Solenoid-based Spectrometers for Heavy Element Production

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Review (again) Solenoid Optics

Operational Experiences (Including Recent TAMU Expt. Related to SHE Production)

Discussion

IRIS Workshops March, 2010 and Nov, 2010

Reminder: Solenoid Optics:

Act as a simple, thick lens with focal length as a function of length and axial field, B_z^2L (the integral) and ion rigidity $B\rho$:

In order1: $f = 4(B\rho)^2 / \langle B_z^2 L \rangle$

Hence we can change image location (which also impacts angular and transverse magnification) as we would for any lens:

$$1/f = 1/i + 1/o$$

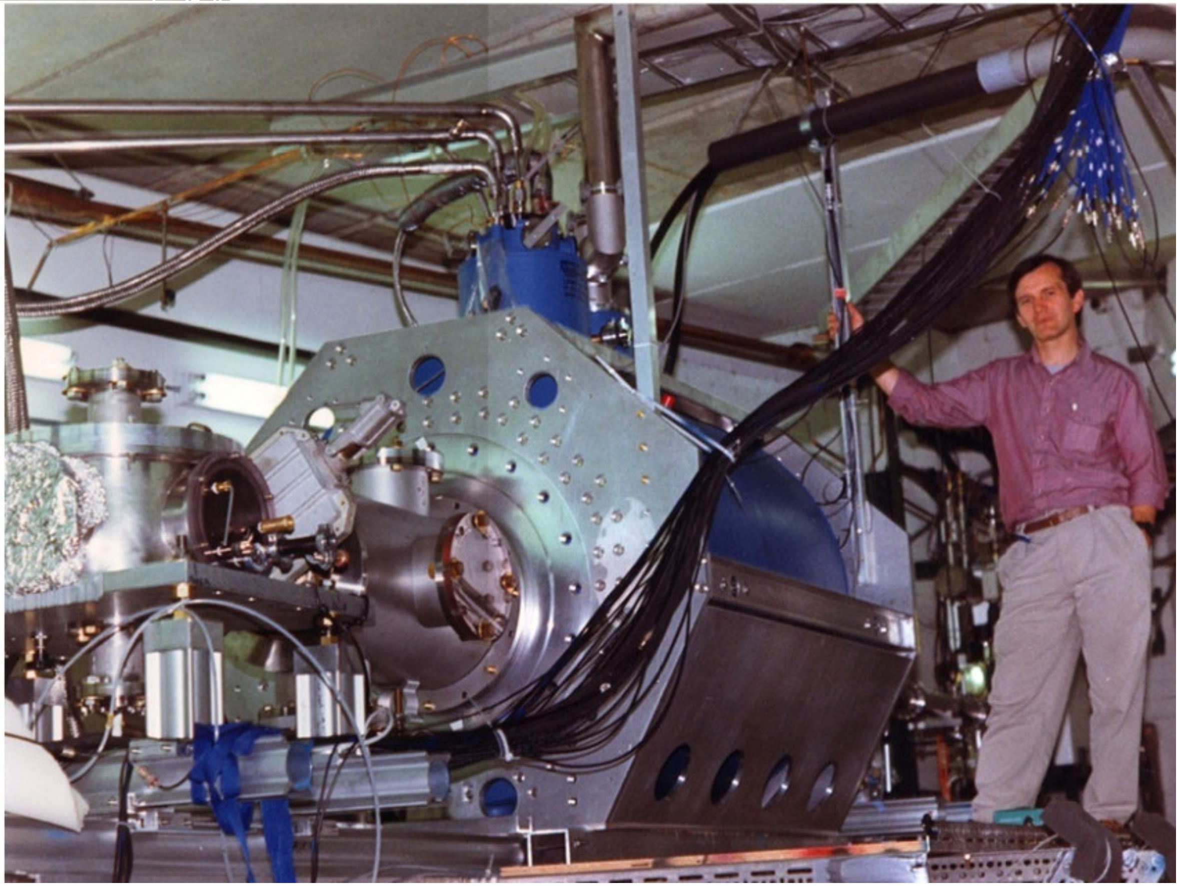
$M_T = -i/o$ (hence dispersion is variable and have similar dispersion along z axis)

$M_T M_A$ = Constant (M_A=angular M)

f/# = f /D=can be "fast" (f/2)=short exposure time

Dispersion: Both transverse and axial can be used.

Led to design and construction of a “portable ” 40 cm bore, 7T sc magnet (“BigSol”) for use at MSU NSCL both as a specialized RNB production device (isomer beams e.g. 200 nsec 18Fm) and as a multi-particle spectrometer (1990s)



F. Becchetti: Solenoid-based spectrometers, IRIS Workshops , 2010

Material from ToD thesis (and related NIM paper)[a]:

A SUPERCONDUCTING-SOLENOID ISOTOPE SPECTROMETER FOR PRODUCTION OF NEUTRON-RICH NUCLEI

$({}^{136}Xe + {}^{nat}C,\ E/A = 30MeV/u)$

by

Thomas W. O'Donnell

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Physics)
in The University of Michigan
2000

a) This and other theses available at UM *TwinSol* web site:
www.physics.lsa.umich.edu/twinsol/ + related NIM/other papers

As lens, can pick object and image distance for given E/A and solid angle (MT,MA, dispersion then set):

So at a few MeV/u one can have *very large solid angle* (depending on q of course):

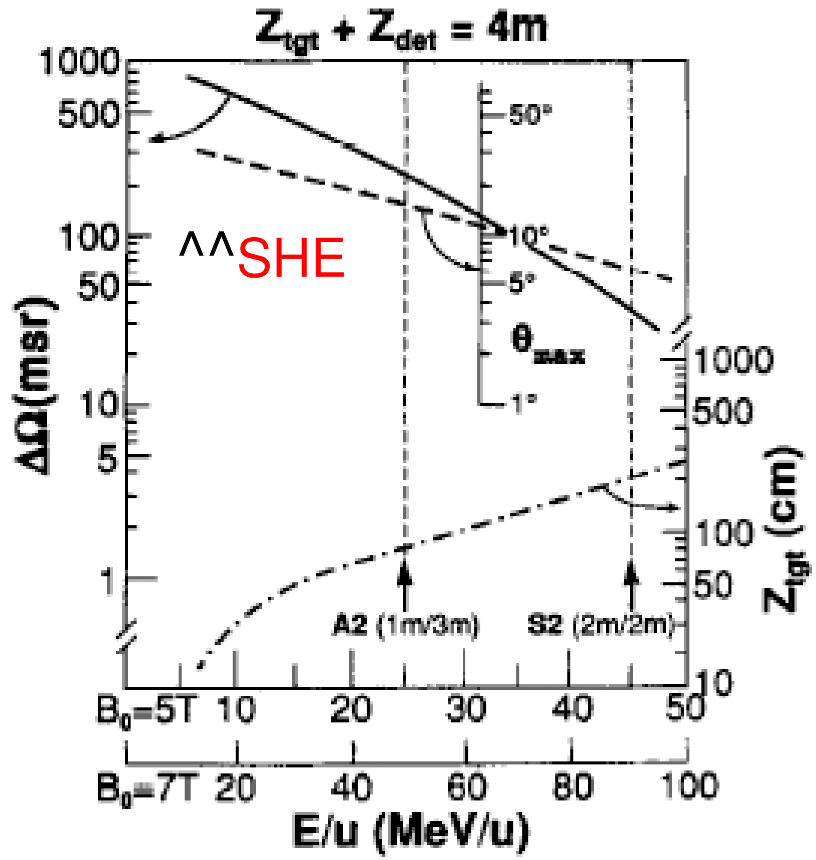


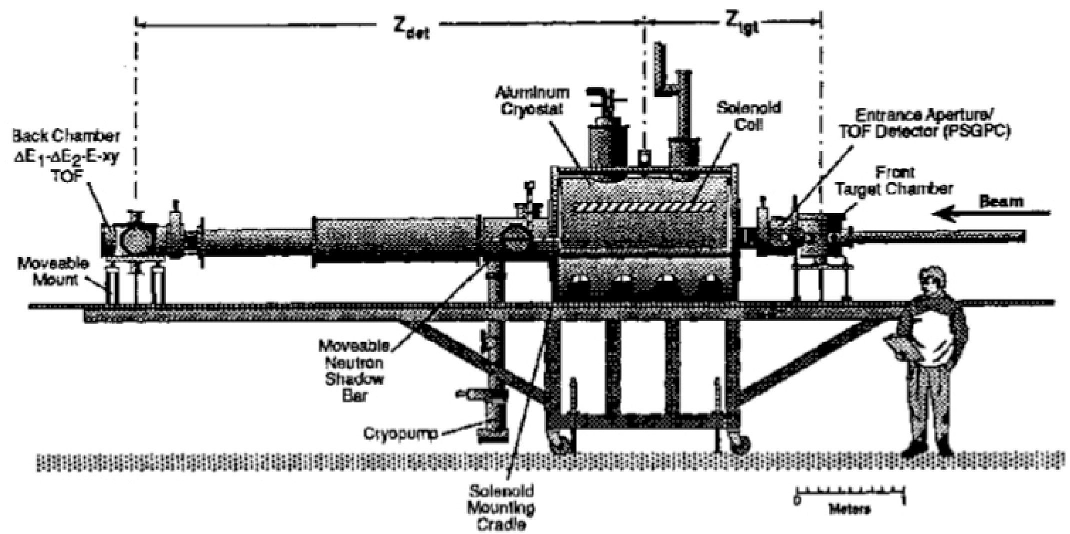
Fig. 2. Typical operating characteristics ($d\Omega$ and Θ_{max}) at $B_{oz} = 5$ T and 7 T for various combinations of Z_{tgt} and Z_{det} (see fig. 1). The initial tests corresponded to $Z_{tgt} \approx 1.5$ m and $Z_{tgt} + Z_{det} \approx 3.5$ m.

As Dr. Dvorak will show, one can get very large angles collected for SHEs (also see TAMU papers)

Configuration of BigSol at MSU NSCL as a multi-particle spectrometer for study of fragment yield 136Xe+ natC, E/A= □30 MeV/u (T. Odonnell, UM PhD 2000-available on line):

Here we set up for long focal length and hence long flight path (6.6 m) for ToF, but still few cm^2 image size to permit use of thin+thick+PSD silicon detectors at focal plane (an advantage of solenoid along with uniform trajectories for sub-nsec ToF):

Use of long object distance (asymmetric mode) requires less field , hence can lower magnet cost (for low q ions).



(note wheels!)

Precise ion-optics of solenoid (if aligned) with minimal aberrations permits accurate XY gating (to < 1mm) to select Bp bites in silicon PSD:

Here image is 25 mm diameter and B ρ bite is a few mm wide.

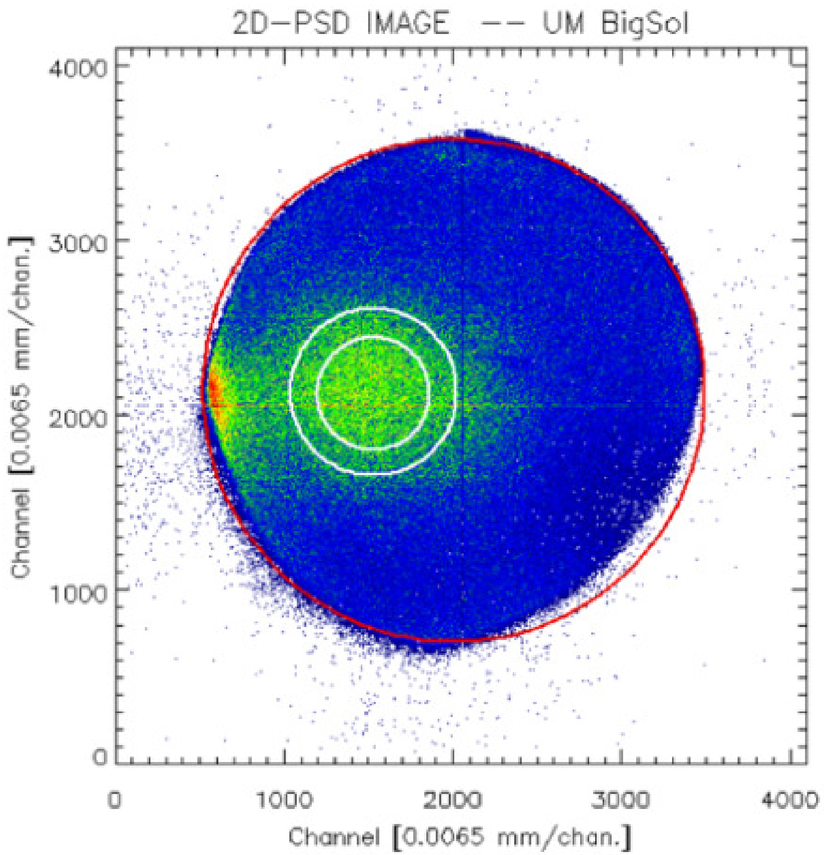


Figure 7.1: Typical 2D PSD image showing $B\rho$ selection software gates at solenoid focal plane. See text for details.

Generating Z,A "identifiers" w/o gating leads to relatively clean Z,A spectra where all events have been used…I,e, none thrown away in gates□.. (dE1,dE2,E are correlated and should not be pre-gated)

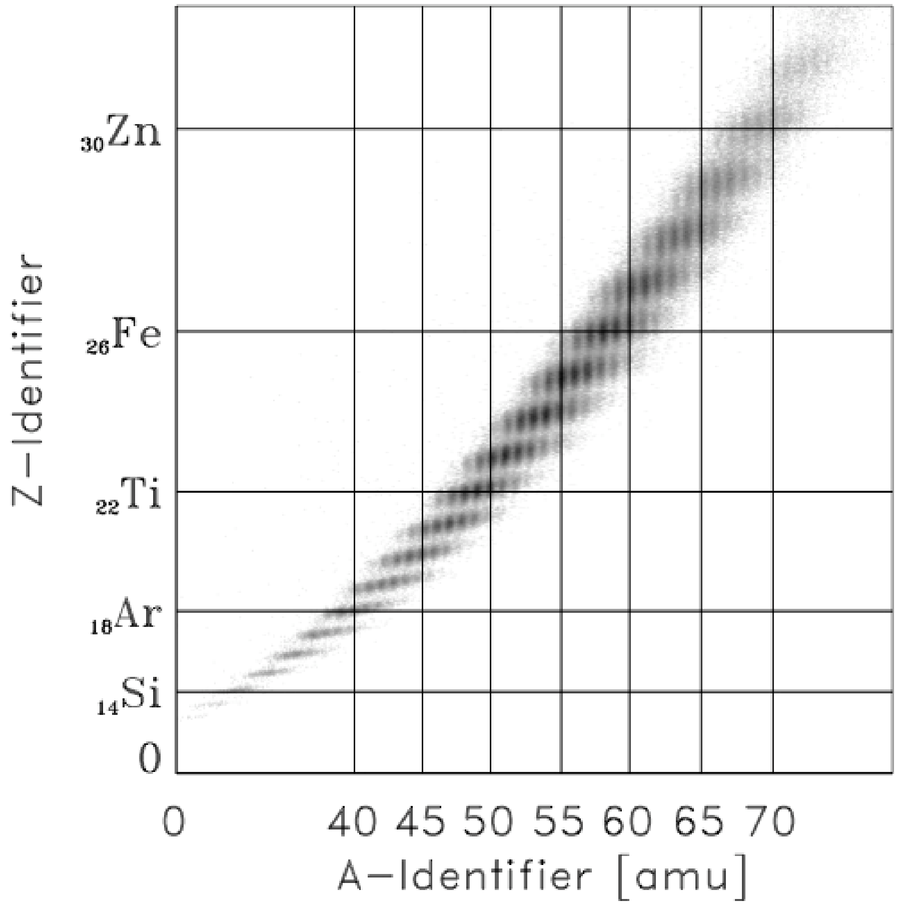
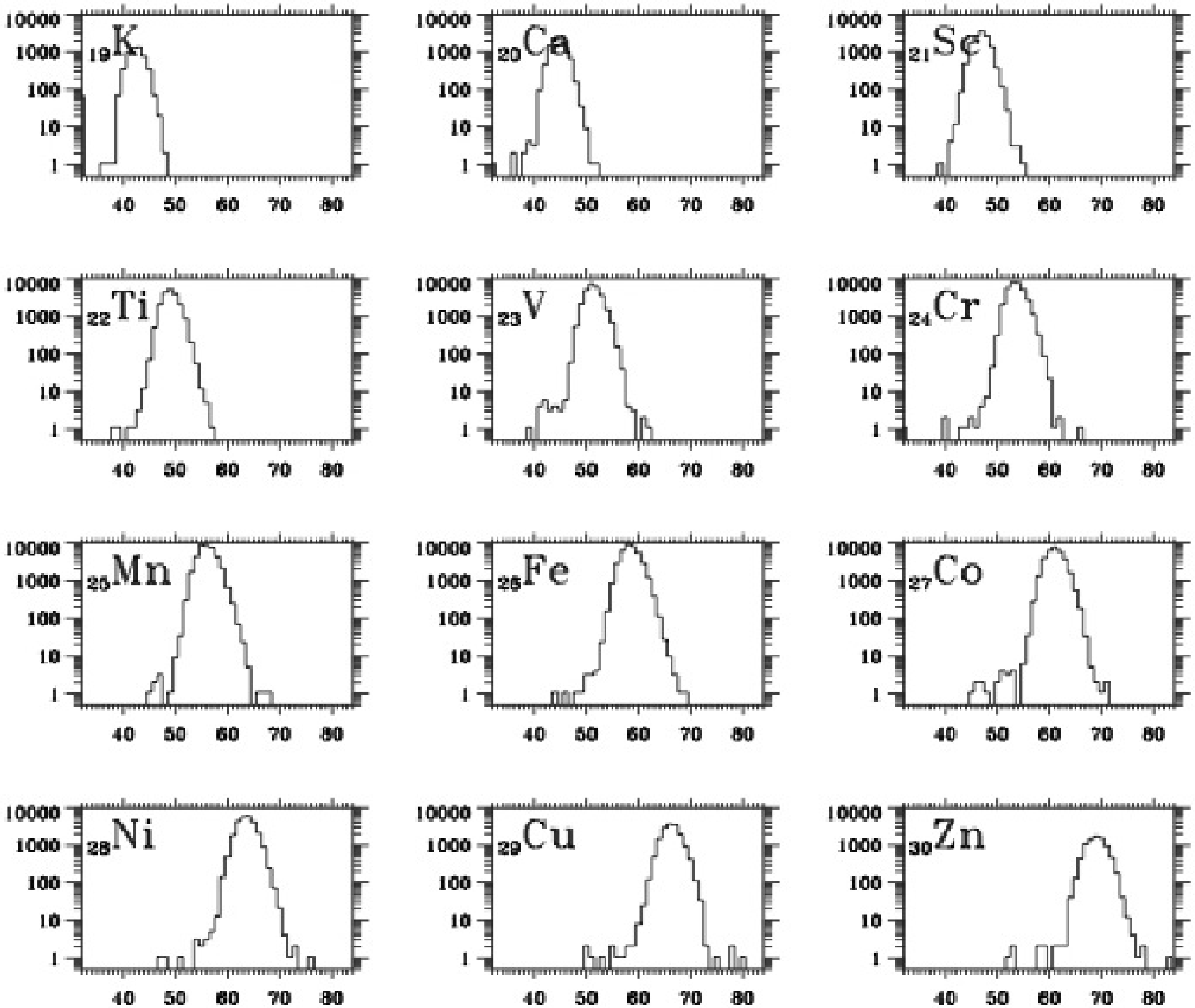
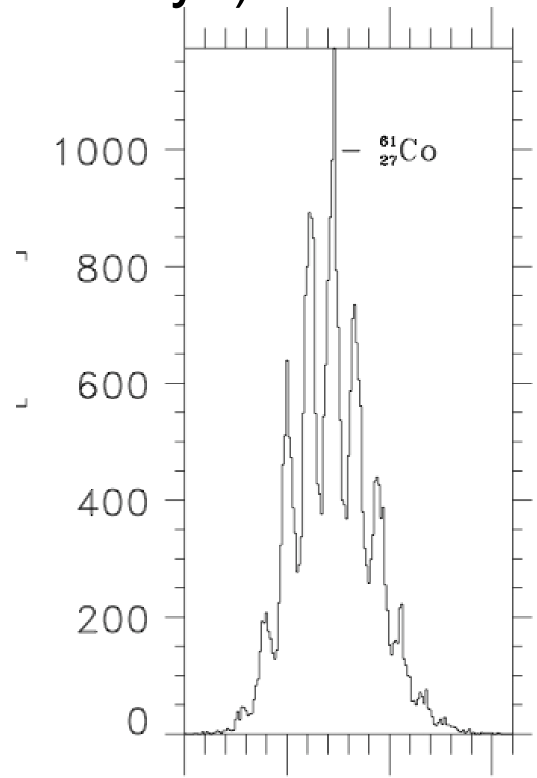


Figure 9.5: 2D Z-identifier vs. A-identifier. Identical to Fig. 9.4 but grey scale and having absolute, calibrated values of Z-identifier and A-identifier shown. Data from 4-5 charge states are positively identified by Z and A values independent of their q-states. Data includes neutron-rich nuclei up to and beyond the most n-rich produced at the time of this experiment.



Several new isotopes were seen this way(2 days)



^{65,66,68,70}Co?

^{74,76}Ni ? Shells?

The isotopes in histograms are generally resolved in Z,A with fast, exponential fall off with N

Advantage: At lower A,Z we could use all silicon focal plane detectors (thin dE and E-XY detectors) High resolution and well calibrated dE and E-XY detectors permitted accurate A,Z i.d.

Problem SHEs: Must use gas detectors for DE in general. (As shown in next experiment)

Limit of solenoids: Only part of axial field is used to focus ions:

BigSol device limited to fragment energies < 20 MeV/u (I.e. below NSCL > 2000 upgrade energies).

So BigSol moved to dedicated beam line at TAMU cyclotron (5-20 MeV/u heavy ions)

(Recall it was designed to be moved as needed)

First TAMU SHE experiment using BigSol

(massive transfer using $^{197}Au(7.5A.MeV) +^{232} Th$ (6 mg/cm2)

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NEW EXPERIMENTAL APPROACH FOR HEAVY AND SUPERHEAVY ELEMENT PRODUCTION

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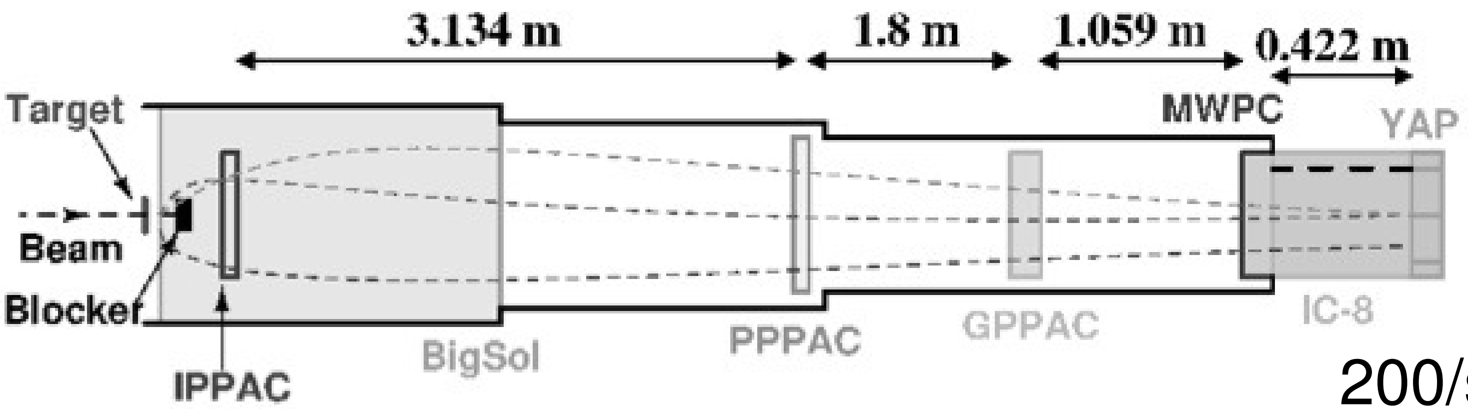
Heavy fragments: Must now use gas XY and dE detectors (Si dE too thick/too small) : PPACs,MWPC+ 8 segment IC+scintillators



200/sec

Fig. 2. The filtering and detection system of SHE elements at Cyclotron Institute.

Problems: Detectors optimized expecting certain Z and E/A for fragments
Front PPAC limits count rate /beam useable

3. SHE candidates in the reaction $^{197}Au(7.5A.MeV) +^{232} Th$

In this reaction Au ions were bombarding thick ($6.3\ mg/cm^2$) Th target. Most of the reaction products and the beam were stopped by the 6^o blocker while products emitted at angles greater than 6 degrees were passing through BigSol to the detection line. There, corresponding ToFs and energy losses were measured (see Sec. 2) for that ions.

6 "interesting" "high Z" events identified (a few days running):

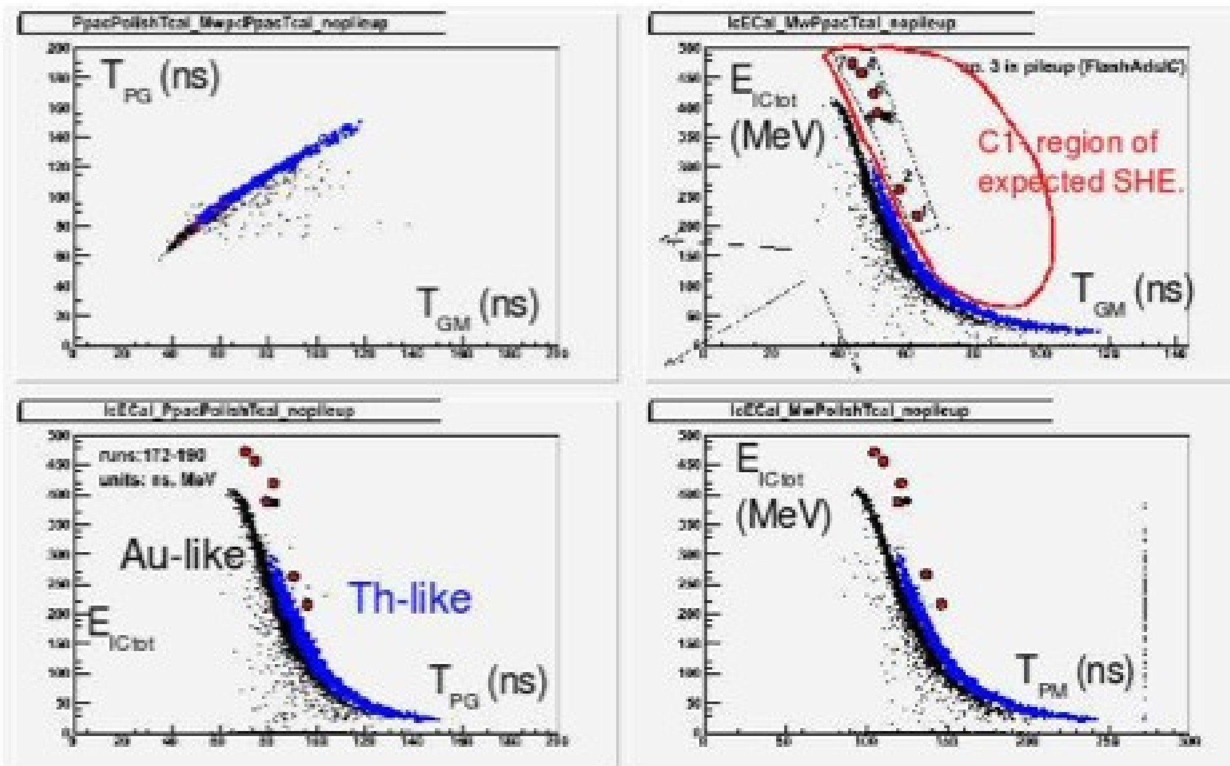


Fig. 3. Isolated SHE candidates (see text for details).

The six "interesting" events identified(SIE), initially as Z= 100-110 with A 260-280 but low E/A :

Table 1. Characteristics of six SHE candidates. V_{PG} and V_{GM} denotes velocity of candidate between PPPAC and GPPAC; GPPAC and MWPC, respectively. Columns 2-5 are measured values while A^{Calc} is a calculated mass. Numbering of SHE candidates is the same as in Fig. 3

SIE no.	V_{PG} (cm/ns)	V_{GM} (cm/ns)	ΔE_M (MeV)	E_{ICtot} (MeV)	A^{Calc} $amu.$
1	2.13	1.66	155.8	219.0	≈262.4
2	2.24	1.80	169.1	267.5	≈260.0
4	2.77	2.23	123.8	459.5	≫226.0
5	2.58	2.01	176.8	390.9	≈271.0
6	2.50	2.06	196.3	420.2	≈280.3
7	2.92	2.37	139.8	474.4	≫211

Problem: Had to extrapolate dE/dx loss curves beyond Z=92 (SRIM etc): Major source of Z i.d. uncertainty, esepcially due to lower E/A than expected.

So considerable data with BigSol also taken to measure dE/dx using direct beams (now published in NIM):

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BEAM INTERACTIONS WITH MATERIALS AND ATOMS

Energy loss of energetic ^{40}Ar, ^{84}Kr, ^{197}Au and ^{238}U ions in mylar, aluminum and isobutane

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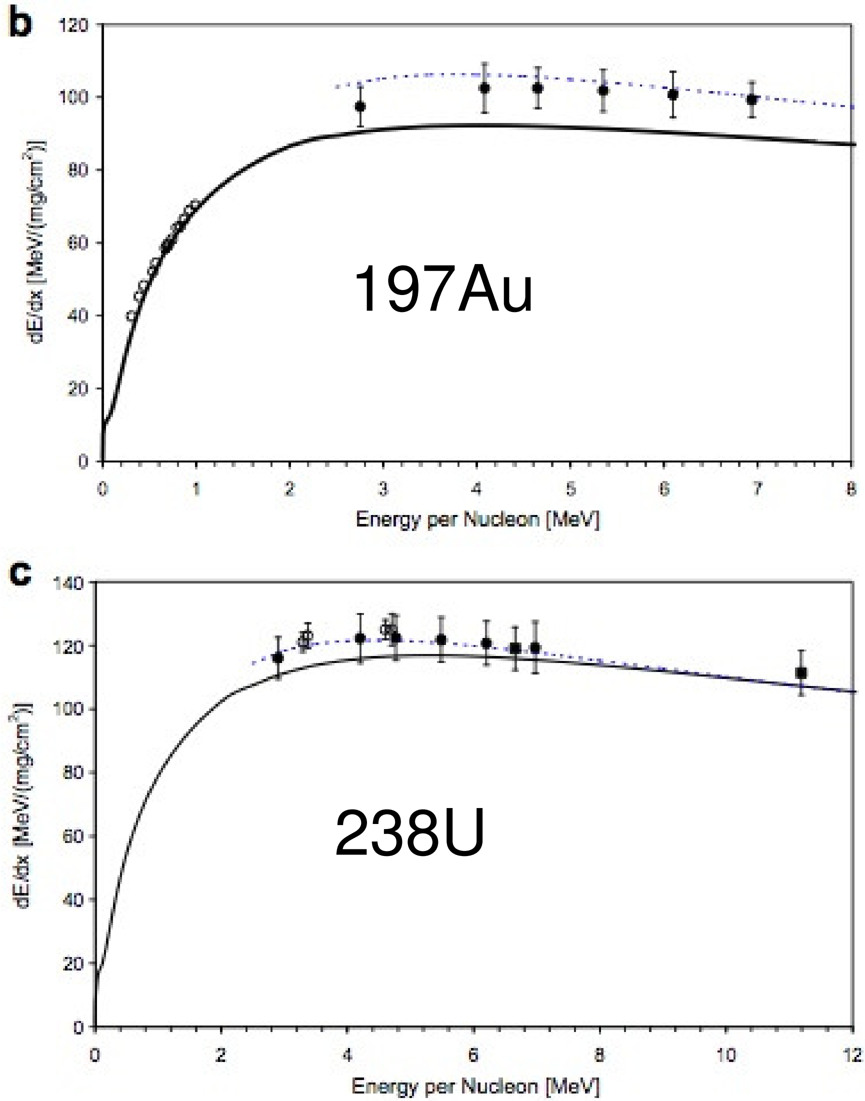
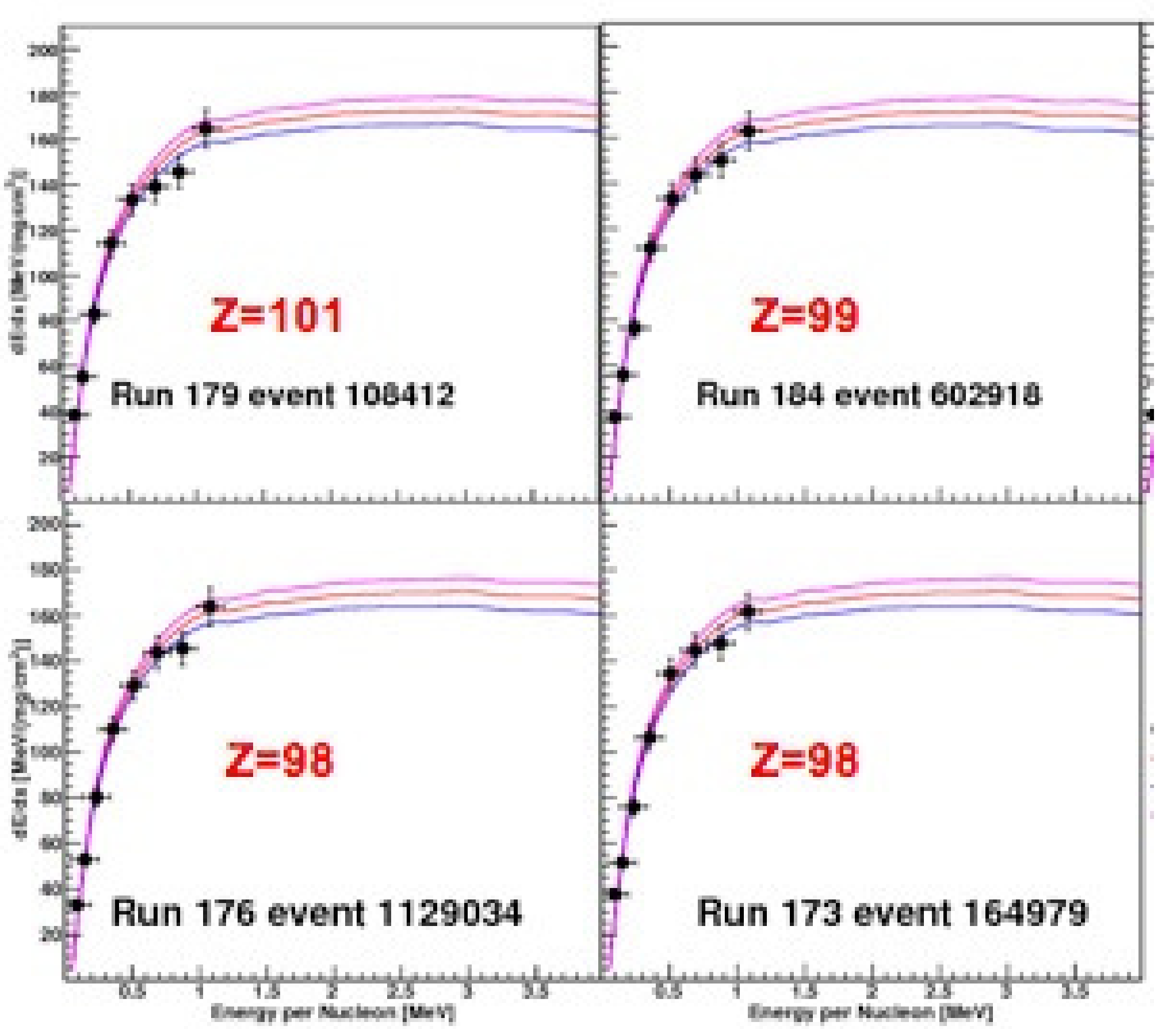


Fig. 4. Stopping power of ^{40}Ar, ^{84}Kr (a) ^{197}Au (b) and ^{238}U ions (c) in aluminum. In panel (a) full circles show the experimental data with ^{40}Ar beam measured in this work, whereas the open circles show result from Refs. [18,20] The squares mark the ^{84}Kr data (full squares this work, open squares Refs. [17,19–21]. In panel (b) the full circles mark the experimental data with ^{197}Au beam measured in this work, whereas the open circles indicate results from Ref. [22]. In panel (c) the full circles and squares mark the experimental data measured in this work with ^{238}U beams at 7.46 MeV/nucleon and 11.93 MeV/nucleon, respectively, whereas the open circles show results from Ref. [17]. The thick line shows the SRIM predictions. The dashed line shows the Hubert table data [11].

So can't depend on SRIM or tables necessarily to extrapolate dE/dx.

Earlier SHE events identified with Z too large due to invalid extrapolation of dE/dx, especially at lower E/A .

Need more energy in IC to get better Z i.d. for high Z :



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Thus the Z of interesting events reassigned now to lower Z (97 to 102) with yields as indicated:

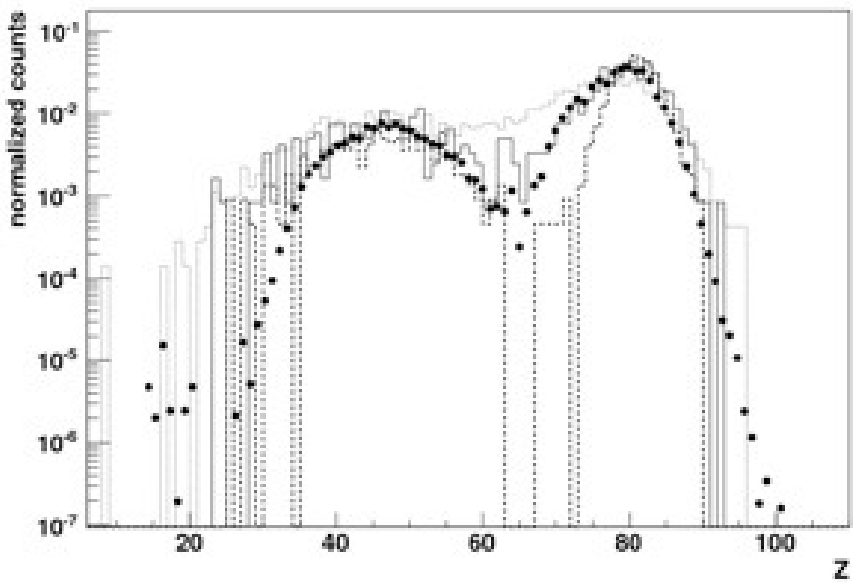

Figure 3: Z distribution of the reaction products. Points show experimental data, lines refer to CoMD calculations (dashed line at 6 MeV/nucleon, solid line CoMD at 6.75 MeV/nucleon, dotted line CoMD at 7.5 MeV/nucleon).

Few events (5) with high atomic number 97<Z<102 were survived the pileup-rejection filters. Unfortunately the energy of those events at the entrance of the IC is about or below 1 MeV/nucleon. At this energy the Z resolution of our detector is relatively poor. More accurate measurements are required in order to improve the result. A rough estimation of the reaction cross section for these very heavy elements gives an upper limit of about 11 nb/event.

So improved detectors planned for future SHE experoments.

Also note upgrade options for use as multi-fragment spectrometer:

A) Add 2nd solenoid as ToF mass spectrometer

B) Run gas filled mode (but can alter ToF-XY): See ANU work

C) Add radial electric field lens or similar (UM RSI paper)

D) Compensating Eloss absorbers (UM NIM paper)

Ideal configuration depends on intended use and Z,A,q of ions to be detected.

TwinSol: UM-UND two 30cm bore x 6T s.c.slenoids for LE RNB research :

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Two magnets can be used in multiple modes with or w/o cross over at center (latter for ToF detector, E-loss absorber, etc.). Opposing B reduces fringe field.

Again long-flight path sub nsec ToF possible (e.g. foils+MCPs)with minimal time dispersion.

Recent Twinsol set up as 8 M ToF system (RNBs) w/MCP at cross over focus:

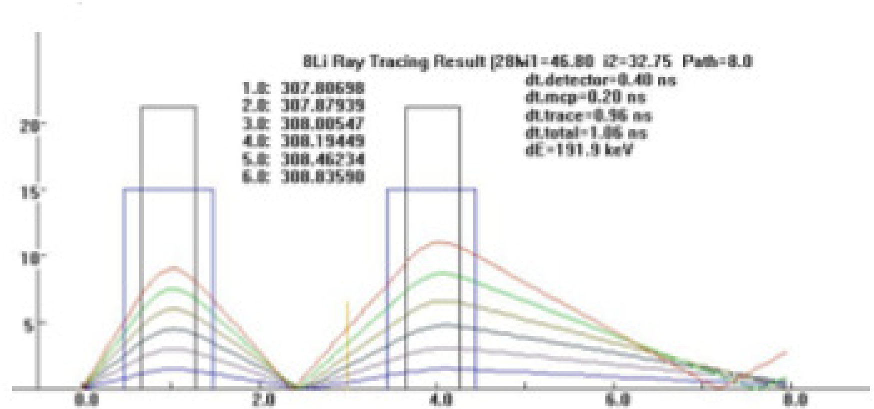

Figure A.11: Ray-trace calculation of a 28 MeV ^{8}Li beam in *TwinSol* with a long flight path (8 m).

Also have run in parallel hi-Bp mode:

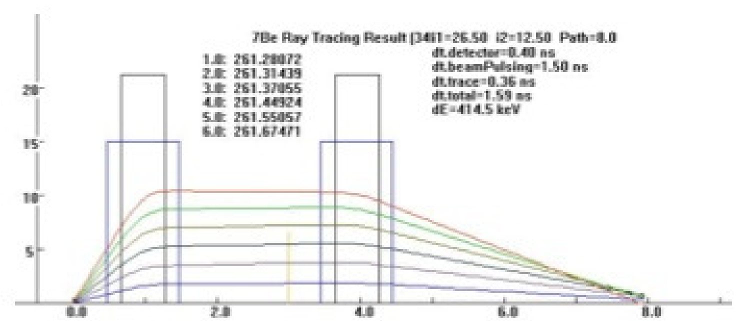

Figure A.12: Ray-trace calculation of 34 MeV ^{7}Be in parallel mode (8 m flight path).

Large-aperture, axially symmetric ion-optical lens systems using new types of electrostatic and magnetic elements

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(Received 4 November 1988; accepted for publication 27 March 1989)

Focusing of multiply charged energetic ions using solenoidal B and radial E lenses

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(Received 28 July 1986; accepted for publication 17 October 1986)

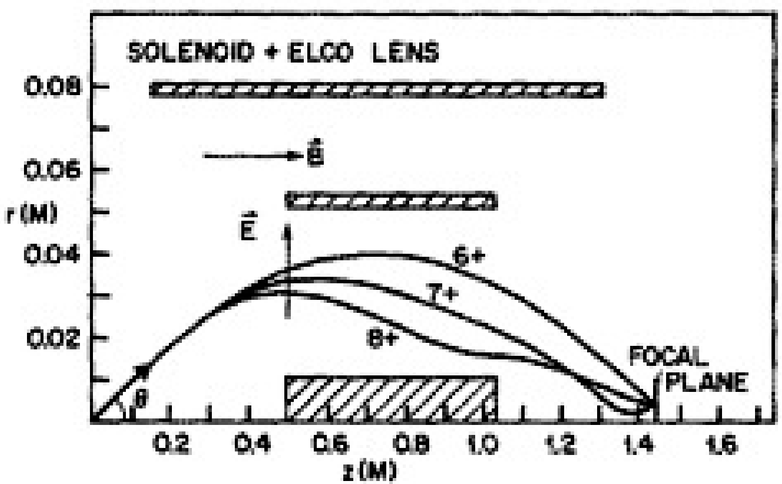

FIG. 3. Calculated ion orbits for a combined magnetic solenoid and radial-electric-field (ELCO) lens system with parameters adjusted to focus a range of charge states for 60 MeV ^{16}O, $\theta = 5°$. Other properties are given in Table I. (Note different horizontal and vertical scales.)

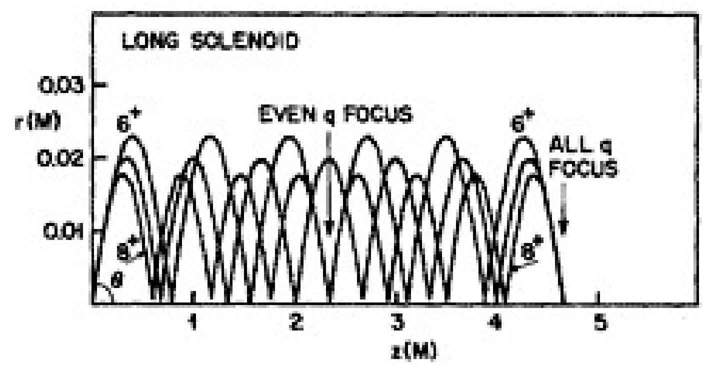

FIG. 1. Calculated orbits for ^{16}O ions ($E = 60$ MeV), $\theta = 5°$, in charge states $q_i = 1^+, 2^+, \ldots, 7^+, 8^+$, in a long, uniform, solenoid lens. The solenoid length and field strength are such that after $n = q_{max} = 8$ orbits [Eq. (1)], all charge states are brought to a first-order focus. The parameter r is distance from the solenoid axis as the particles spiral through the magnet. Other properties are given in Table I. (Note different horizontal and vertical scales.)

New magnets can have built in cryo-coolers, and can have active shields (tho latter is x 1.5 $$..i.e. 0.7 M$ vs. ca. 0.4 M$).

(For magnet shown, can be split-coil design for use also as an ion trap or other applications needing side access. In UM queue for submission to US NSF)

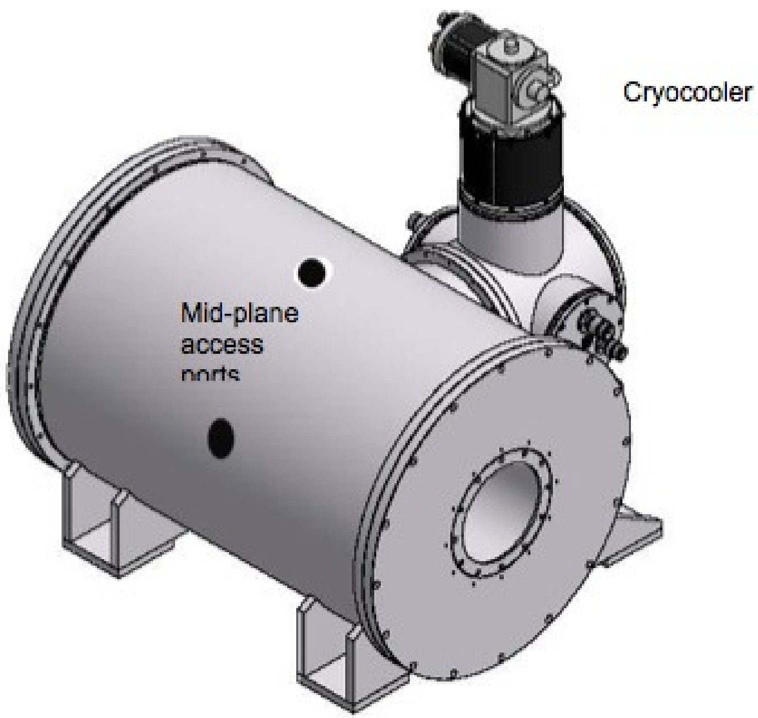

Figure 1. A schematic diagram of the proposed magnet system (power supplies, ion-optics instrument insert and atomic-physics instrument insert not shown).

Just kW's needed, no LHe

Per last meeting: Conclusions:

Solenoid-based systems can be cost- and space-effective and provide a multi-mode, multi-functional spectrometer system, but need high fields, long coil for low-q ions.

Given their relative simplicity and moderate costs , could be well-suited to SHE research should massive transfer (angles> zero) be a suitable SHE production mechanism.

Some references : *www.physics.lsa.umich.edu/twinsol/*

Thank you