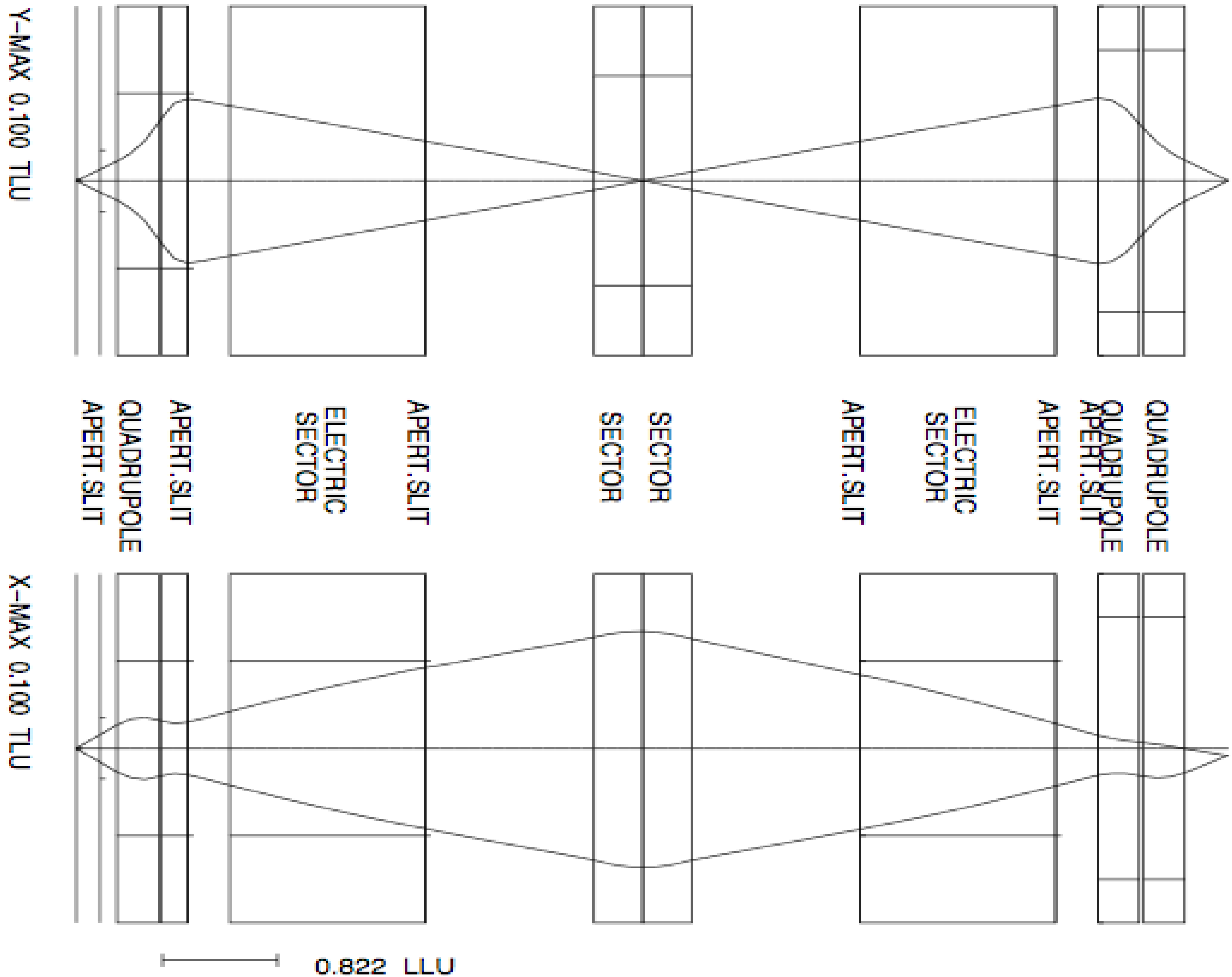
- **Separates reaction products from primary beam particles at 0º.**
- **Focuses and disperses the reaction products at the focal plane by M/Q (Mass/Charge). The M/Q groups are physically separated from one another.**
- **With achromatic optics, we can measure particle energy using time-of-flight, since, for a given energy, all paths are isochronous.**

Fragment Mass Analyzer (FMA)



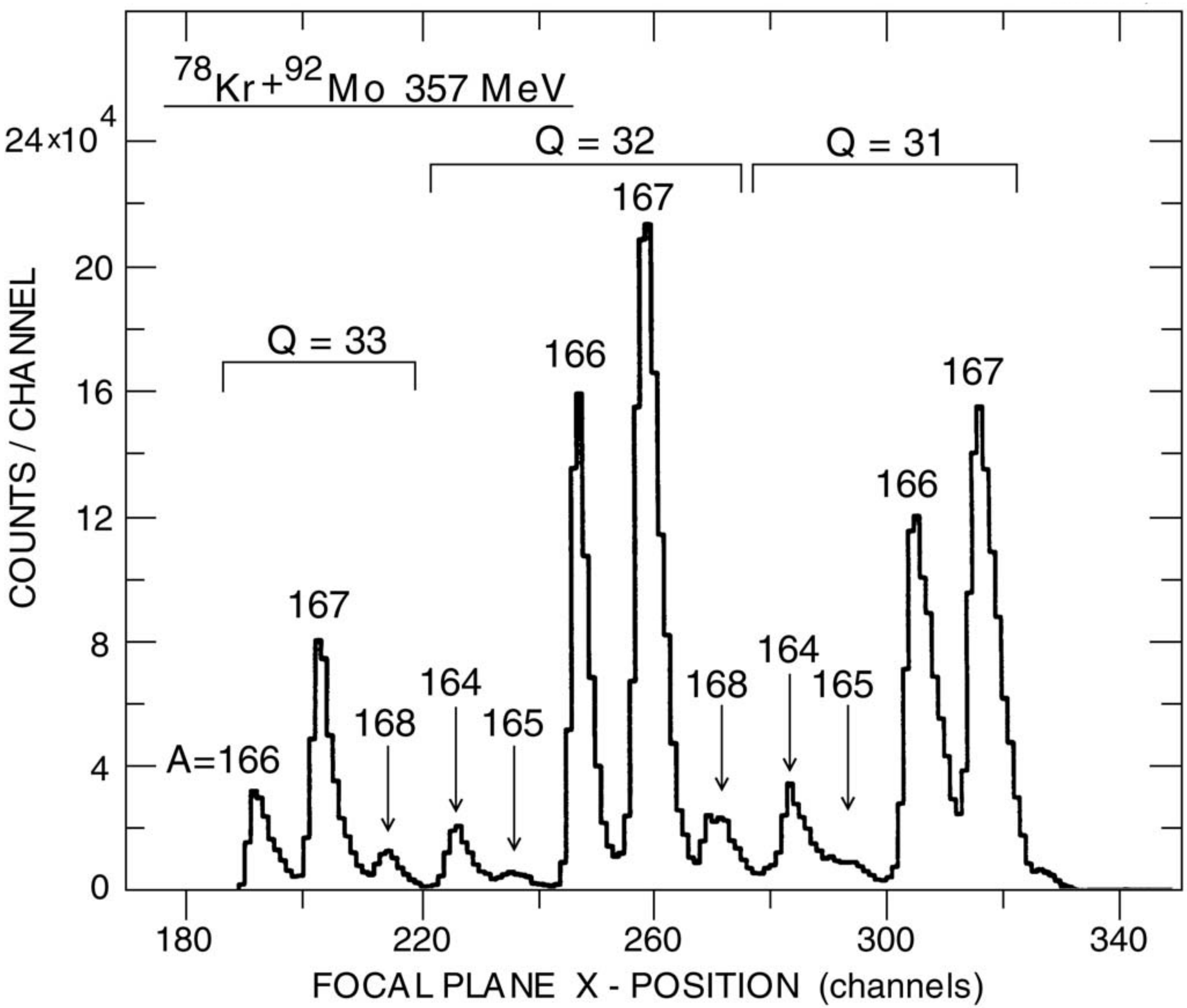
• **Solid Angle acceptance**	**8 msr**
• **Energy acceptance**	**± 20%**
• **M/q acceptance**	**± 7%**
• **M/q dispersion**	**0 → 20 mm/%**
•**Mass resolution**	**1/350**
• **Length**	**8.2 m**

Ion Optics of the FMA



The FMA at ATLAS

FMA Focal Plane M/Q Spectrum



Types of Experiments Performed at the FMA

- **Fusion-evaporation reactions at 0º,**
  e.g. **$^{92}Mo(^{78}Kr,p2n)^{167}Ir$**
- **Transfer reactions, *e.g.*** **$^{2}H(^{56}Ni,p)^{57}Ni$,**
  $^{4}He(^{44}Ti,p)^{47}V$.
- **Radiative capture reactions, *e.g.*** **$H(^{18}F,\gamma)^{19}Ne$**

Chronology I

- **Proposal prepared for DOE in 1986, based on Legnaro design having one quadrupole doublet at the entrance. Submitted to DOE June 1986.**
- **Competition with ORNL. Approval awarded to ANL in summer 1987.**
- **Immediately began design study with consultant Dan Larson. Tried symmetric quadrupole doublets, which showed performance vastly improved over just one.**
- **Prepared Request for Quotations, sent to vendors in the spring of 1988.**

Chronology II

- **FMA Contract awarded to Bruker GmbH in Karlsruhe in summer of 1988. Includes 2 quadrupole doublets, 2 electric dipoles, 1 60 degree bending magnet, Hall probe magnetometer, all magnet power supplies. Expected delivery: 1 year.**

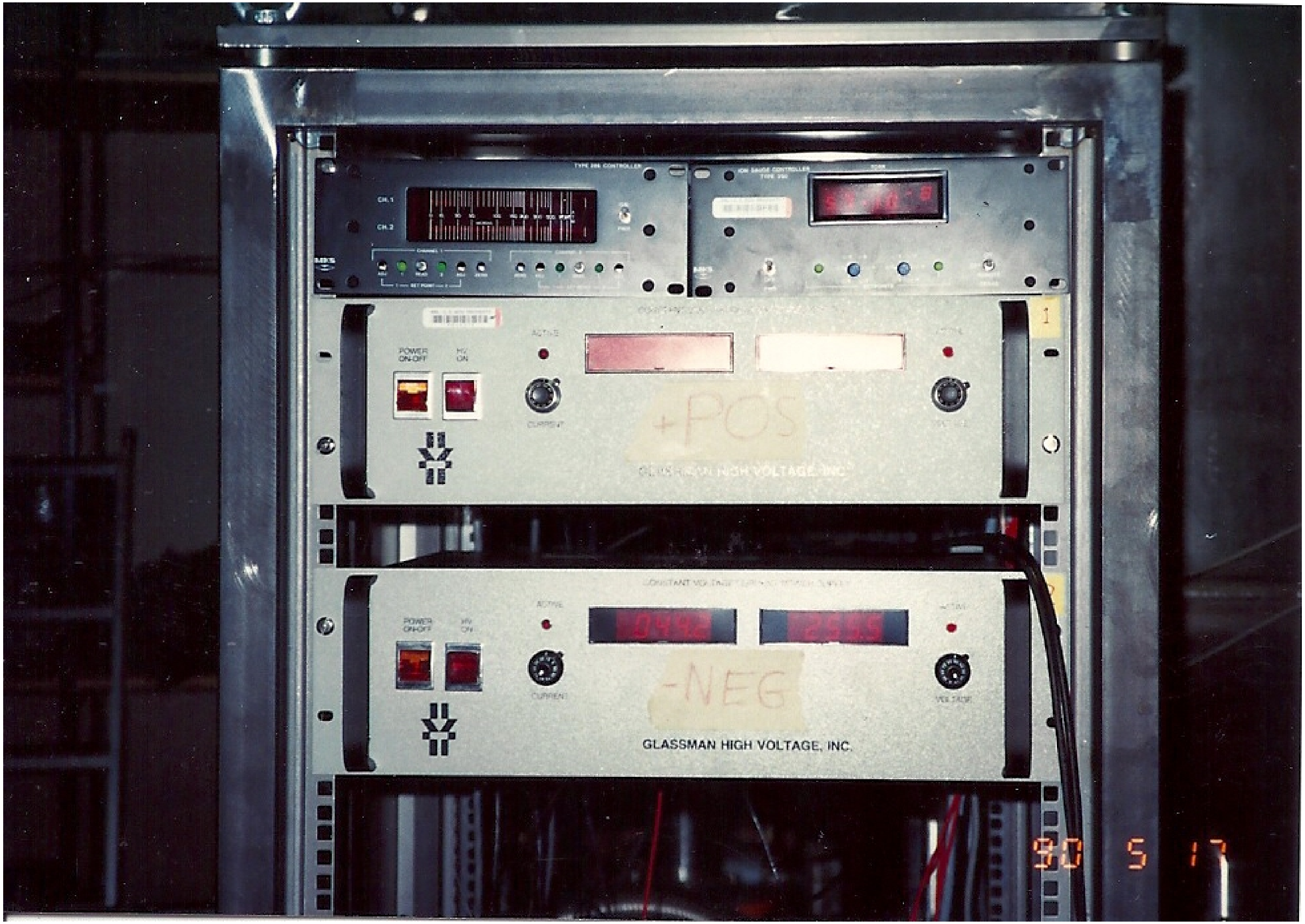

90 5 18

Chronology III

- **New addition to Target Room 3 ready in early 1989.**

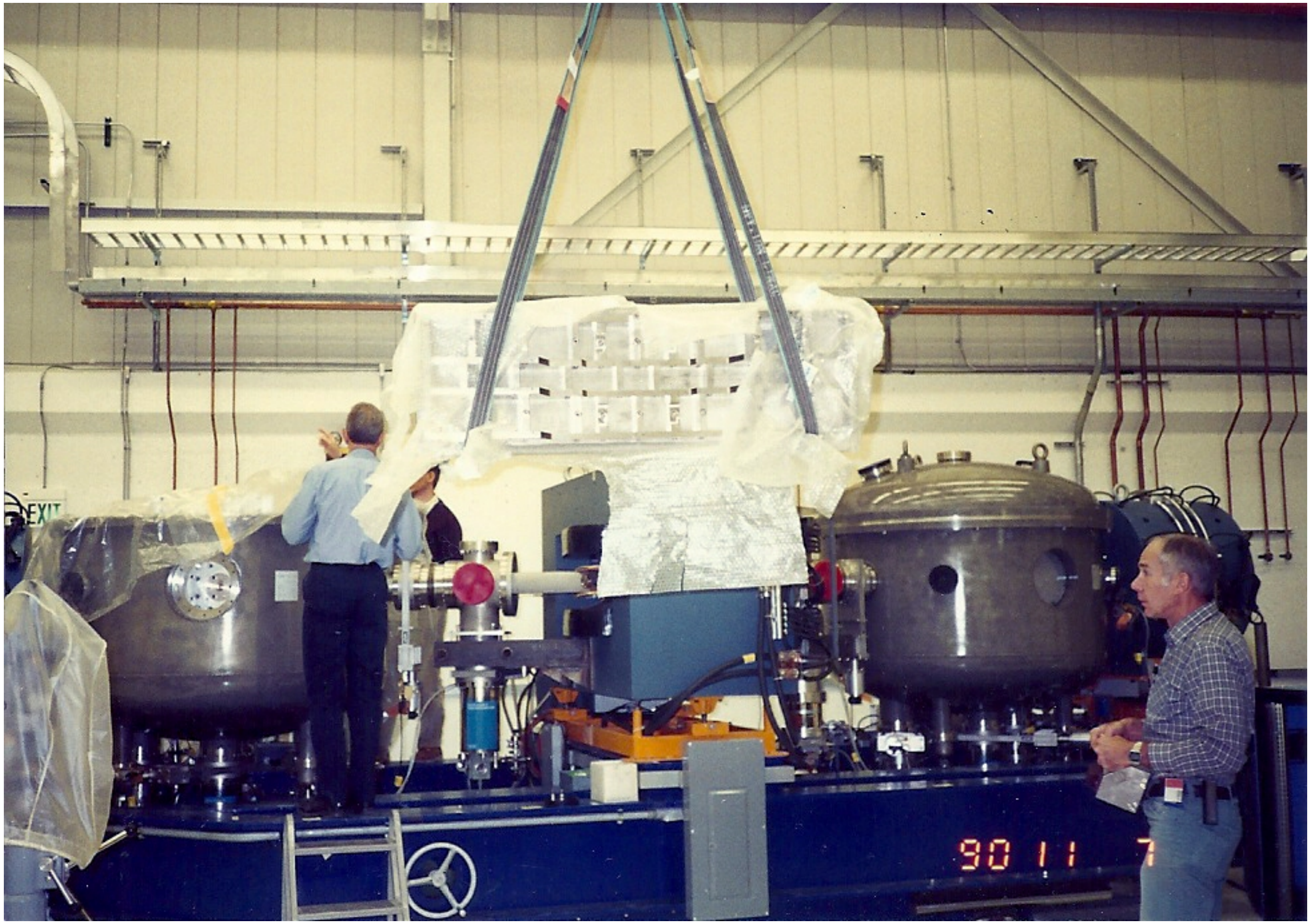
Chronology IV

- **Developed internal 300 kV power supplies for electric dipole. Shipped to Karlsruhe along with vacuum equipment in 1989 for factory tests on dipoles. Conditioned up to 255.5 kV on each plate (511 kV across gap). Assistance on various trips provided by Birger Back, Walter Kutschera, and Thomas Happ.**


POWER ON-OFF
HV ON
+POS
-NEG
GLASSMAN HIGH VOLTAGE, INC.
90 5 17

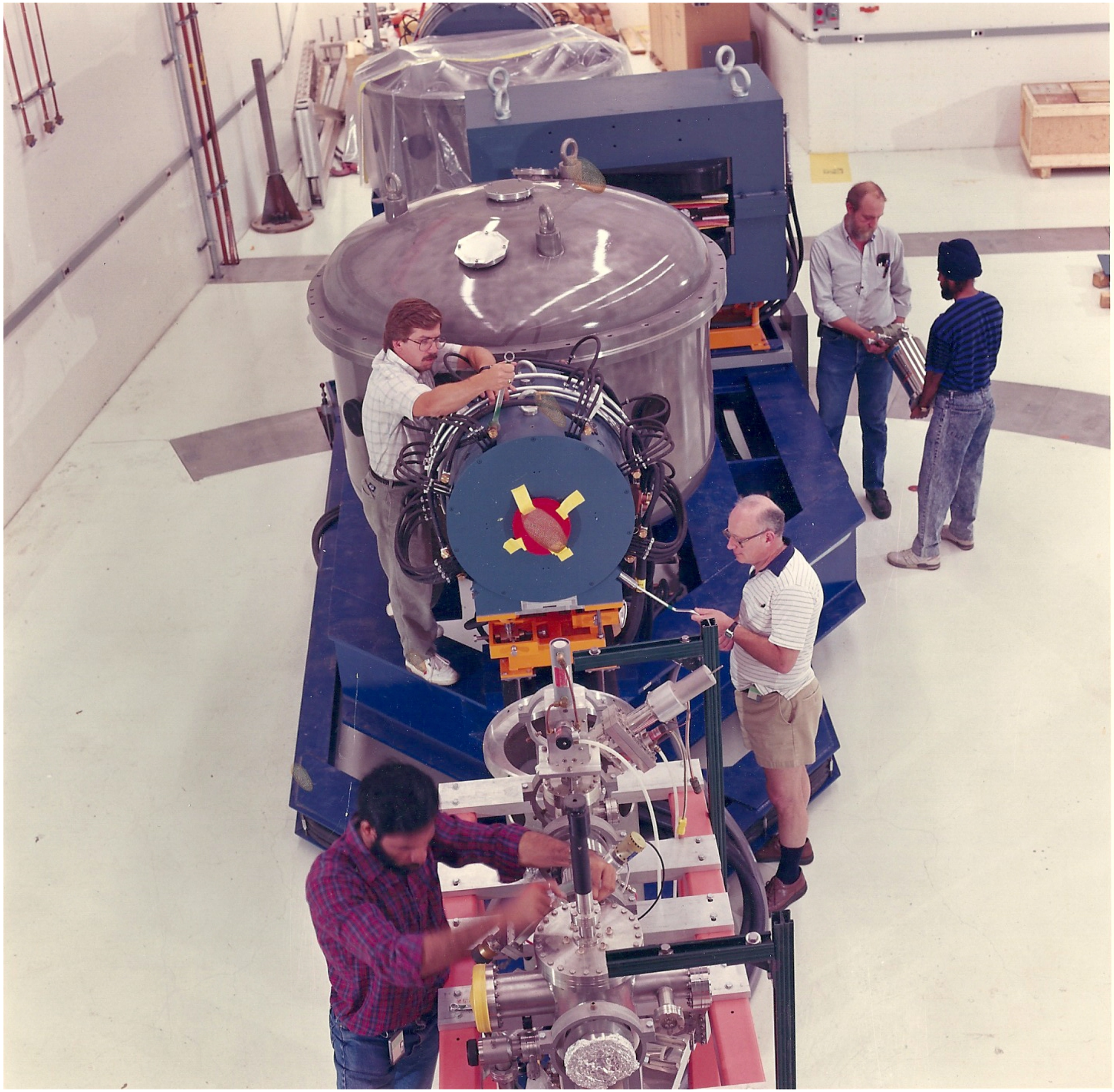
Chronology V

- **FMA components delivered in the summer of 1990 (2 years). Immediately began assembly.**



Chronology VI

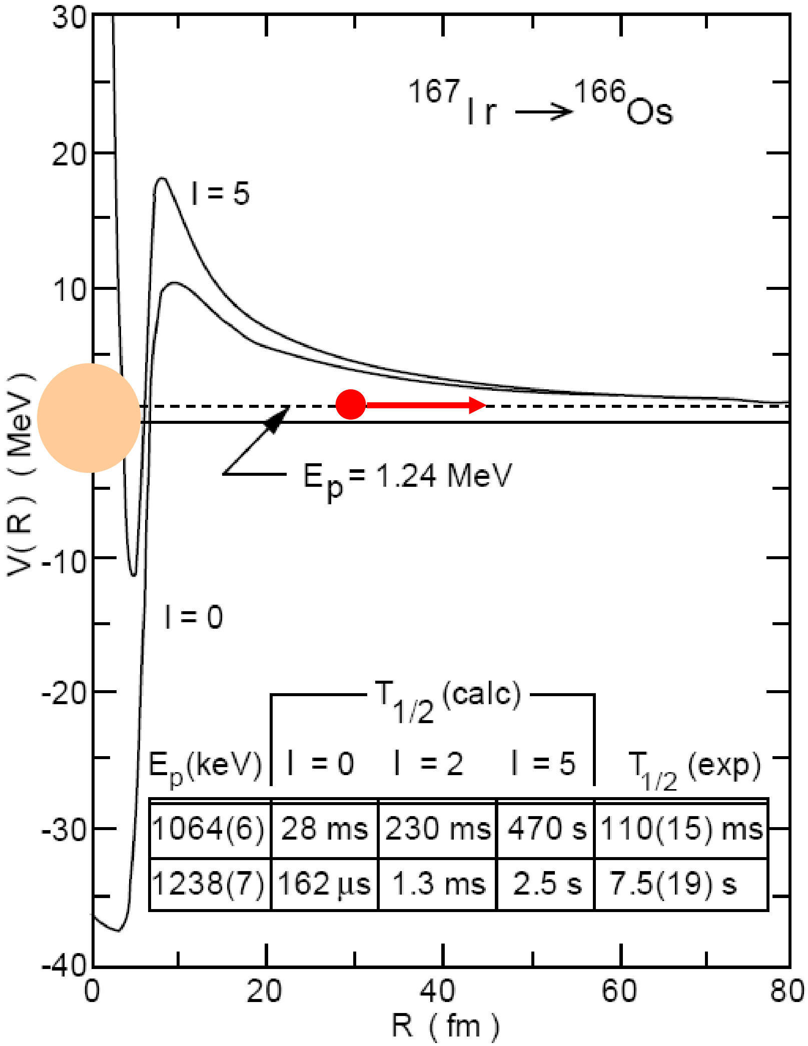
- **A few months into assembly, a safety incident at ATLAS caused a shutdown of the accelerator (Tiger Teams descended on ATLAS). This benefited the FMA assembly because technical manpower was available whenever needed.**
- **FMA assembly was completed in the summer of 1991. Obtained the first mass spectrum in August, aided by Akunuri Ramayya, Birger Back, and Walter Kutschera.**



FMA status
as of 8am 10/22/2010

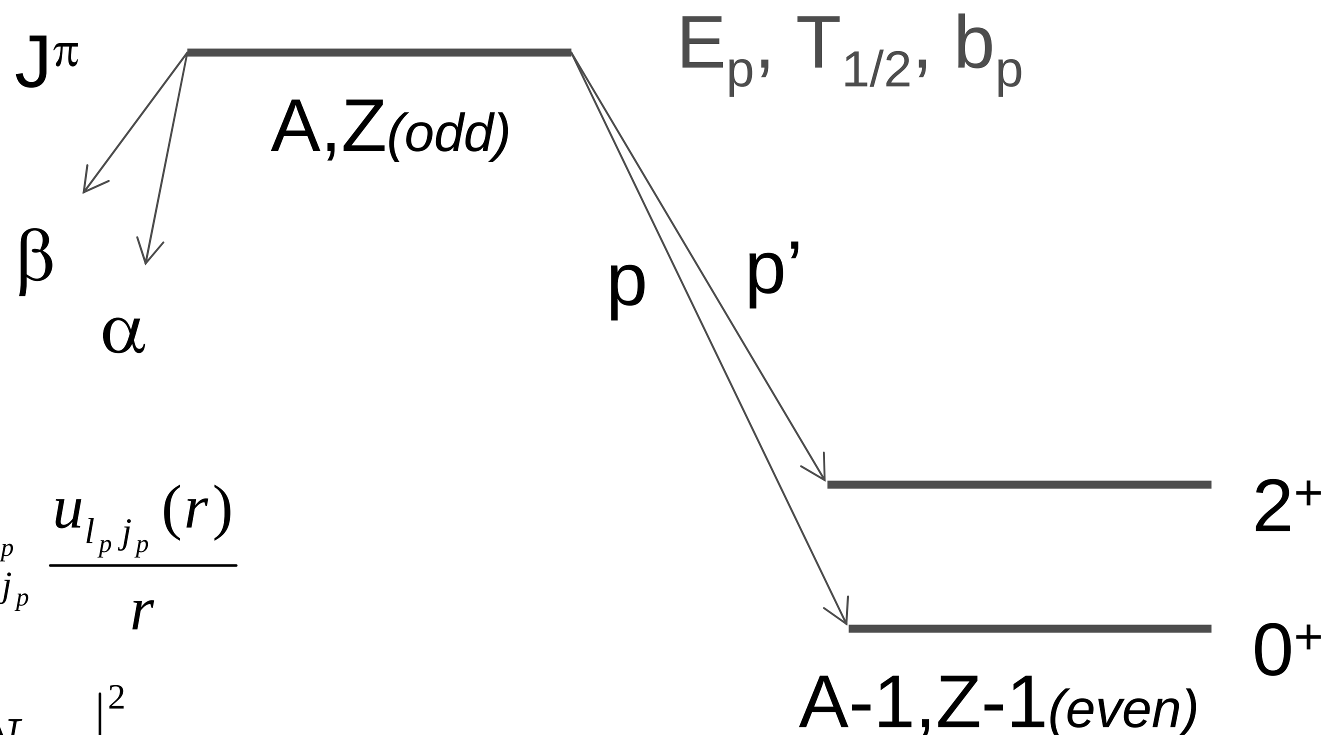
Spontaneous Proton Emission

one of the early experimental programs in collaboration with Univ. of Edinburgh



- ✓ **Analogous to α decay**
- ✓ **No pre-formation factor**
- ✓ **Decay rates sensitive to E_p and l_p**
- ✓ **Unique laboratory to study tunneling through a 3D barrier**
- ✓ **Source of information on nuclear structure and masses far from stability**
- ✓ **Γ_p important for (p,γ) cross sections in light p-rich nuclei in the path of the rp-process**

Proton Decay Observables

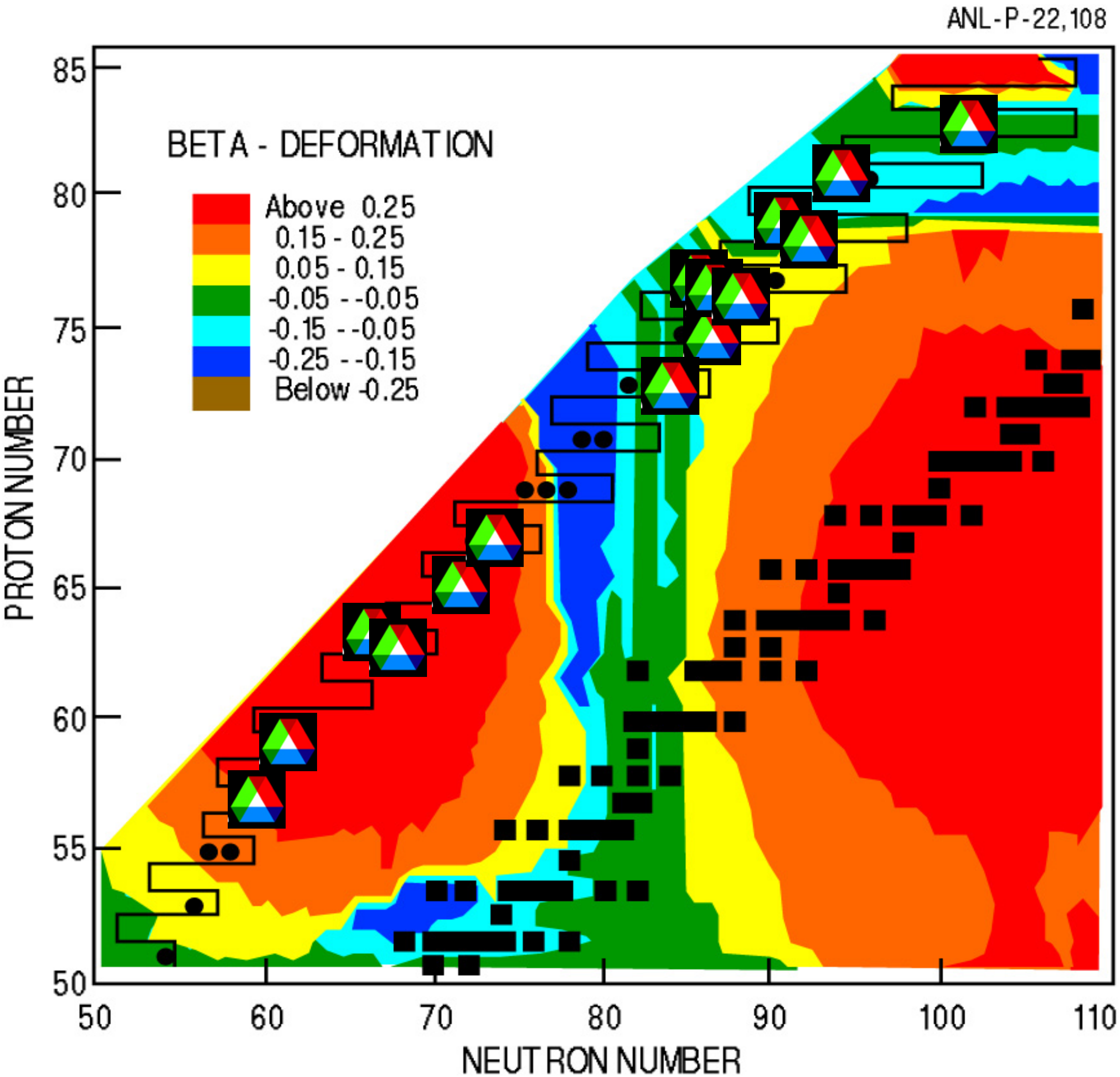


$$\psi_{K_p}^{inside}(r) = \sum_{l_p j_p} c_{l_p j_p}^{K_p} \frac{u_{l_p j_p}(r)}{r}$$

$$\Gamma_{l_p j_p}^{sph} = \frac{\hbar}{\tau} = \frac{\hbar^2 k}{\mu} \left| N_{l_p j_p} \right|^2$$

$$\Gamma_{K_p}^{def} = \frac{\hbar}{\tau} = \frac{2(2R+1)}{2I+1} \sum_{l_p j_p} \left| \langle j_p K_p R0 \mid I K_p \rangle \right|^2 \boxed{\left| c_{l_p j_p}^{K_p} \right|^2} \Gamma_{l_p j_p}^{sph}$$

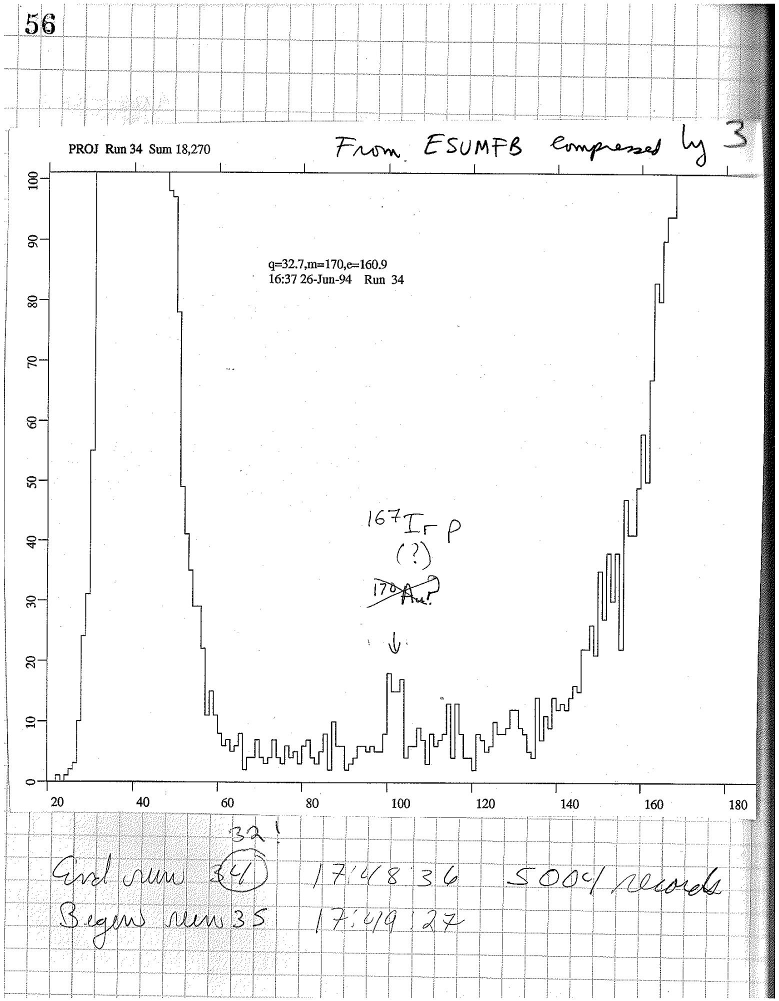
Proton emitter landscape



- ✓ 15 new isotopes!
- ✓ ~20 mass units away from the line of stability
- ✓ Often less exotic neighbors not known

new subfield in nuclear structure emerged and even triggered a series of conferences on proton emitting nuclei

^{167}Ir – 1st new proton emitter observed at ATLAS June 1994



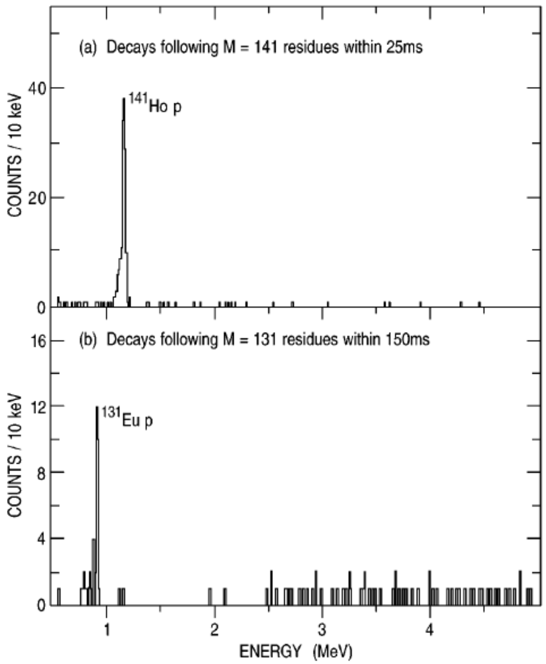
Experiment to search for ^{171}Ag

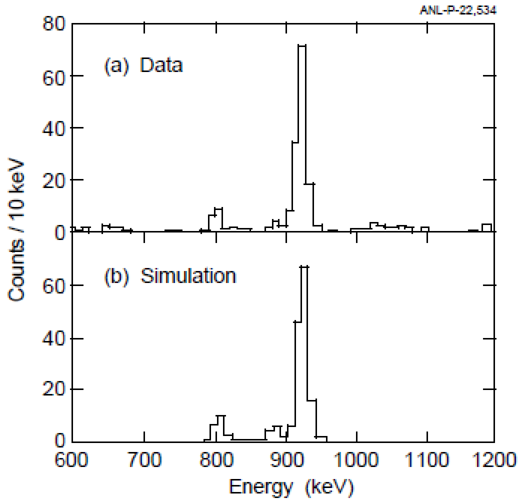
^{78}Kr+^{96}Ru->^{171}Ag+p2n

Instead found:

^{167}Ir+αp2n

Deformed proton emitters at ANL





- ✓ Spherical
- ✓ Axially deformed
- ✓ Odd-odd axially deformed
- ✓ Coupling to vibrations
- ✓ Non-axial deformation

Theory by
C.N. Davids
and
H. Esbensen

First deformed proton emitters
Anomalous decay rates explained by introducing deformation

First fine structure

C.N. Davids et al., PRL C55 (1997)2255

A. Sonzogni et al., PRL 83 (1999)1116

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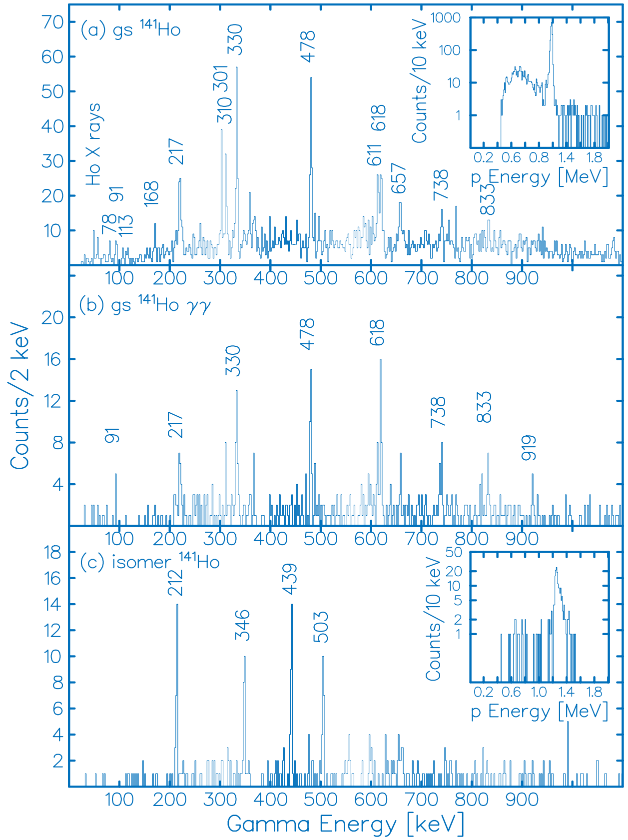
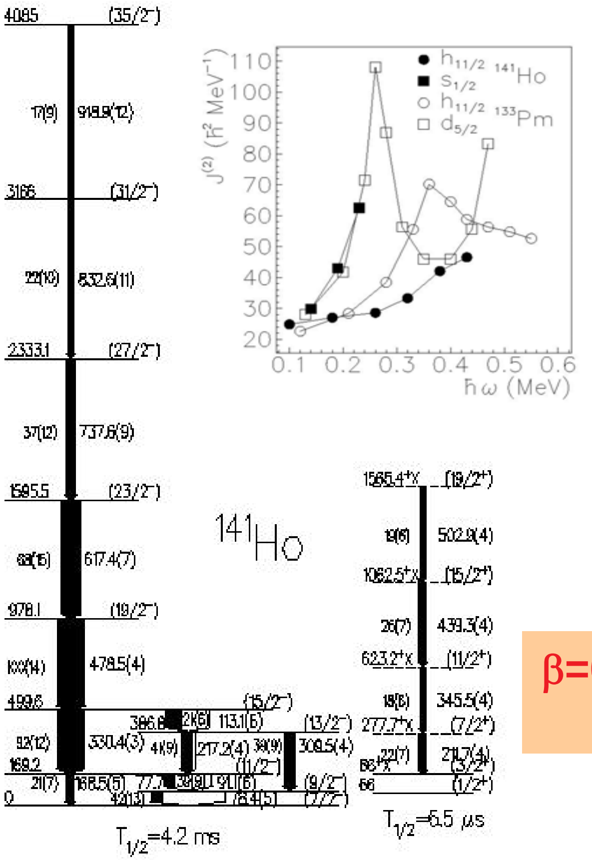
Rotational bands in the deformed proton emitter ^{141}Ho



σ = 300 nb out of 500 mb



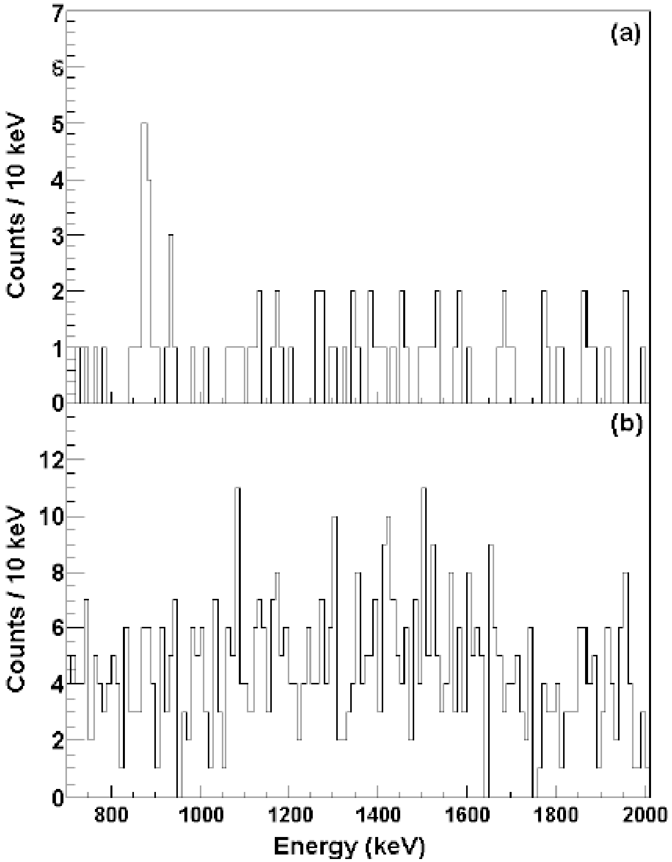
7/2⁻[523] ½⁺[411]

Unexpectedly large signature splitting indicates triaxial shape!

β=0.25(4) from Harris formula

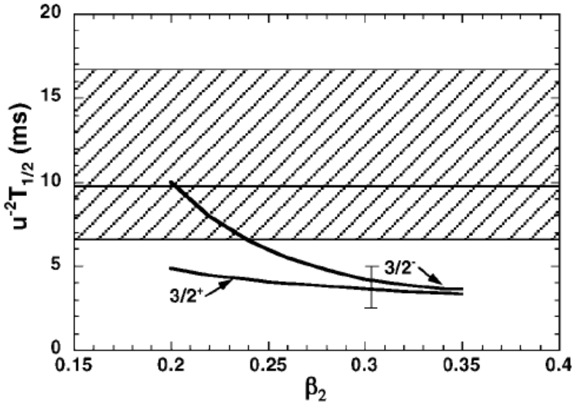
D. Seweryniak et al., PRL C86(2001)1458

^{121}Pr proton emitter
recent developments

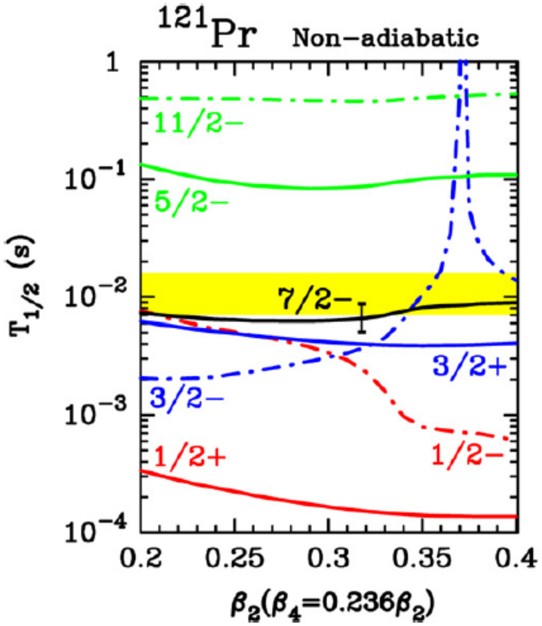


σ = 300 pb

adiabatic calculations



non-adiabatic quasi-particle calculations with Coriolis interaction



Partial rotational alignment

A. Robinson et al., PRL **95,** (2005) 032502

M.C. Lopes et al., Phys. Lett. B 673 (2009) 15

To be continued …

Highlights of Research with the FMA and Future Perspectives

Darek Seweryniak

for FMA "collaboration"

ATLAS 25th Anniversary Celebration

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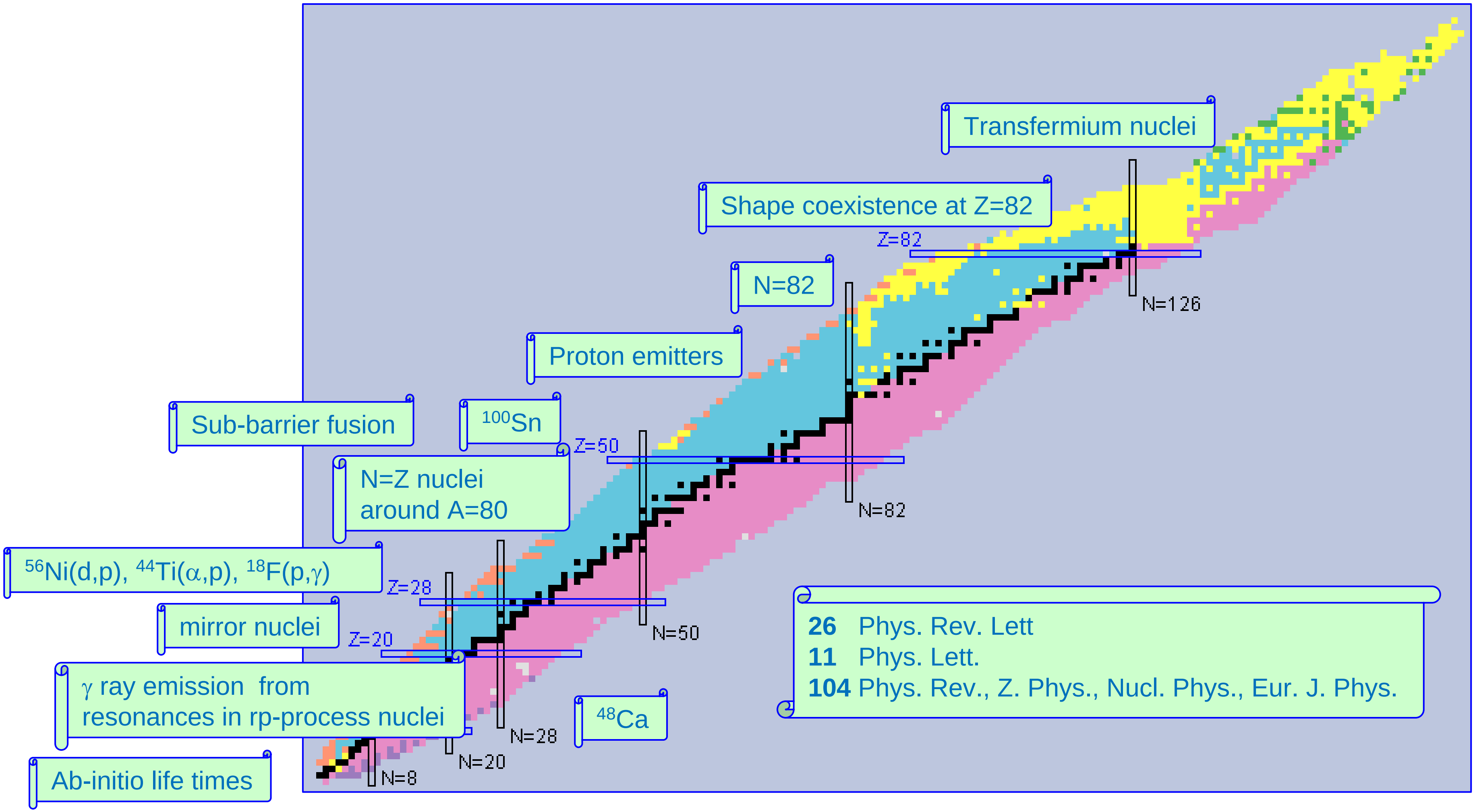
Research with the Fragment Mass Analyzer



26 Phys. Rev. Lett

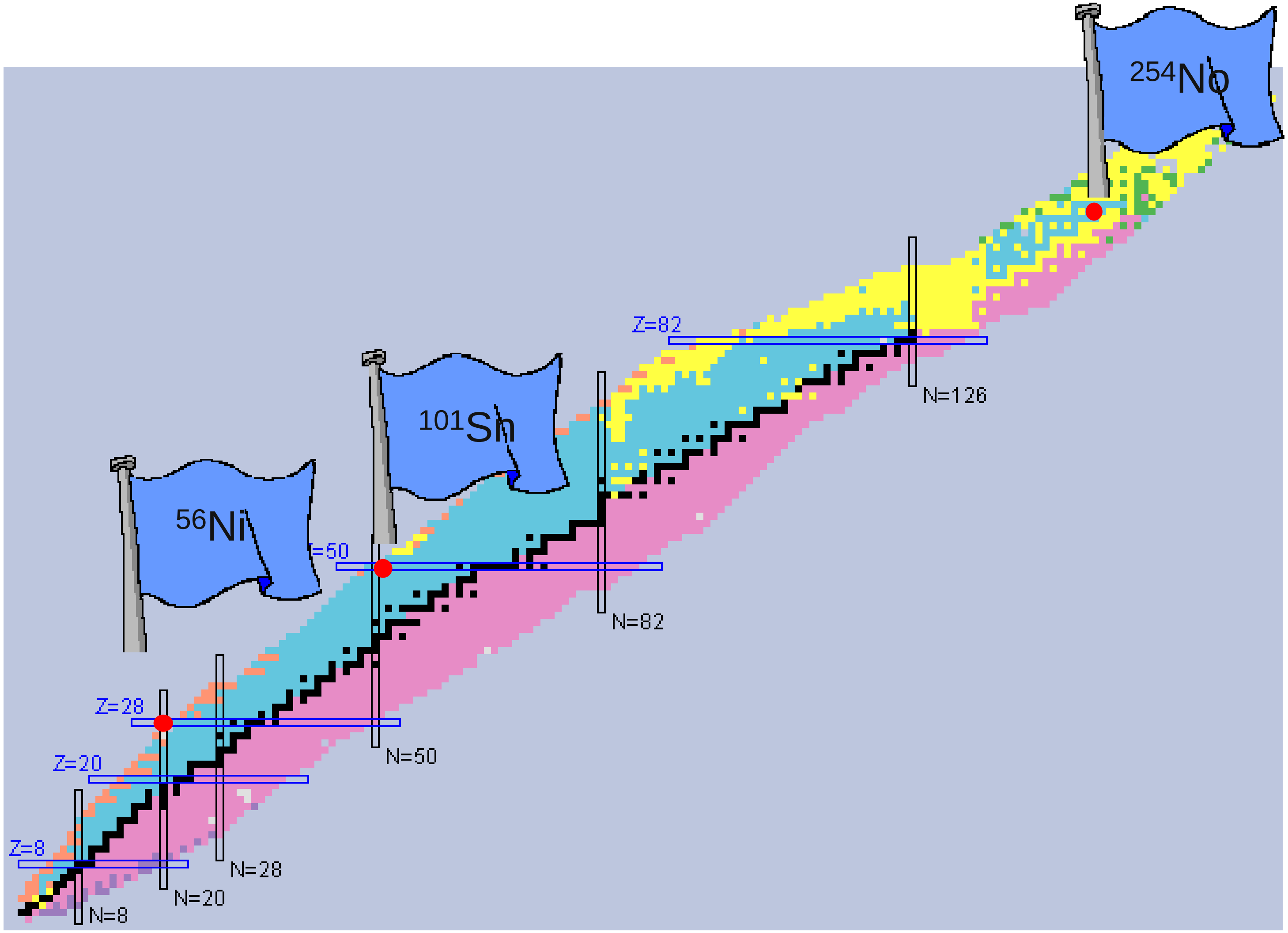
11 Phys. Lett.

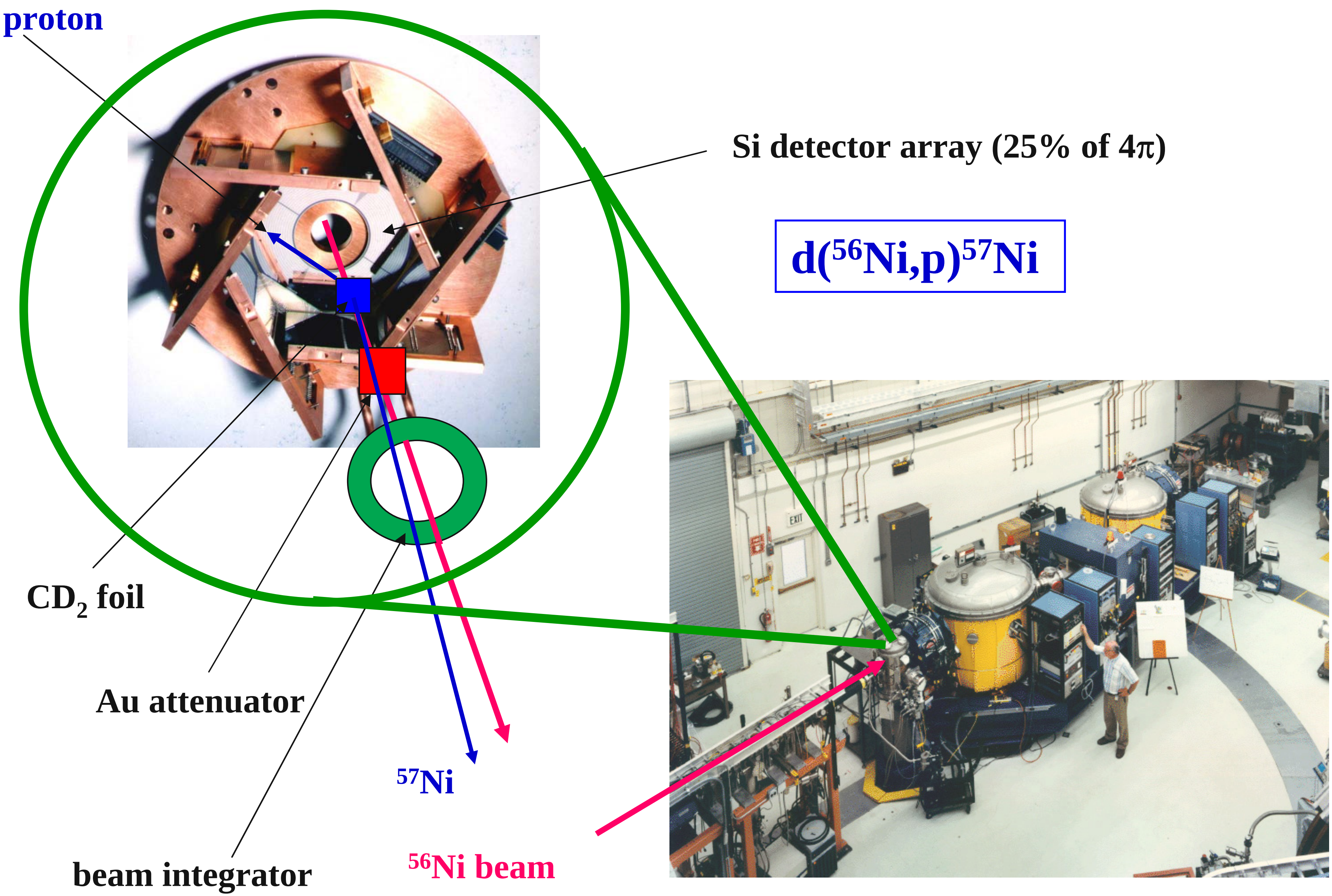
104 Phys. Rev., Z. Phys., Nucl. Phys., Eur. J. Phys.

Experiments with the Fragment Mass Analyzer

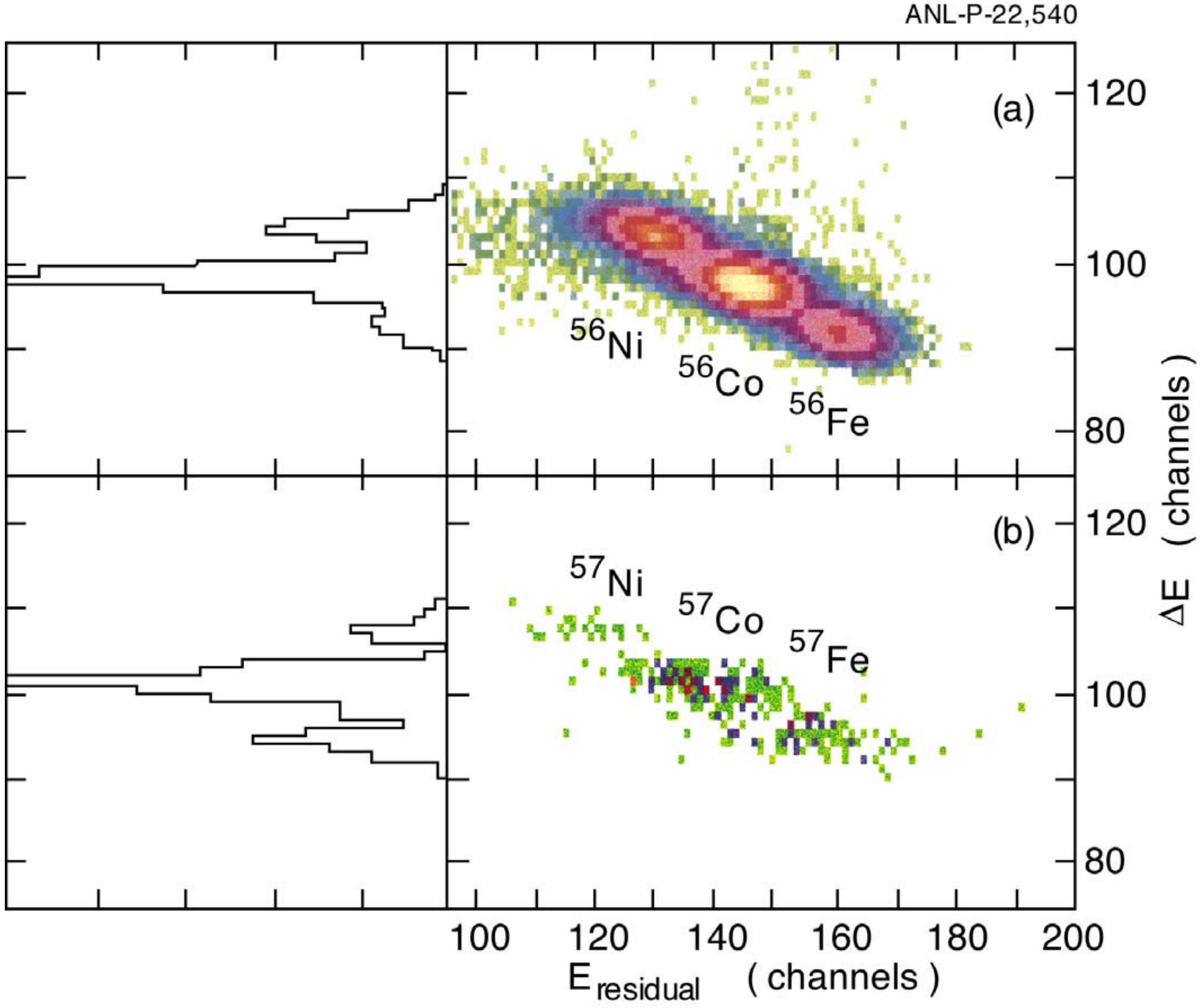
- From ^{10}Be to ^{257}Rf
- Mostly proton- but also neutron-rich nuclei
- Stable and radioactive beams
- Stable and radioactive targets
- Radiative capture, transfer, fusion-evaporation and everything in between
- In-beam spectroscopy at the target position
- Decay spectroscopy at the focal plane
- Nuclear structure, reactions, astrophysics, …

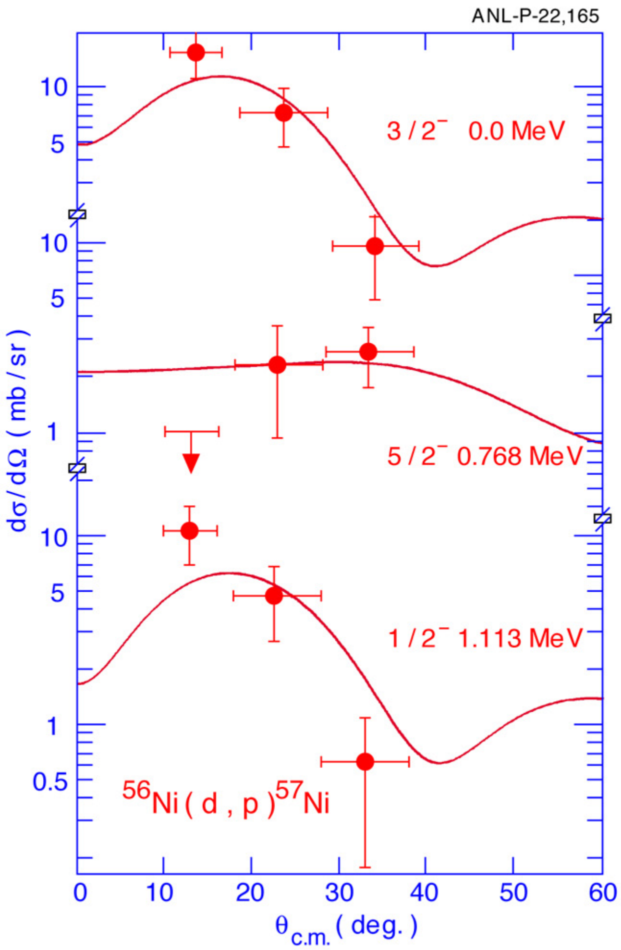
Selected results obtained with the FMA

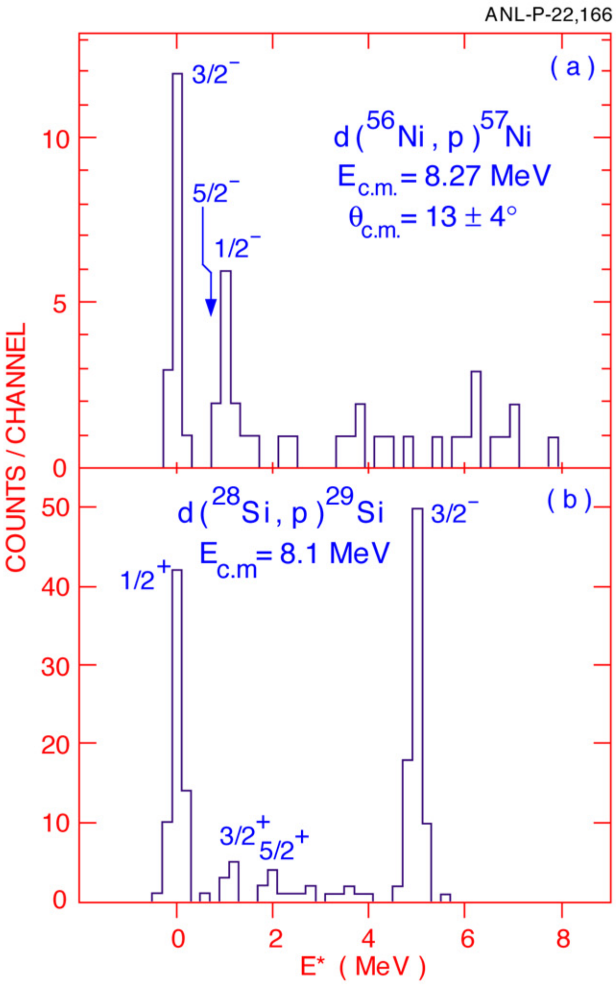




Fragment Mass Analyzer


ANL-P-22,540
(a)
(b)
56Ni
56Co
56Fe
57Ni
57Co
57Fe
120
100
80
ΔE (channels)
100
120
140
160
180
200
E residual (channels)



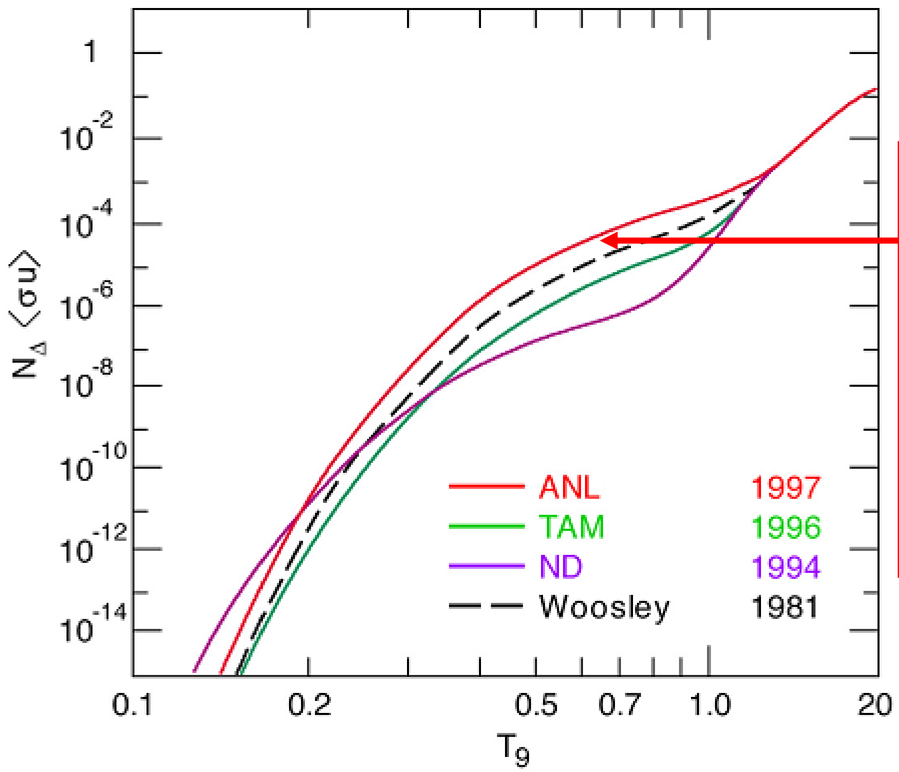


3/2⁻, 5/2⁻, 1/2⁻

⟹

Are Good Single -Particle States

S≃0.9



^{56}Ni(p,γ) reaction rate higher than previously assumed. More material can pass through the ^{56}Ni bottleneck towards heavier nuclei

Astrophysical Reaction Rate

$^{56}Ni\,(p,\gamma)^{57}Cu$

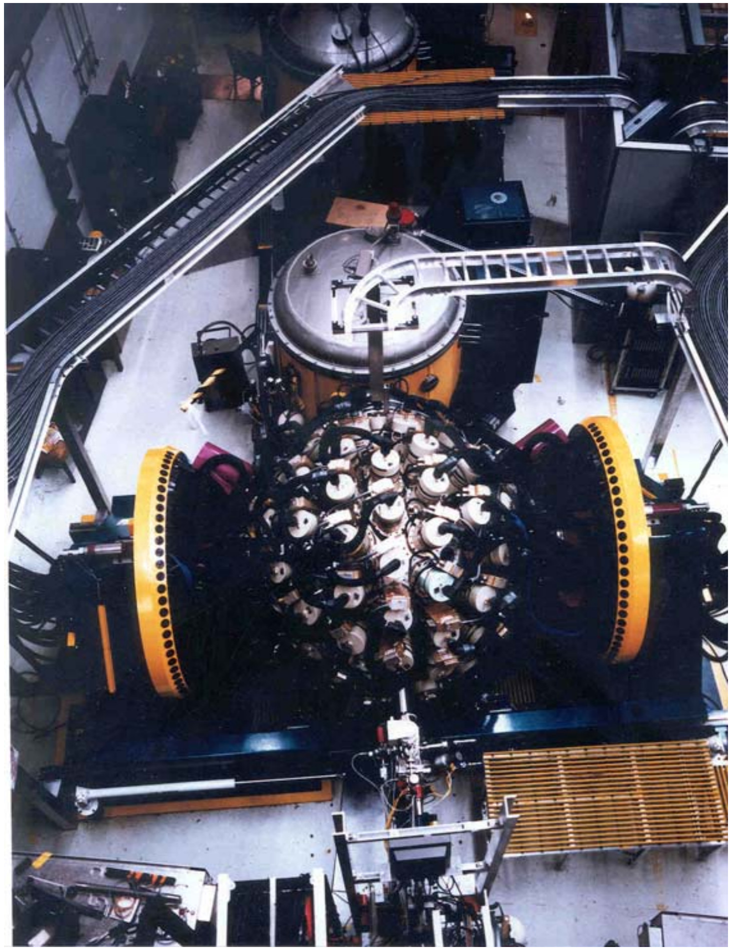
$$\Gamma_p\,(E,\ell) = C^2S \cdot \Gamma_p^{s.p.}\,(E,\ell)$$

PRL 80, 676 (1998)

Reaction rate:

$$r = N_p N_{Ni} \int v\sigma(v) f(v)\,dv$$

GAMMASPHERE+FMA

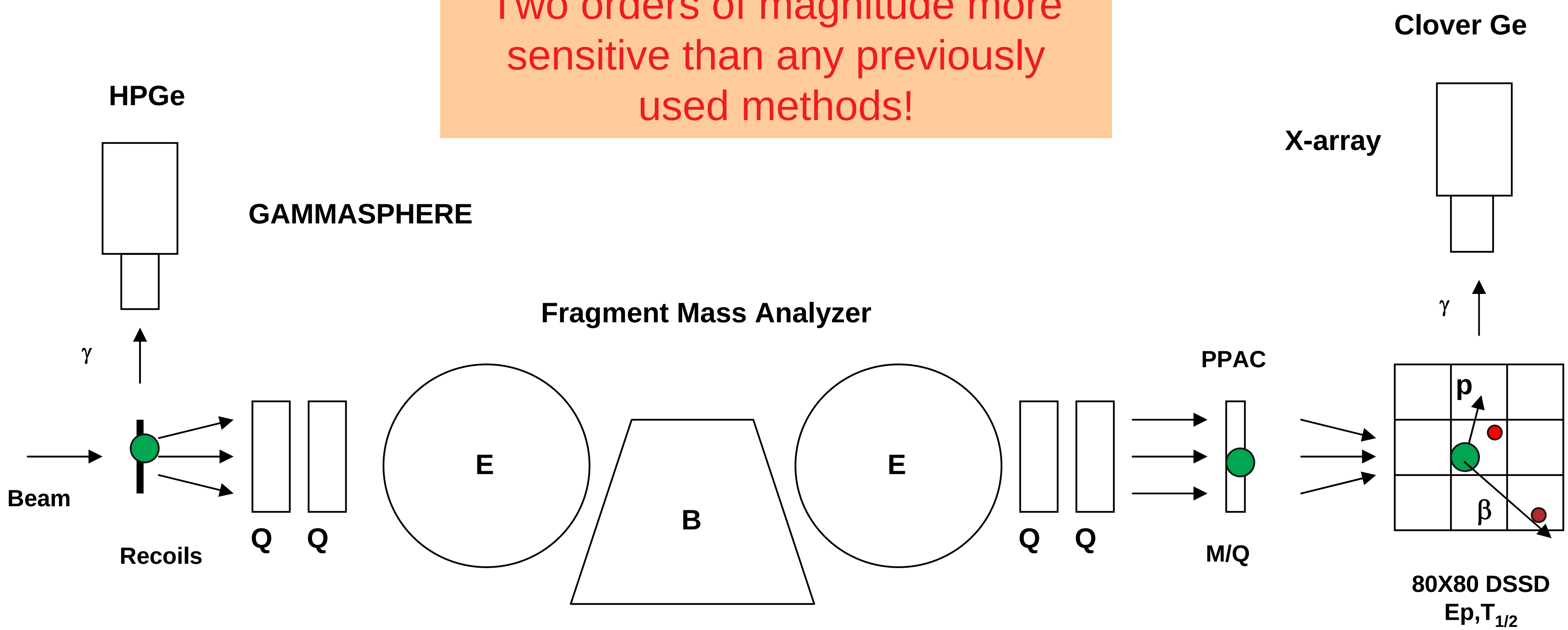


GAMMASPHERE and FMA with its auxiliary detectors is a unique combination of a large γ-ray efficiency and high reaction channel selectivity.

Implementation of a novel technique **Recoil-Decay Tagging** resulted in observation of many exotic nuclei across the nuclidic chart.

Recoil-Decay Tagging

Two orders of magnitude more sensitive than any previously used methods!



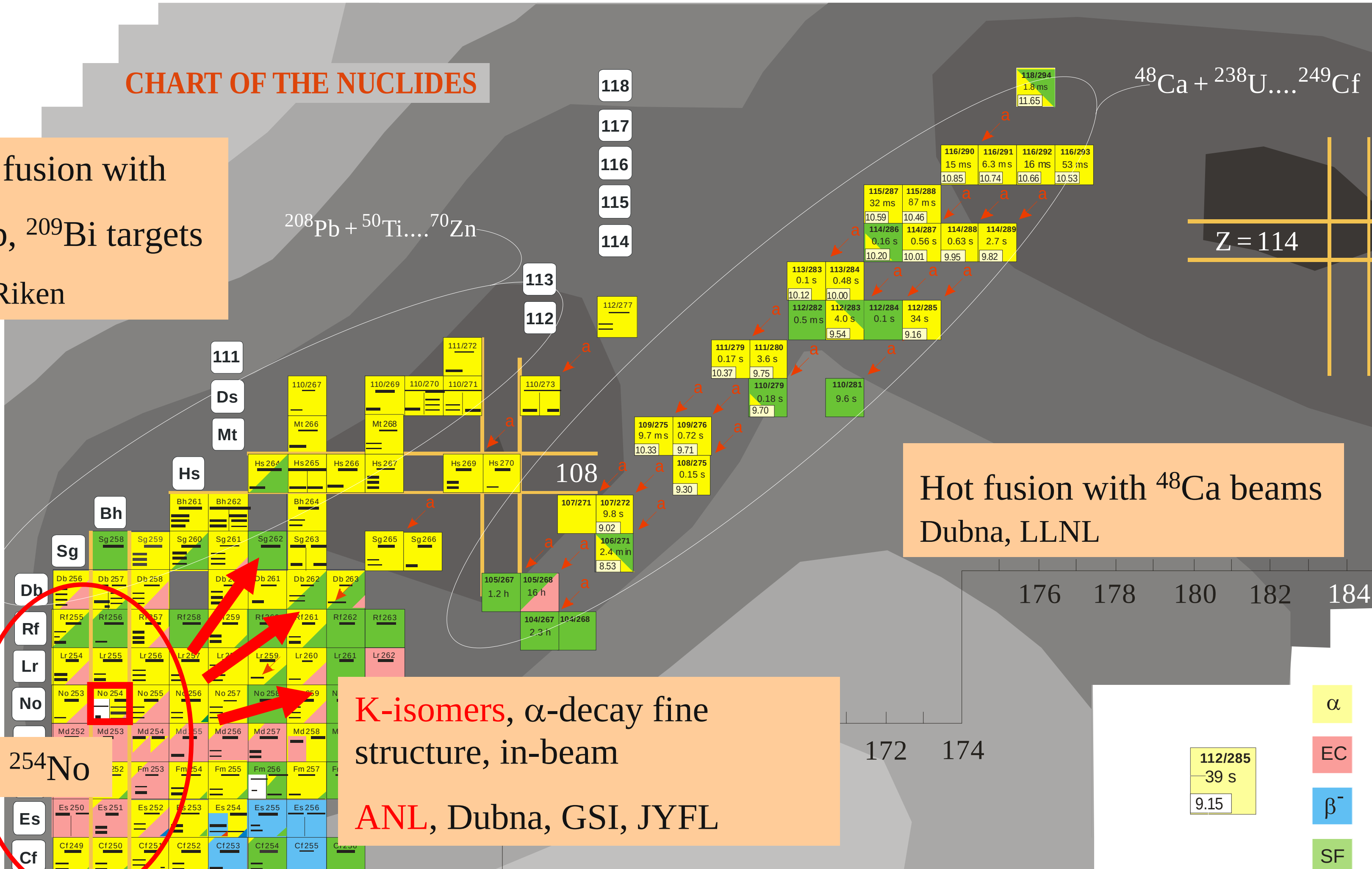
Prompt γ rays
Recoils
Implants

Spatial and time correlations in the DSSD

characteristic decays or chains of decays:

- Protons
- Alphas
- β-delayed particles
- Isomers
- β decay

Spectroscopy of Trans-Fermium Nuclei



Cold fusion with

^{208}Pb, ^{209}Bi targets

GSI, Riken

Hot fusion with ^{48}Ca beams

Dubna, LLNL

^{254}No

K-isomers, α-decay fine structure, in-beam

ANL, Dubna, GSI, JYFL

Chart courtesy of Y. Oganessian

^{254}No – first in-beam spectrum in a Transfermium nucleus

VOLUME 82, NUMBER 3 PHYSICAL REVIEW LETTERS 18 JANUARY 1999

Ground-State Band and Deformation of the $Z = 102$ Isotope ^{254}No

P. Reiter,[1] T. L. Khoo,[1] C. J. Lister,[1] D. Seweryniak,[1] I. Ahmad,[1] M. Alcorta,[1] M. P. Carpenter,[1]
J. A. Cizewski,[1,3] C. N. Davids,[1] G. Gervais,[1] J. P. Greene,[1] W. F. Henning,[1] R. V. F. Janssens,[1]
T. Lauritsen,[1] S. Siem,[1,8] A. A. Sonzogni,[1] D. Sullivan,[1] J. Uusitalo,[1] I. Wiedenhöver,[1] N. Amzal,[2]
P. A. Butler,[2] A. J. Chewter,[2] K. Y. Ding,[3] N. Fotiades,[3] J. D. Fox,[4] P. T. Greenlees,[2] R.-D. Herzberg,[2]
G. D. Jones,[2] W. Korten,[5] M. Leino,[6] and K. Vetter[7]

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[4]*Florida State University, Tallahassee, Florida 32306*
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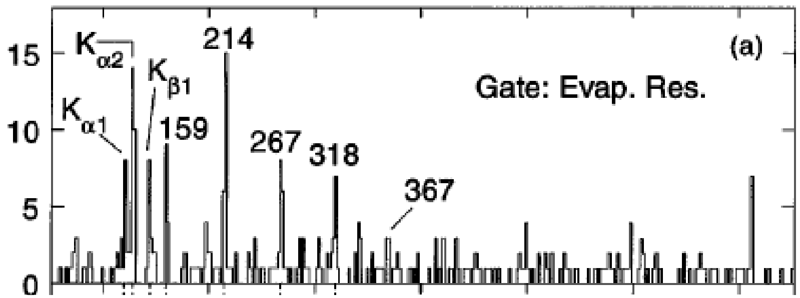
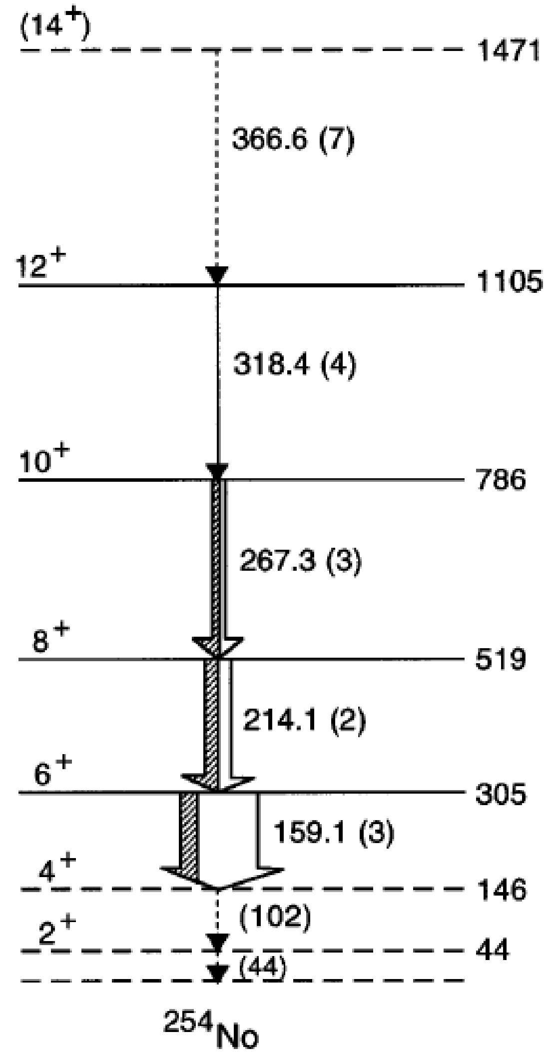
[6]*University of Jyväskylä, Jyväskylä, Finland*
[7]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[8]*University of Oslo, Oslo, Norway*

(Received 21 October 1998)



gs rotational band: β=0.27
^{254}No survives up to 14hbar



^{254}No - Entry point distribution

VOLUME 84, NUMBER 16 PHYSICAL REVIEW LETTERS 17 APRIL 2000

Entry Distribution, Fission Barrier, and Formation Mechanism of $^{254}_{102}$No

P. Reiter,[1,2] T. L. Khoo,[1] T. Lauritsen,[1] C. J. Lister,[1] D. Seweryniak,[1] A. A. Sonzogni,[1] I. Ahmad,[1] N. Amzal,[3] P. Bhattacharyya,[4] P. A. Butler,[3] M. P. Carpenter,[1] A. J. Chewter,[3] J. A. Cizewski,[1,5] C. N. Davids,[1] K. Y. Ding,[5] N. Fotiades,[5] J. P. Greene,[1] P. T. Greenlees,[3] A. Heinz,[1] W. F. Henning,[1] R.-D. Herzberg,[3] R. V. F. Janssens,[1] G. D. Jones,[3] H. Kankaanpää,[7] F. G. Kondev,[1] W. Korten,[6] M. Leino,[7] S. Siem,[1,8] J. Uusitalo,[1] K. Vetter,[9] and I. Wiedenhöver[1]

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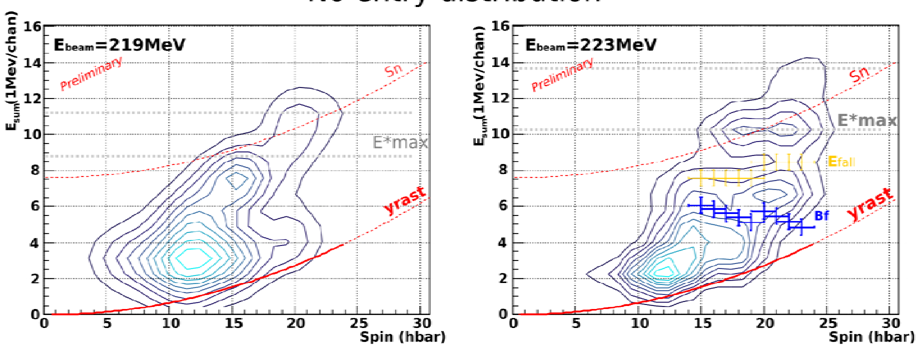
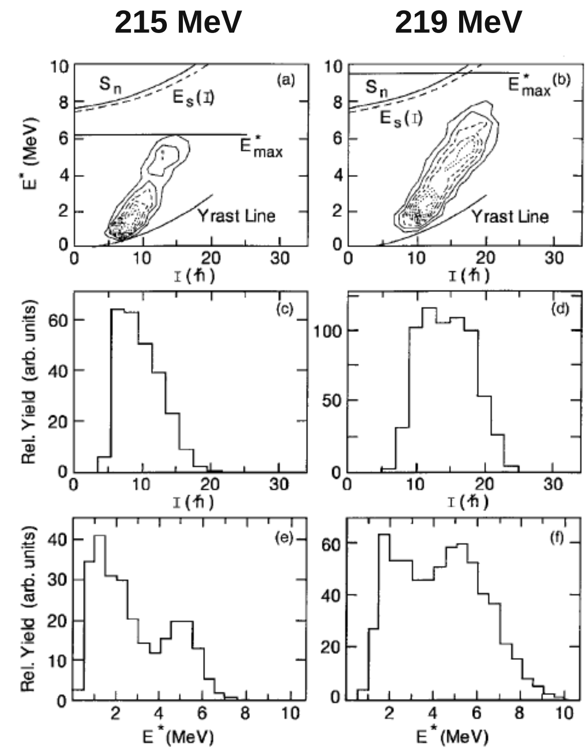
(Received 3 January 2000)

^{254}No entry distribution

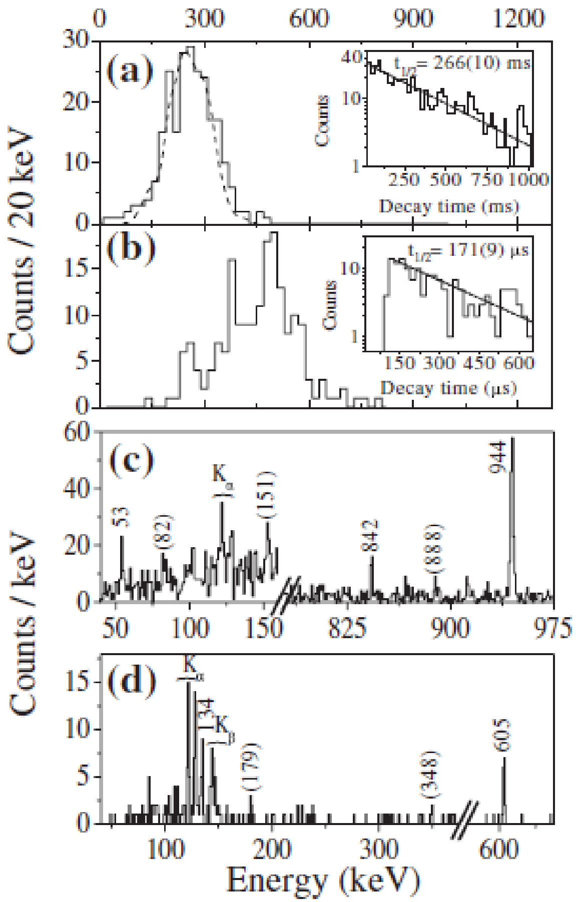


2010 experiment – G. Henning et al.



Maximum spin 22 hbar
Shell-correction persists at high spin
Fission barrier > 5MeV

^{254}No – K-isomers



Conversion electrons

γ rays

PRL 97, 082502 (2006) PHYSICAL REVIEW LETTERS week ending 25 AUGUST 2006

***K* Isomers in ^{254}No: Probing Single-Particle Energies and Pairing Strengths in the Heaviest Nuclei**

S. K. Tandel,[1] T. L. Khoo,[2] D. Seweryniak,[2] G. Mukherjee,[1,2,*] I. Ahmad,[2] B. Back,[2] R. Blinstrup,[2] M. P. Carpenter,[2] J. Chapman,[2] P. Chowdhury,[1] C. N. Davids,[2] A. A. Hecht,[2,4] A. Heinz,[5] P. Ikin,[3] R. V. F. Janssens,[2] F. G. Kondev,[2] T. Lauritsen,[2] C. J. Lister,[2] E. F. Moore,[2] D. Peterson,[2] P. Reiter,[6] U. S. Tandel,[1] X. Wang,[2,7] and S. Zhu[2]
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[5]*Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06511, USA*
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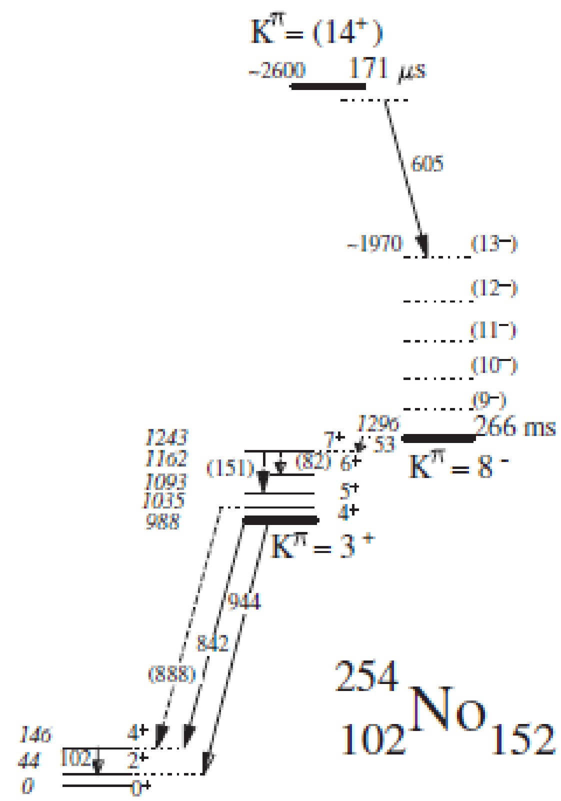
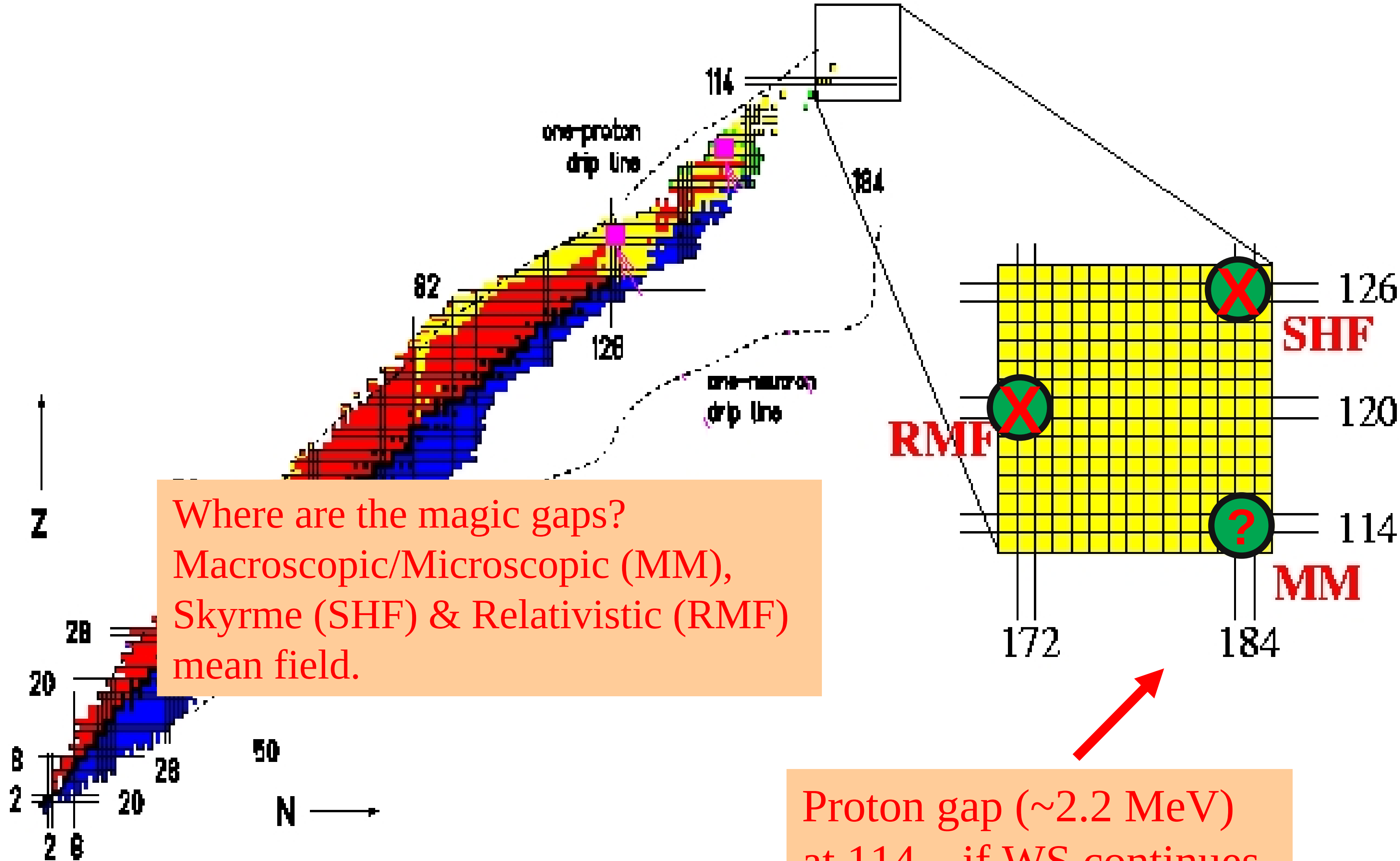
[7]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
(Received 13 April 2006; published 22 August 2006)



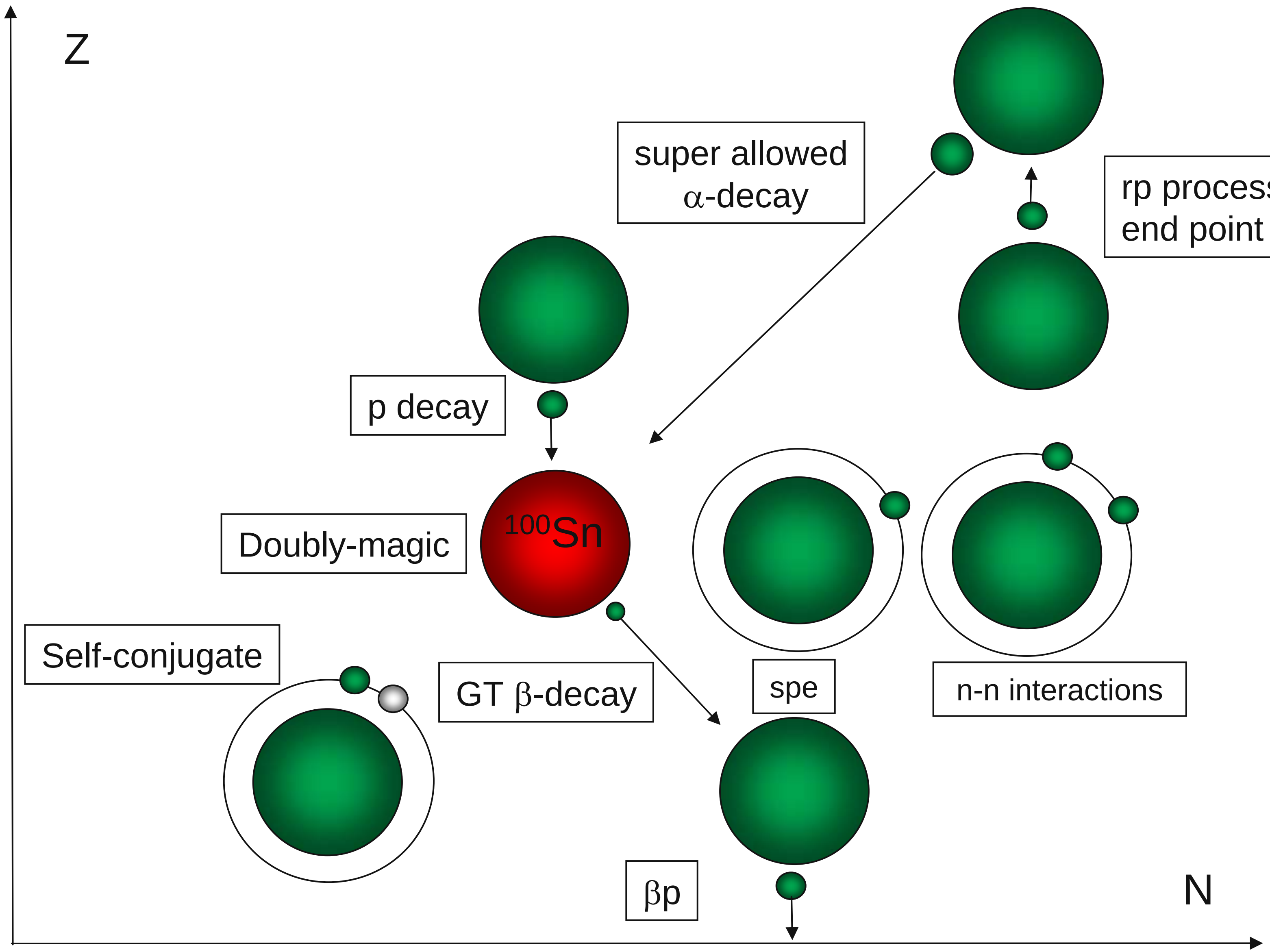
Stringent test of spe including the states relevant for the shell gaps in super-heavy nuclei



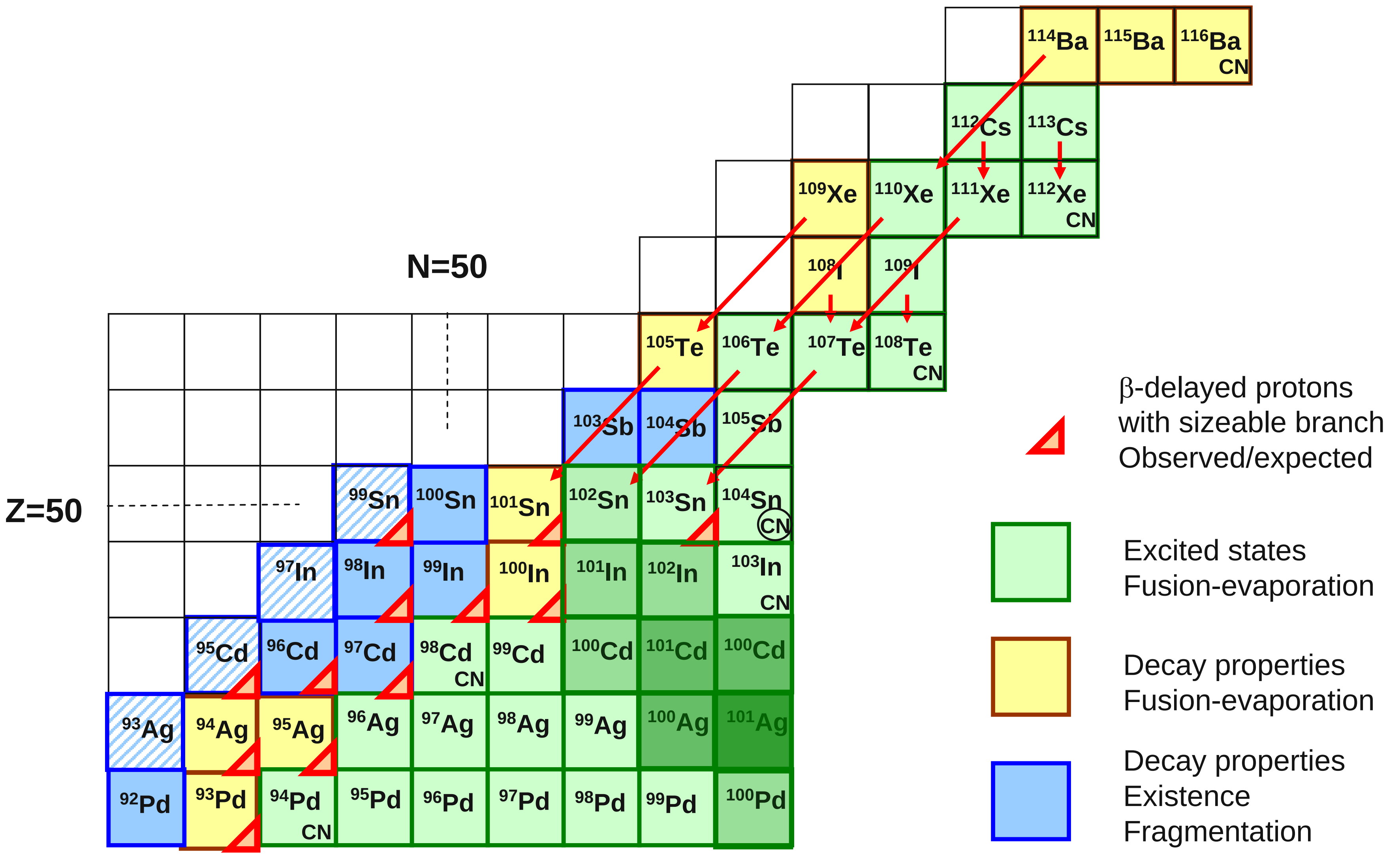
Where are the magic gaps? Macroscopic/Microscopic (MM), Skyrme (SHF) & Relativistic (RMF) mean field.

Proton gap (~2.2 MeV) at 114 – if WS continues to apply for Z>102.

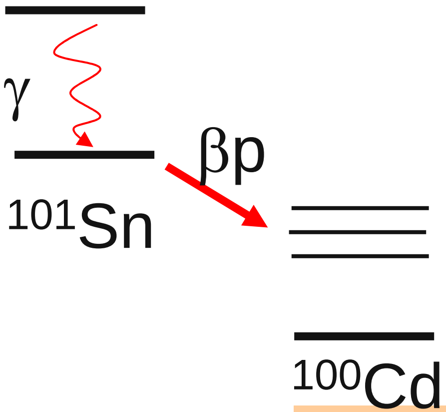
^{100}Sn physics

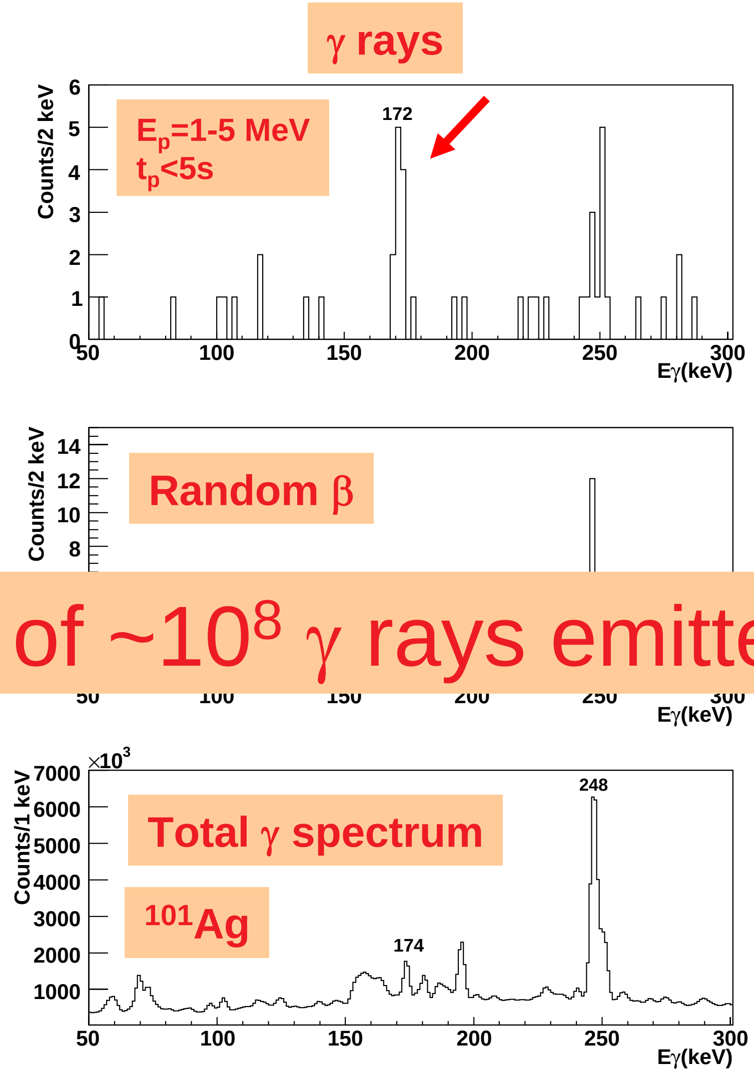


^{100}Sn region experimental status

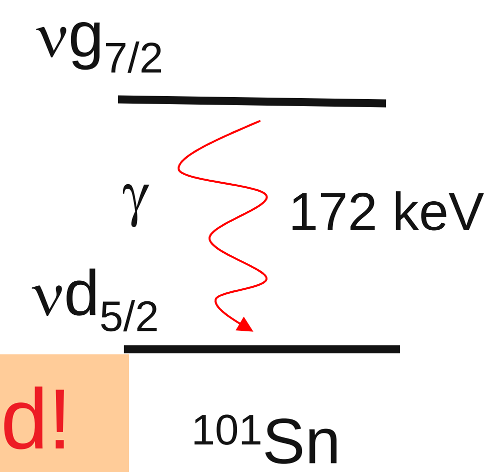


^{101}Sn prompt γ rays





1 out of ~10^8 γ rays emitted!



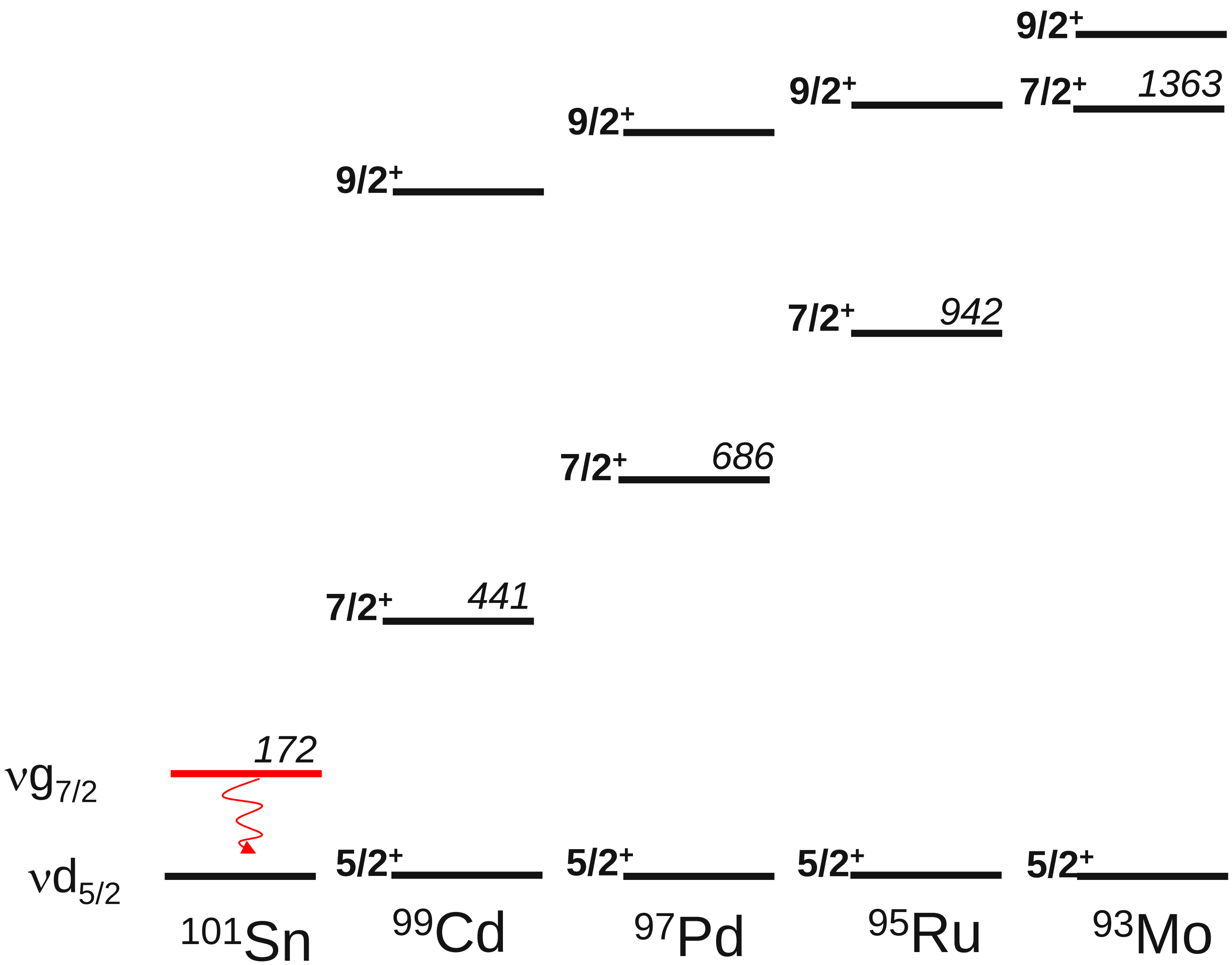
Ep=1.5-5 MeV

$T_{1/2}$=1.9(3)s

$b_{\beta p}$~15%

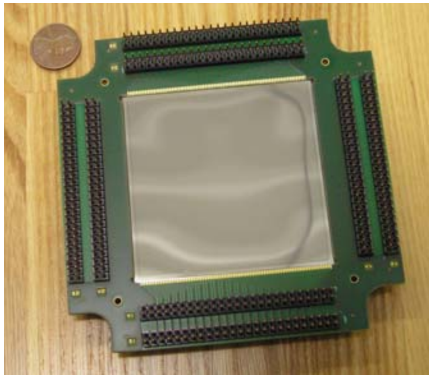
σ=70 nb

N=51 isotones

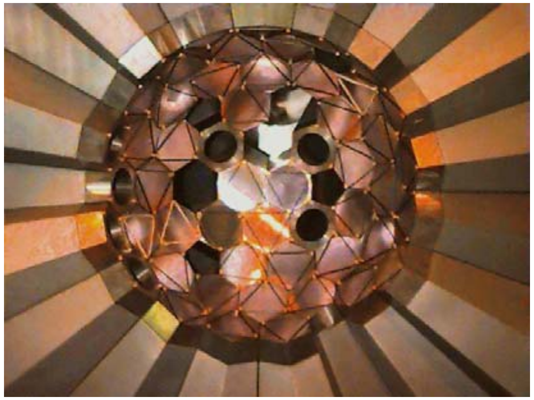


FMA upgrades
preparation for intense beams after energy and intensity upgrade

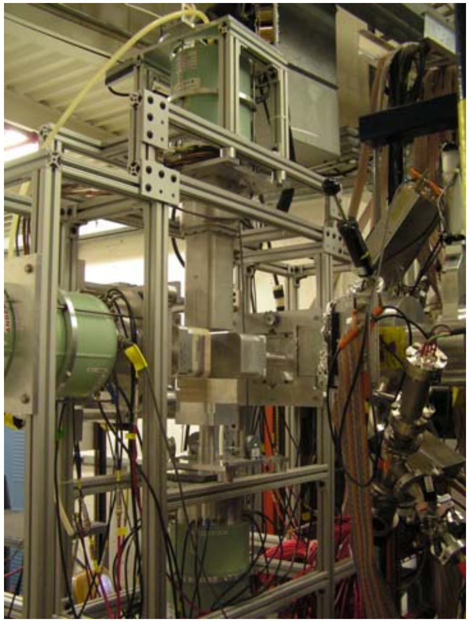
Beam dump



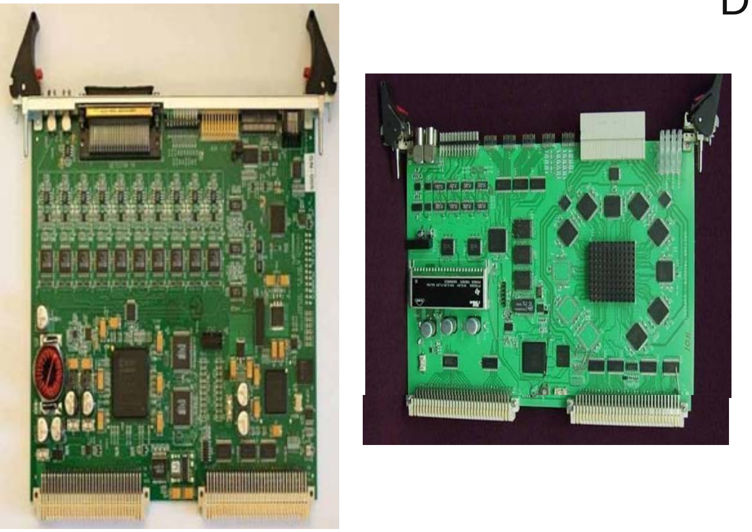
High-granularity DSSD



Digital GAMMASPHERE

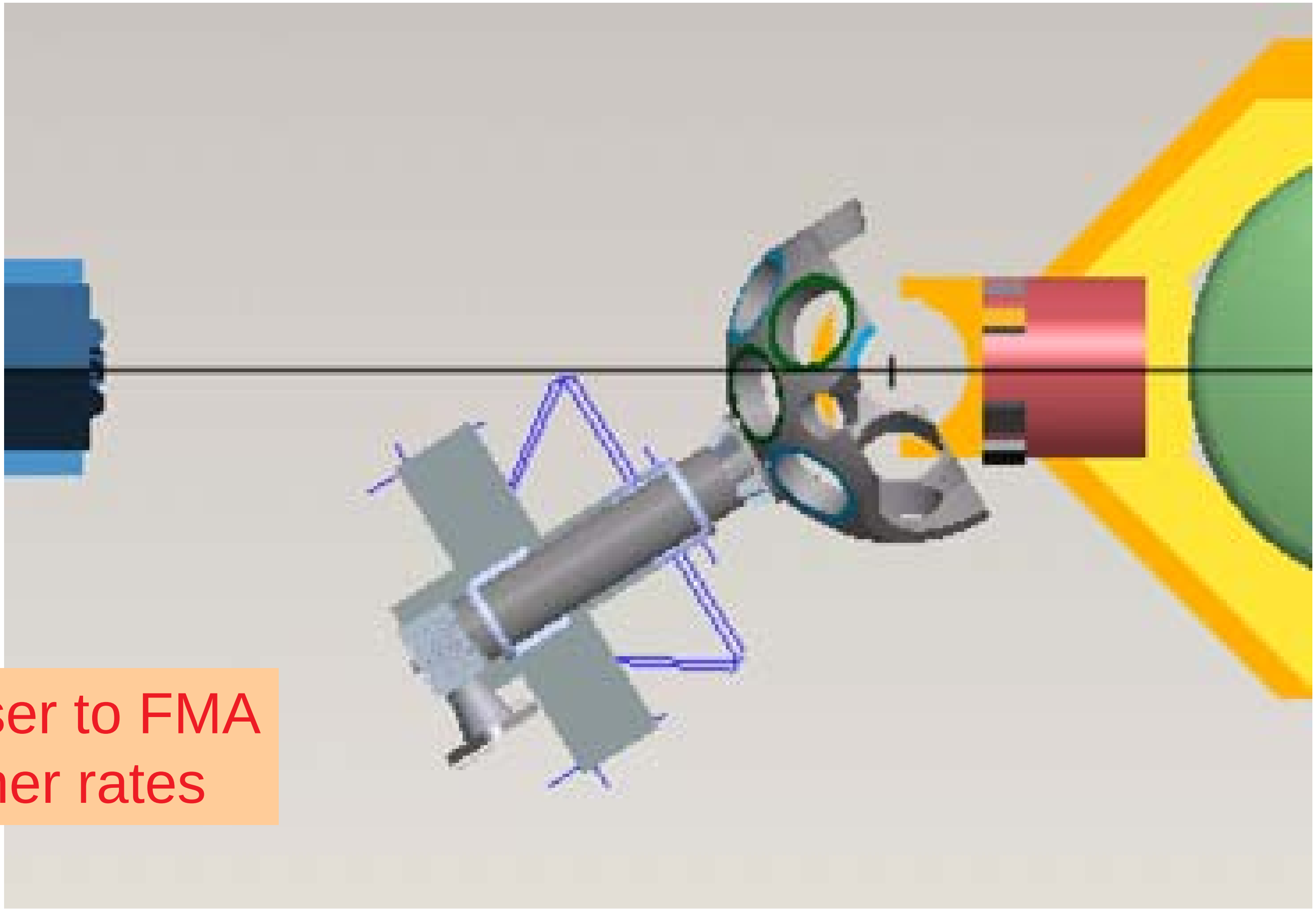


X-array



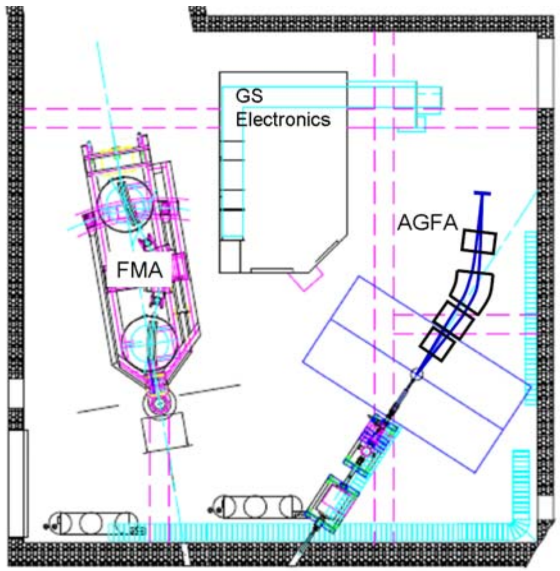
GRETINA Digital electronics

GRETINA at the FMA

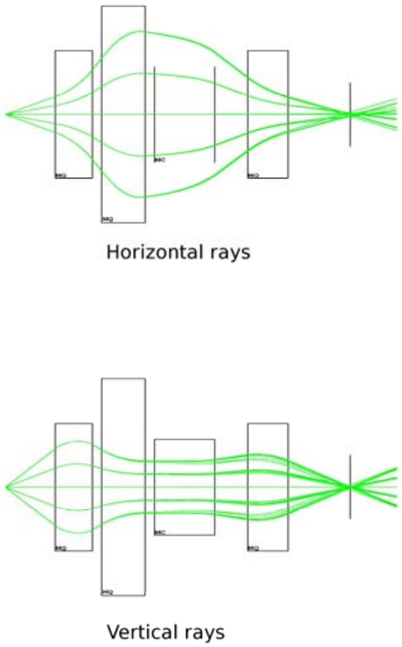


Closer to FMA
Higher rates

AGFA – Argonne Gas Filled Analyzer
FMA little brother



Large efficiency, no mass resolution



Optics by D. Potterveld

Target distance 40 cm – $\theta x=55$ mrad / $\theta y=155$ mrad
Target distance 80 cm – $\theta x\sim 45$ mrad / $\theta y=100$ mrad
small focal plane
In-beam and decay spectroscopy

Possible experiments

- Proton decay, 2p decay
- Super-allowed alpha decay chain ^{108}Xe-^{104}Te-^{100}Sn
- Excited states in ^{100}Sn
- Secondary fusion-evaporation reactions with in-flight radioactive beams
- Z>102 nuclei
- …

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Without dedicated ATLAS crew none of these experiments would be possible.

Thank you and Happy Anniversary!

Thank you for your attention!