U.Michigan-U. N. Dame *TwinSol* LE RIB facility at UNDame

Fred Becchetti , University of Michigan-Ann Arbor

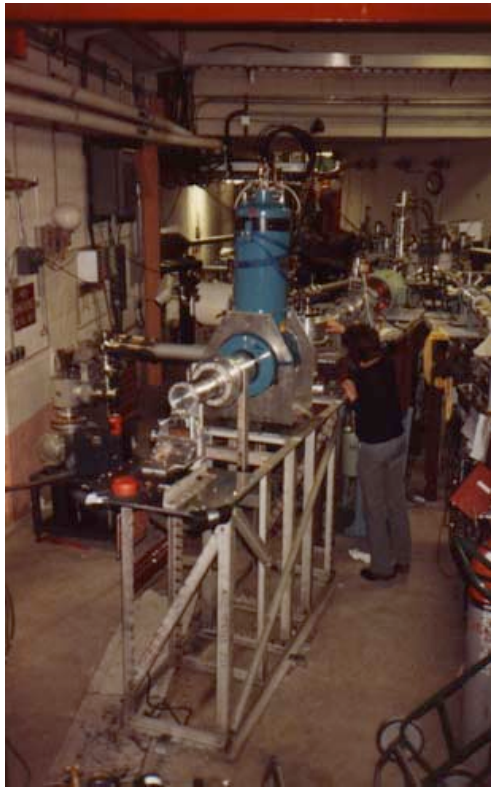
- History: UM-UND collaboration 1987-2005
- Present facility
- Sample of recent research
- Future upgrade plans -Relevance to RIA
- RIBRAS (New *TwinSol* type facility at Sao Paulo Brazil)

ORNL fusion workshop 12/3/2005

Unusual : UM & UND collaborating rather than competing.

Football in particular…(US football)

UM-UND collaboration began with installation of a UM DoE-surplus 3.5 T solenoid at ANL* in 1984-87 for use as a small-angle spectrometer following design of similar (but two solenoid) device at Orsay*



Tests of a large air-core superconducting solenoid as a nuclear-reaction-product spectrometer

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(Received 6 February 1987; accepted for publication 23 March 1987)

An air-core superconducting solenoid, with a diameter of 0.2 m and a length of 0.4 m, has been configured for use as a heavy-ion reaction-product spectrometer ($E/A \leqslant 5$ MeV/u) near $\theta = 0°$. The spectrometer has a large solid angle (10–35 msr) and properties suitable for time-of-flight measurements with flight paths $\gtrsim$ 2 m. The performance of the spectrometer was established using α-particle sources and nuclear-reaction products from heavy-ion collisions. The characteristics of air-core magnets are compared to those of steel-yoke magnets. The simplicity and ease of operation of the air-core magnet, without significant problems from the (axial) fringe fields, suggests that larger air-core magnets with $d\Omega \geqslant 20$ msr and capable of focusing ions with $E/A \geqslant 30$ MeV/u are feasible. Other applications of solenoids and combinations of solenoids with radial electric-field lenses (ELCO lenses) are also discussed, including designs which focus more than one charge state simultaneously.

(Whatever happened to our collaborator D. Kovar??)

UM had a second solenoid..but no room for it!

*UM PHD thesis project of Ms. Robin Stern [RSI **58**(1987) p1682]

*(Schapira et al..but ran as single solenoid spectrometer due to a destructive quench of the second solenoid)

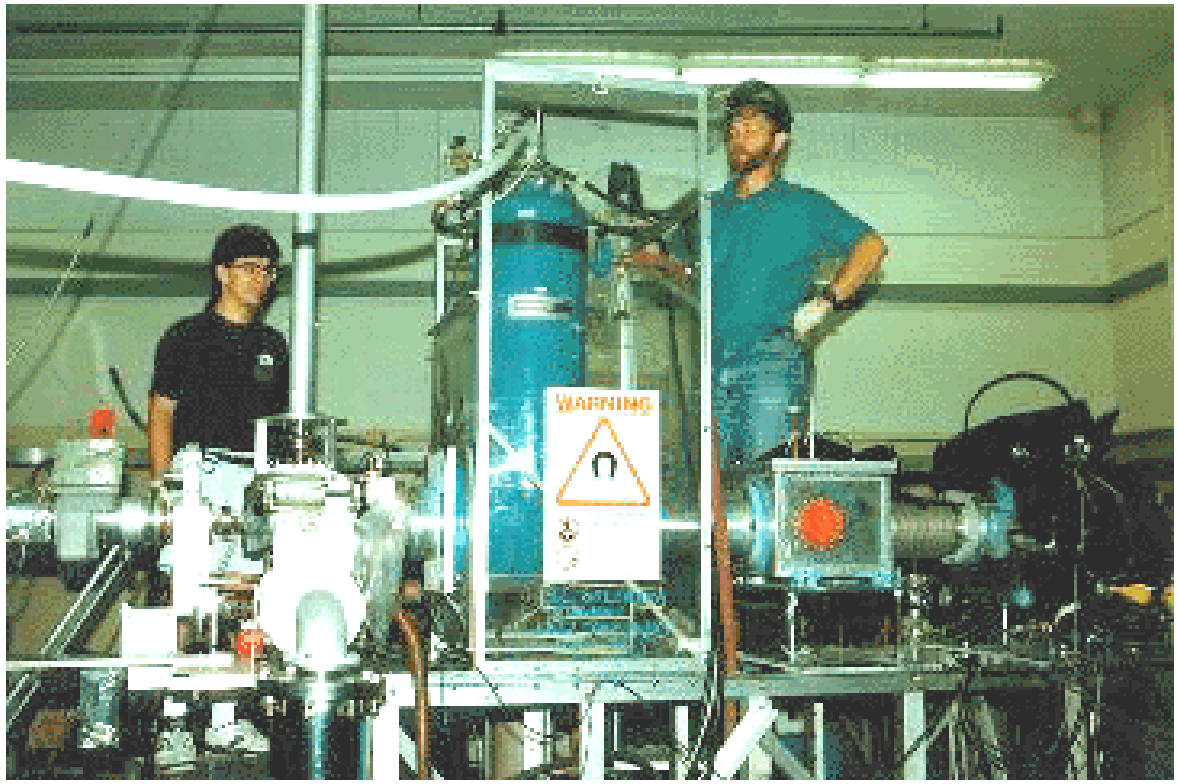
Did not work well as small angle spectrometer e.g. for 18O on Ni to study 4n transfer (R. Stern PhD) . Too many “background” particles I.e. “garbage”..like 15O,18F,18Ne..but these are desirable secondary radioactive beams!

And as we know, one persons garbage is another’s treasure…

Device moved to U N Dame (1987) as collaborative NSF-UM-UND funded effort between UM (FB) and UND (JJKolata) to establish a low-energy RIB facility based on an upgraded UND FN Tandem.

Included installation of SNICs source to increase primary beam intensity.

Became LilSol , one of first operational LE RIB facilities* in USA (and world in fact)



* Part of UM PhD project of Mr. W. Liu (PhD, 1990)

separators to collect and focus secondary beam.

Didn't work at LE (tho OK at HE) !!! Too much background from scattered primary beam etc..

UM approach: Adapt superconducting solenoid zero degree "spectrometer" as primary RNB element :

Simple, "clean" optics (its a simple lens)

Thus easy to block out scattered primary beam with simple apertures, etc

Good time of flight to separate b.g. etc

Solenoid: Simple ion optics so unwanted primary beam and other beams can be blocked to a large extent via simple apertures”

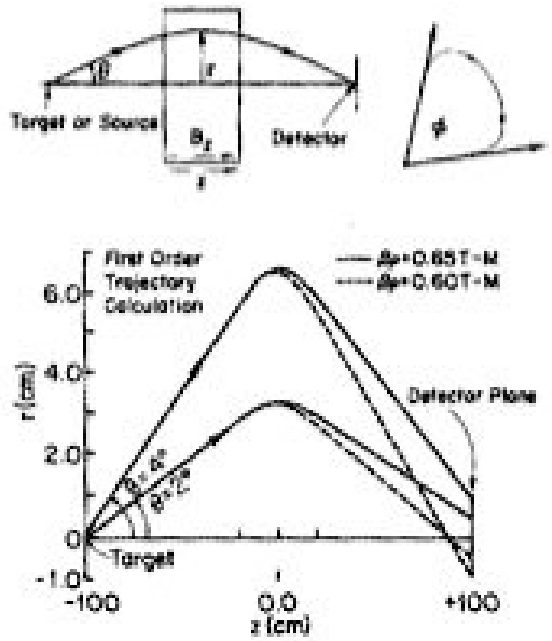


FIG. 1. Top: Geometry of the solenoid spectrometer and corresponding particle trajectories. The angle ϕ is the spiral angle of the ion orbit from target (object) to detector (image). Bottom: A set of calculated ion trajectories [Eq. (2)] for a range of energies and scattering angles (see, also, Table IV). Note the different vertical and horizontal scales.

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Intense,scattered primary beam can be brought to a focus and easily blocked while RIB of interest as (in a ring image) passes around the aperture and can be brought to focus on a secondary reaction target :

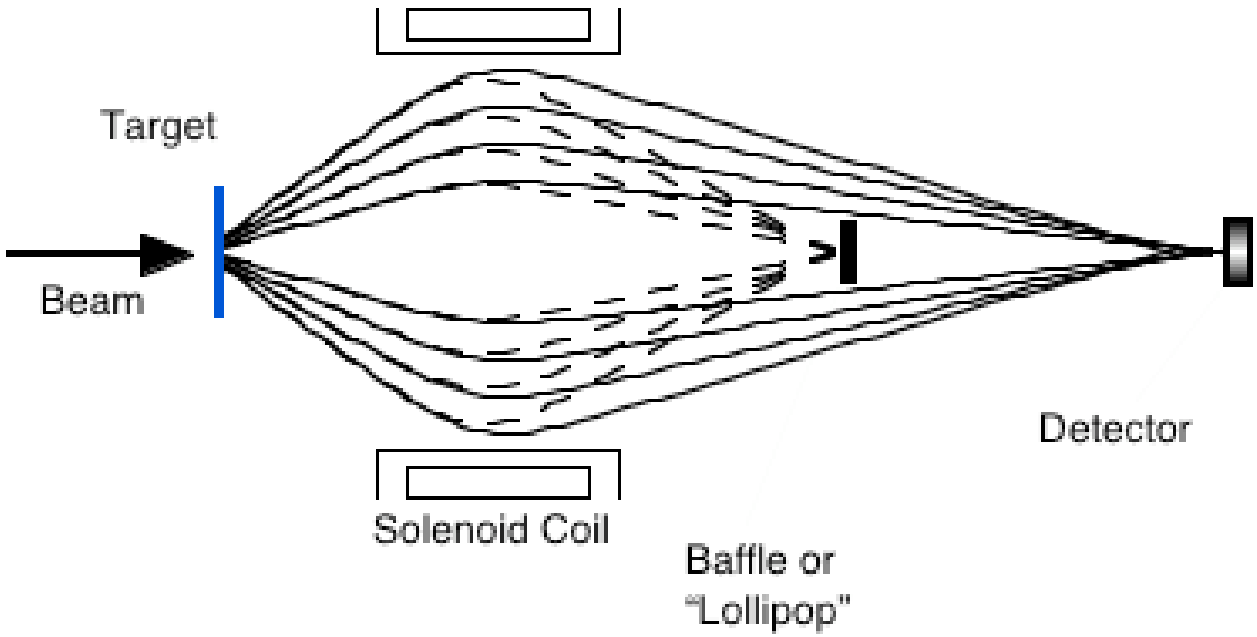

Figure 2.12 Example of using a baffle to stop a low-Bρ contaminant beam from reaching the particle detectors. Although, the less-rigid contaminant beam may not be focused onto the detectors, if they are not stopped in the lollipop (or baffle) they may undergo multiple scattering and eventually reach the detectors.

At focus

Off focus
(Blocked areas due to entrance aperture supports. Note rotation of image of those)

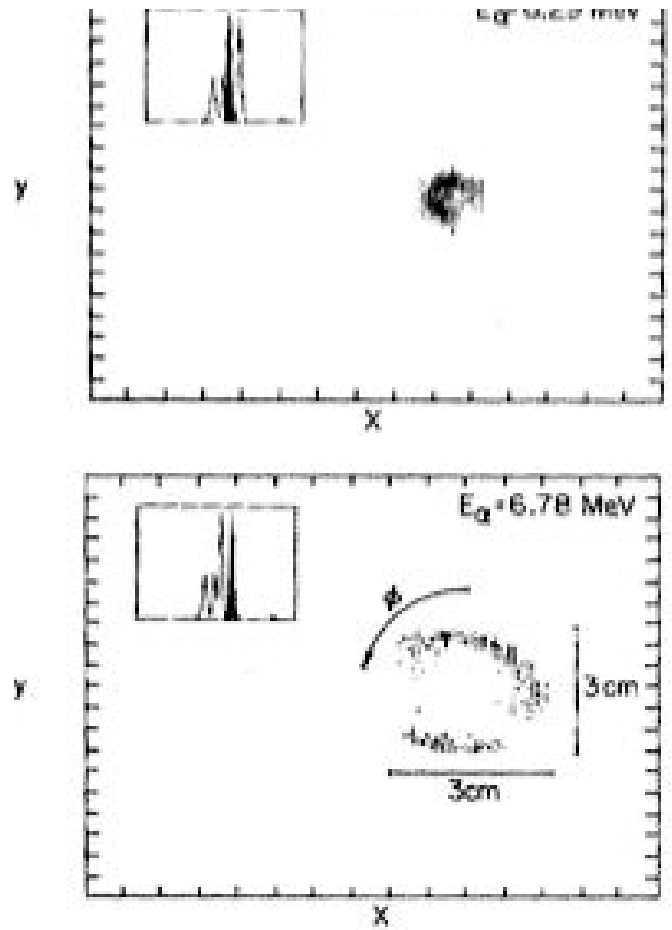

FIG. 10. α-particle images obtained at the solenoid-spectrometer focal plane for specific ^{228}Th groups. These were obtained using the $xy - \Delta E - E - t$ gas proportional counter detector (see Fig. 7) with an energy gate set on the selected α groups as indicated. The on-focus image (E_α = 6.29 MeV) represents the circle of least confusion. The off-focus image (E_α = 6.78 MeV) is a ring with two small areas blocked off, corresponding to the aperture and Faraday cup supports. Rotation of the image by the spiral angle φ is evident. The aperture used was a ring with an opening of 5.2°–6°.

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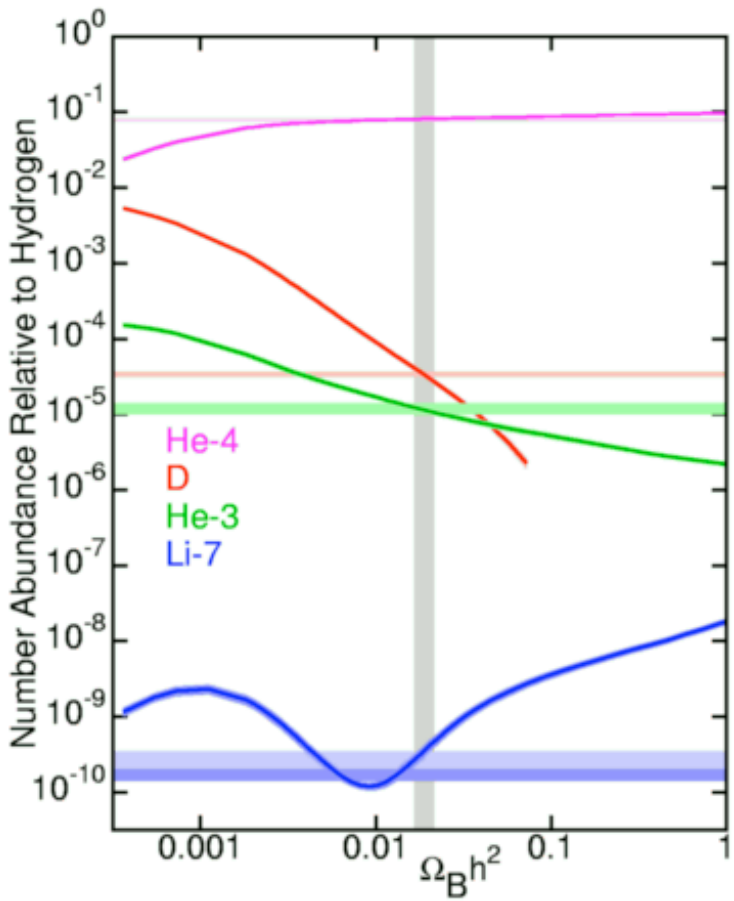
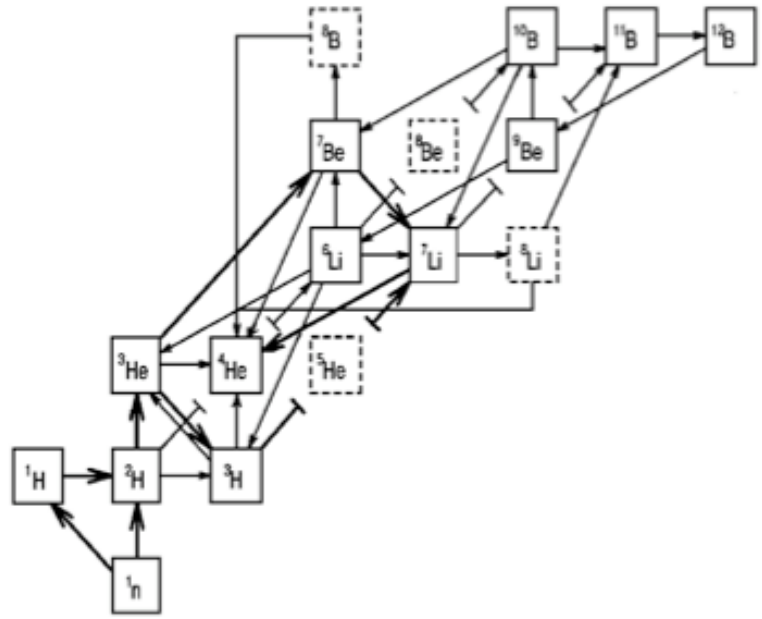
Among first experiments:

Measurement of 8Li(d,p)9Li and 8Li(d,t)7Li cross sections

(motivated by astrophysics and missing mass problem of 1980's)





We see that 8Li reactions result in "break out"

Studied LE 8Li (d,t), 8LI(p,alpha), 8Li(p,n) etc with LilSol

But first paper on 8Li(d,t) including description of apparatus to make useable high-intensity LE RIBs, submitted to Phys. Rev. Letters (1988 or so) ..and rejected!!!

Referee comment: Topic too specialized and such RIB studies would not likely ever be of general interest to PRL readers.

Of course in the next ten years several PRLs /PRCs etc based on LilSol and research at other RIB facilities were published (with better statistics etc of course)..including a later PRL (with OSU) on 8Li(d,t) and 8Li(d,n) (but similar results as first UM-UND experiment):

8Li(d,t)

Ex fnt

8LI(d,n)

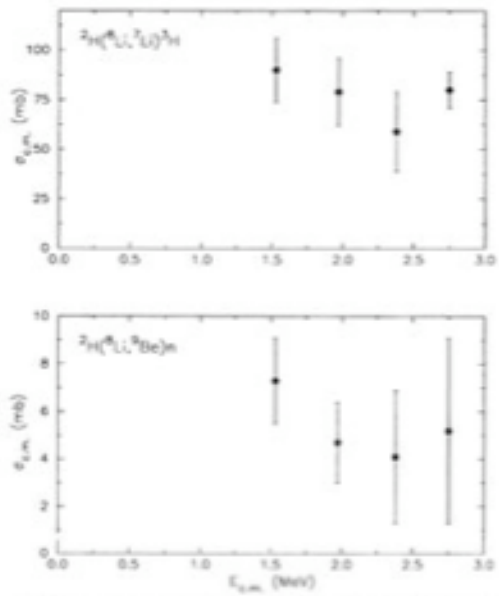


FIG. 2. Excitation functions for the ^{8}Li$(d,t)^7$Li and ^{8}Li$(d,n)^9$Be(ground state) reactions. Error bars indicate statistical and systematic uncertainties for each datum. There is also a possible systematic error of order 33% due to the symmetry or lack thereof about 90°.

^{9}Be(excited states) would not synthesize any ^{9}Be, it could be very important as a ^{8}Li destruction mechanism; this reaction is presently under study [20]. Because the cross section upper limit observed for ^{8}Li$(d,p)^9$Li is so small, it could not be important either for making ^{9}Be (from β decay of ^{9}Li), or for destroying ^{8}Li.

The astrophysical S factors for the ^{8}Li$(d,t)^7$Li and ^{8}Li$(d,n)^9$Be(g.s.) reactions at each energy were calculated from the measured excitation functions according to the standard prescription [21]. The best estimate of the S factor for each reaction, which was assumed to be energy independent (in the absence of sufficient data to define the possible resonance structure), was then calculated via a weighted averaging of the four measured values. This procedure resulted in a reaction rate of

$$N_A\langle\sigma v\rangle = 9.63\times10^8 S(E_0) T_9^{2/3} \exp(-10.324 T_9^{-1/3}) \times (1.0+0.0404 T_9^{1/3})\ \mathrm{cm^3 s^{-1}},$$

where T_9 is the temperature in 10^9 K. $S(E_0)$ is the astrophysical S factor, given by $S(E_0) = 1760 \pm 410 \pm 480$ keV b for the ^{2}H(^{8}Li,^{7}Li)t reaction, and $S(E_0) = 98 \pm 47 \pm 32$ keV b for the ^{2}H(^{8}Li,^{9}Be(g.s.))n reaction, where the first quoted error is the standard deviation in the S-factor excitation function from a flat line (thus implicitly including the statistical and systematic errors represented by the error bars in Fig. 2). The second quoted error represents the 33% systematic error due to the uncertainty in the back angle behavior of the cross section angular distributions.

The effect of the strong ^{8}Li$(d,t)^7$Li reaction on the

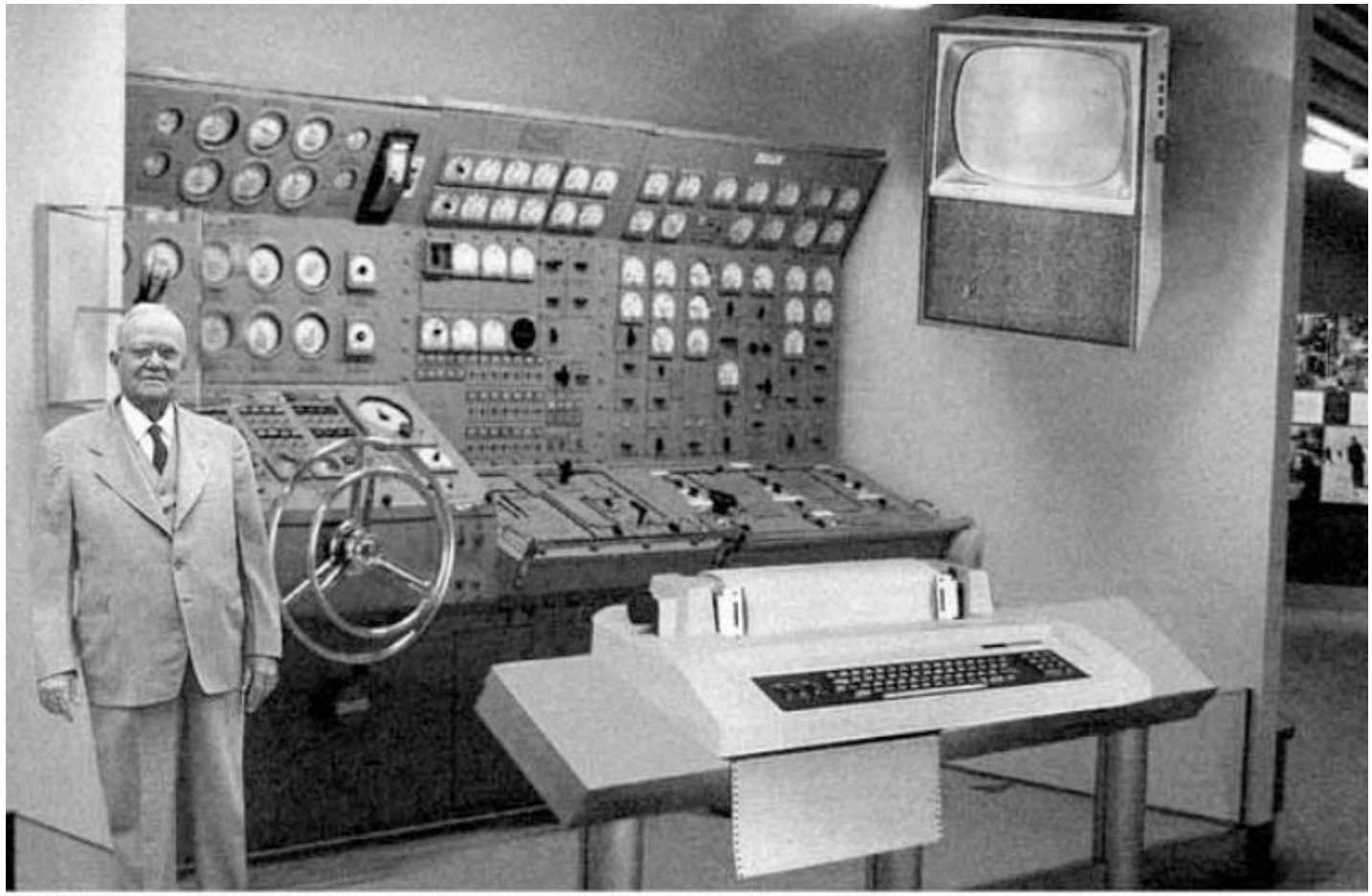
(Since we are at LE using inverse kinematics we are near astro CM energies)

Ecm 1.5-3.5 MeV

So as Yogi Berra (or it might have been Casey Stengel..a NY Yankee in any case) once said:

"Its hard to make predictions, especially about the future"

A prediction made in 1954 on how a home computer of the future (1970) might look like:



Scientists from the RAND Corporation have created this model to illustrate how a "home computer" could look like in the year 2004. However the needed technology will not be economically feasible for the average home. Also the scientists readily admit that the computer will require not yet invented technology to actually work, but 50 years from now scientific progress is expected to solve these problems. With teletype interface and the Fortran language, the computer will be easy to use.

LilSol used to demonstrate production of a useable isomer RIB:

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RAPID COMMUNICATIONS

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Production of an isomeric, excited radioactive nuclear beam

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A momentum-analyzed, isomeric, radioactive $^{18}F^m$ beam ($E_x = 1.12$ MeV, $T_{1/2} = 163$ ns) has been produced with the reaction $^{12}C(^{17}O,^{18}F^m)^{11}B$ at $E(^{17}O) = 70$ MeV. The $^{18}F^m$ ions were focused onto a secondary target using a compact superconducting solenoid lens and scattering of $^{18}F^m$ from Au and carbon targets was observed. A conversion efficiency of $> 10^3$ $^{18}F^m$/s per 100 particle nanoamps of ^{17}O was obtained using a 1.1 mg/cm^2 natural carbon production target.

18Fm isomer made using highly selective 12C(17O,18Fm 5+)11B reaction :

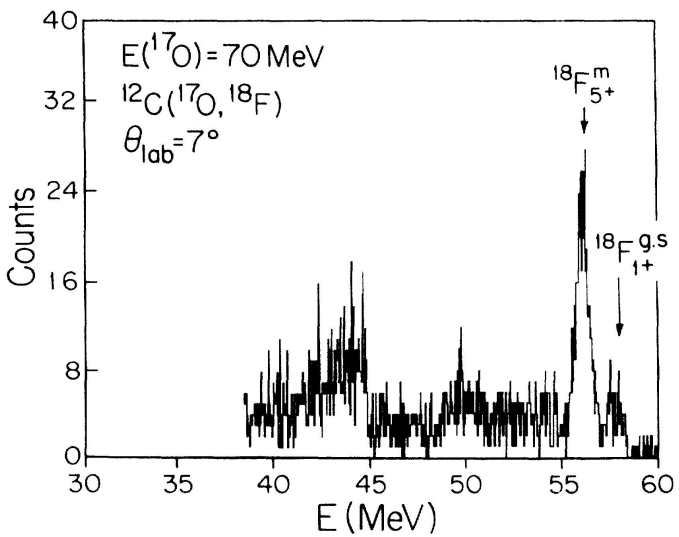


FIG. 2. The ^{18}F production spectrum observed for the ^{12}C(^{17}O,^{18}F)^{11}B reaction at $E(^{17}\mathrm{O})=70$ MeV using a 0.1 mg/cm^2 carbon target.

Which we used at NSCL at higher energy to measure 18Fm+p elastic scattering via gamma tagging etc:

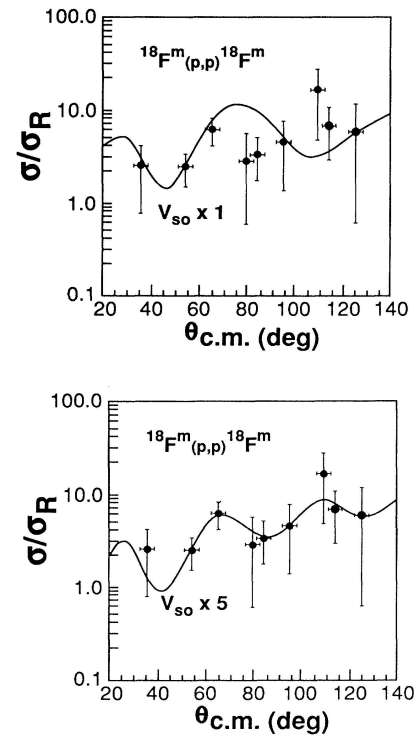


FIG. 11. Top: Elastic scattering angular distribution of γ-tagged $^{18}\mathrm{F}^m + p$, $E_{\mathrm{c.m.}} \doteq 20$ MeV as ratio to Rutherford scattering. The filled circles are the experimental points and the curve is an optical model calculation based on ^{18}O+p and ^{20}Ne+p OM parameters (see Ref. [26]). Bottom: Same as above, but with the spin-orbit strength (V_{SO}) increased by $\times 5$.

18Fm 5+ needs x5 p+18F VSO??

Caution then: HE heavy RIBs made via fragmentation or transfer reactions may not be in g.s., rather an isomer (yrast trap of course)..even some ISOL beams

At NSCL majority of 18F made was in 18Fm (which we wanted in this case)

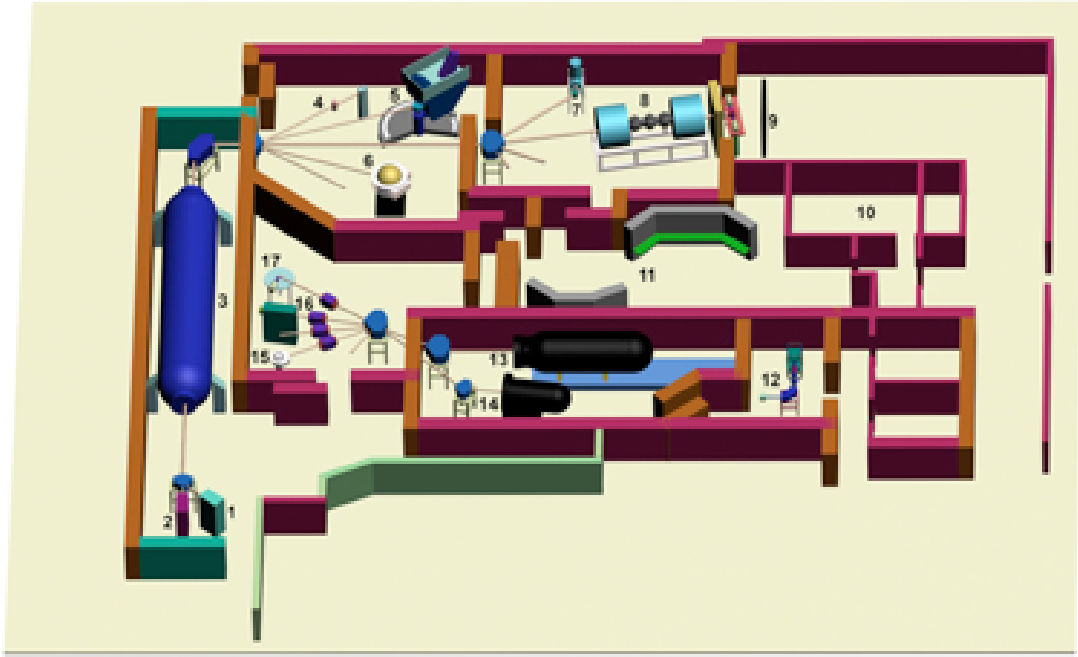
…but need to know state of beam one is using (has that always been done?? If not data are mixed g.s./isomer data ??)

Relevant to RIA fragment beams…

After many years of successful operation (1987-1997) a proposal for a larger, twin-solenoid multi-mode RIB/Spectrometer system was proposed to NSF and was funded NSF-UM-UND for construction in 1995. And was built and operational in 1997. Included UND FN upgraded with chain system and SF6 insulating gas for higher voltage. (LiLSol then used for beta decay expts.A.Garcia et al)

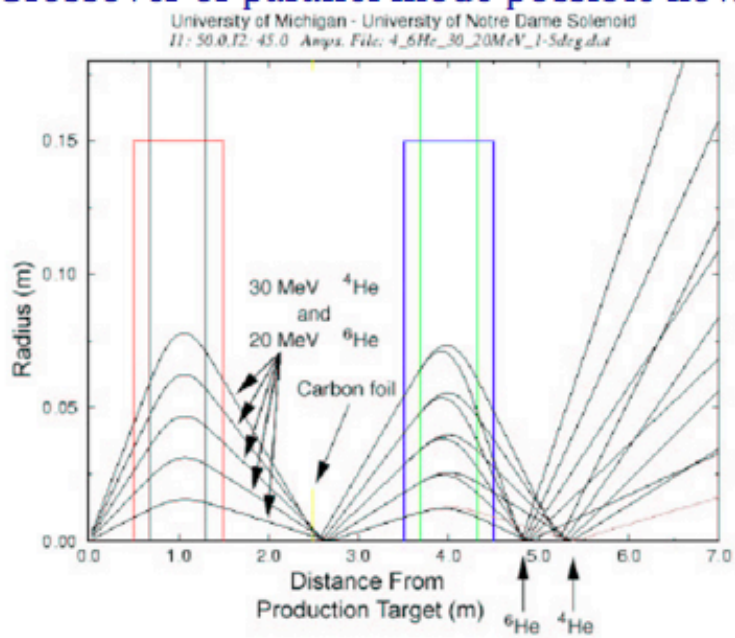
TwinSol at UND 1995-

1. SNICS Ion Source
2. HIS Ion Source
3. FN Van de Graaff Accelerator
4. Gamma Spectroscopy Beamline
5. Spectrograph Beam Line
6. R2D2 Beam Line (1 m scattering chamber)
7. Weak Interaction Beam Line
8. RNB Beam Line
9. Neuton Detection Wall
10. Conference Room
11. Accelerator Control Consoles
12. ECR Ion Source Test Setup
13. KN Van de Graaff Accelerator
14. JN Van de Graaff Accelerator
15. ORTEC Scattering Chamber
16. Windowless Gas Target Beam Line
17. Gamma Table



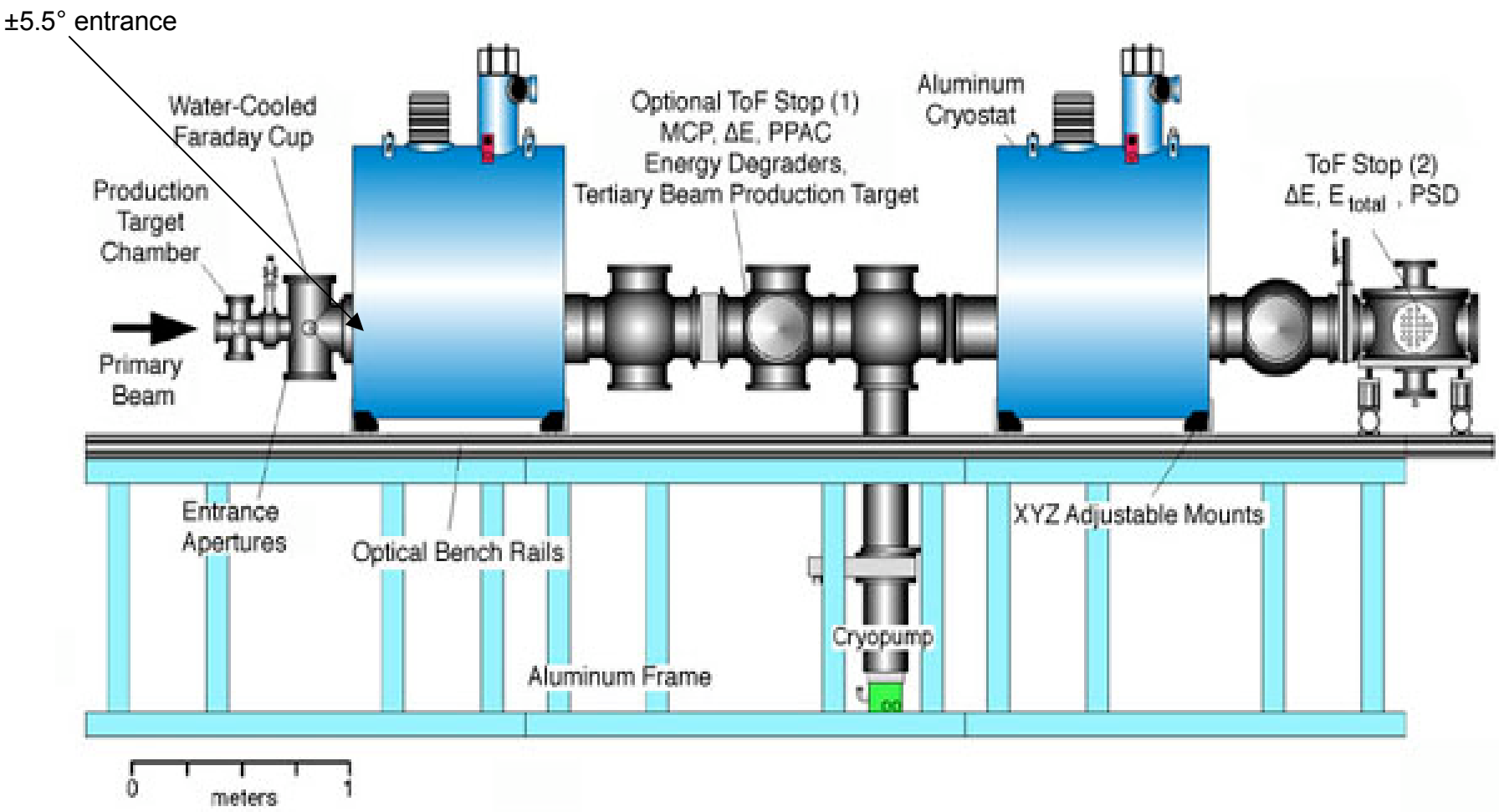
Not to be confused with website
of French rock group:

Crossover or parallel mode possible now:



See next slide

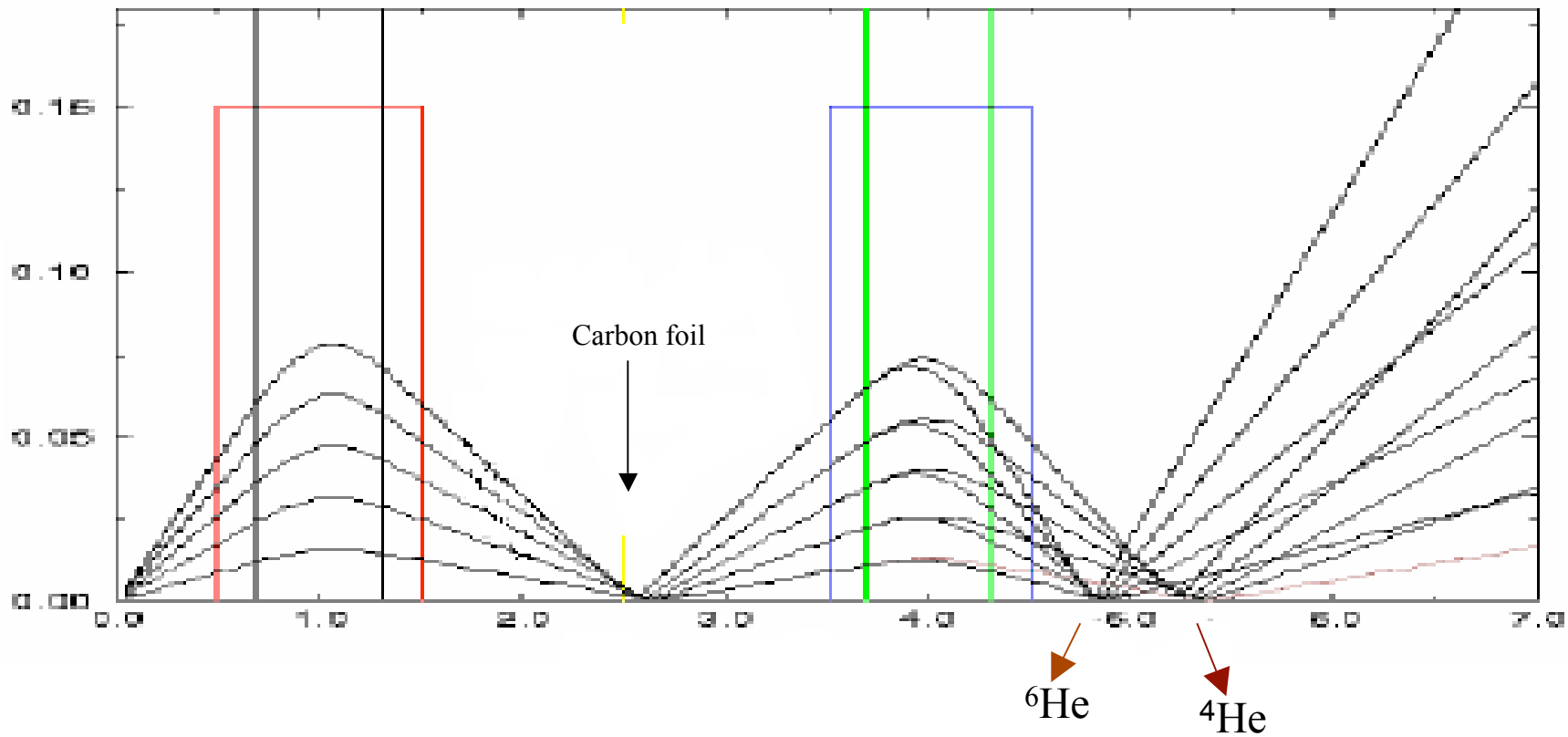
TwinSOL: RNB production facility



6 meter long= flight path

In order to better purify the RIB :

Ray-trace simulation, two helium isotopes of the same Bρ are focused by the first magnet onto a carbon foil. The more massive, yet less energetic ^{6}He ions lose disproportionately more energy in the foil and are subsequently separated from the alpha particles using the second magnet.



As in dipole RIB systems , we can use an absorber between magnets to get better RIB purity (+ ToF if needed using a pulsed beam)

Unique (??) feature: magnets generally run in persistent mode..I.e. power supply turned off (stable, reproducible focus ..and scales linearly.).Uses very little LHe so no LHe liquifier needed .

..and nice when running in Indiana in the spring and summer storm season..magnets stay on and set !

TwinSol project again part of a PhD thesis (Mu Lee) :

TWINSOL: A DUAL SUPERCONDUCTING SOLENOID ION-OPTICAL SYSTEM
FOR THE PRODUCTION AND STUDY OF LOW-ENERGY
RADIOACTIVE NUCLEAR BEAM REACTIONS

by

Mu Young Lee

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Physics)
in The University of Michigan
2002

Doctoral Committee:

Professor Frederick. D. Becchetti, Dissertation Chair
Professor Henry C. Griffin
Professor Jean P. Krisch
Professor Gregory Tarlé

Thesis etc can be downloaded from *TwinSol* web site:

www.physics.lsa.umich.edu/twinsol/

__ Accelerator: Upgraded FN Tandem, 10 MV, ~ μA, DC or pulsed beam (1.5- 2 nsec pulse width)

__ Radioactive beams: ^{6}He, ^{8}Li, ^{7}Be, ^{10}Be, ^{8}B,.. ^{18}F^{m}… 10^{4}-10^{8} /s

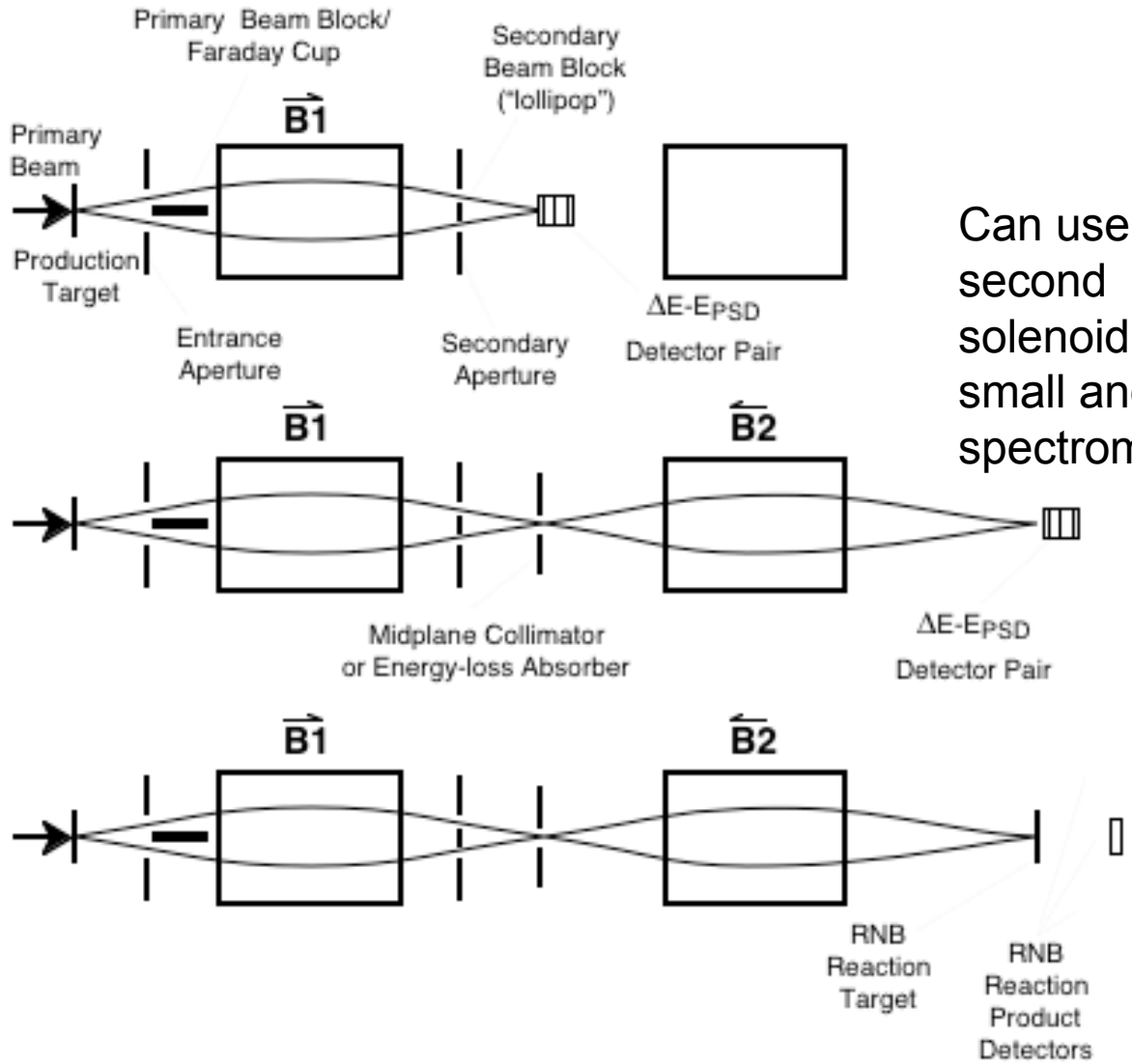
Reactions: e.g. ^{9}Be(^{7}Li, ^{6}He) ^{10}B, ^{3}He(^{6}Li, ^{8}B)n

__ Experiments: LE elastic-, inelastic-scattering ,

sub-barrier fusion/fission, RIB break up, exotic cluster transfer reactions, fusion-gamma gamma, n-alpha , n- ToF, ……etc

Twin magnets permit many useful modes of operation (we/ve run most of these):

Note we typically run opposing fields to minimize fringe field at cross over..(recall reversing field in a solenoid changes direction of rotation but it's still a focusing lens)



Can use second solenoid as small angle spectrometer

Figure 3.14 Basic components and steps required in crossover mode of operation to deliver an RNB to the back chamber.

Since we are using reverse kinematics with unstable beams we can use stopped beam technique with H,D..tgts to measure excitation functions e.g. here 7Be+p (Rogachev et al)

Related to solar neutrino problem. We find a predicted LE resonance doesn't exist:

PROTON ELASTIC SCATTERING FROM ^{7}Be AT LOW . . .

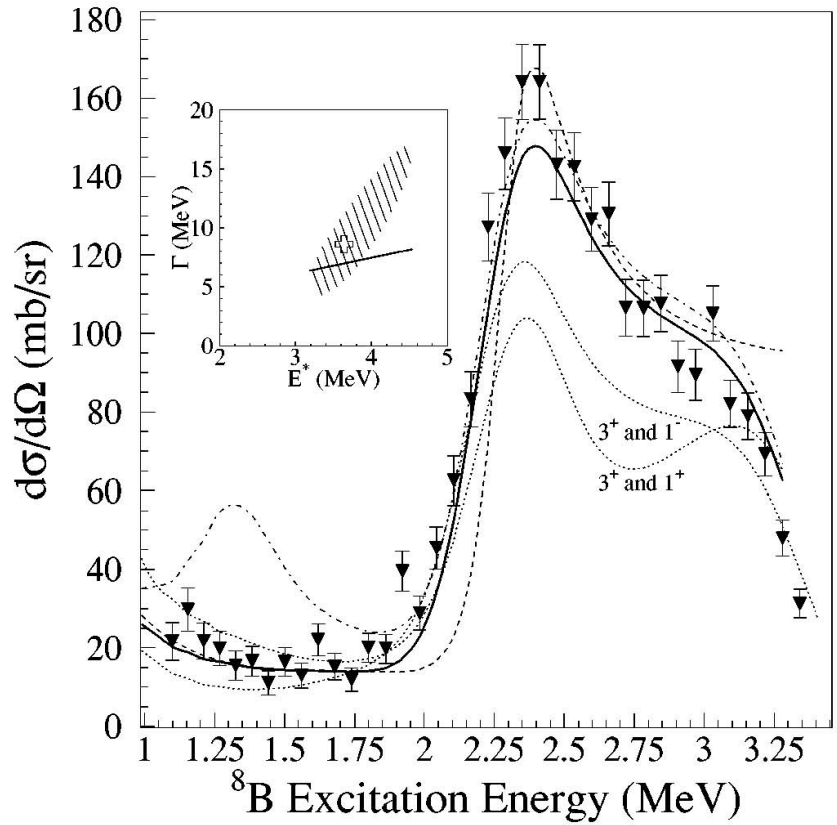


FIG. 3. Elastic data compared with the full R-matrix calculation, including the 2^- level at 3.5 MeV. The dashed curve shows the calculation prior to convolution with the experimental response function. The dash-dotted curve shows the comparison with a calculation including a predicted 1^+ state at 1.4 MeV. Dotted curves show the behavior of the excitation function in case of different spin-parity assignments for the new resonance (1^-,1^+). The insert gives a confidence band for the excitation energy and width of the 2^- resonance. The cross indicates the best fit point; the solid line is the Wigner limit for the 2^- state calculated for a channel radius of 4.3 fm.

P-Halo 8B exhibits large Nucl-Clx interference far below “classical” barrier..other RIBS also?? Impacts extraction of BE2s etc for RIBs

VOLUME 84, NUMBER 9 PHYSICAL REVIEW LETTERS 28 FEBRUARY 2000

Nuclear and Coulomb Interaction in ^{8}B Breakup at Sub-Coulomb Energies

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(Received 24 September 1999)

The angular distribution for the breakup of ^{8}B $\rightarrow$ ^{7}Be + p on a ^{58}Ni target has been measured at an incident energy of 25.75 MeV. The data are inconsistent with first-order theories but are remarkably well described by calculations including higher-order effects. The comparison with theory illustrates the importance of the inclusion of the exotic proton halo structure of ^{8}B in accounting for the data.

PACS numbers: 25.60.Gc, 21.10.Gv, 27.20.+n

Coulomb dissociation reactions have been used in recent years as a means to obtain information on capture reactions of astrophysical interest. An example is the experiment of Motobayashi *et al.* [1] who studied the breakup of ^{8}B $\rightarrow$ ^{7}Be + p on a Pb target and related their result to radiative proton capture at solar energies. This reaction corresponds to the projectile breaking up into a core and a valence nucleon due to interactions with virtual photons in the strong Coulomb field of a high-Z nucleus. Although this mechanism is, in principle, a time-reversed capture reaction, $E2$ photons contribute to Coulomb dissociation while radiative capture at solar energies proceeds almost exclusively by $E1$ transitions. Thus, in extracting information on astrophysical proton capture reactions from the measured dissociation cross section, it is crucial to determine the relative contribution of photons having different multipolarity.

The relative importance of $E1$ and $E2$ contributions to the Coulomb dissociation of ^{8}B has been investigated both experimentally [2–5] and theoretically [6–8]. The earliest experiments [2,3] suggested that the $E2$ strength was much smaller than all published theoretical estimates. Davids *et al.* [4] measured the asymmetry in the longitudinal momentum distribution of ^{7}Be fragments from the dissociation of ^{8}B on Pb at 44 and 81 MeV per nucleon. The 44 MeV/nucleon data gave a clear signal corresponding to an $E2$ strength that was 70% of that predicted by the model of Esbensen and Bertsch [8]. This model prediction itself is a factor of 2 smaller than that of Kim *et al.* [9]. Nevertheless the extracted $E2$ strength, though considerably quenched, is still larger than implied in Refs. [2] and [3]. Most recently, Iwasa *et al.* [5] report a limit on the $E2$ strength that is at least an order of magnitude smaller than that of Davids *et al.*

It was noted in Ref. [4] that the description of the data by the model of Esbensen and Bertsch is not precise, and that the best-fit values for the $E1$ and $E2$ strengths differ by (20–30)% from the model predictions. The $E2/E1$ interference term is, of course, model dependent. The earlier experiment of von Schwarzenberg *et al.* [2] attempted to avoid model dependence by measuring the breakup at sub-Coulomb energies for a low-Z target (^{58}Ni) for which multiple Coulomb excitation was expected to be minimal. At these energies, the $E2$ component is enhanced relative to $E1$. The very small cross section reported in that paper, which was less than that predicted by any reasonable structure model for ^{8}B [10], has generated considerable interest. Nunes and Thompson [10], and Dasso, Lenzi, and Vitturi [11] independently suggested that the explanation for this result might be strong destructive nuclear-Coulomb interference effects, despite the fact that at the angle where the measurement was made the classical distance of closest approach is nearly 20 fm, i.e., far outside the range of the nuclear force for a “normal” nuclear system. A strong nuclear-dominated peak in the differential cross section at a center-of-mass angle of 70°–90° (well inside the expected 100°–110° for the onset of nuclear breakup of a normal nucleus) was predicted in Refs. [10] and [11], although it was pointed out that the corresponding calculations are only first order in the nuclear and Coulomb fields and might be modified by multistep excitations. Furthermore, it was suggested in Ref. [10] that even pure Coulomb excitation would be considerably modified from that expected in the normal “point-Coulomb” approximation which ignores the extended size of the valence proton wave function in ^{8}B (see Ref. [10] for a more complete discussion of this approximation). This leads to a further reduction in the calculated breakup cross section. Both effects are directly attributable to the exotic “halo” structure of ^{8}B, so it is important to verify, if possible, the implications of these calculations.

The experiment was carried out at the Nuclear Structure Laboratory of the University of Notre Dame. To produce the low-energy secondary radioactive ^{8}B beam, we used the *TwinSol* radioactive ion beam facility [12] and the ^{6}Li(^{3}He, n)^{8}B direct transfer reaction. A gas target containing 1 atm of ^{3}He was bombarded by a high-intensity (up to 300 particle nA), nanosecond-bunched primary ^{6}Li beam at an energy of 36 MeV. The entrance

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6He(p,n) IAS

VOLUME 92, NUMBER 23 PHYSICAL REVIEW LETTERS week ending 11 JUNE 2004

Analog States of ^{7}He Observed via the ^{6}He(p, n) Reaction

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Isobaric analog states of ^{7}He have been investigated by a novel technique involving the observation of the resonant yield of neutrons from the ^{6}He(p, n) reaction in coincidence with γ rays from the decay of the $(0^-, T = 1)$ state in ^{6}Li. The γ rays provide a clean signature for the isospin-conserving neutron decay of the low-lying isobaric analog resonances. It is conclusively shown that the analog of the recently observed low-lying spin-orbit partner of the ^{7}He ground state does not exist. Evidence is presented that this state lies at much higher energies, in agreement with microscopic calculations.

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Studies of neutron-rich nuclei can provide fundamental insights into nuclear structure and interactions that are not manifest in the valley of stability. Light exotic nuclei such as the heavy helium isotopes are the perfect proving ground for our understanding of the behavior of nuclear matter at extreme neutron to proton ratios. While modern theoretical methods are capable of *ab initio* calculations for nuclei with $A \leq 10$, experimental studies of neutron-rich nuclei near the drip line are difficult. One can, however, study properties of these nuclei as isobaric analog states (IAS). For example, it is possible to study the IAS of nucleus (N, Z) via resonant elastic scattering of the $(N-1, Z)$ nucleus on hydrogen [1,2]. Information obtained this way can be directly related to the spectroscopy of the (N, Z) nucleus. In very neutron-rich drip-line nuclei, the analog states can undergo isospin-symmetric neutron decay as well as proton decay (see the inset in Fig. 3 for the case of ^{7}Li). The following relationship holds true for the total wave function of the IAS with $T_> = T_z + 1$ if isospin is a good quantum number:

$$\Psi(T_>) = \frac{1}{\sqrt{1+2X}}(\psi_{N-1,Z}\psi_p + \sqrt{2X}\psi_{N-2,Z+1}\psi_n), \quad (1)$$

where $X = T_z + 1/2$. Once the IAS of a neutron-rich nucleus is populated, neutron decay will dominate, so the resonance yield of protons from population of analog states of neutron-rich nuclei is very small [1], about an order of magnitude smaller than that for resonant proton scattering at the limits of proton stability [3,4].

In this Letter, we report on the measurement of the IAS of ^{7}He. The resonance yield of n-γ coincidences in the interaction of ^{6}He with ^{1}H was observed. This experiment takes advantage of two aspects of the decay of the IAS: domination by neutron decay, and suppression of subsequent nucleon decays from the $T_>$ states in the daughter nucleus due to the isospin conservation law. Furthermore, the $\Delta T = 1$ γ-ray transitions should be especially strong [5], and neutron decay followed by a strong γ-ray transition is a unique signature for population of the IAS of neutron-rich nuclei.

Only the IAS of the ^{7}He ground state in ^{7}Li has previously been observed [6], and its width was found to be 268 ± 30 keV. There are no reports of the decay modes of this state. In ^{7}He, until very recently only the ground state was known [7], but excited states have now been reported in Refs. [8–11]. A $1/2^-$ state is reported recently at a very low excitation energy of 0.6 MeV [10,11]. This is particularly important since the confirmation of this result would provide evidence for the complete breakdown of the shell model in neutron-rich drip-line nuclei.

The experiment was carried out with the TwinSol radioactive nuclear beam facility [12] at the University of Notre Dame. A beam of ^{6}He was produced via the ^{2}H(^{7}Li, ^{6}He)^{3}He reaction. The experimental setup is shown in Fig. 1. A primary ^{7}Li beam with an average intensity of 200 electrical nA and an energy of 35 MeV was incident on a 2.5 cm (length) gas cell containing deuterium at a pressure of 1.3 atm. A Faraday cup placed after the gas cell was used to stop the primary beam. Two large superconducting solenoids act as thick lenses to separate ^{6}He from the scattered primary beam and other reaction products. ^{6}He ions were focused into a 1 cm (diameter) spot at the secondary target position. Under these conditions, a ^{6}He beam was obtained with an intensity of 2×10^5 s^{-1}, an energy of 24 MeV, and an energy spread of 750 keV full width at half maximum (FWHM). The secondary beam was further analyzed using two parallel-plate avalanche counters (PPACs) placed after the solenoids. The distance between the PPACs was 2.0 m, and the first PPAC was position sensitive in both the x and y directions. The PPACs were used

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Search for proposed excited state of triton (we find it's a 3 body resonance ..not state in triton per se)

PHYSICAL REVIEW C **68**, 024602 (2003)

Final state interaction or a ^{3}H excited state?

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An inclusive α-particle spectrum from the ^{1}H(^{6}He,α) reaction has been measured at a ^{6}He laboratory energy of 23.9 MeV. A resonancelike structure is observed at an α-particle lab energy of about 20 MeV, which corresponds to an energy of $E_{n,d}=0.6$ MeV in the n-d channel. An analysis of the spectrum shows that it cannot be explained by the effect of binary final-state interactions. The hypotheses that this structure represents (a) a new excited state of tritium or (b) a three-body final-state interaction are discussed.

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I. INTRODUCTION

There have been numerous attempts to identify resonances in the three-nucleon system. All experimental data available up to 1989 are summarized in Refs. [1–3]. According to these reviews, no unambiguous evidence for resonances in the three-nucleon system has been obtained, and only two levels are presently known: the ground states of ^{3}H and ^{3}He. In a few cases where deviation from phase space was observed and interpreted as resonances, there was always ground for skepticism. For example, it was shown that resonant structure found in the ^{3}He(π^-,π^+)3n reaction [4] could be the result of two-particle final-state interactions (FSI) [5].

Recently, resonancelike structure observed in the ^{1}H(^{6}He,α) reaction [6] was interpreted as an excited state of ^{3}H, having a width $\Gamma=0.6\pm0.3$ MeV and an excitation energy of 7.0 ± 0.3 MeV. This energy is 0.8 MeV above the n-d threshold and the state is wide enough to be readily visible in the n-d total reaction cross section, but the existing experimental data [7,8] show no evidence for comparable structure in n-d scattering. Modern theoretical studies of bound and continuum states of the three-nucleon systems have achieved a very high degree of precision (see, e.g., Refs. [9–11]), and are in very good agreement with the experimental scattering data. They show no indication for low-lying states in the N-d continuum (N here denotes a nucleon). However, it was shown in Ref. [12] that low-energy n-d scattering can be interpreted in terms of a virtual state in the vicinity of the n-d threshold, though this work leaves open the question of the observability of such a structure. Another interesting idea was put forward in Ref. [6] and discussed in detail by Barabanov [13]. It was suggested that the existence of a previously unknown excited state of tritium would not be in contradiction with the available experimental data if a very special structure was assumed for this resonance. Specifically, it must primarily consist of a "dineutron" bound to a proton (see Ref. [13] for detailed discussion of properties of such state).

The aim of the present work was twofold. First of all, the importance of the main conclusion of Ref. [6], viz., the existence of an unknown state in one of the best-studied nuclear systems, cannot be overestimated. However, the previous experiment was not without problems and it is desirable to confirm the results with a better experimental setup and over a broader range of excitation energy in ^{3}H. The second question that must be carefully considered is, whether the aspects of the reaction dynamics other than the interaction in the n-d channel can lead to resonancelike behavior. A detailed analysis of this question was not presented in Ref. [6].

The main results of the present work are as follows: (i) the measured spectrum is in good agreement with the results reported in Ref. [6] (there is a peak in the α-particle spectrum corresponding to low energy in the n-d channel); (ii) none of the individual pairwise final-state interactions in the system, except for a hypothetical state in the triton, can describe the experimental data; (iii) the peak can however be qualitatively explained by taking three-body final-state interactions into account, together with the fact that the total energy available for the three particles (α,n,d) in the final state is limited and rather low. The latter explanation, if correct, is of some importance as a novel and unexpected effect of final-state interactions for weakly bound nuclear systems.

II. EXPERIMENT

The experiment was carried out with the *TwinSol* radioactive nuclear beam facility [14] at the University of Notre Dame. The ^{1}H(^{6}He,α) reaction was used, as in Ref. [6]. The experimental setup is illustrated in Fig. 1. A radioactive beam

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Recent PRL on new technique using RIBs

(using gamma-ray doppler-shift information)

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Doppler Shift as a Tool for Studies of Isobaric Analog States of Neutron-Rich Nuclei: Application to ^{7}He

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We have developed a new technique to study exotic neutron-rich nuclei via their isobaric analog states (IAS). We populate high-isospin states in resonant reactions of radioactive ion beams with protons. Characteristic γ rays emitted from excited decay products were used to identify the population of the IAS. We show that information on the differential and total cross section for formation of the IAS can be extracted from the energy spectrum of the Doppler-shifted γ rays. This technique was applied to the study of $T = 3/2$ states in ^{7}Li, which are analogs of states in ^{7}He. The analog of the ^{7}He ground state was clearly observed, whereas the presence of the analog of a narrow $1/2^-$ state at 0.6 MeV excitation in ^{7}He reported by M. Meister *et al.* [Phys. Rev. Lett. **88**, 102501 (2002)] was excluded at the 90% confidence level. Evidence is presented for a broad $1/2^-$ state at a higher excitation energy in ^{7}He.

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The availability of radioactive beams has opened new opportunities for the investigation of exotic dripline nuclei. Many features of radioactive ion beams (RIBs) (such as low intensity) are quite different from those of more conventional stable beams, creating significant challenges for the experimentalist. The purpose of this Letter is to introduce a new experimental technique that allows the study of exotic neutron-rich nuclei in inverse kinematics. The technique has two components: the population of isobaric analog states (IAS) of exotic nuclei through resonant reactions in a thick proton target [in line with ideas discussed in Ref. [1]], and subsequent measurement of the Doppler-shift profile of the γ rays emitted after neutron decay of the IAS. This approach allows for the simultaneous measurement of the excitation function of the resonant (p, n) process, which leads to the population of IASs over a wide energy range from the initial RIB energy to zero, and provides some information on the double differential cross sections in one self-consistent measurement. The first application of this technique is presented in this Letter for the case of the IAS of ^{7}He in ^{7}Li. The correct identification of single-particle states in ^{7}He tests our present understanding of nuclear forces and *ab initio* nuclear models. The structure of this nucleus has generated some sizable controversy in both theoretical and experimental studies [2–12]. Specifically, the controversy is focused on the existence of a surprisingly low-lying $1/2^-$ resonance ($E_{ex} \simeq 0.6$ MeV) with significant single-particle strength. This state was reported in Refs. [2,6], but its analog in ^{7}Li has not been found [9]. In this Letter, we use a new technique to show that there are no excited states with substantial single-particle strength up to 1.5 MeV of excitation energy in ^{7}He. Instead, we present evidence for a $1/2^-$ resonance at higher excitation energies and give limits on its width and excitation energy.

The Doppler-shift method we describe here involves the population of the IAS in neutron-rich nuclei and the measurement of a characteristic γ ray emitted from a decay product of the compound nucleus. Because of isospin conservation, only two decay channels are allowed for the IAS: proton decay to the initial channel and neutron decay with the population of $T_> = T_z + 1$ states in the daughter nucleus (see the decay scheme of $T = 3/2$ resonances of ^{7}Li in Fig. 1. Here $T_> = 1$).

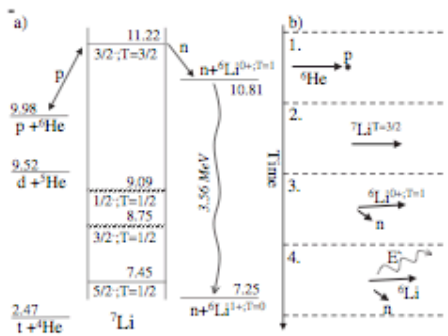

FIG. 1. (a) Decay pathways for the $T = 3/2$ resonance in ^{7}Li, and (b) the successive kinematics stages of the studied reaction.

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Recently have studied some RIB cluster transfer reactions .

(3He and 4He) and an “exotic “ transfe

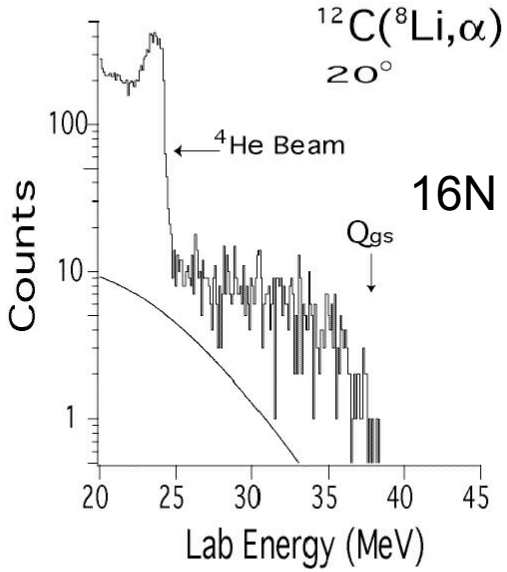


Fig. 2-bottom

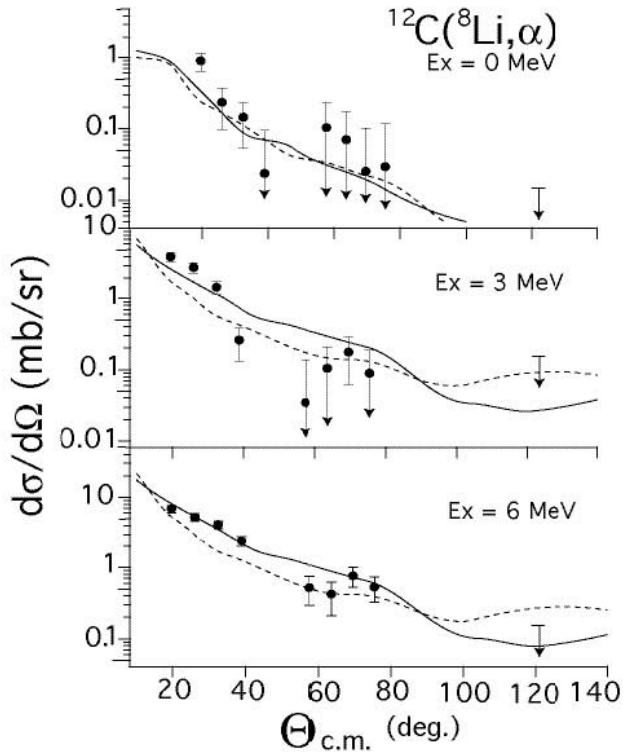


Fig.6-top

Appears to populate 16N “directly” and fit well by DWBA..one or two step 4H transfer (could be used to measure n rich masses via Qgs??).

Very recent: 12C (7Be,3,4He) 16,15O : A new tool for cluster transfer studies?? [Analog to (7Li,t) but different kinematics/OM etc etc..In fact we know outgoing OM well vs energy ..and can measure incident one easily]

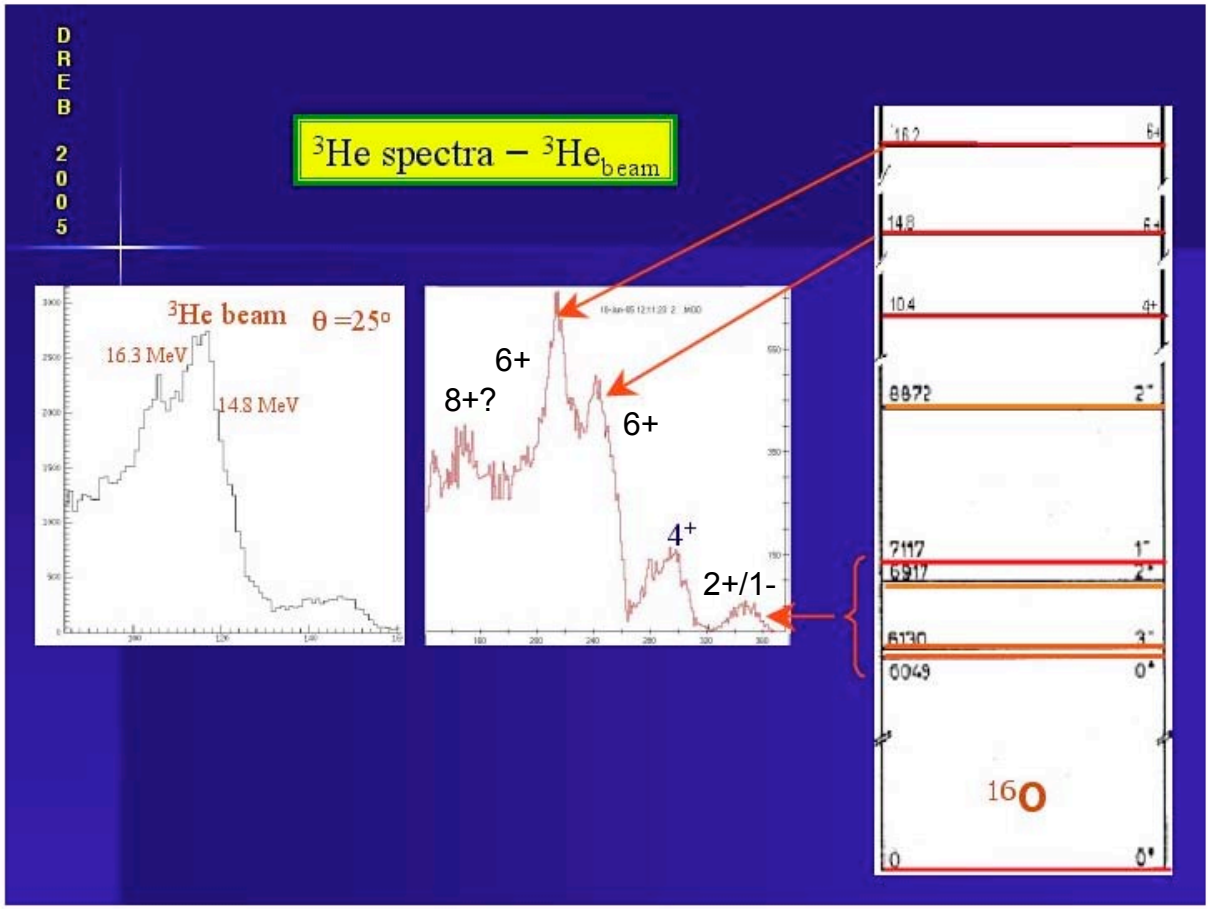


Fig 4. Alpha transfer spectrum on 12C from 7Be,3He reaction (16O g.s. not shown)

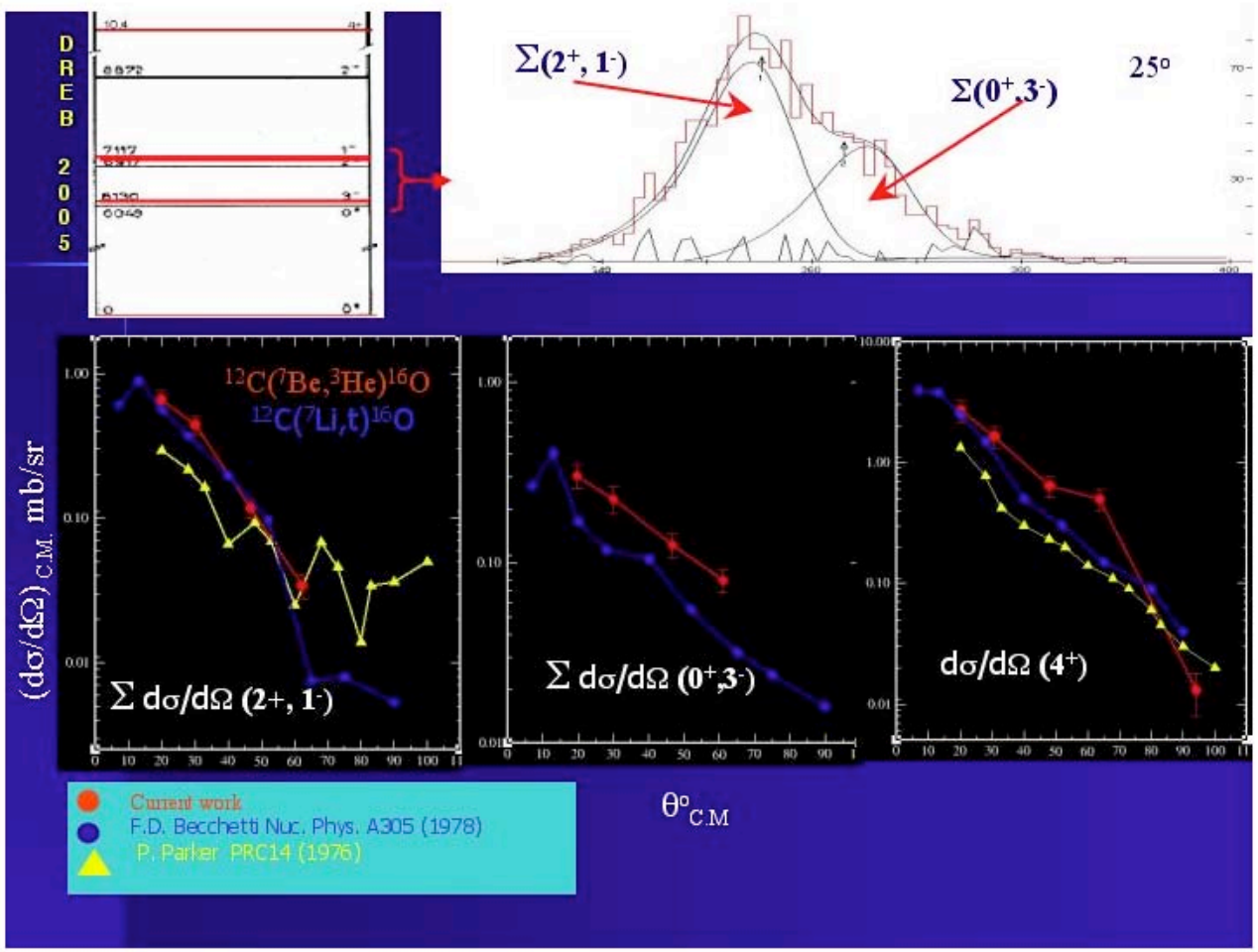


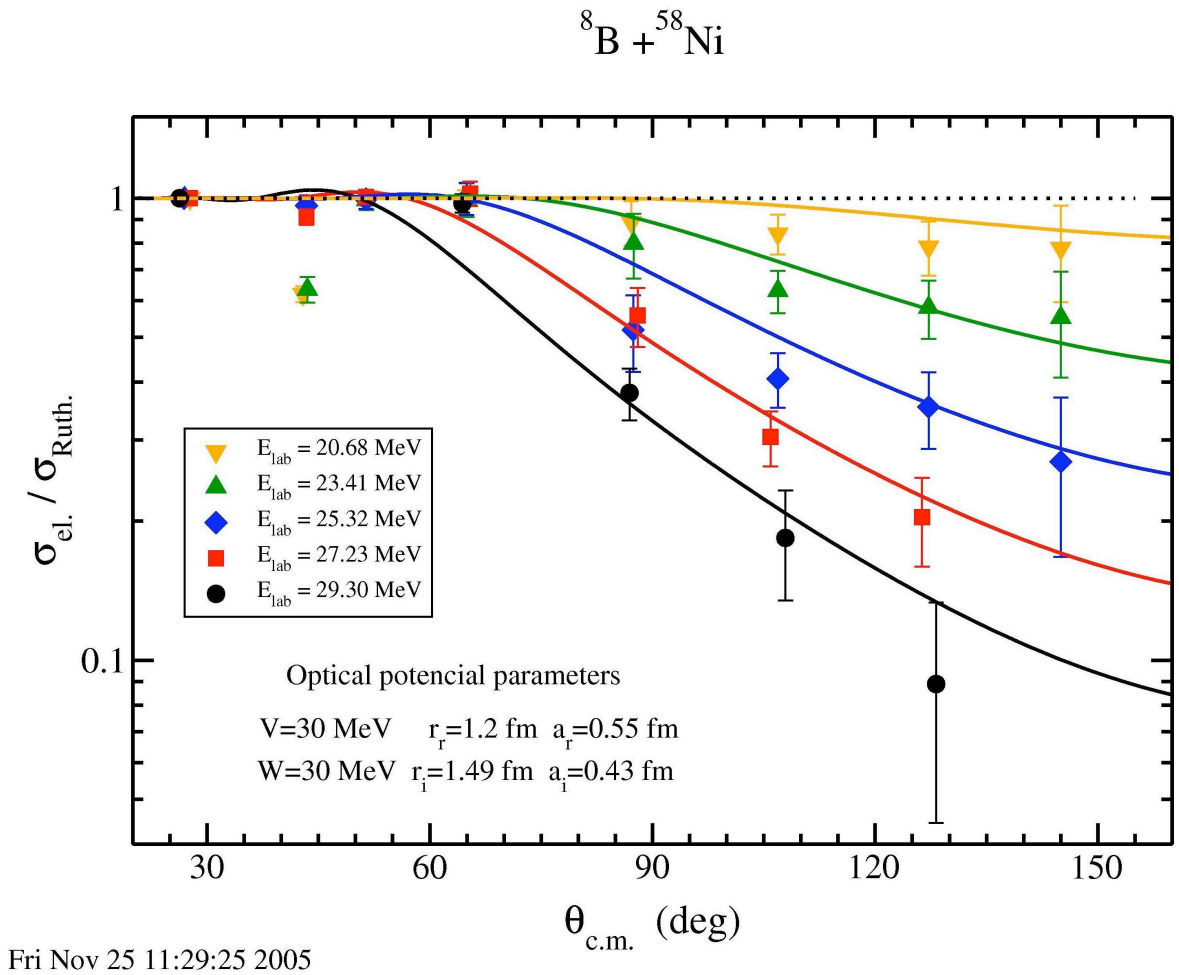
Fig. 5. Cross sections observed for 12C(7Be,3He) compared with those from (7Li,t)

Large cross sections: Need per usual, better energy resolution, remove 3He in RIB.

Extensive work done on sub-barrier fusion (and fission in some cases) 6He,8Li,8B,10Be,…on various nuclei A=60-210 (see JJK talk yesterday for one example)

Data from Aguilera et al..a few weeks old : 8B+58NI elastics to deduce sub-barrier reaction cross sections

8B (proton halo nucleus) is non trivial RIB to make..we use selective 2p transfer: 6Li(3He,n)8B



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We also can focus RIBs thru a shielding wall to a low b.g. area for gamma ray and n ToF measurements:

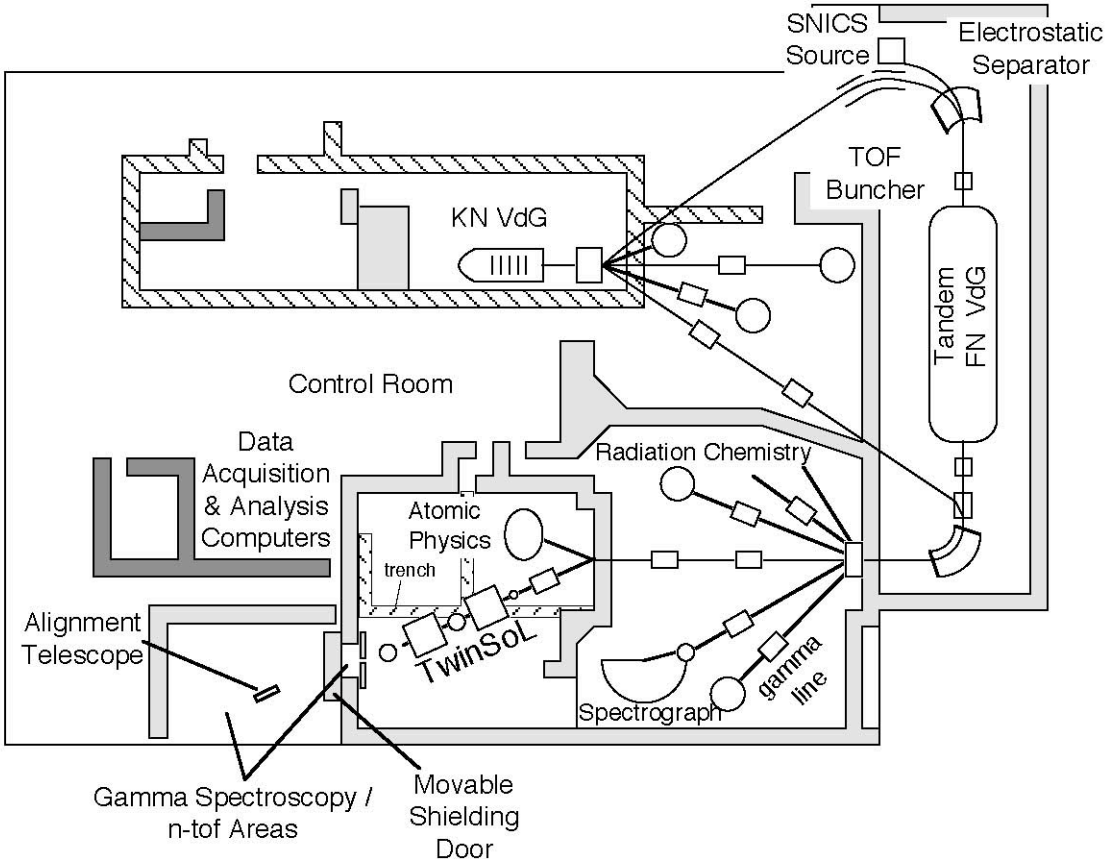


Figure 2.6 Floor plane of the University of Notre Nuclear Structure Laboratory, site of the TwinSol project.

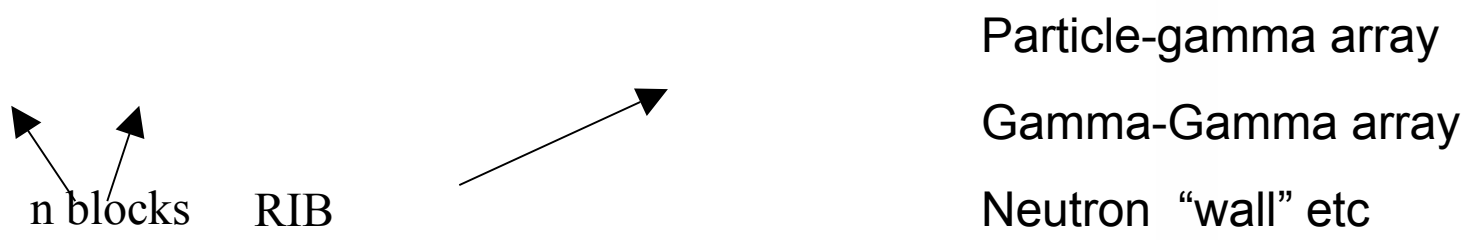
TwinSOL in Parallel Mode

Intense primary beam → production of background radiation (p,n,γ,..)

- TwinSol can used as a long, high-Brho, single-magnet for bending the ions of the most magnetically-rigid beams.

- Or, In parallel mode (no cross over) a substantial radiation shielding wall can be built between the second solenoid and the final focal point.

Radiation wall (borated water jugs)



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Nuclear Instruments and Methods in Physics Research A 491 (2002) 426–436

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Gamma-ray spectroscopy with a low-energy ^{6}He radioactive ion beam

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Abstract

A gamma-ray spectroscopy program has been established at the University of Notre Dame using a low-energy radioactive beam of ^{6}He for fusion–evaporation reactions. There are many experimental difficulties to overcome in the design of any such facility, most notably the large neutron flux associated with producing the secondary beam. Solutions to the problems are discussed and illustrated with the reaction ^{6}He + ^{63}Cu.
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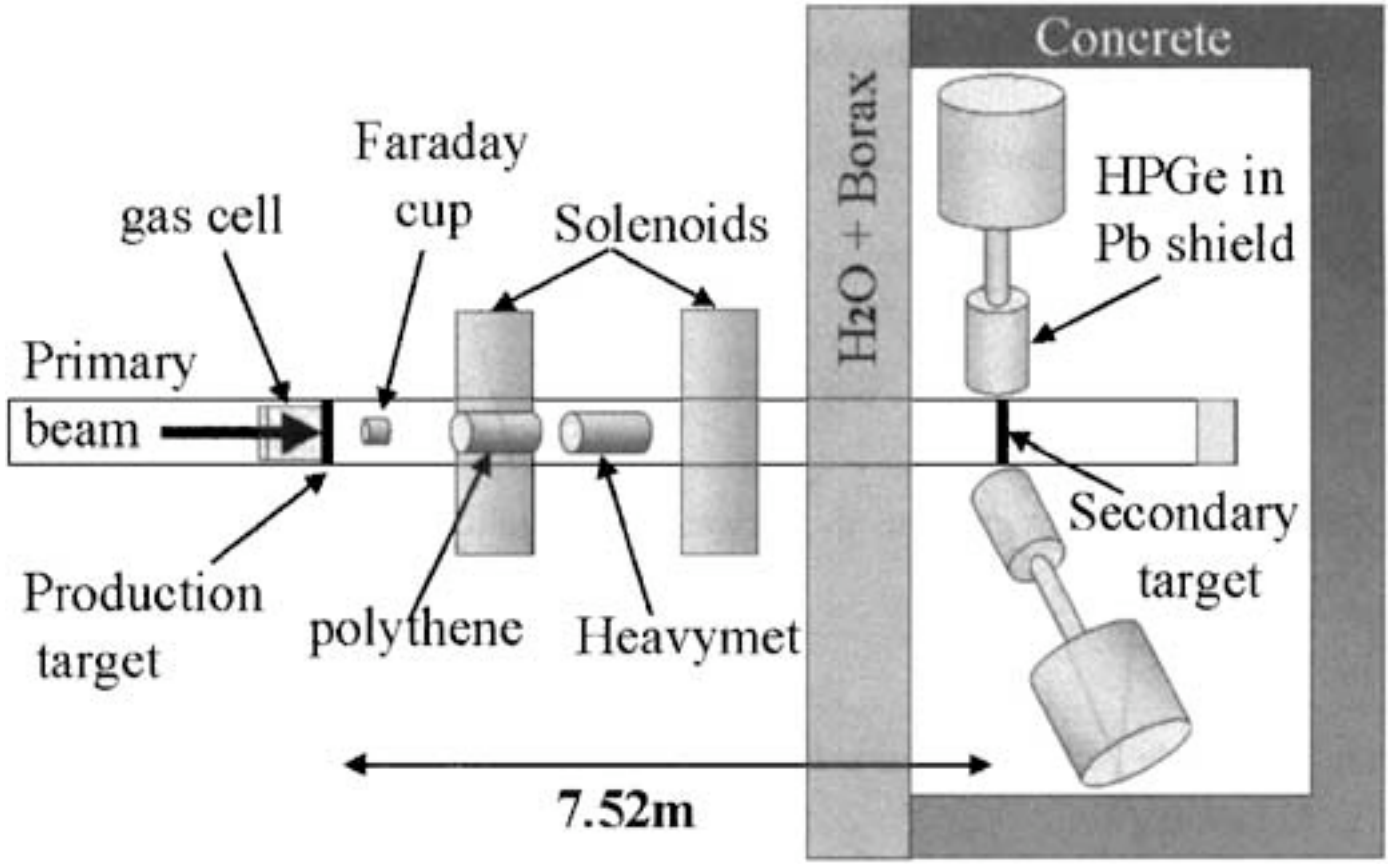
PACS: 29.30.Kv; 21.10.−k; 29.27.Fh; 29.90.+w

Keywords: Gamma-ray spectroscopy; Radioactive beam; Fusion–evaporation reaction; Near-yrast energy levels; ^{66}Zn

LE 6He+63,65 Cu fusion reaction gamma-gamma coincidence
(LE: Only a few open channels thus selective wrt final nuclei)



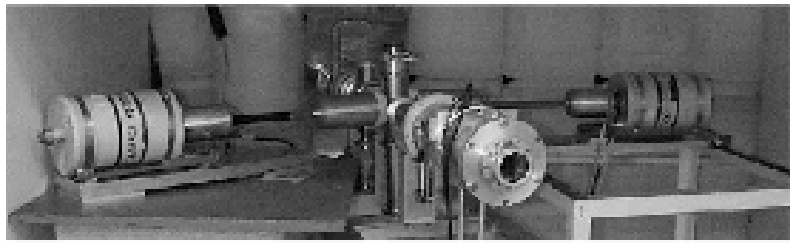


Fig. 4. Photograph of the shielded secondary target chamber, taken with the back concrete wall (door) open. The HP germanium detectors (with lead shields removed) are facing the target position, with an electron suppressed beam stop in closest view. The gaps in the water wall around the beam pipe are plugged with flexible plastic jugs filled with borated de-ionised water.

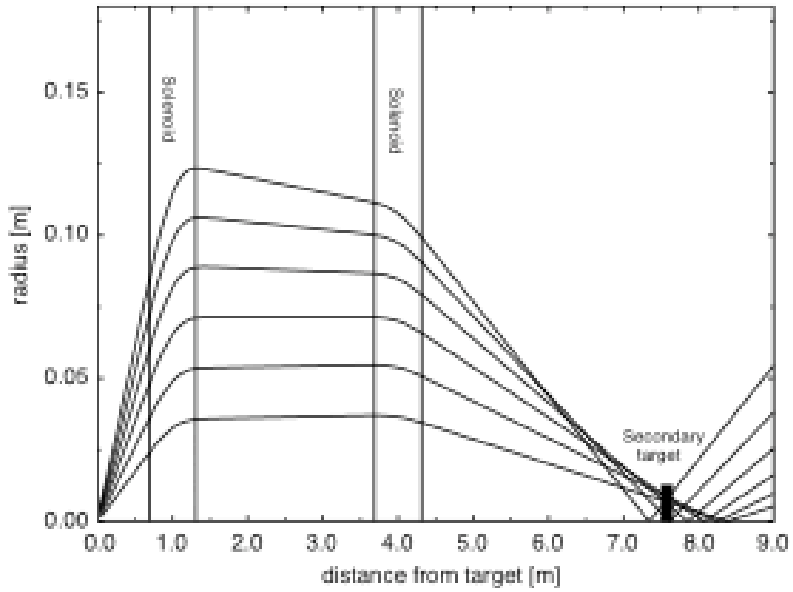


Fig. 5. Trajectory calculation for the ^{6}He RNB using the University of Michigan ion-optical tracing code 'Twinsol'. The trajectories shown are for ^{6}He production in the lab frame of reference between angles 2° and 7°. The calculation does not account for straggling and the final experimental beam spot observed was closer to that predicted at around 8 m. Namely, an intense spot in the centre corresponding to the ions following trajectories with smaller scattering angles, and a diffuse, less intense halo extending out beyond the edges of the target.

Gamma spectra gated by coincident gammas in specific residual CN nucleus:

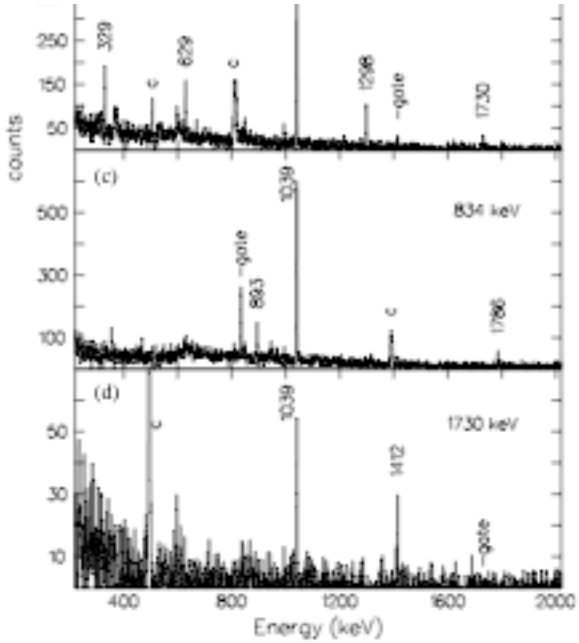


Fig. 8. Gamma–gamma spectra gated by (a) 1039 keV $2^+ \rightarrow 0^+$, (b) the 1412 keV $(4^+) \rightarrow 2^+$, (c) the 834 keV $2^+ \rightarrow 2^+$ and (d) the 1730 keV $(6^+) \rightarrow (4^+)$ transitions. Contaminant lines from neutron activation, pair production and background radiation are marked with a 'c'.

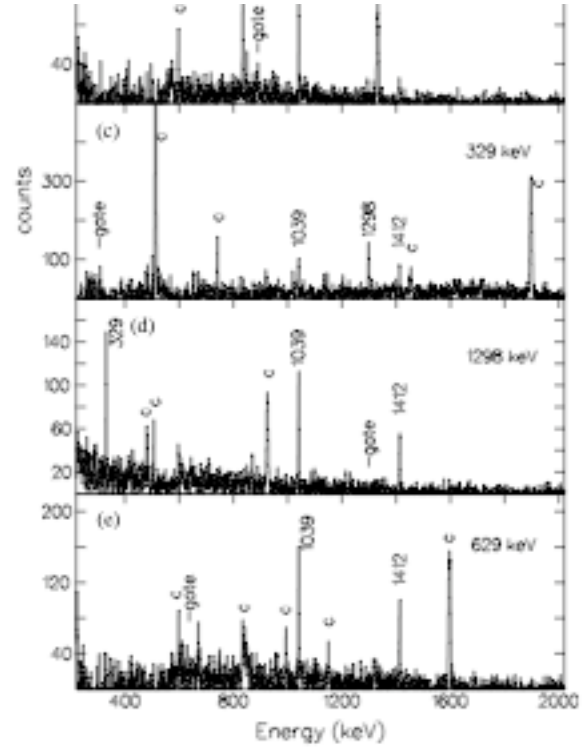


Fig. 9. Gamma–gamma spectra gated by (a) the 1786 keV, (b) the 893 keV, (c) the 329 keV, (d) the 1298 keV and (e) the 629 keV transitions. Contaminant lines from neutron activation, pair production and background radiation are marked with a 'c'.

hydrogen neutron-capture gamma ray. Despite this, it is shown that fusion-evaporation residues can be seen with the radioactive beam. An extended experiment was then performed to accumulate gamma coincidence events. These results are shown in Figs. 8 and 9.

3. Results

Although the secondary beam intensity was very low, it was possible to observe coincident gamma rays following the fusion-evaporation reaction with enough intensity to allow the construction of a level scheme from 8.7 days of data collection, constituting 3.75×10^{11} ^{6}He particles on target, and a total of 75×10^6 γ–γ events. Various gates were placed on the transitions in ^{66}Zn, and the resulting projections are shown in Figs. 8 and 9. Fig. 8 shows gamma-ray spectra in coincidence with the previously known transitions in ^{66}Zn;

Able to I.d. and identify new decay branch in 66Zn:

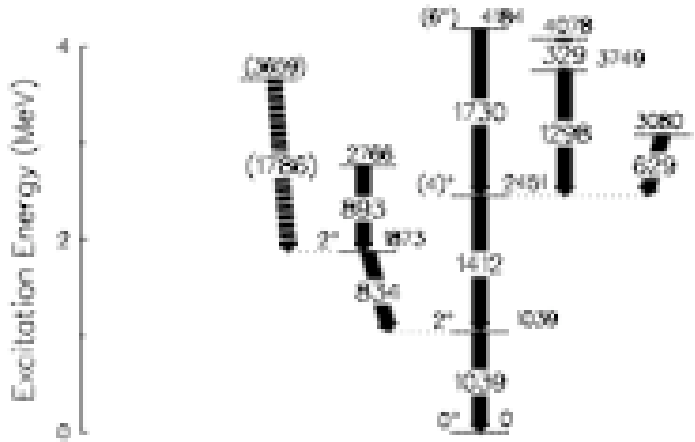


Fig. 10. Partial decay scheme for ^{66}Zn. The 1786 keV transition was deduced and placed in the decay scheme using the results from this experiment.

A large coverage HPGe clover array now available at UND (A. Aprahamian)

Recent addition: 2 nd generation large coverage neutron wall in low b.g. extension(see JJK talk..6He breakup/transfer etc):

Fig. 1. UND-Hope-UM neutron wall at end of extended low background TwinSol beam line at UN Dame.

Recent experiment (Dr. Hanan Amro UM): 8Li+208PB particle - gamma coincidence study.

Goal: Remeasure 8Li Clx using 8Li-gamma coincidence..try to verify very large BE2 up we/ve seen for 8LI* from 8LI+Ni inelastic scattering.

(Example of an RIB where one must measure BE2 via BE2 up directly owing to allowed M1 down..thus LE RIB preferable)

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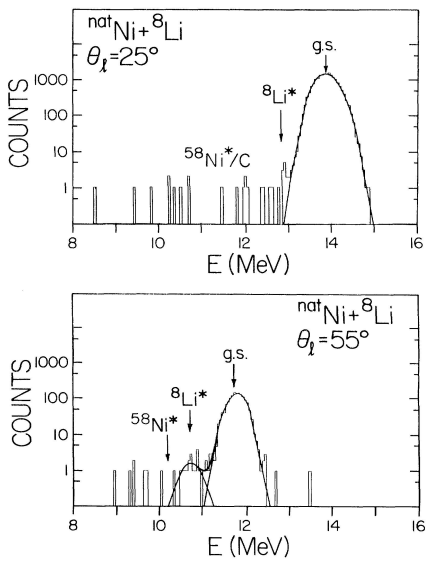


FIG. 2. Data and line-shape fits, similar to those displayed in Fig. 1, at forward and backward angles taken simultaneously using two small-aperture, good-energy-resolution Si detector telescopes.

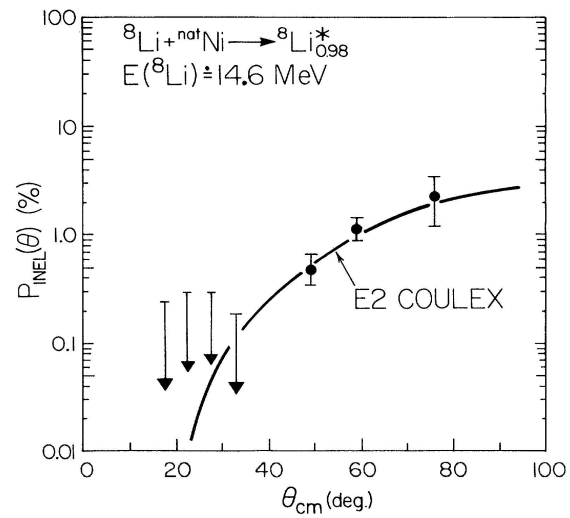


FIG. 3. Observed inelastic excitation probability (Table I) as a function of $\theta_{c.m.}$ for the $^8Li^*_{0.98}$ group seen in the $^8Li + {}^{nat}Ni$ spectra. The curve is an $E2$ COULEX calculation with $B(E2\uparrow)$ adjusted to fit the data (see text).

Deduced BE2 up large..about x5 that of 6,7Li

Secondary Reaction: $^{8}Li + ^{208}Pb \longrightarrow$ { $^{7}Li + ^{209}Pb$ [Q_{val}=+1.9561] ; $^{8}Li, ^{8}Li^{*}$ }

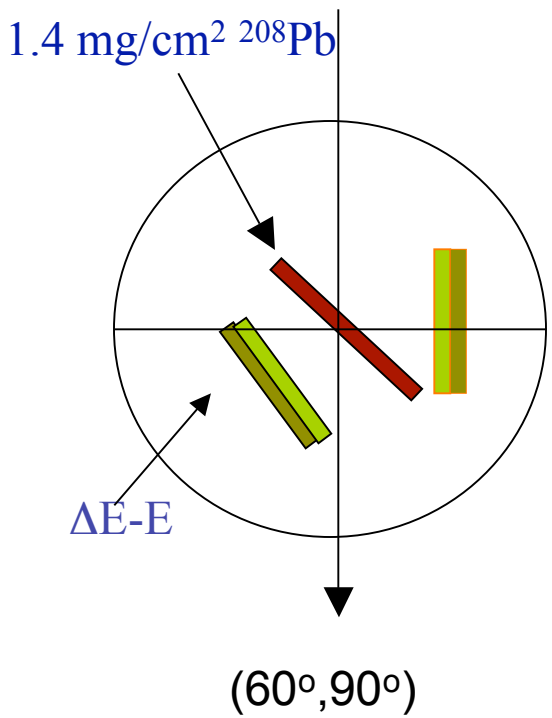
Coulomb barrier ($^{8}Li + ^{208}Pb$)= 31.04 MeV

^{8}Li beam energy: 28 MeV

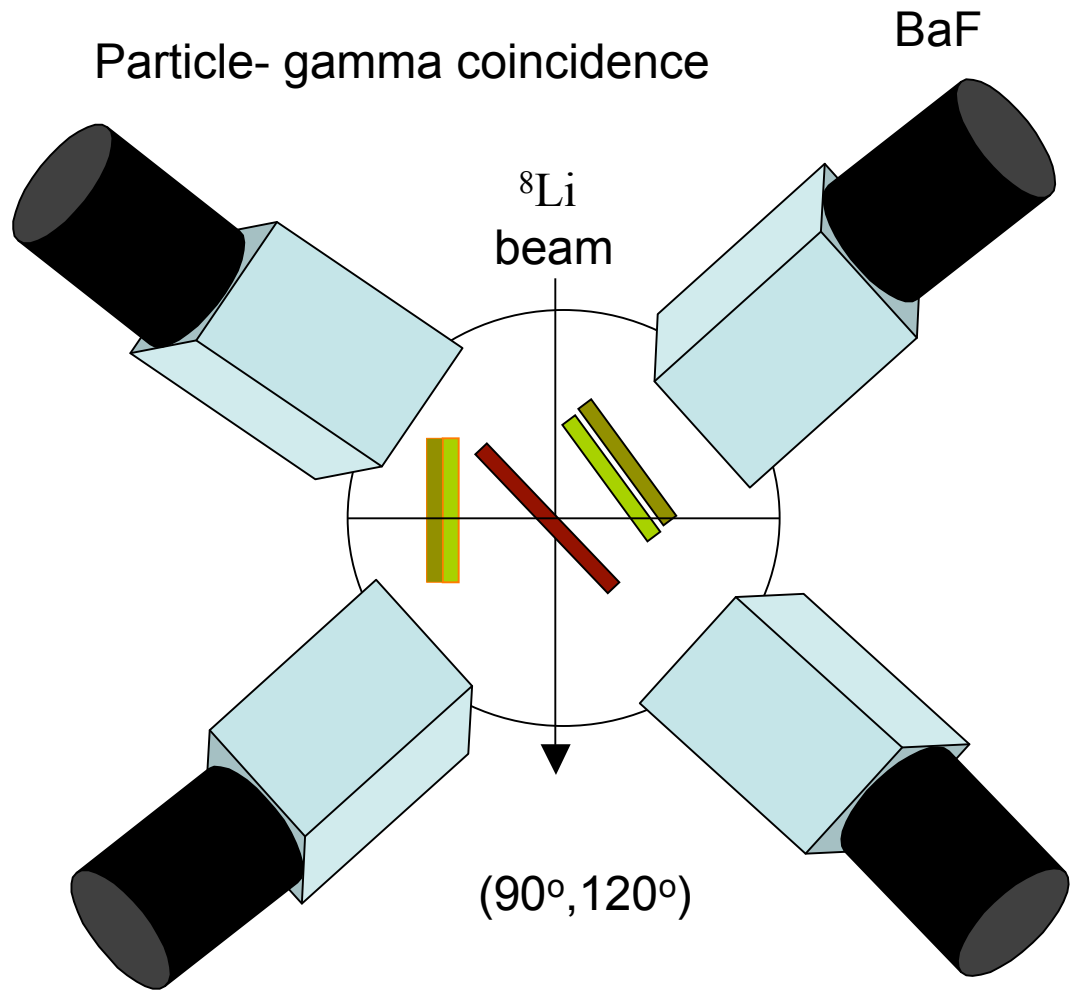
E_{loss}~0.6MeV → E(^{8}Li beam)=27.4 MeV < Coulomb barrier (sub barrier)

Two ΔE dets: start master trigger and TAC

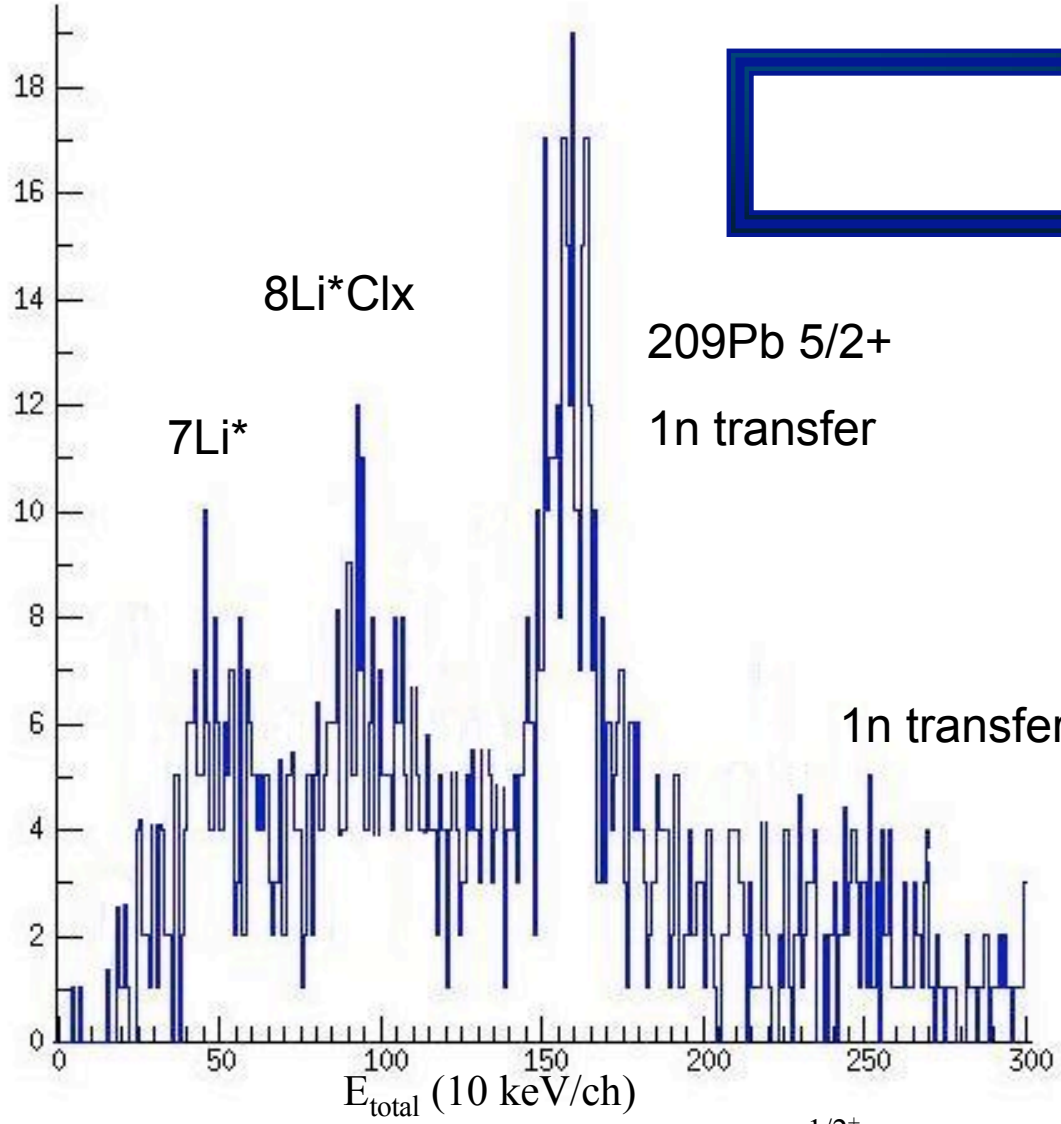
Four BaF detectors: individually stop TAC

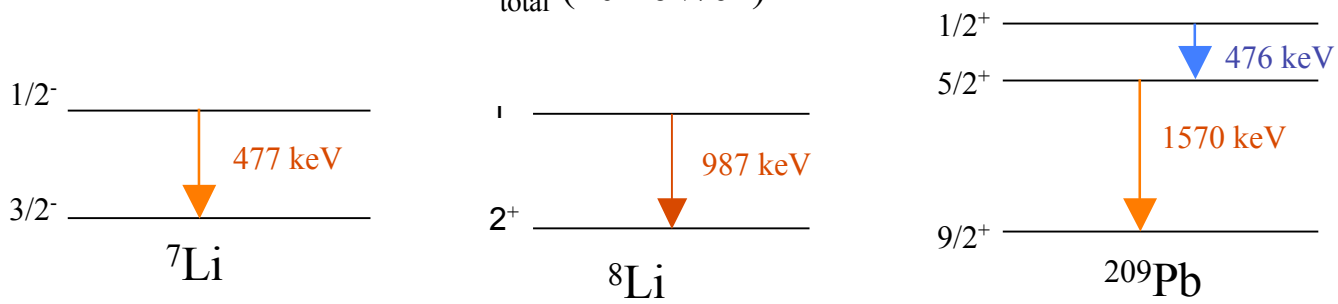


Particle- gamma coincidence



Preliminary results!!





BE2 extracted ambiguous..Coul-Nuclear interference even “sub barrier” ??

Need further study..may impact “Clx” at higher E also even at forward “safe” angles.

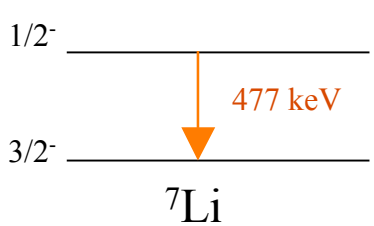
One-neutron removal channel

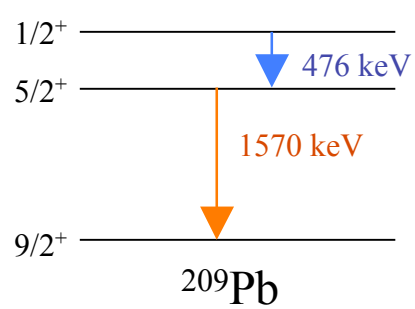
A strong ^{7}Li group was also observed!!

- Transfer reaction: $^{8}Li + ^{208}Pb \rightarrow ^{7}Li + ^{209}Pb$
- Breakup reaction: $^{8}Li + ^{208}Pb \rightarrow n + ^{7}Li + ^{208}Pb$

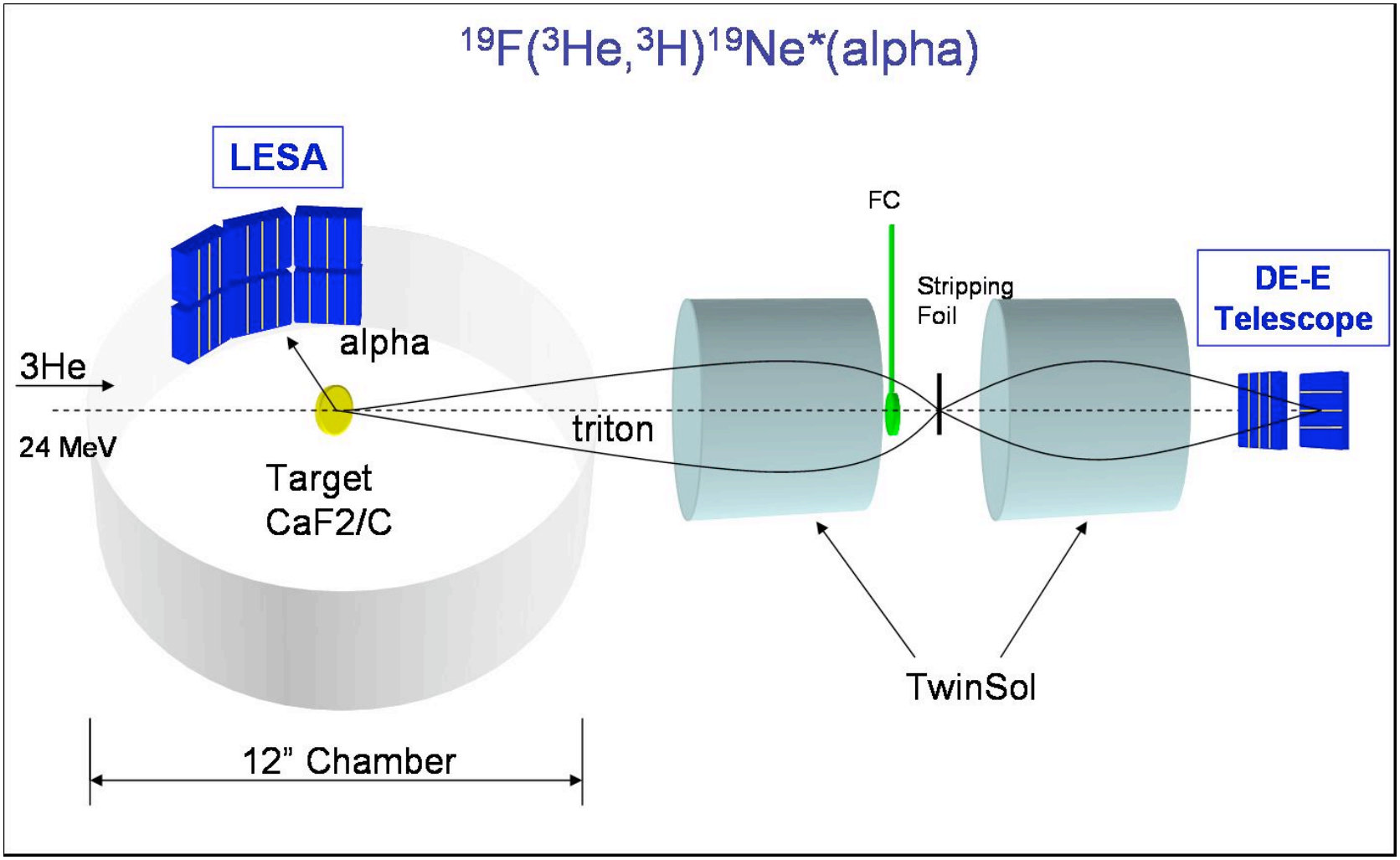
…..must be considered even “subbarrier” fusion …

Previous conclusion: transfer channel dominates! A. M. Moro *et. al.* Phys. Rev. C(2003)

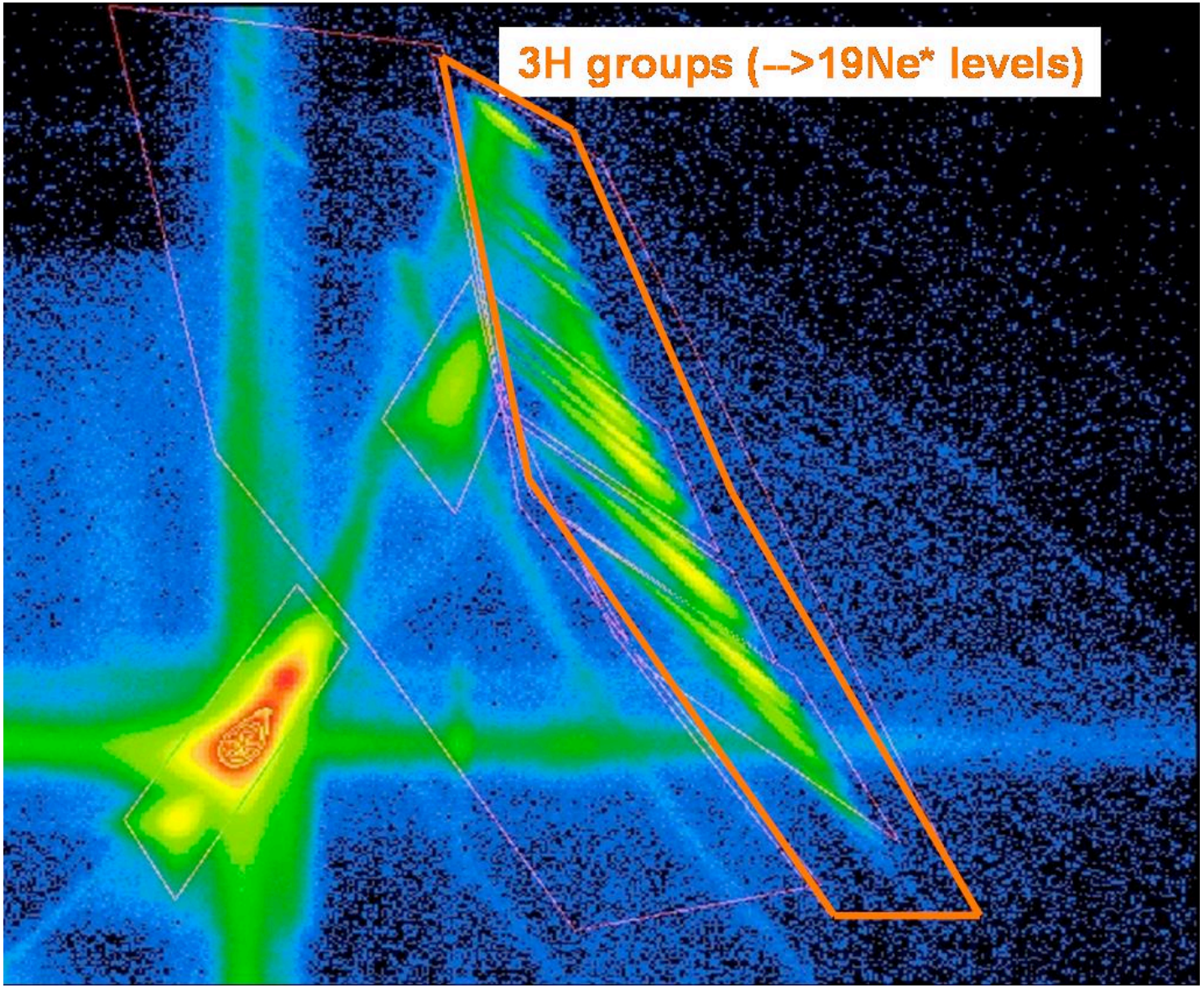




TwinSol also used as small-angle, large solid angle paticle-particle coincidence spectrometer with stable beams (Wiescher et al):



Recent data detecting 3H from small angle 19F(3He,3H)19Ne :



Proposed at ORNL HRIF (see Liang talk):

Sub-barrier fusion with heavy exotic nuclei.. a doorway to superheavy elements?!!

$^{132,134}Sn+^{64}Ni$

We measured the fusion-evaporation cross sections in the vicinity of the Coulomb barrier. Large sub-barrier fusion enhancement was observed → attributed to:

- The large N/Z ratio of $^{132,134}Sn$ reducing the barrier height.
- The presence of a large number of nucleon transfer channels which can serve as doorway states to fusion.

$^{124,132,134}Sn+^{48,40}Ca$

- closed shell neutron-rich $^{132,134}Sn$
- doubly magic target ^{48}Ca

→

compound systems with:

- lower excitation energies
- smaller fissility, i.e. higher survival probability.

Upgrades :

Better energy resolution ,perhaps via better particle-by-particle ToF.. E.g. MCP at cross over focus?? But at cross over have 10^6-10^8/s RIBS+stable beams…so a major challenge..(Dan??)

..BUT could get 100-200 KeV RIB E spread (or less) using long flight path mode:

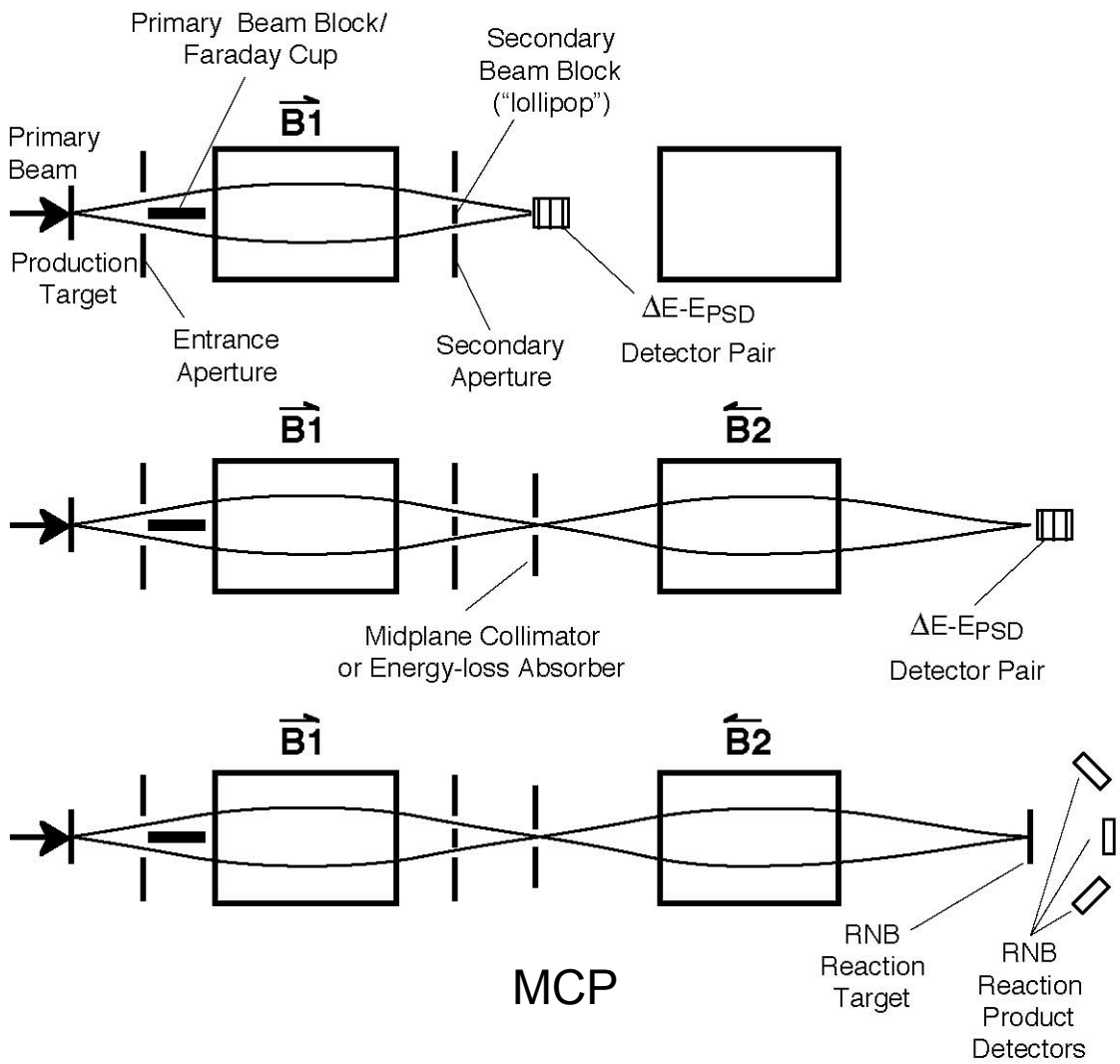


Figure 3.14 Basic components and steps required in crossover mode of operation to deliver an RNB to the back chamber.

Also needed for optimal experiments:

Larger scattering chamber (1.2 m dia. vs present 0.4 m dia.) and associated stripe detector array , etc etc …

(NSF equipment proposal submitted F05…..yet again)

RIA-related R&D:

Add electric element to separate Z's and/or make "achromat"??

Test gas filled or "foil filled" mode for HI recoil detection (eg ER)*

Test "harmonic" q focusing for multi-q HIs/ERs, etc

Add 3rd solenoid for very long path ToF (Proposal into UM for one. LHe free so portable. Similar to one shown but larger bore)

* News flash: I'm told ANU Canberra has verified gas-filled mode works!

Picture from Cryomagnetics,Inc Oak Ridge TN

From past UM-UND RSI papers (W. Liu et al):

"Harmonic orbits" q focusing

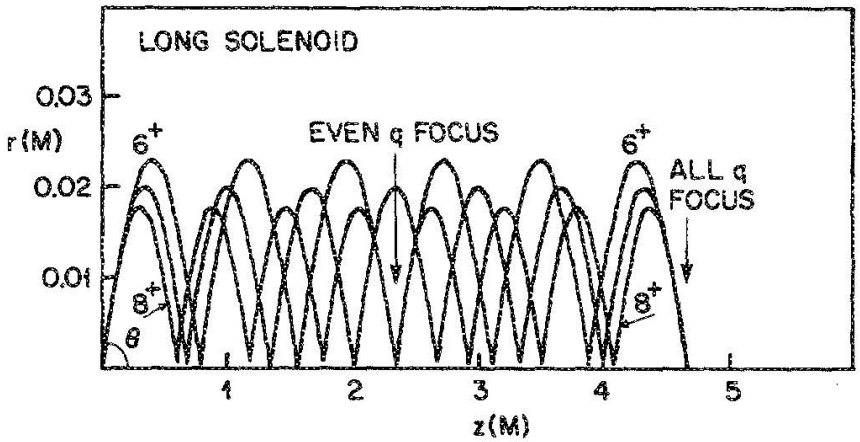


FIG. 1. Calculated orbits for ^{16}O ions ($E = 60$ MeV), $\theta = 5°$, in charge states $q_i = 1^+, 2^+, \ldots, 7^+, 8^+$, in a long, uniform, solenoid lens. The solenoid length and field strength are such that after $n = q_{max} = 8$ orbits [Eq. (1)], all charge states are brought to a first-order 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.)

Radial E lens (ExB)

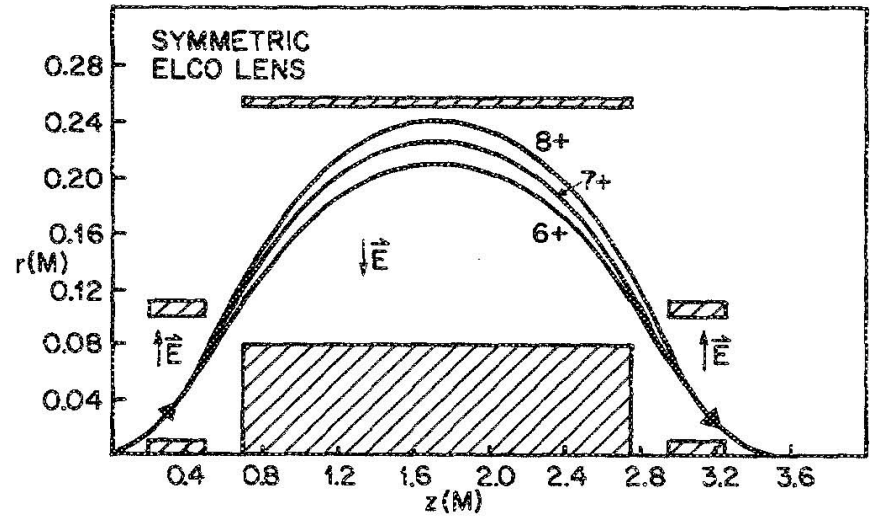
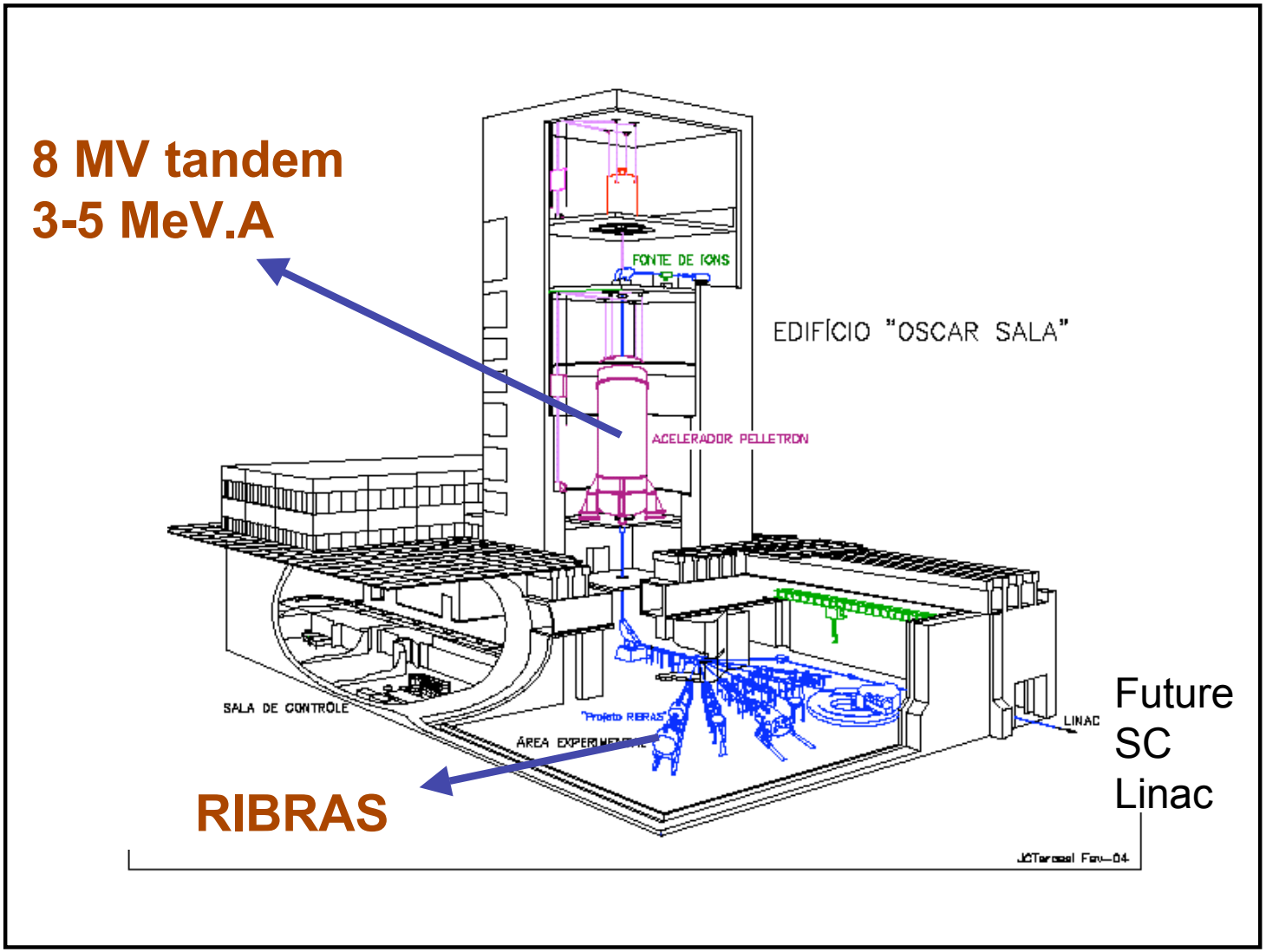


FIG. 2. First-order calculations, i.e., neglecting fringe fields, of 60 MeV ^{16}O ion orbits, $\theta = 5°$, in a radial-electric-field lens (ELCO lens) consisting of inner and outer concentric cylinders. (Note different horizontal and vertical scales.)

Likely will be part of a new UM or UND PhD thesis project .

São Paulo Pelletron Laboratory



Two superconducting solenoids

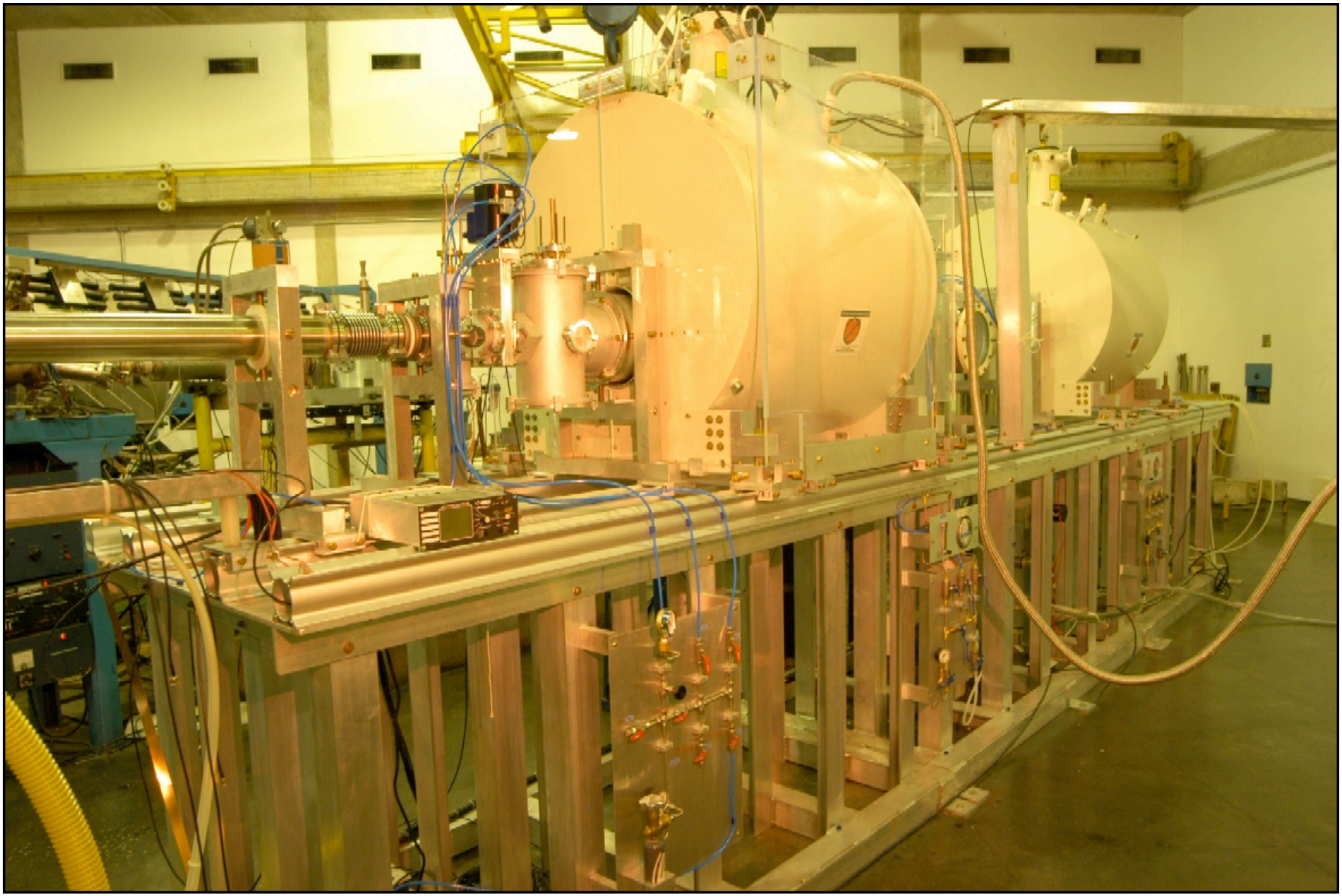
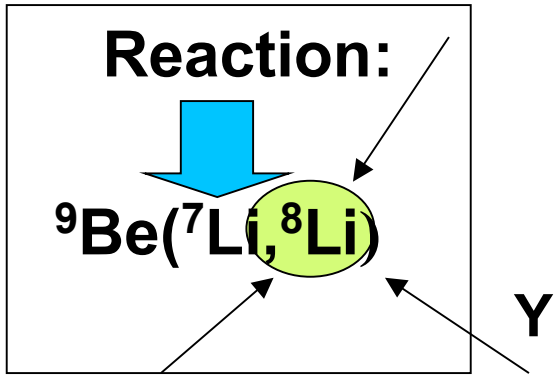
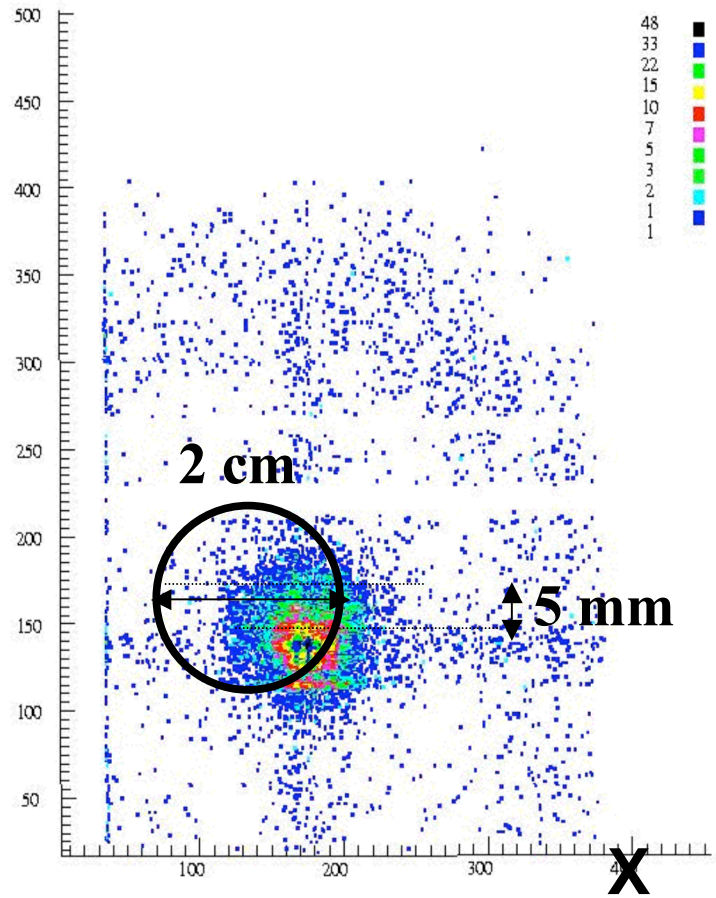


foto Orly Camargo

Secondary beam profile at the crossover point

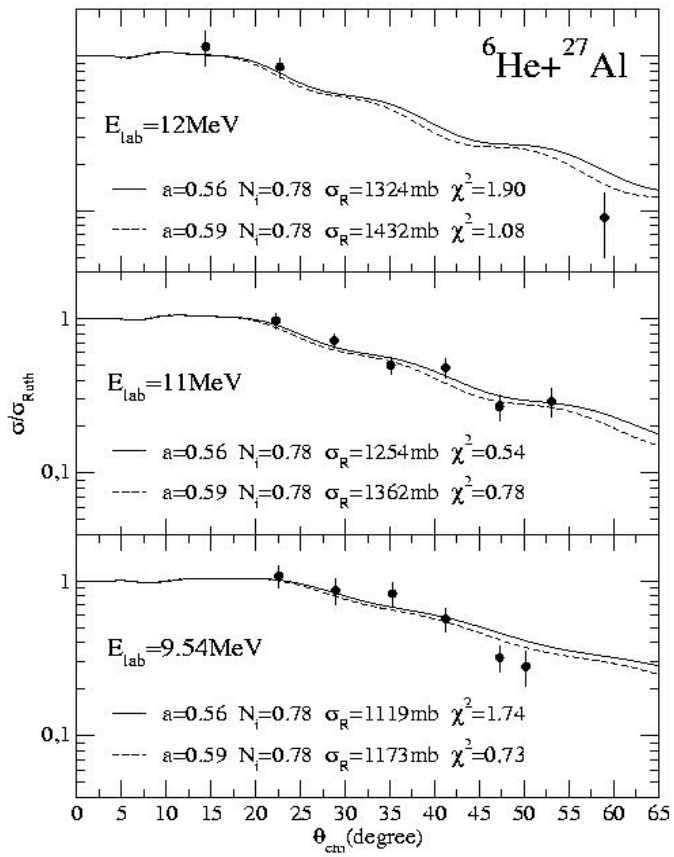


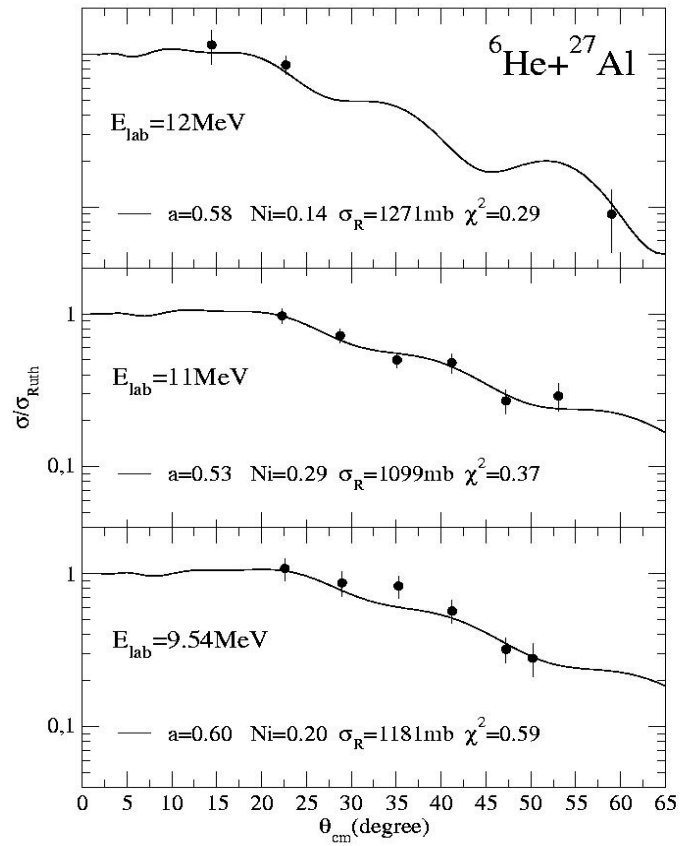


5 mm beam spot
Angular divergence
:1-2 deg

Parallel Plate Avalanche Counter (PPAC)
X-Y position sensitive gas detector

Angular distributions at 9.54,11,12MeV for $^{6}He+^{27}Al$





Optical model São Paulo potential
L. Chamon et al.

→ Imaginary part reduced, fit improved

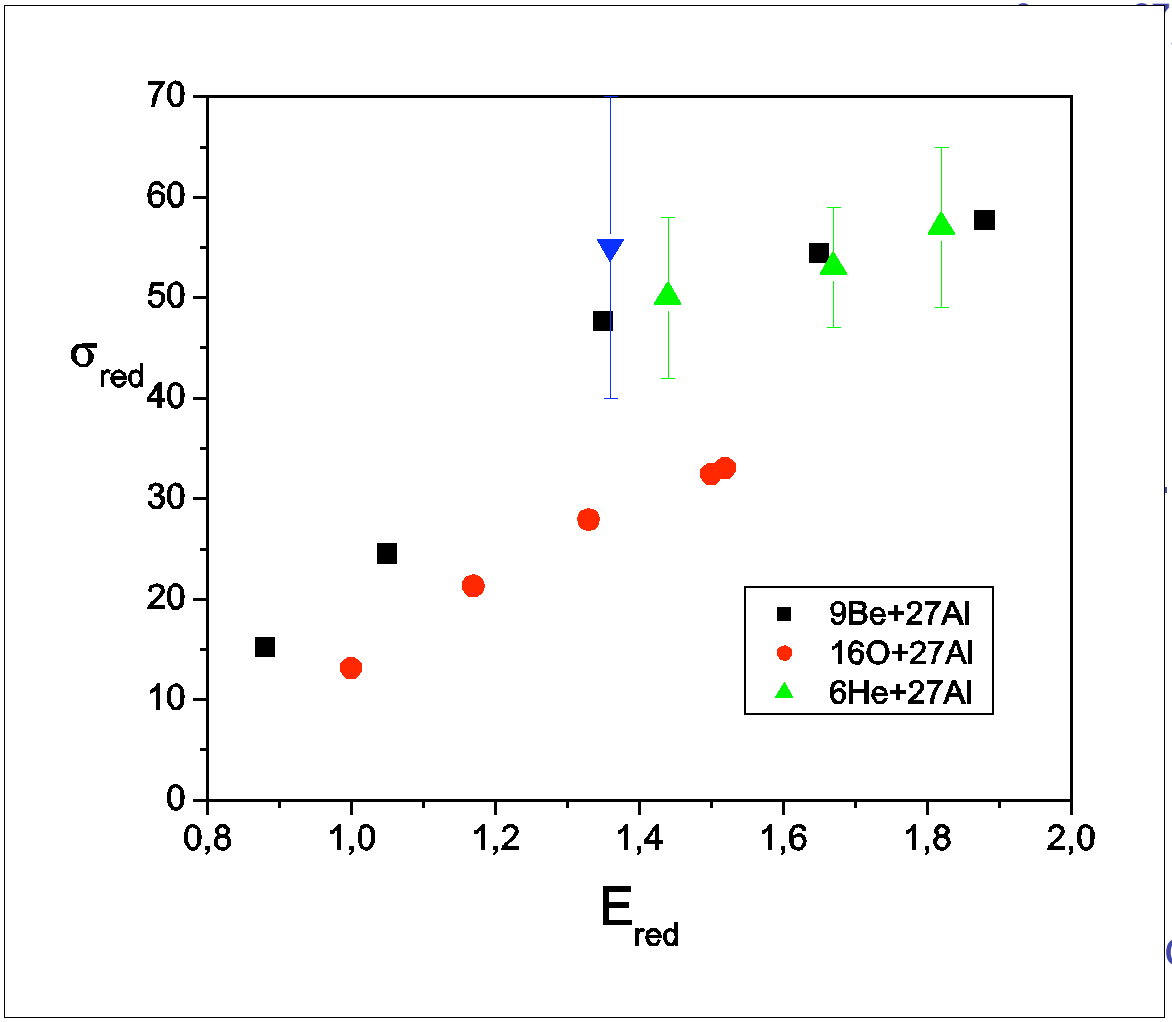
Reaction cross sections

Obtained from elastic scattering angular distributions

$^{16}O+^{27}Al$ – D. Pereira et al

$^{9}Be+^{27}Al$ - P.R.S. Gomes et al

Al and $^{7}Be+^{51}V$ - RIBRAS



reduced reaction cross-section

(P.R.S. Gomes)

$= _/(A_1^{1/3} + A_2^{1/3})^2$

reduced energy

$_{cm}(A_1^{1/3} + A_2^{1/3}) / ZpZt$

Eventually RIBRAS will be coupled to SC Linac there..(whenever latter becomes operational)

Game plan(FB/JJK): Eventually do RIB experiments in Brazil on unique RIBRAS + SC Linac facility during our midwest winters (summer there!). Maybe during Carnival?? (but then who will actually *do* the experiments??)

http://www.colorfotos.com.br/rio_de/fotosri

Finito