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

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filling in for
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What Can a Recoil Separator Do for Us?

• Separates reaction products from primary beam particles at 0°.

• 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

![Diagram of Fragment Mass Analyzer](image)
Ion Optics of the FMA
The FMA at ATLAS
FMA Focal Plane M/Q Spectrum

\[ ^{78}_{\text{Kr}} + ^{92}_{\text{Mo}} \rightarrow 357 \text{ MeV} \]

COUNTS / CHANNEL

Q = 32, Q = 31, Q = 33

A = 166

166, 164, 165, 168

FOCAL PLANE X - POSITION (channels)
Types of Experiments Performed at the FMA

• Fusion-evaporation reactions at 0º, e.g. $^{92}\text{Mo}(^{78}\text{Kr},p2n)^{167}\text{Ir}$

• Transfer reactions, e.g. $^2\text{H}(^{56}\text{Ni},p)^{57}\text{Ni}$, $^4\text{He}(^{44}\text{Ti},p)^{47}\text{V}$.

• Radiative capture reactions, e.g. $\text{H}(^{18}\text{F},\gamma)^{19}\text{Ne}$
**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.
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.
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 $I_p$
- Unique laboratory to study tunneling through a 3D barrier
- Source of information on nuclear structure and masses far from stability
- $\Gamma_p$ important for $(p,\gamma)$ cross sections in light p-rich nuclei in the path of the rp-process
Proton Decay Observables

\[ J^\pi \rightarrow A,Z_{(odd)} \]

\[ \beta \rightarrow E_p, T_{1/2}, b_p \]

\[ A^{-1}, Z^{-1}_{(even)} \rightarrow \]

\[ ^{2+}_0 \]

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

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

\[ \Gamma_{K_p}^{def} = \frac{\hbar}{\tau} = \frac{2(2R+1)}{2I+1} \sum_{l_p,j_p} \left| \left\langle j_p K_p R0 \right| I K_p \right| \left| c_{l_p,j_p}^{K_p} \right|^2 \Gamma_{l_p,j_p}^{sph} \]
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.
$^{167}\text{Ir} – 1^{\text{st}}$ new proton emitter observed at ATLAS
June 1994

Experiment to search for $^{171}\text{Ag}$
$^{78}\text{Kr} + ^{96}\text{Ru} \rightarrow ^{171}\text{Ag} + p2n$
Instead found:
$^{167}\text{Ir} + \alpha p2n$
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

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

Unexpectedly large signature splitting indicates triaxial shape!

$\beta = 0.25(4)$ from Harris formula

$\sigma = 300 \text{ nb out of } 500 \text{ mb}$

$7/2^- [523] \quad 1/2^+ [411]$

D. Seweryniak et al., PRL C86(2001)1458
$^{121}$Pr proton emitter
recent developments

non-adiabatic quasi-particle calculations with Coriolis interaction

adiabatic calculations

Partial rotational alignment

$\sigma = 300$ pb

A. Robinson et al., PRL 95, (2005) 032502
To be continued …
Highlights of Research with the FMA and Future Perspectives

Darek Seweryniak
for FMA “collaboration”
ATLAS 25th Anniversary Celebration
October 22, 2010
Research with the Fragment Mass Analyzer

- Transfermium nuclei
- Shape coexistence at Z=82
- N=82
- N=126
- Z=82
- N=50
- N=62
- N=82
- N=28
- N=50
- N=20
- N=8

Proton emitters

- $^{56}\text{Ni}(d,p)$, $^{44}\text{Ti}(\alpha,p)$, $^{18}\text{F}(p,\gamma)$

100Sn

Sub-barrier fusion

100Sn

Mirror nuclei

N=Z nuclei around A=80

N=Z nuclei

Shape coexistence at Z=82

γ ray emission from resonances in rp-process nuclei

Ab-initio life times

26 Phys. Rev. Lett
Experiments with the Fragment Mass Analyzer

- From $^{10}\text{Be}$ to $^{257}\text{Rf}$
- 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
proton

Si detector array (25% of $4\pi$)

$\text{d}^{(56}\text{Ni},\text{p})^{57}\text{Ni}$

CD$_2$ foil

Au attenuator

beam integrator

$^{56}\text{Ni}$ beam

$^{57}\text{Ni}$

Fragment Mass Analyzer

Argonne National Laboratory
3/2^-, 5/2^-, 1/2^- are good single-particle states; S ≈ 0.9
The $^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}$ reaction rate is higher than previously assumed. More material can pass through the $^{56}\text{Ni}$ bottleneck towards heavier nuclei.

**Reaction rate:**

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

**Astrophysical Reaction Rate**

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

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

PRL **80**, 676 (1998)
GAMMASPHERE+FMA

GAMMASPHERE and FMA with its auxiliary detectors is a unique combination of a large $\gamma$-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 $\gamma$ rays
Recoils
Implants

characteristic decays or chains of decays:
Protons
Alphas
$\beta$-delayed particles
Isomers
$\beta$ decay

Spatial and time correlations in the DSSD

HPGe
GAMMASPHERE
Clover Ge
X-array

Fragment Mass Analyzer

PPAC
80X80 DSSD $E_p, T_{1/2}$
Spectroscopy of Trans-Fermium Nuclei

Cold fusion with $^{208}\text{Pb}$, $^{209}\text{Bi}$ targets
GSI, Riken

Hot fusion with $^{48}\text{Ca}$ beams
Dubna, LLNL

K-isomers, $\alpha$-decay fine structure, in-beam
ANL, Dubna, GSI, JYFL

Chart courtesy of Y. Oganessian
$^{254}$No – first in-beam spectrum in a Transfermium nucleus

gs rotational band: $\beta=0.27$

$^{254}$No survives up to 14hbar
$^{254}$No - Entry point distribution

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

2010 experiment – G. Henning et al.
No – K-isomers

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

Conversion electrons

γ rays
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

- Super allowed $\alpha$-decay
- Rp process end point
- P decay
- Doubly-magic
- Self-conjugate
- GT $\beta$-decay
- Spe
- N-n interactions
- $\beta p$
100Sn region experimental status

N=50

Z=50

β-delayed protons with sizeable branch
Observed/expected

Excited states
Fusion-evaporation

Decay properties
Fusion-evaporation

Decay properties
Existence
Fragmentation
$^{101}\text{Sn}$ prompt $\gamma$ rays

- $\gamma$ from $^{101}\text{Sn}$
- $\beta^-$ from $^{101}\text{Sn}$
- $\gamma$ from $^{100}\text{Cd}$

1 out of $\sim10^8$ $\gamma$ rays emitted!

- $E_p = 1.5 - 5$ MeV
- $T_{1/2} = 1.9(3)$ s
- $b_{\beta^p} \sim 15\%$
- $\sigma = 70$ nb

Total $\gamma$ spectrum
$N=51$ isotones

\[\begin{array}{cccccc}
101^{\text{Sn}} & 99^{\text{Cd}} & 97^{\text{Pd}} & 95^{\text{Ru}} & 93^{\text{Mo}} \\
\end{array}\]

\[\begin{array}{cccccc}
7/2^+ & 9/2^+ & 9/2^+ & 7/2^+ & 1363 \\
7/2^+ & 9/2^+ & 7/2^+ & 942 \\
7/2^+ & 686 & 441 & 172 \\
5/2^+ & 5/2^+ & 5/2^+ & 5/2^+ & 5/2^+ \\
\end{array}\]
**FMA upgrades**
**preparation for intense beams after energy and intensity upgrade**
GRETINA at the FMA

Closer to FMA
Higher rates
AGFA – Argonne Gas Filled Analyzer
FMA little brother

Large efficiency, no mass resolution

Target distance 40 cm – θx=55 mrad / θy=155 mrad
Target distance 80 cm – θx~45 mrad / θy=100 mrad
small focal plane
In-beam and decay spectroscopy

Optics by D. Poterveld
Possible experiments

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

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

Thank you and Happy Anniversary!
Thank you for your attention!