Proton Transfer Reactions Studied Using the VANDLE Neutron Detector Array

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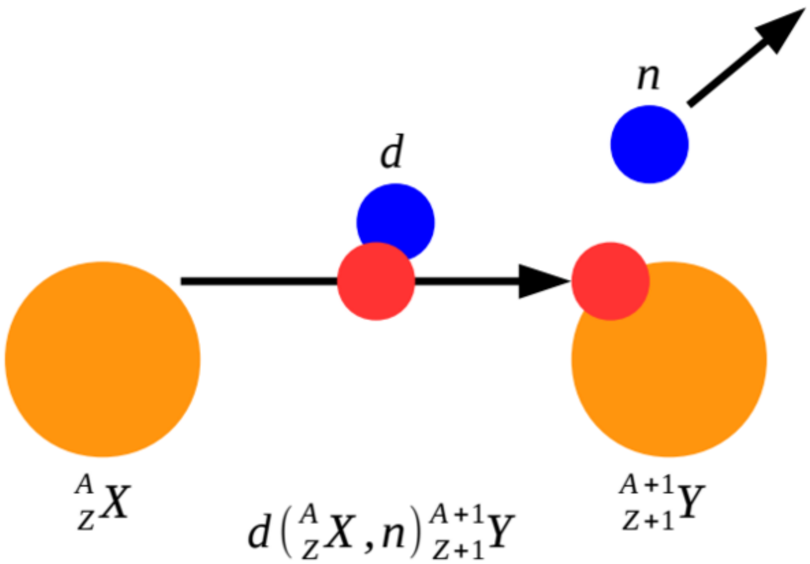
1 - University of Tennessee, Knoxville, 2 - University of Notre Dame,
3 – Rutgers University, 4 - Oak Ridge National Laboratory,
5 – Louisiana State University,
6 - Formerly Oak Ridge National Laboratory

(d,n) in Inverse Kinematics



(d,n) can provide a probe of single-particle proton states of short lived nuclei

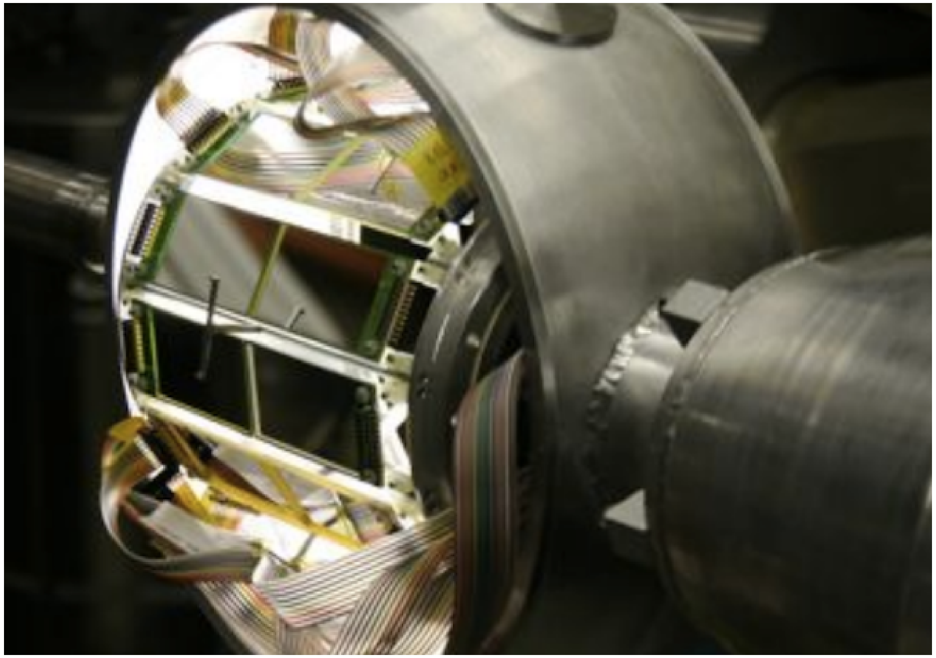
Transfer proton, measure neutron. Outgoing neutron carries information from residual.

Motivation

Proton transfer reaction measurements, e.g. (d,n), compliment those performed using neutron transfer, e.g. (d,p).

Radioactive ion beam (RIB) rates are typically low ($<10^6$ pps). Need good detection efficiency.

Due to its modular nature and large angular coverage, VANDLE could be a valuable tool for (d,n) measurements using RIBs.



The Oak Ridge Rutgers University Barrel Array (ORRUBA) charged particle detector array for (d,p)

The VANDLE Array*

"Versatile Array of Neutron Detectors at Low Energy"

Bars of Eljen EJ-200 (BC-408) organic plastic scintillator.

Small bars have dimensions of 3x3 cm^2 and 60 cm in length.

2" dia. Hamamatsu PMTs are used to measure light at both ends of the bar.

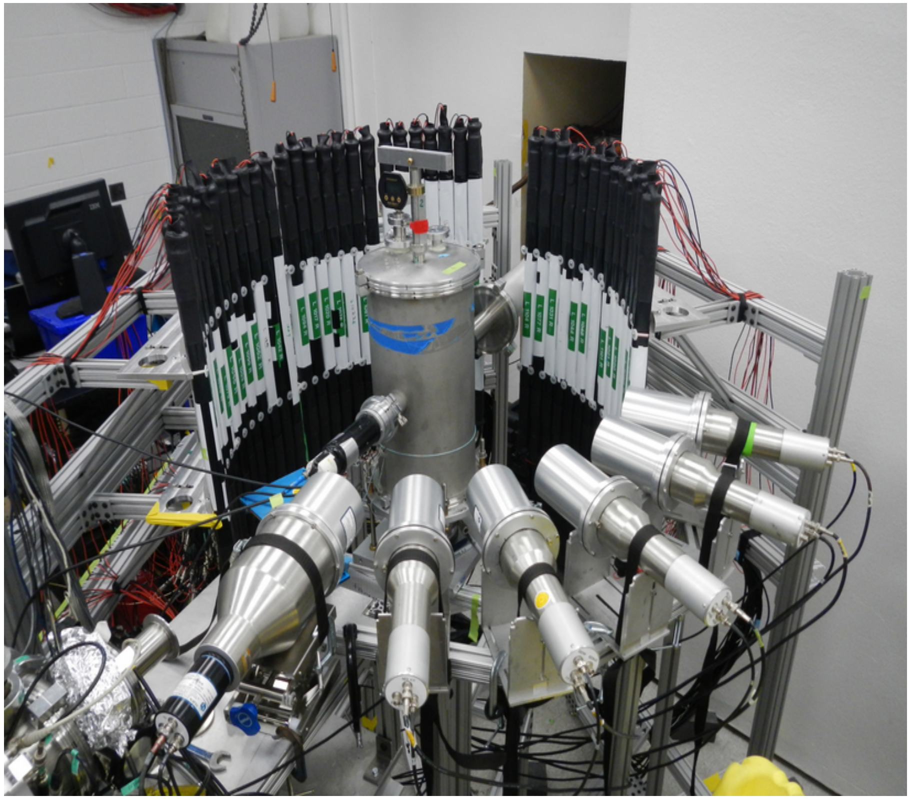
XIA Pixie-16 12-bit 250 MSPS digitizers used to record output of PMTs to disk.

Uses time-of-flight (ToF) technique to measure neutron energy.

* - W.A. Peters et al., NIM A836, 122 (2016)

(d,n) With Radioactive Ion Beams

d(^{7}Be,n)^{8}B at Notre Dame (2014)

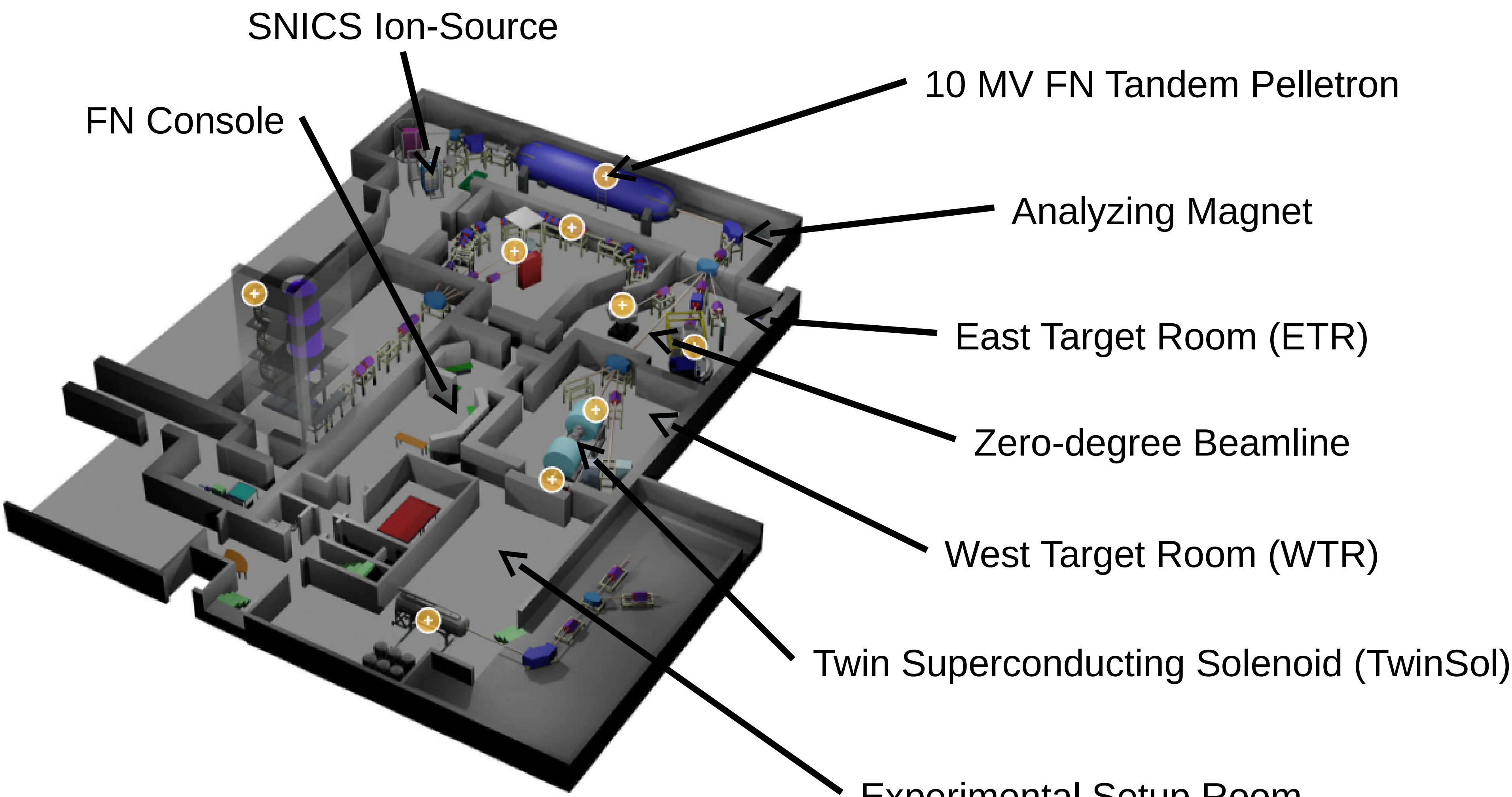


Of interest due to the proton halo structure of ^{8}B.

(d,n) reaction produces the same product as the nucleosynthesis of ^{8}B via ^{7}Be(p,γ)^{8}B.

This reaction is an indirect method of measuring the stellar reaction ^{7}Be(p,γ)^{8}B, but at a higher energy

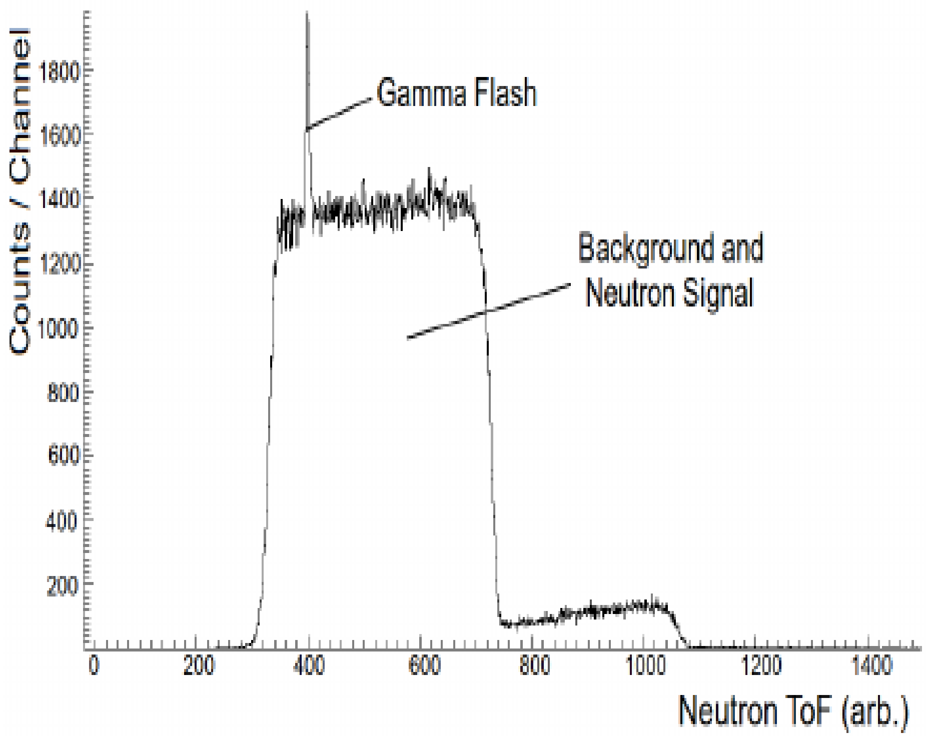
Notre Dame Nuclear Structure Laboratory

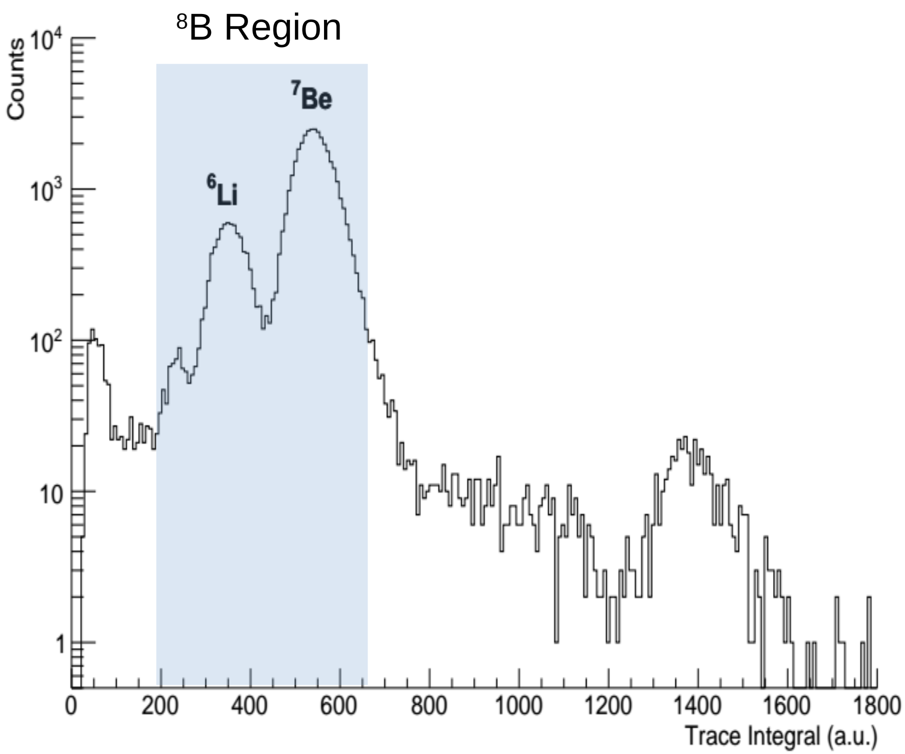


Source: http://isnap.nd.edu/research/facility/

Background Considerations

Plastic neutron detectors are sensitive to neutrons *and* gamma rays.



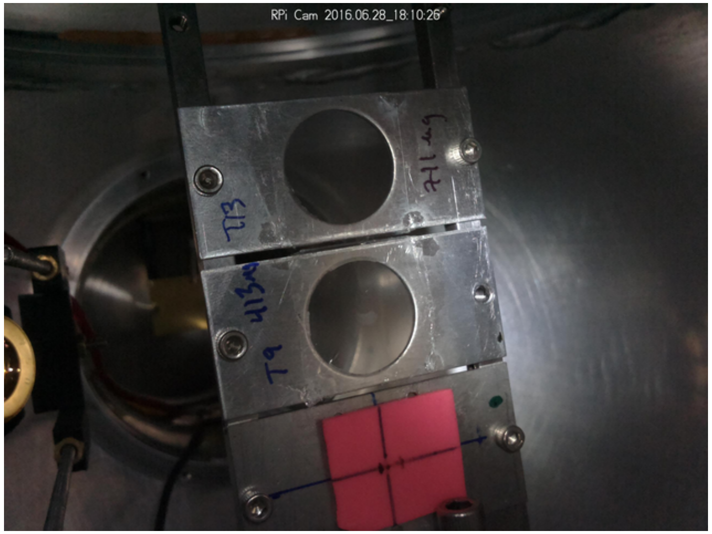


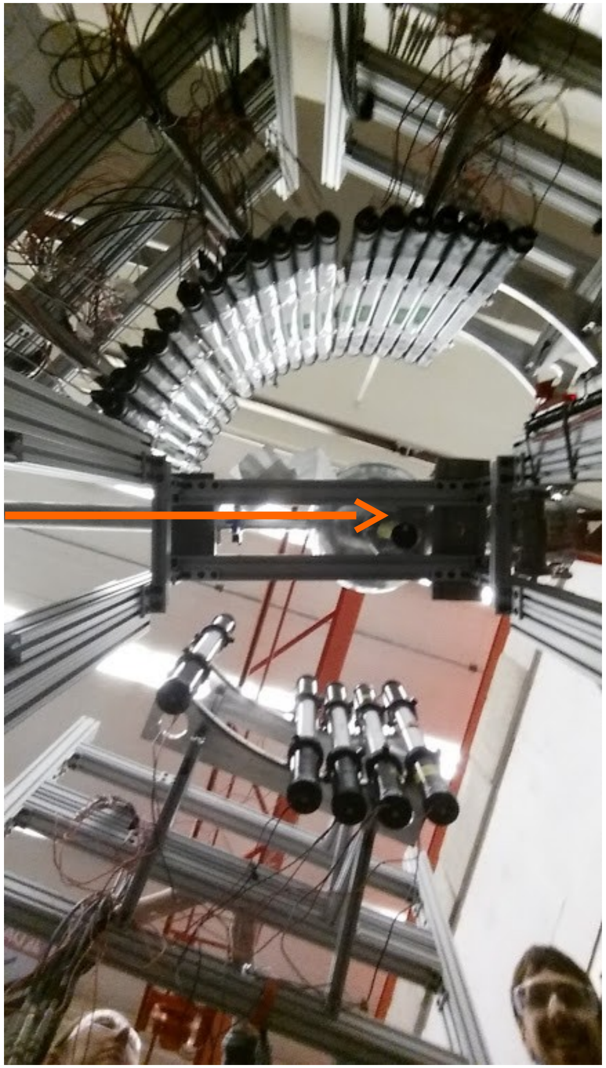
With no recoil identification, no way to separate events of interest from background.

(d,n) With Stable Beams

Performed at the University of Notre Dame in summer of 2016 using beams of ^{12}C and ^{16}O.

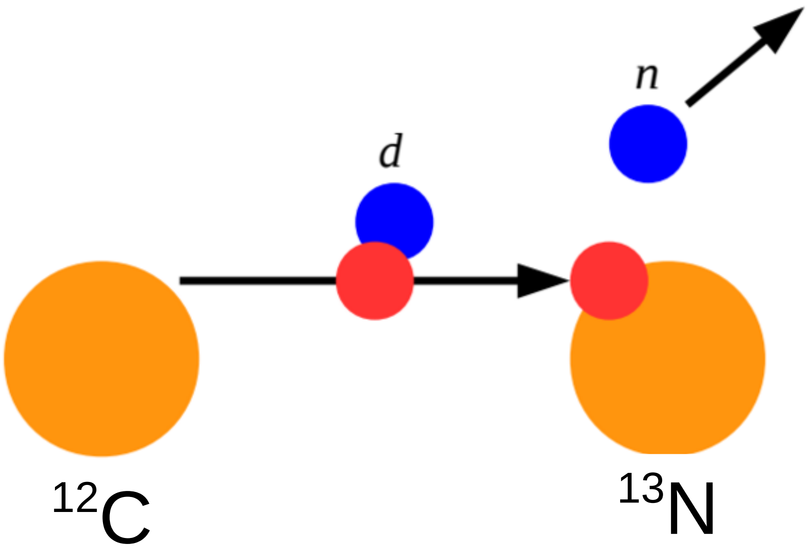
Use high rate stable primary beam as proof-of-concept for using VANDLE for (d,n) measurements.



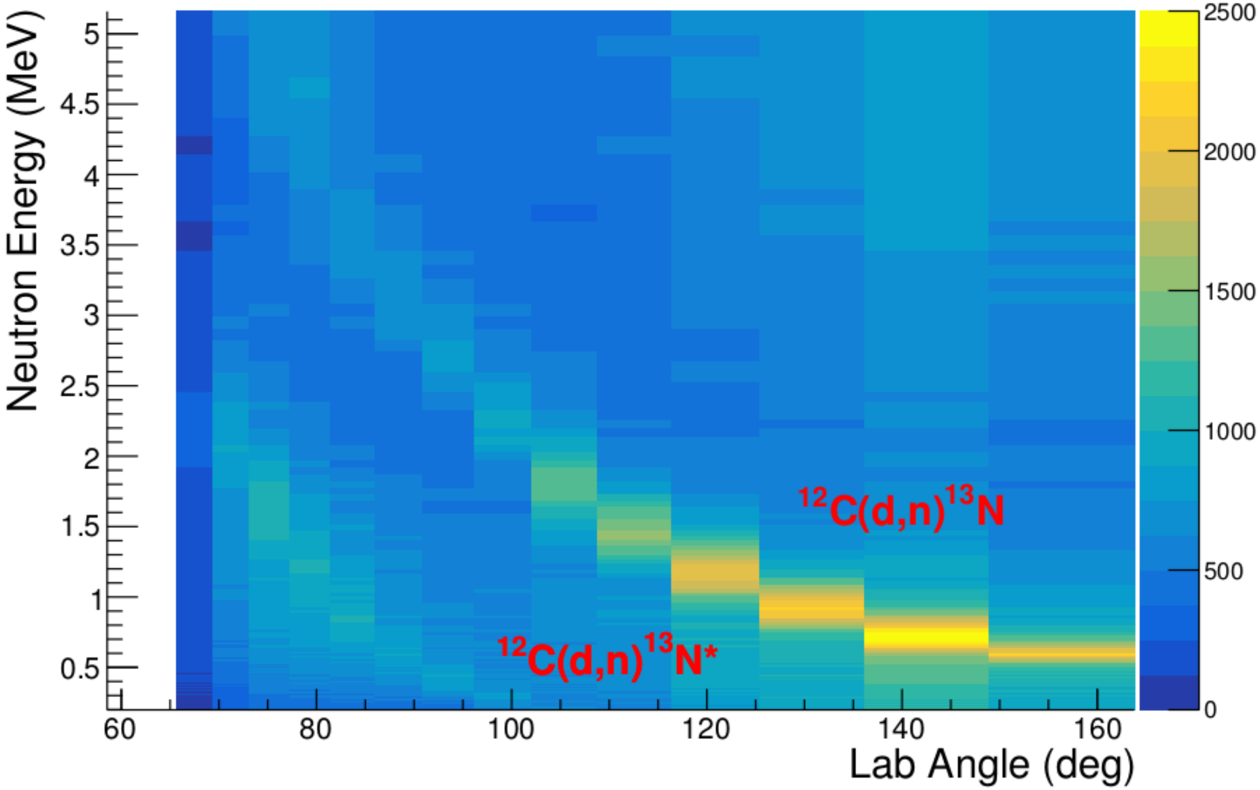


Stable ^{12}C

$d(^{12}C,n)^{13}N$



d(^{12}C,n)^{13}N

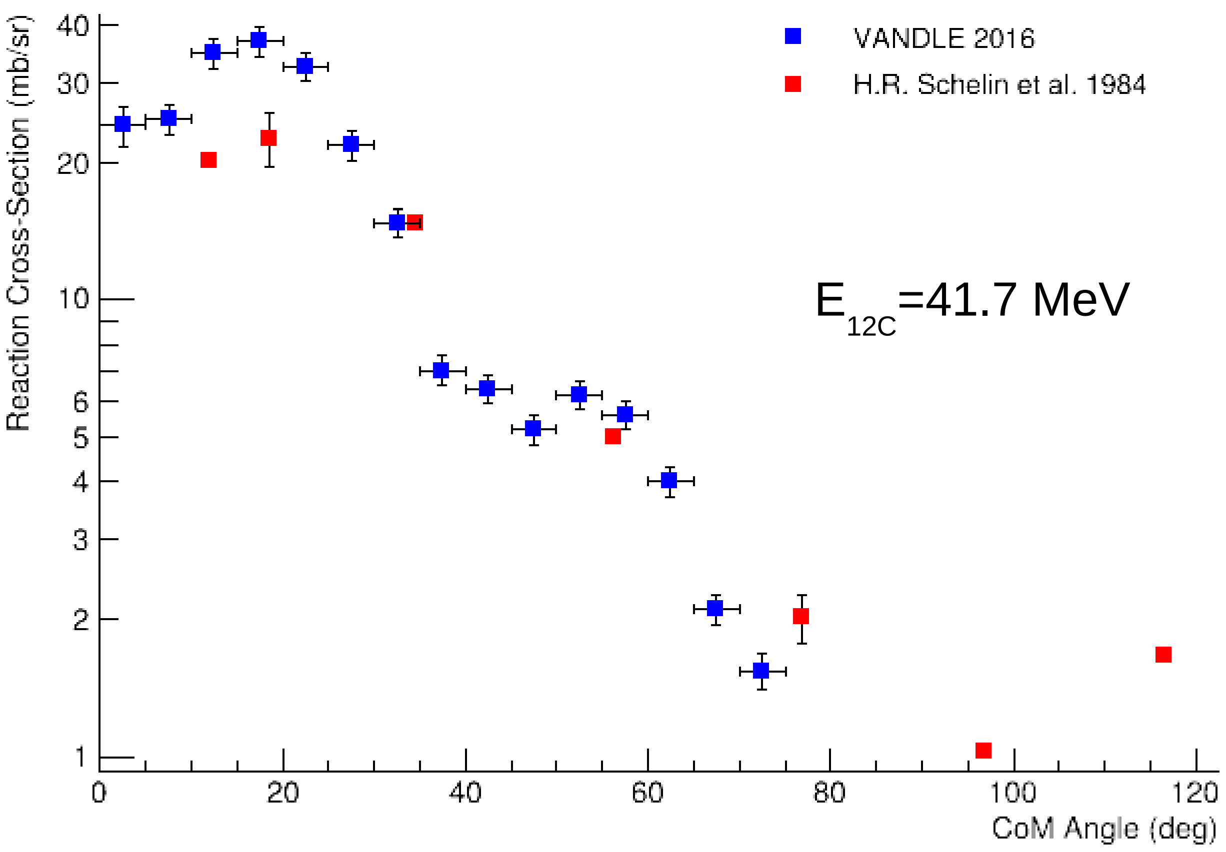


Measured 8 energy steps between C.M. energies of 2.6 MeV and 6.0 MeV (deuteron energies from 3.16 to 7.0 Mev).

Deuteron E of 7.0 MeV[1] and ~3 MeV[2] originally intended to be used to measure neutron efficiency of arrays.

[1] – H.R. Schelin et. al., Nucl. Phys. A, 414, 1 pg. 67-84 (1984)
[2] – R.E. Benenson et. al., Phys. Rev. 101, 1 (1956)

d(^{12}C,n)^{13}N for E_d=7 MeV



[1] – H.R. Schelin et. al., Nucl. Phys. A, 414, 1 pg. 67-84 (1984)

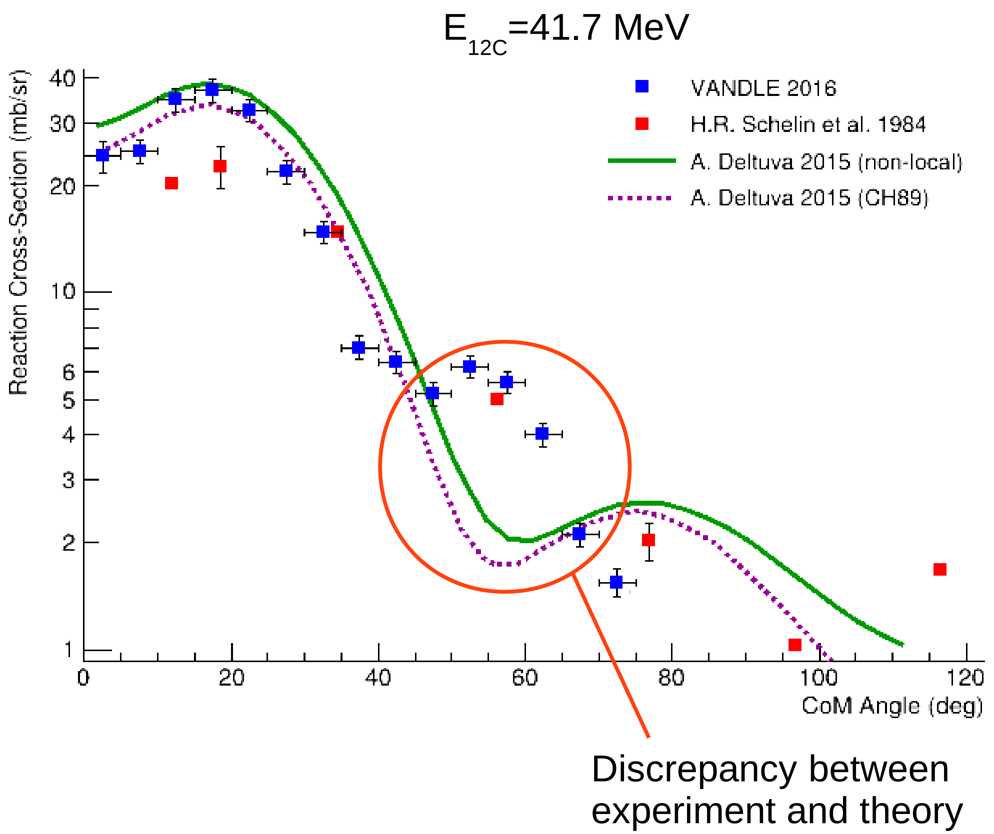
Faddeev-AGS* Exact Three-Body

Numerical calculations performed using exact Faddeev-type[1] Alt-Grassberger-Sandhas (AGS)[2] scattering formalism

Once converged, discrepancies between results and experiment may be attributed to choice of potentials or inadequacy of three-body model.

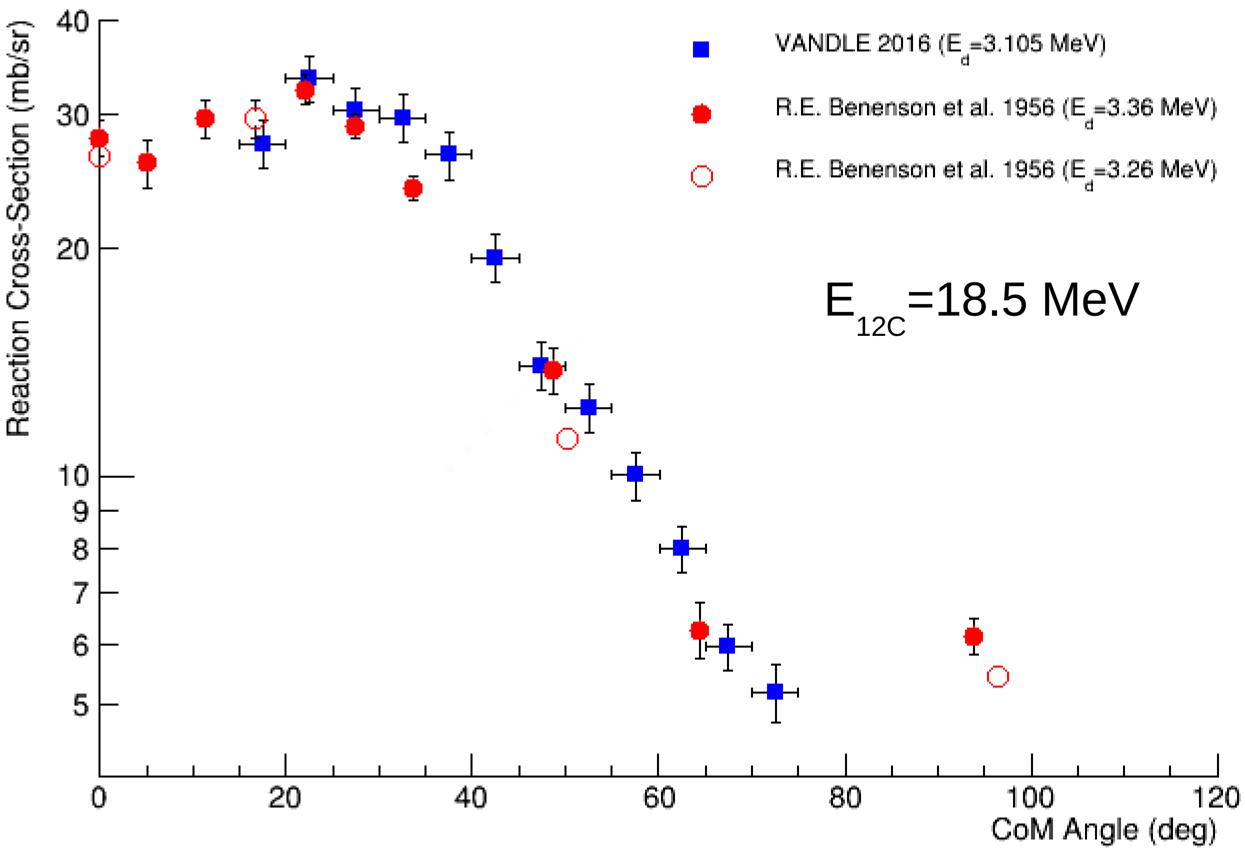
Calculation of (d,n) is more demanding than (d,p) in terms of Coulomb screening radius.

Realistic CD Bonn[3] used for p-n potential. Relatively insensitive to this potential. Results are sensitive to the nucleon-core optical potentials.



[1] – L.D. Faddeev, Sov. Phys. JETP 12, 1014 (1961)
[2] – E.O. Alt, P. Grassberger, and W. Sandhas, Nucl. Phys. B 2, 167 (1967)
[3] – R. Machleidt, Phys. Rev. C 63, 024001 (2001)
* – A. Deltuva, Phys. Rev. C 92, 064613 (2015)

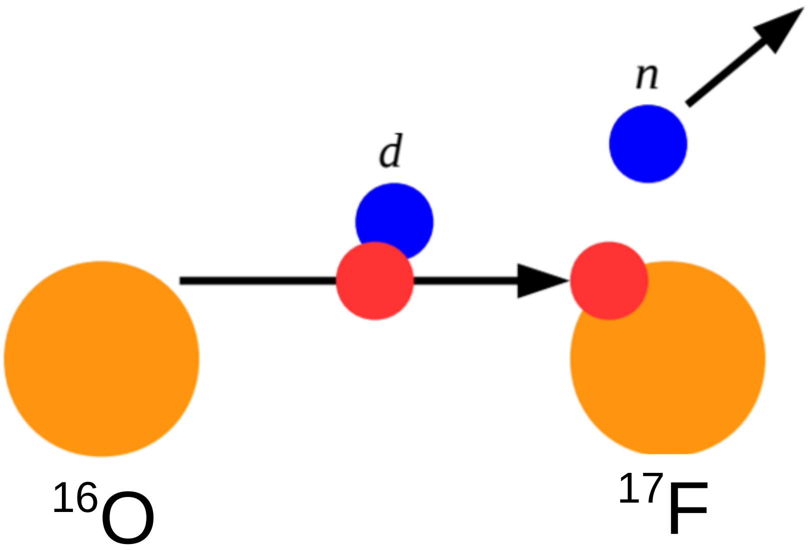
d(^{12}C,n)^{13}N for E_d=3.1 MeV



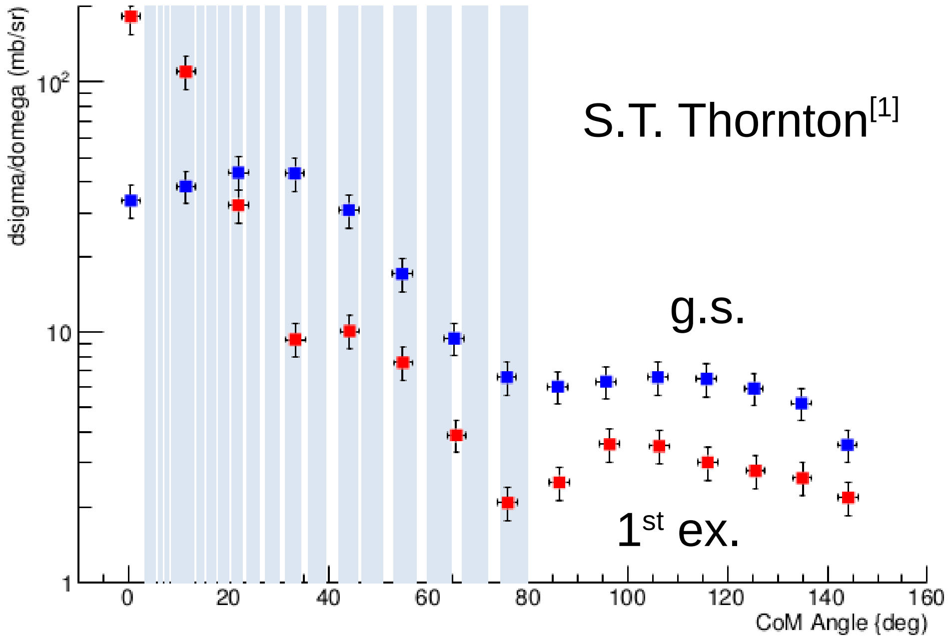
[1] – R.E. Benenson et. al., Phys. Rev. 101, 1 (1956)

Stable ^{16}O

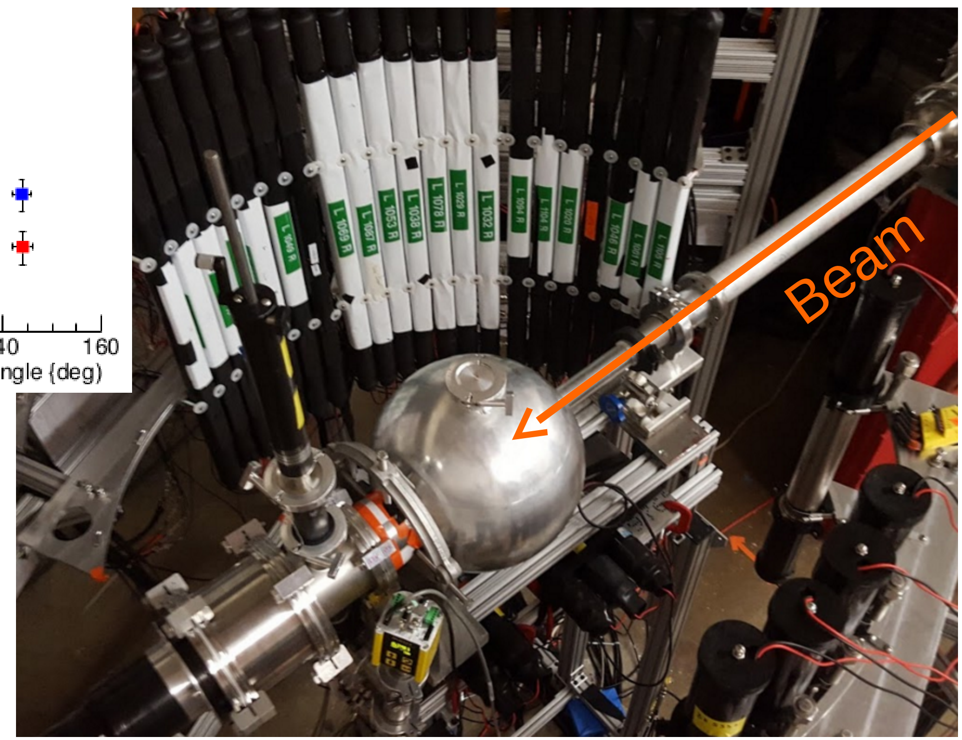
$d(^{16}O,n)^{17}F$



d(^{16}O,n)^{17}F



E_d = 8.0 MeV corresponds to ^{16}O energy of ~ 64 MeV in inverse kinematics.



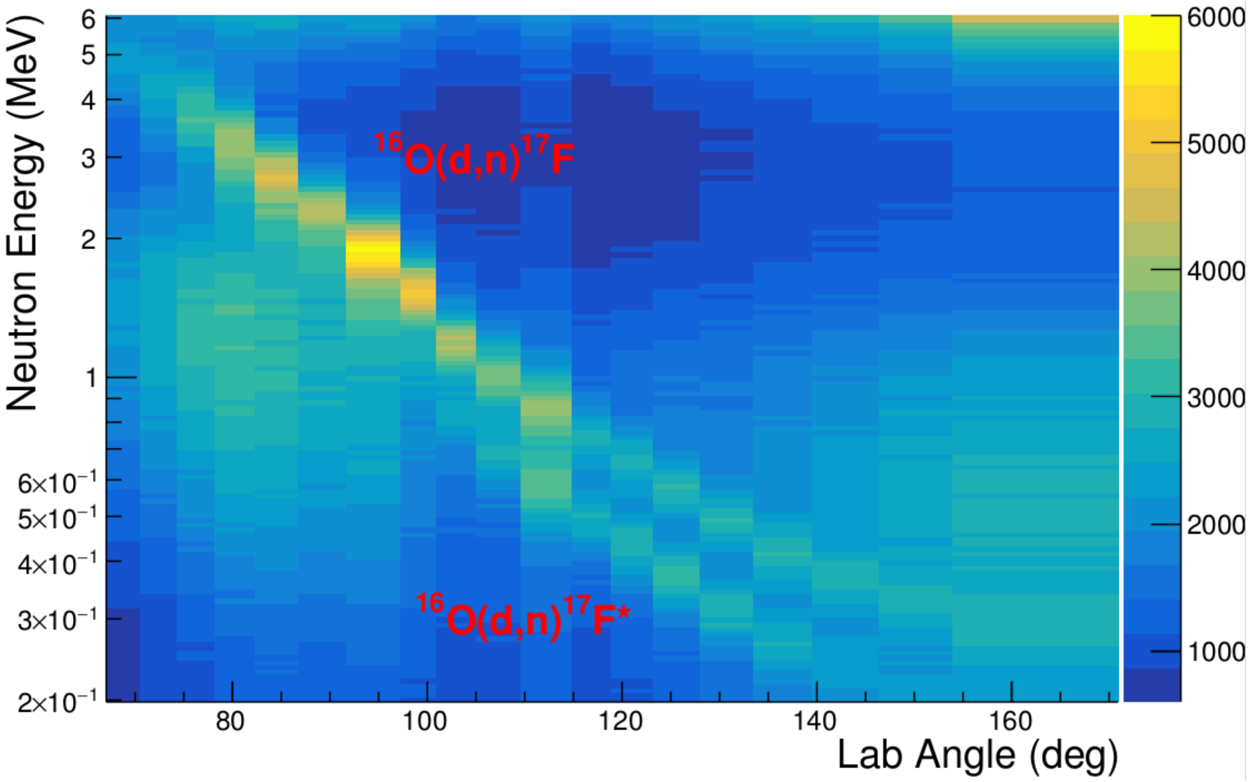
Reaction with a known cross-section[1,2] as a proof-of-concept proton transfer experiment using VANDLE.

[1] - S.T. Thornton, Nucl. Phys. A, 137 531-544 (1969)
[2] - C.J. Oliver, Nucl. Phys. A, 127 567-576 (1969)

d(^{16}O,n)^{17}F contd.

Neutron kinematic curves with high statistics for both the ground and first excited states of ^{17}F.

Low energy neutron detection threshold of about 150 keV due to following beam packet.



Cross-section computation more difficult in this case due to contamination from relatively close-lying first excited state (0.495 MeV).

Outlook

1) Finalize ^{16}O and ^{12}C proton transfer cross-sections for the ground and first excited states for all energies.

2) Repeat d(^{7}Be,n) RIB experiment with experimental improvements

   a) Using better recoil separators (e.g. phoswich detectors and ion chambers) and using new liquid scintillator bars.

   b) Use larger detectors with a longer flight path to improve energy resolution.

Thank You

S. Burcher[1], A.B. Carter[1], I. Cox[1], Z. Elledge[1], R. Gryzwacz[1], K.L. Jones[1], T.T. King[1], M. Madurga[1], S.V. Paulauskas[1], K. Smith[1], S. Taylor[1], M. Vostinar[1], J. Allen[2], D.W. Bardayan[2], D. Blankstein[2], M.R. Hall[2], P.D. O'Malley[2], C. Reingold[2], W. Tan[2], A. Atencio[3], J.A. Cizewski[3], A. Fijalkowska[3], A. Lepailleur[3], D. Walter[3], K.A. Chipps[4], M. Febbraro[4], S.D. Pain[4], S.T. Marley[5], W.A. Peters[6]

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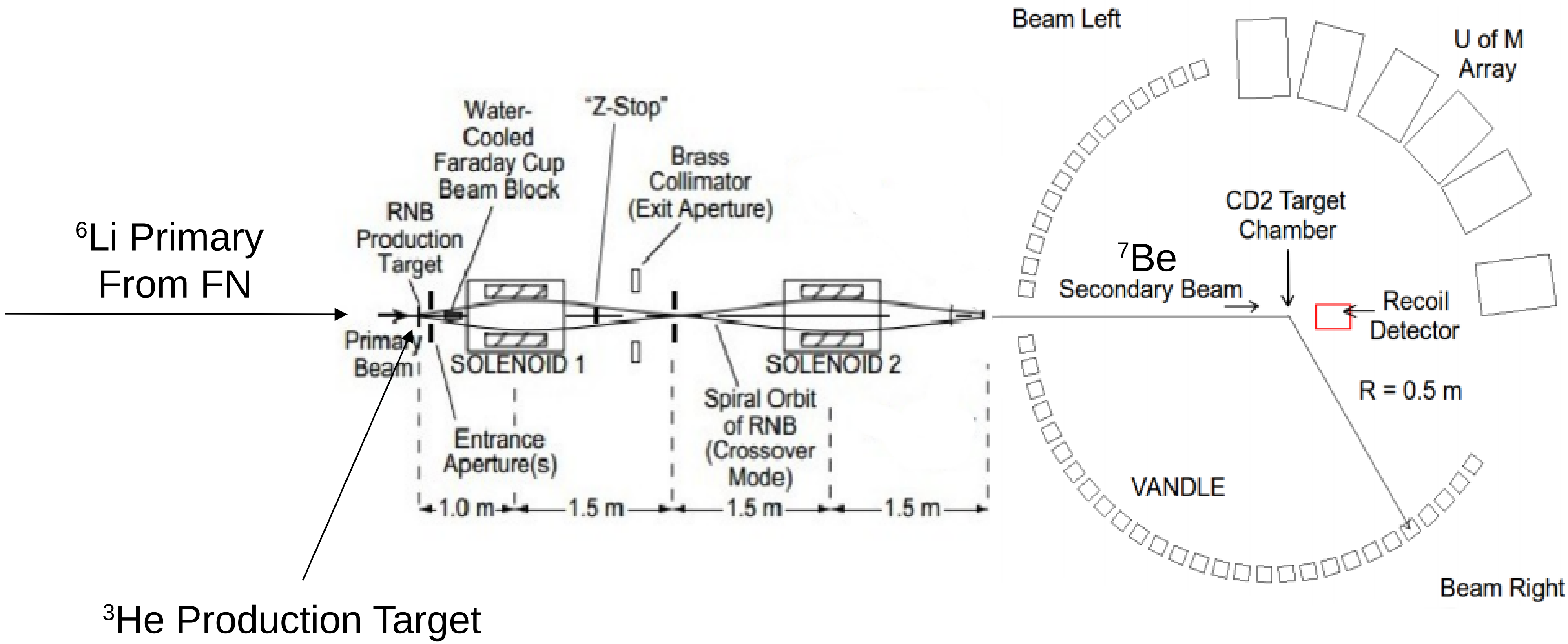
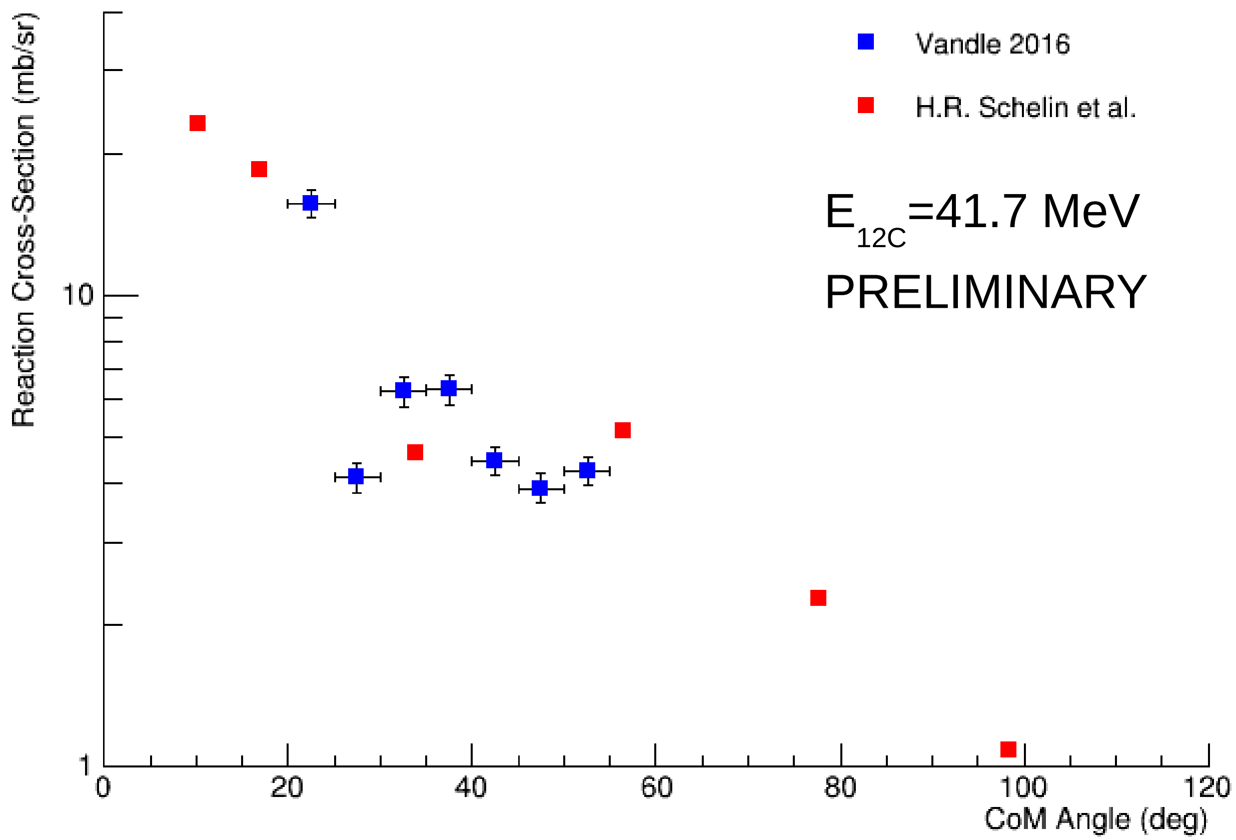
^{7}Be Beam Production



Requires coincidence between recoil detector and neutron detector arrays

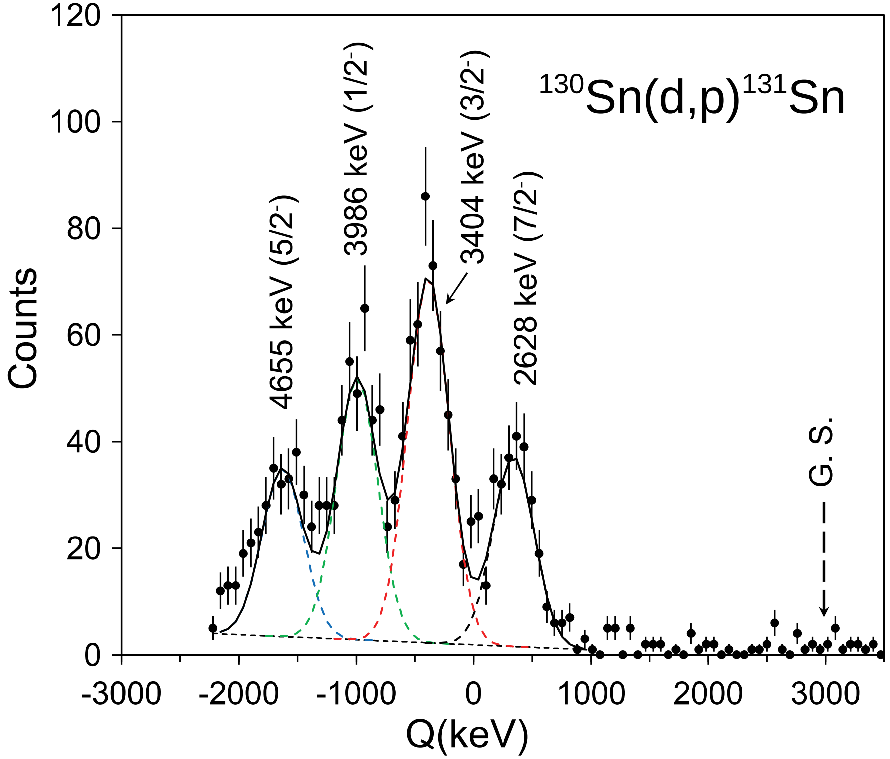
*Not to scale

d(^{12}C,n)^{13}N for E_d=7, E_x=2.365 MeV



[1] – H.R. Schelin et. al., Nucl. Phys. A, 414, 1 pg. 67-84 (1984)

Single Nucleon Transfer Reactions



- Transfer reactions populate various excited states in residual (A+x).
- Outgoing ejectile (b) kinematics show properties of these excited states.
  - Ejectile energies reflect Q-value to populate excited states of residual.
  - If ground state (g.s.) masses known precisely, spectrum of excited states may be extracted.

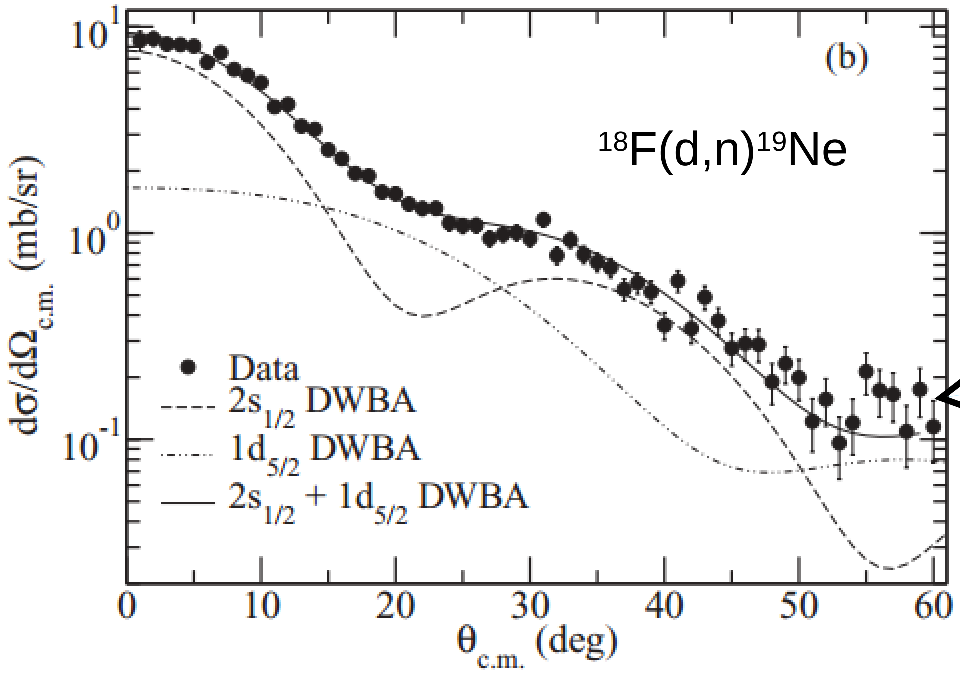
$$Q_{g.s.} = M_{beam} + M_{targ} - M_{ejectile} - M_{residual}$$

$$Q_{final} = Q_{g.s.} - (EX_{residual} + EX_{ejectile})$$

Figure source: R.L. Kozub et al, PRL 109, 172501 (2012)

Single Nucleon Transfer Reactions

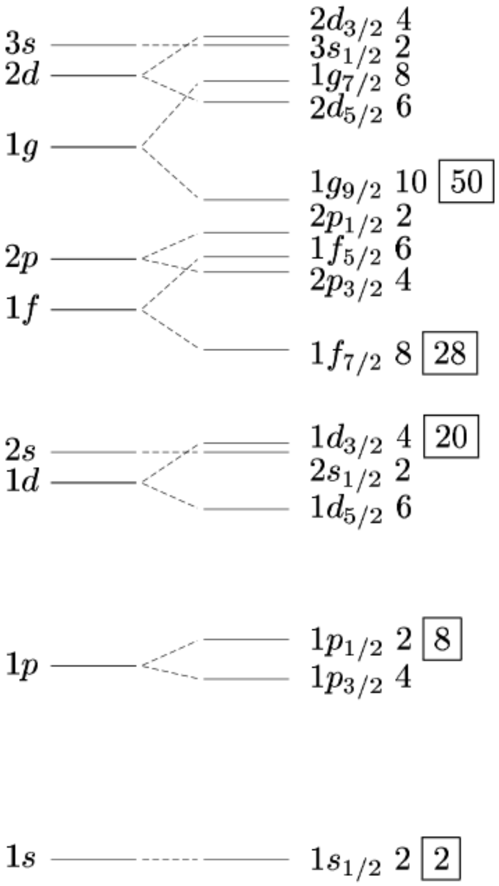
Angular distributions of ejectile depend upon angular momentum transferred to the residual nucleus.

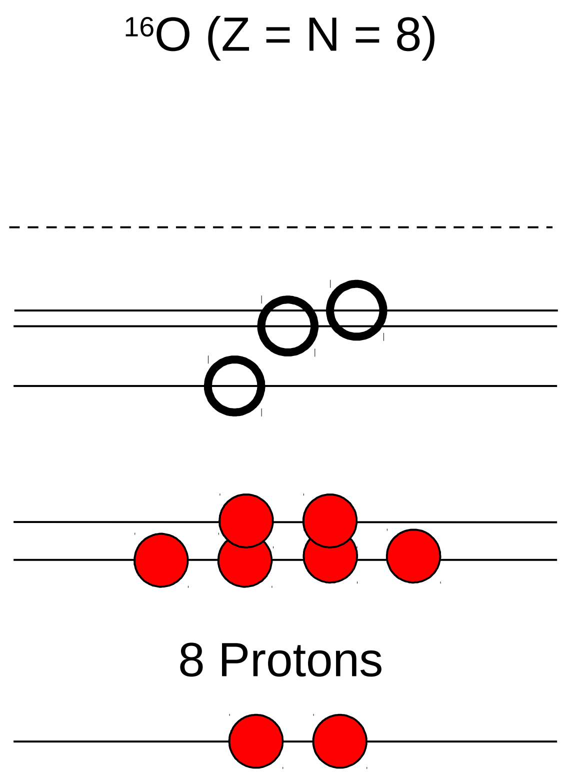


Transfer to the 6289 keV state of ^{19}Ne

Figure source: A.S. Adekola, et al. Phys. Rev. C; 83, 052801(R) (2011)

Transfer Into Single Particle Proton States





Both protons and neutrons are in closed shells.

Protons transferred to ^{16}O will go into the next available shell.

s and d levels are available in the empty shell.

We expect angular momentum transfers of l=0 and l=2.

Calculating (d,n) Reaction Cross Sections

Num. Detected Neutrons → $N_{det} = \varepsilon_{geom}\varepsilon_{intr}N_{actual}T$ ← Time (sec)

Geometric Efficiency

Intrinsic Efficiency

$N_{actual} = \sigma_{d,n}I_{beam}\rho_{targ}$ ← Target Density (p/cm³)

$\frac{i}{Q} = I_{beam}$ $\rho_{targ} = \frac{N_A\tau_{targ}}{M_{targ}}$

Beam Current (enA)

Beam Particle Charge (nC)

Target Thickness (mg/cm²)

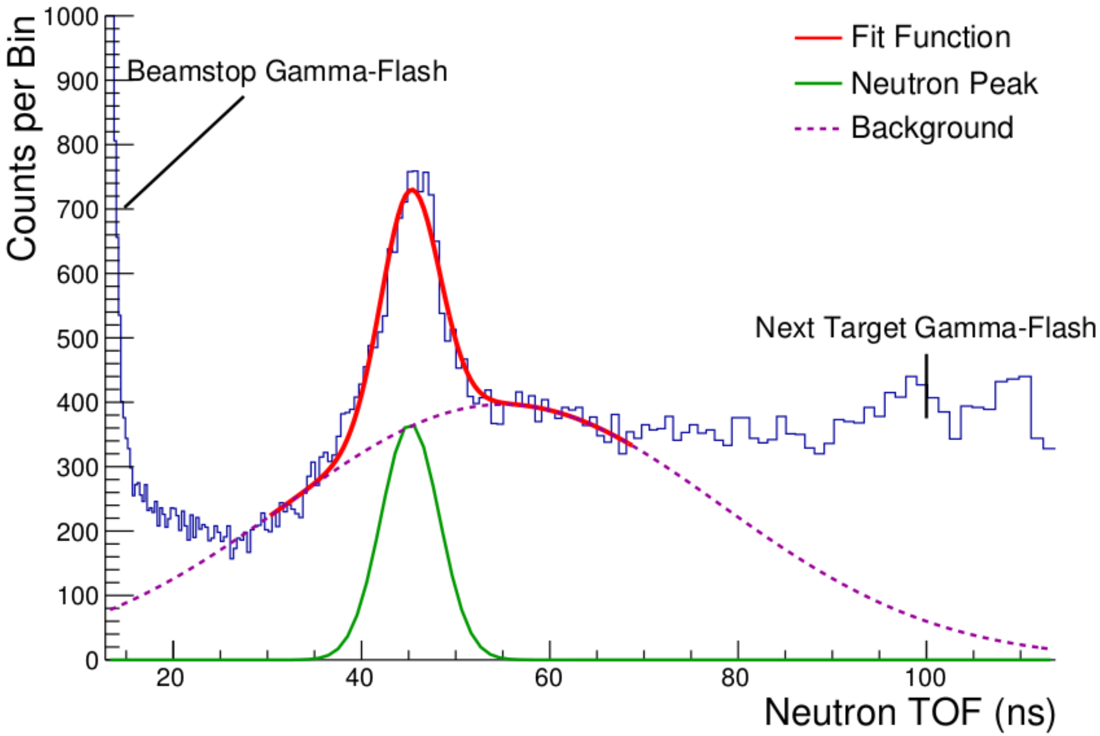
Target Molar Mass (mg/mol)

$$\boxed{\sigma_{d,n} = \frac{N_{det}QM_{targ}}{\epsilon_{geom}\epsilon_{int}iN_A\tau_{targ}T}}$$

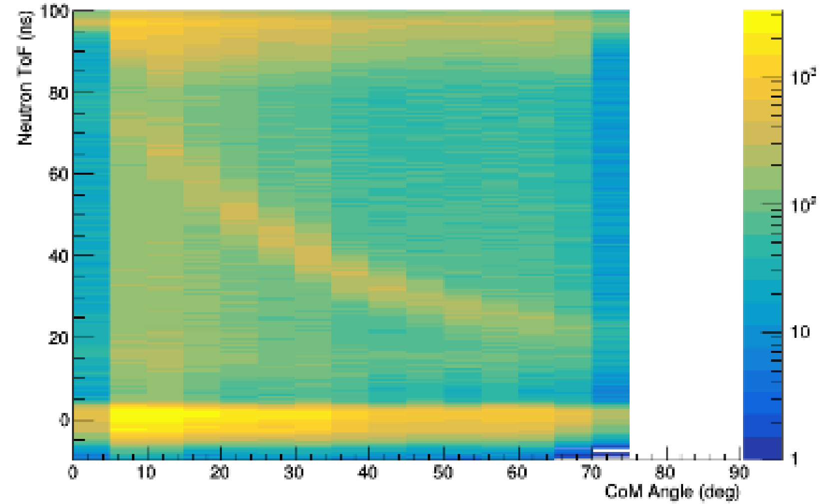
Cross section has units of cm^2 (1 b = 10^{-24} cm^2)

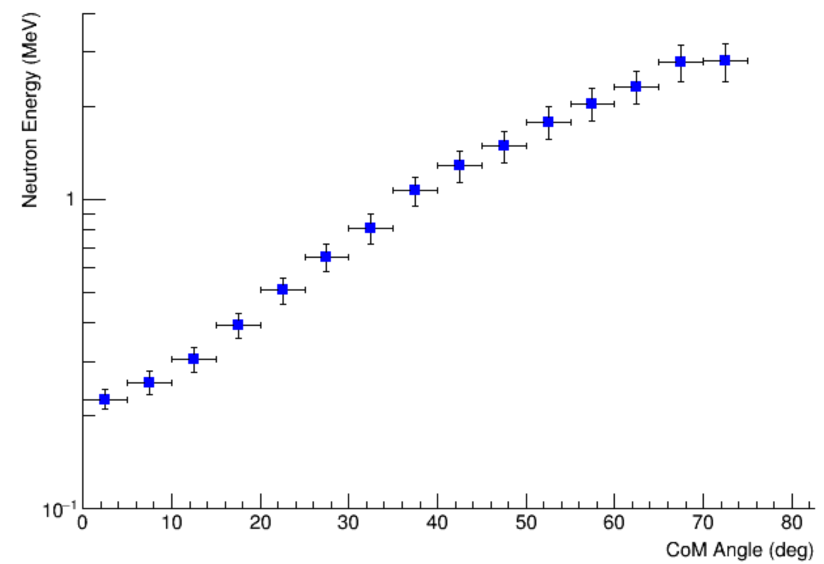
Integrated Neutron Counts

$$\sigma_{d,n} = \frac{N_{det} Q M_{targ}}{\epsilon_{geom}\epsilon_{int} i N_A \tau_{targ} T}$$



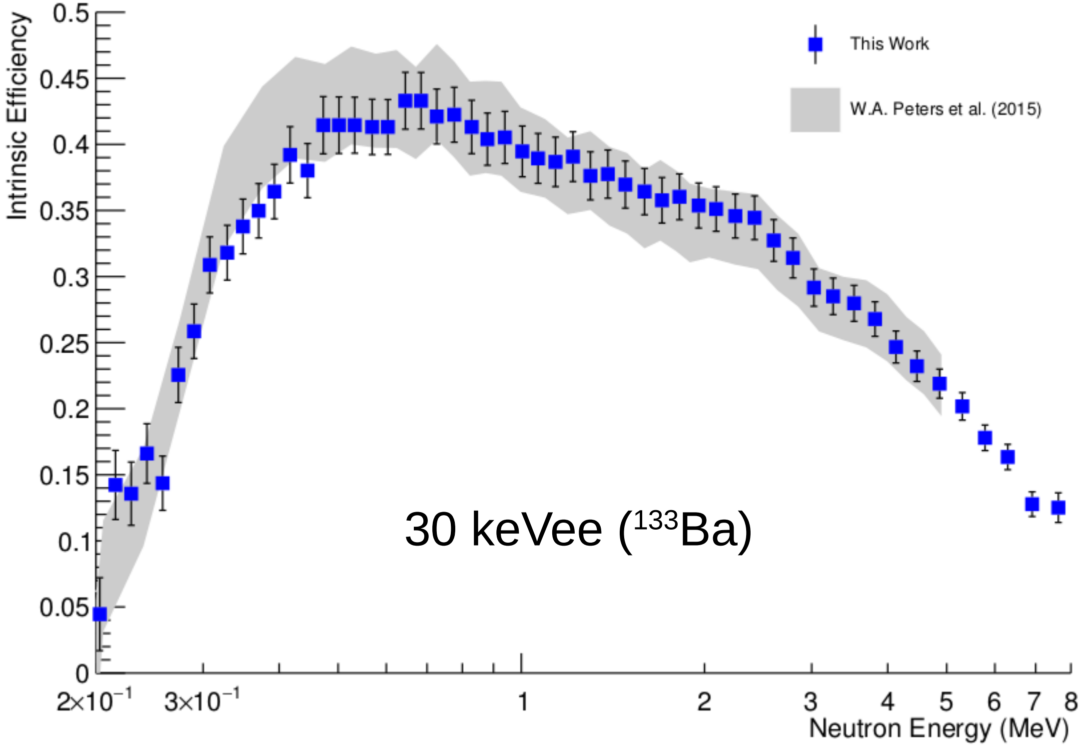
23.5 MeV ^{12}C

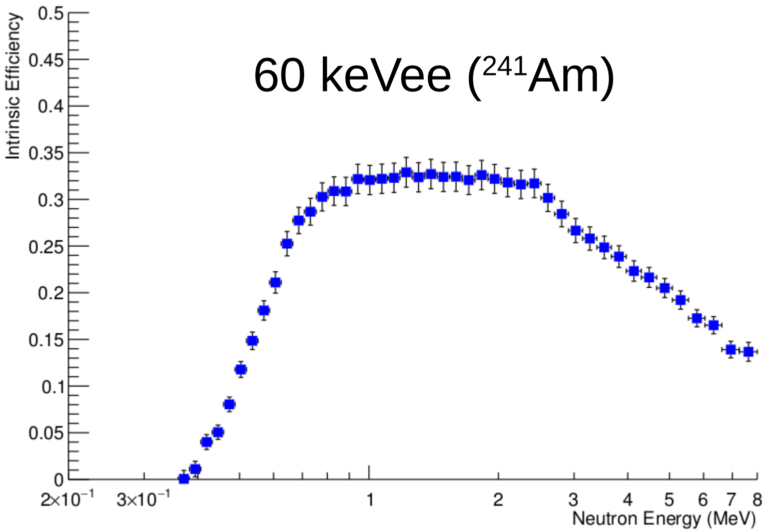




Intrinsic Efficiency Correction

$$\sigma_{d,n} = \frac{N_{det} Q M_{targ}}{\epsilon_{geom} \epsilon_{int} N_A \tau_{targ} T}$$



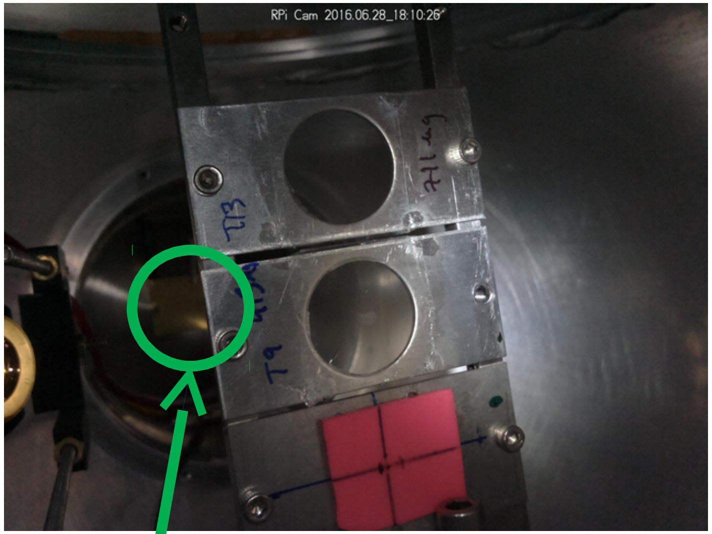


(left) Intrinsic neutron detection efficiency of a small VANDLE bar with a light response threshold of 30 keVee.

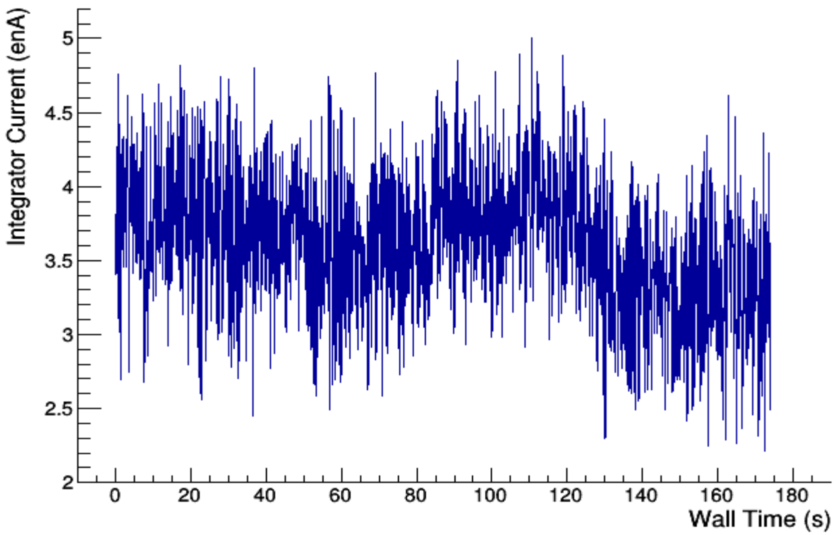
(shaded) Measured detection efficiency (W.A. Peters et al.).

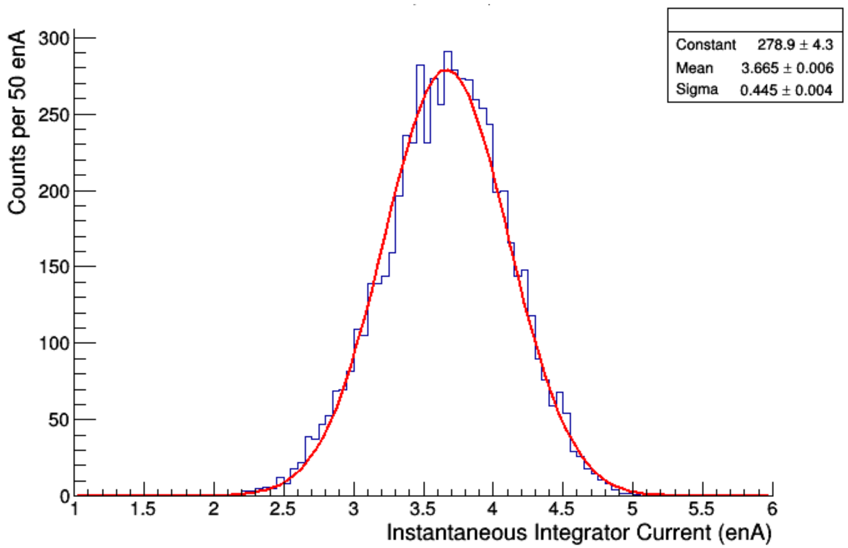
Beam Current Normalization

$$\sigma_{d,n} = \frac{N_{det} Q M_{targ}}{\epsilon_{geom} \epsilon_{int} i N_A \tau_{targ} T}$$



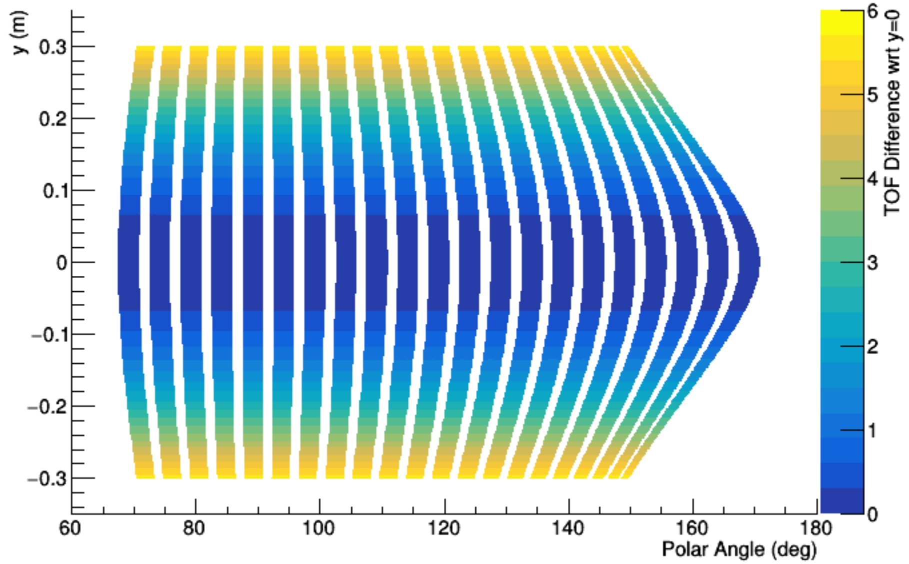
Beam current read from isolated brass beam blocker attached to a secondary target ladder behind primary ladder.



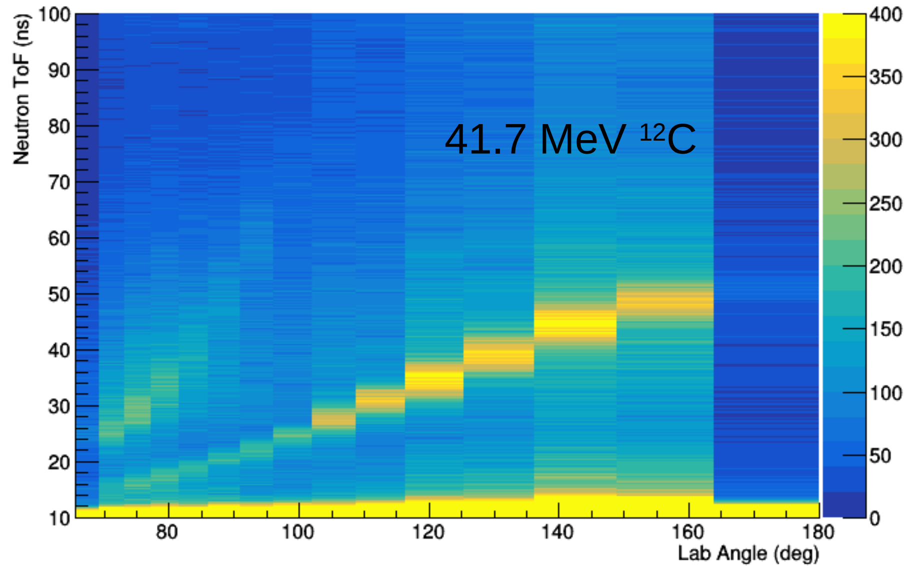


Angular Binning

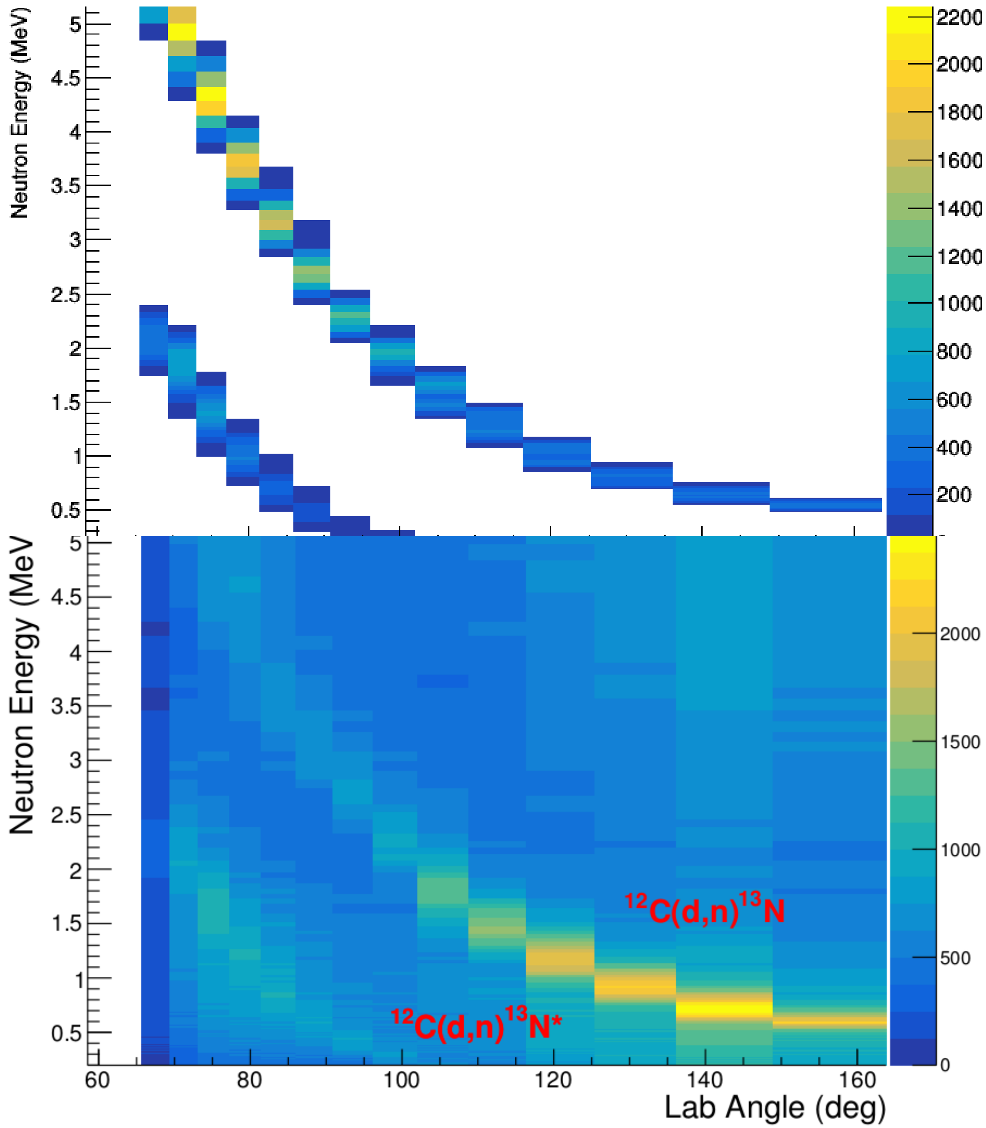
Each detector covers multiple angles (and thus energies). Effect is worse at back angles, where the most interesting physics is.



One solution is to bin neutrons into fixed width CoM bins based on recoil excited state. This makes comparing cross-sections at different energies more convenient.



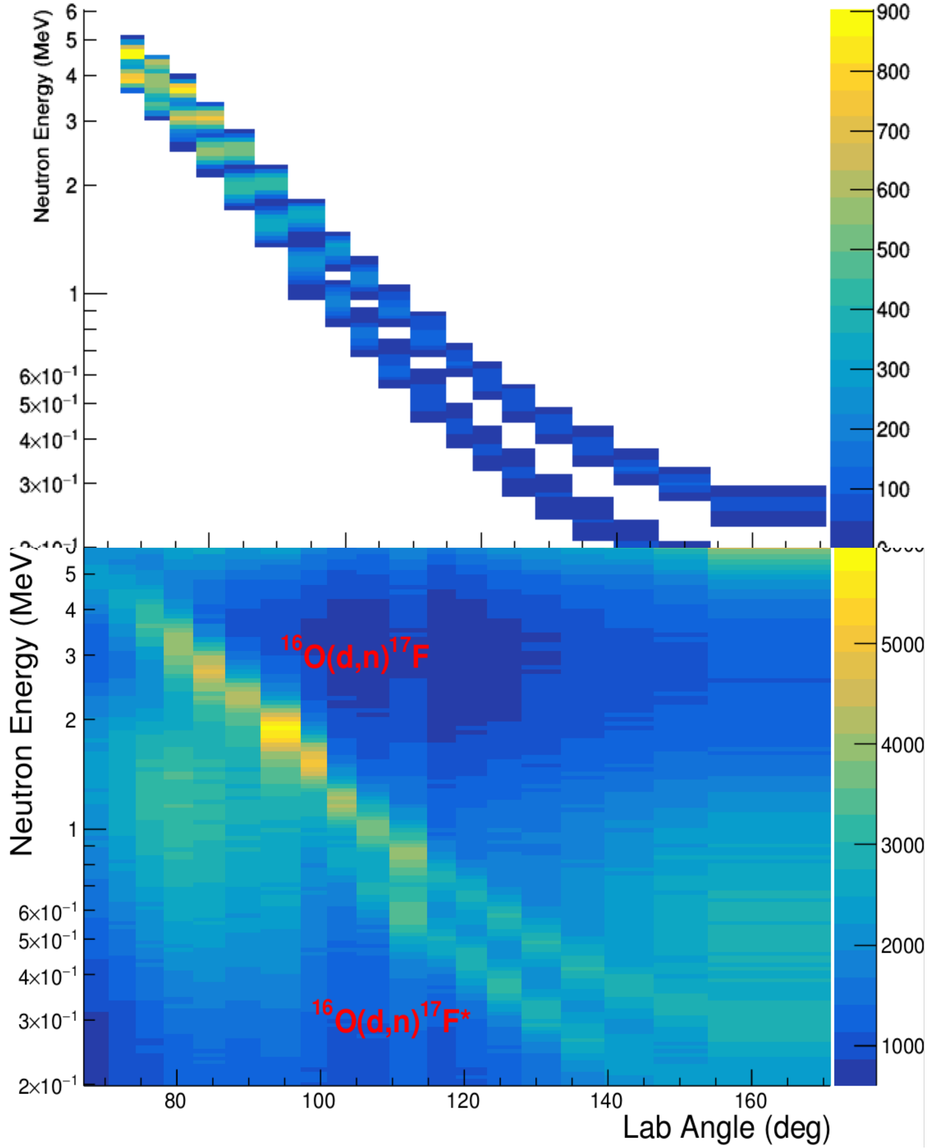
Monte Carlo Comparisons



$d(^{12}C,n)^{13}N$

E_{12C}=41.7 MeV
E_d=7.0 MeV

Monte Carlo Comparisons



$d(^{16}O,n)^{17}F$

E_{16O}=64.0 MeV

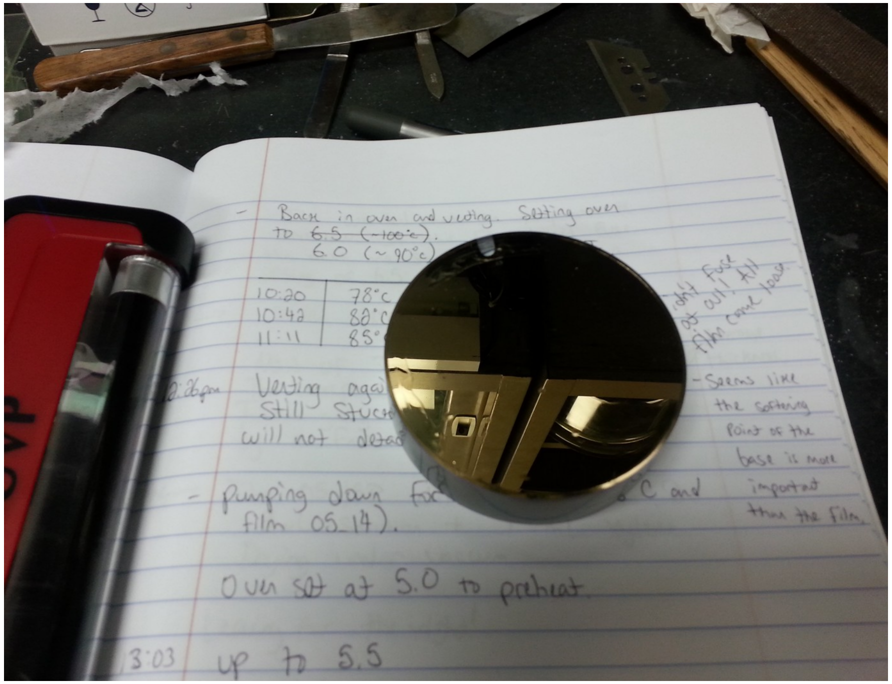
E_d=8.0 MeV

Improvements for (d,n) With RIBs

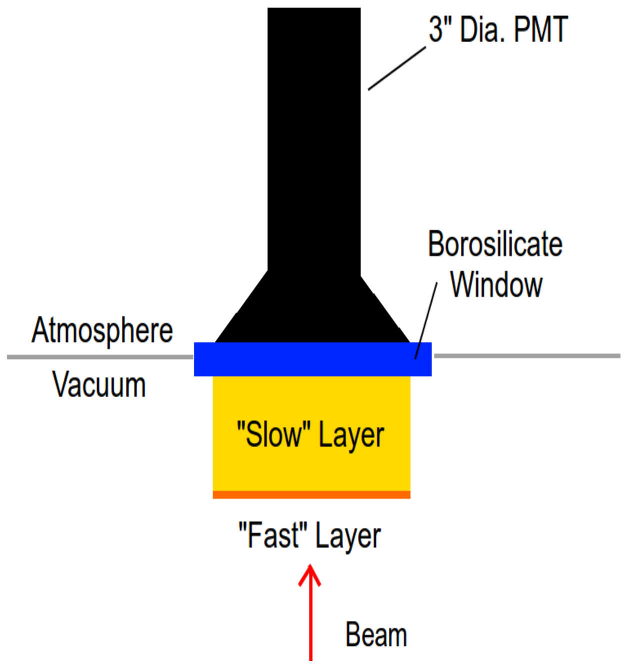
Recoil separation with devices such as phoswich detectors and ion chambers.

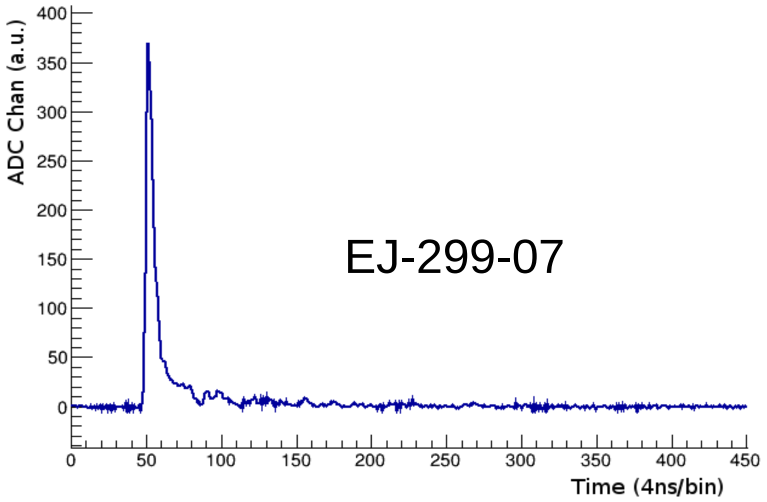
Using liquid scintillator detectors to perform η-γ discrimination.

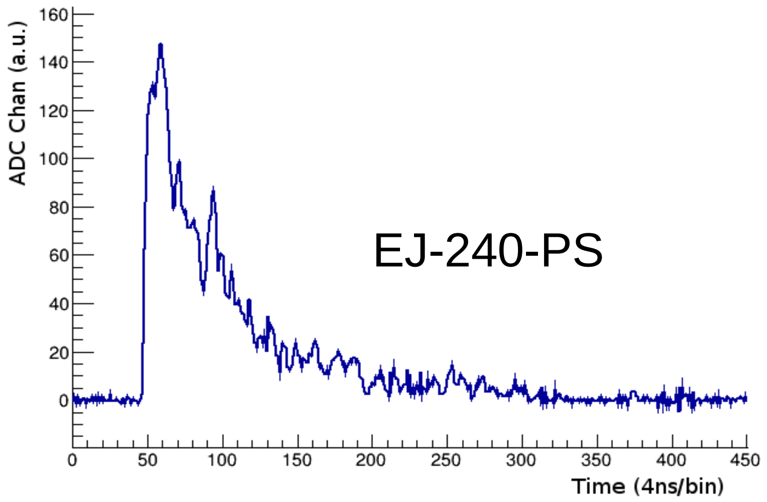
Use larger detectors and a longer flightpath for better energy resolution.



Plastic Phoswich



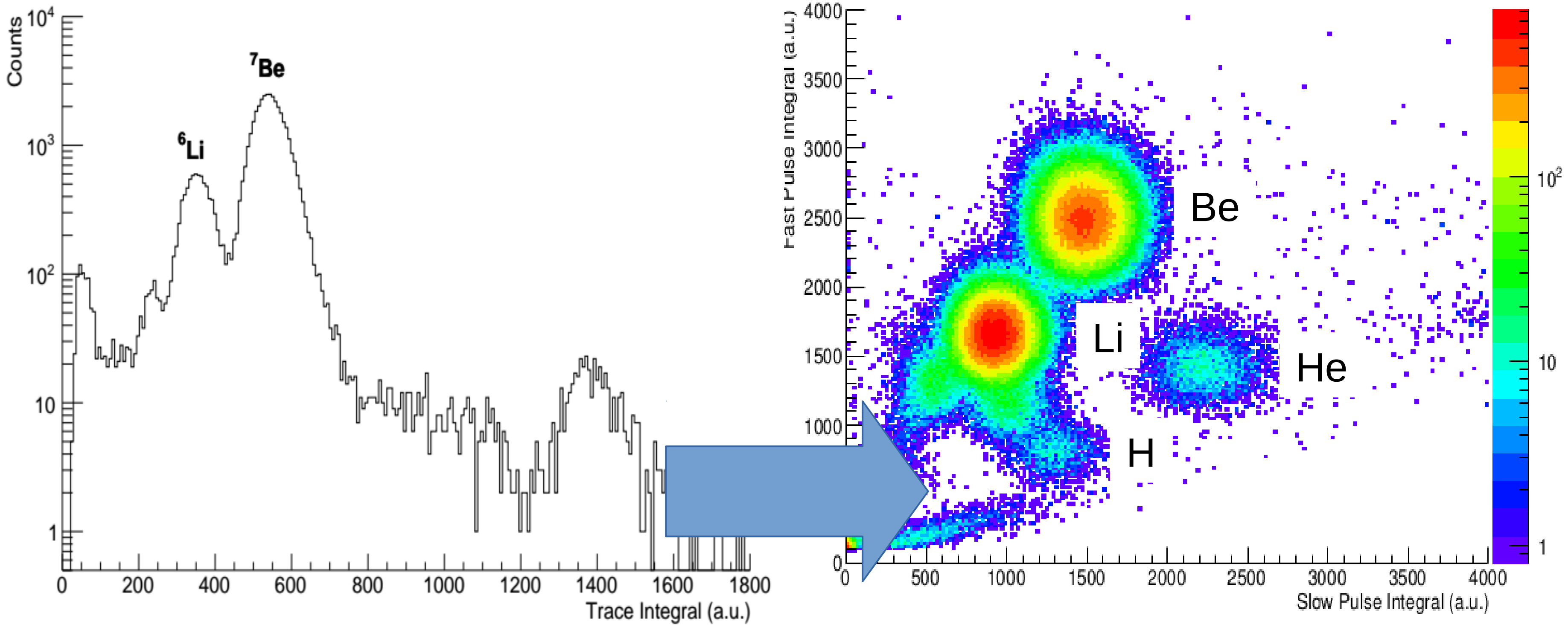




Short for “phosphor sandwich”

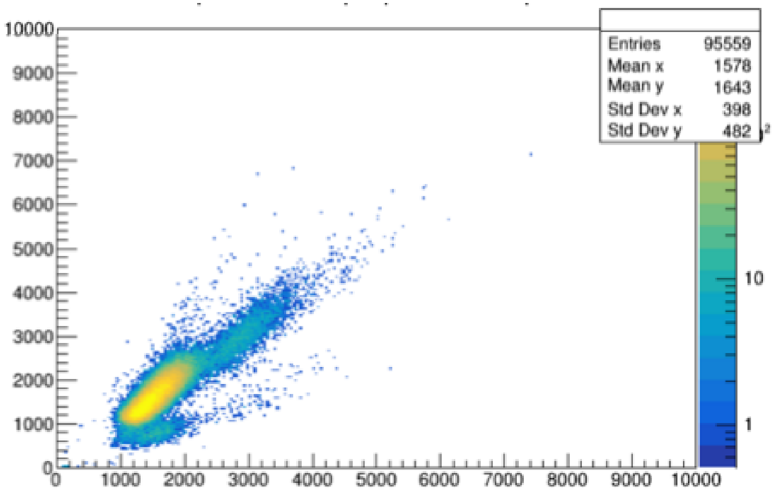
Thin plastic scintillator film dE layer pressed onto a thick plastic E layer.

Using a Phoswich as a Recoil Detector

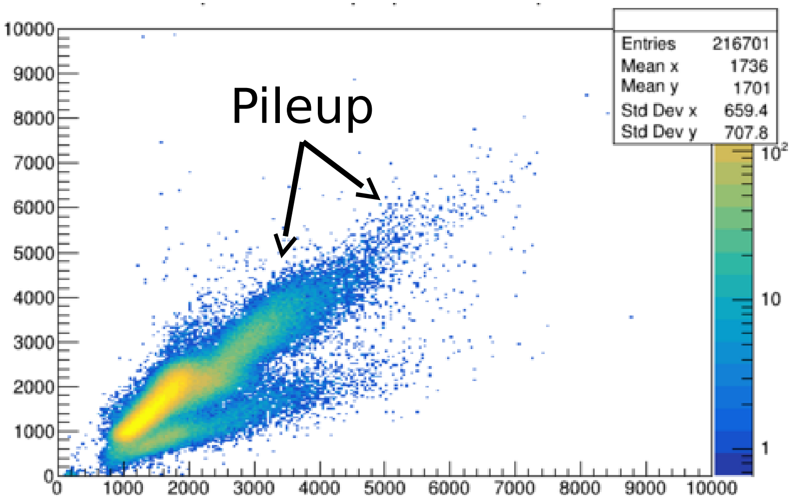


Both plots show similar TwinSol ^{7}Be tunes.
The phoswich allows proton number discrimination.

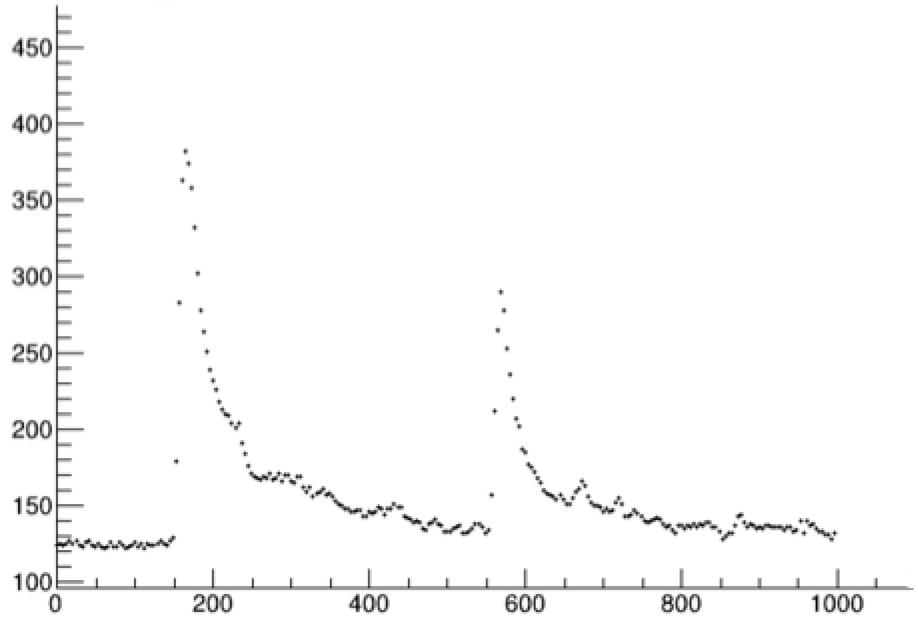
Preliminary Stable Beam Phoswich Data



^{12}C with no target.



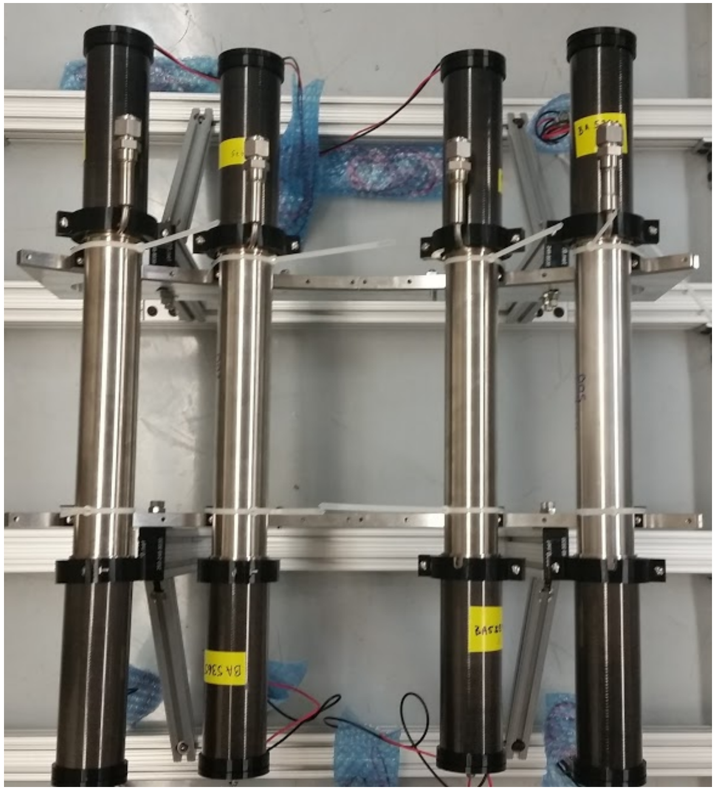
^{12}C with 711 ug C_2D_4.



A typical phoswich light pulse showing pileup. The second pulse lies inside the tail integration region of the first.

The SABRE Array

Brand new detector system for reaction studies!



The “Scintillating Array of Bars for Reaction Experiments”

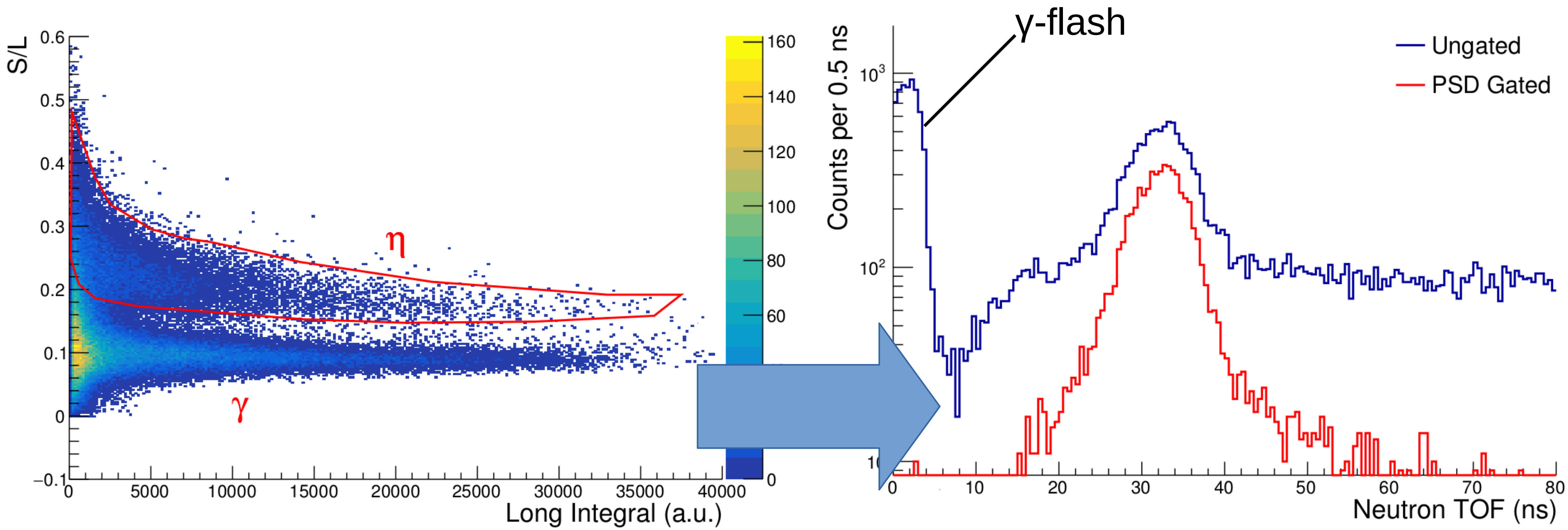
New array of 11” long liquid scintillator bars.

Aluminum housings made by machine shop at UTK.

Liquid scintillator made in house at ORNL.

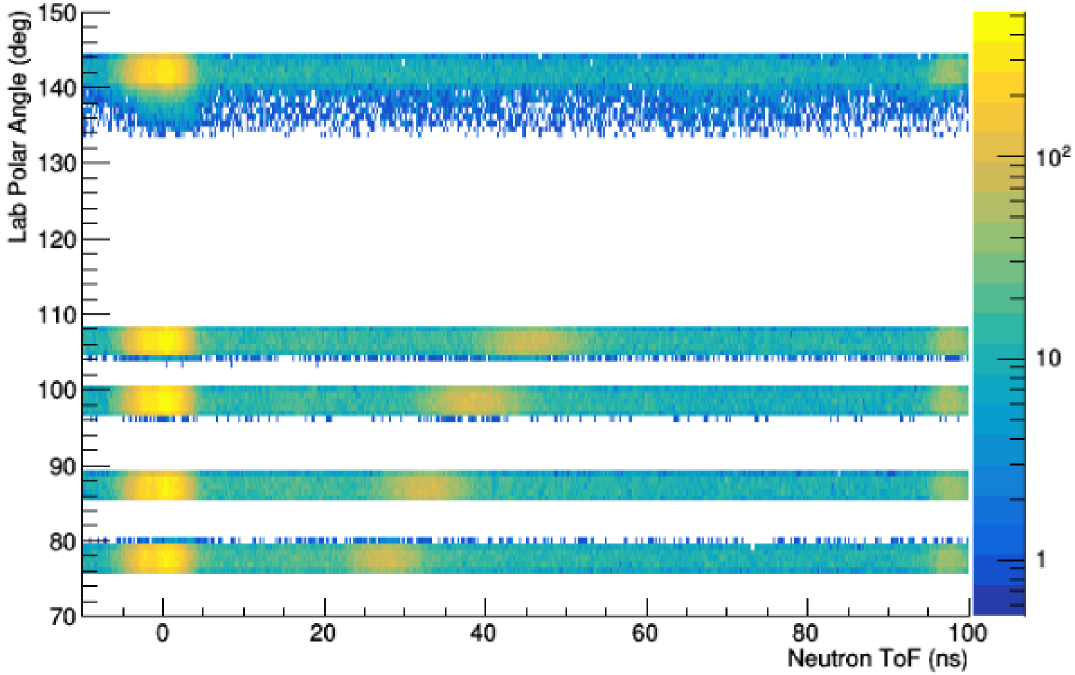
Research sponsored by the Laboratory Directed Research and Development Program of
Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy.

Preliminary SABRE Data



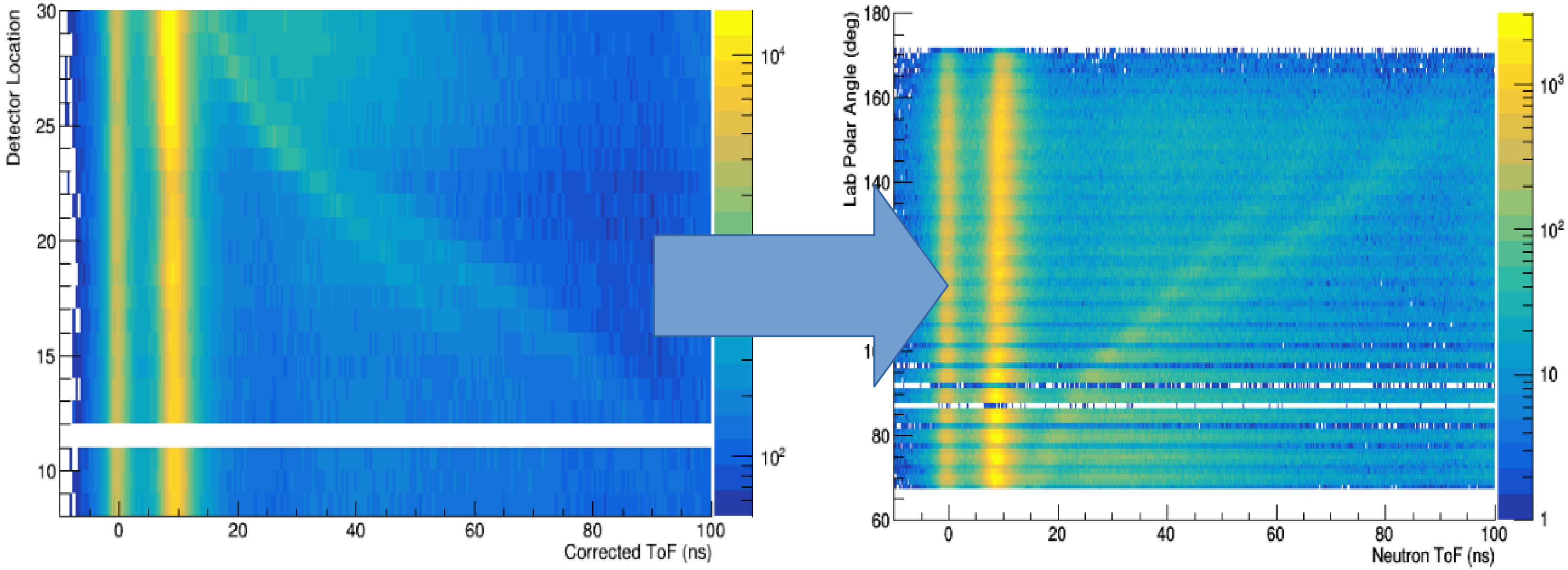
Liquid bar n-γ discrimination shows neutrons from (d,n).

Preliminary SABRE Data contd.



Coordinate Transformations

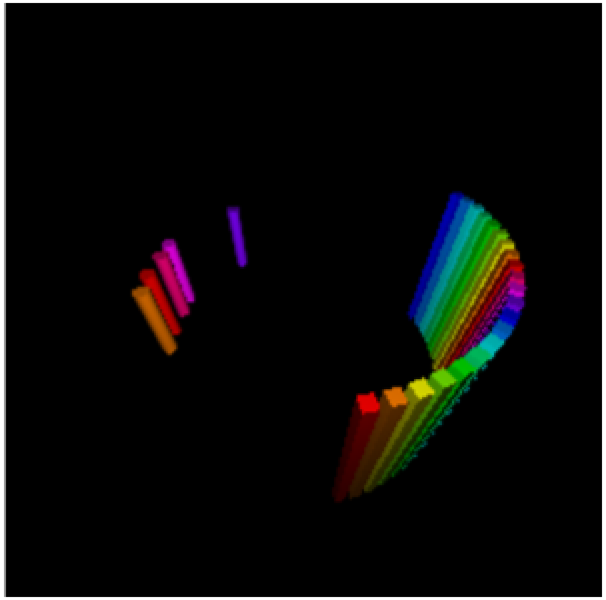
Cylindrical Spherical

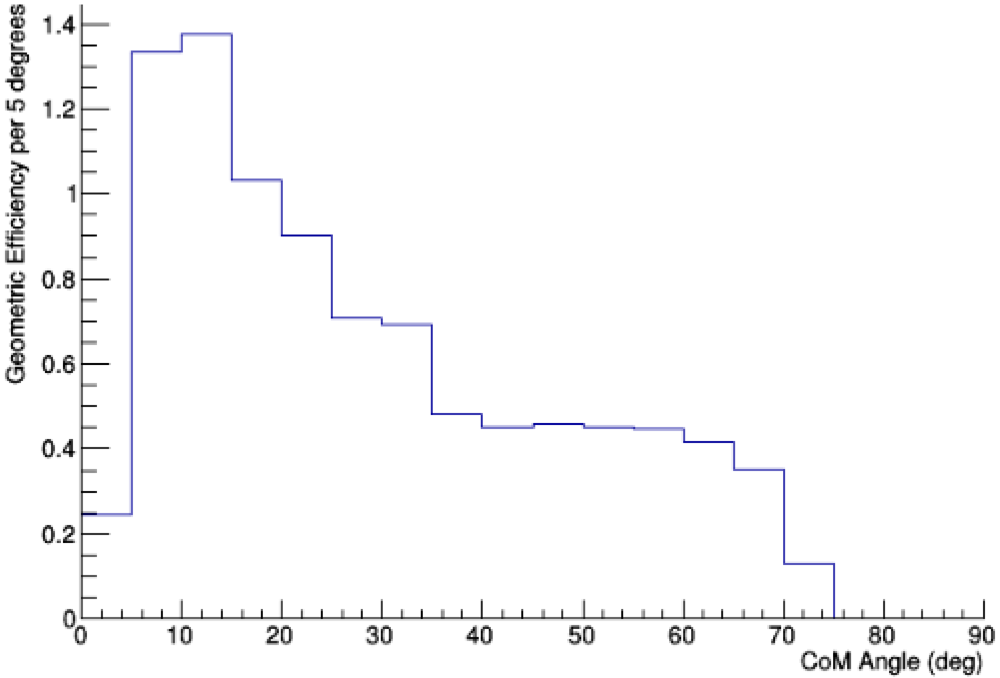


VANDLE is naturally suited to the cylindrical coordinate system. But we must convert to spherical to calculate reaction cross-sections.

Geometric Efficiency Correction

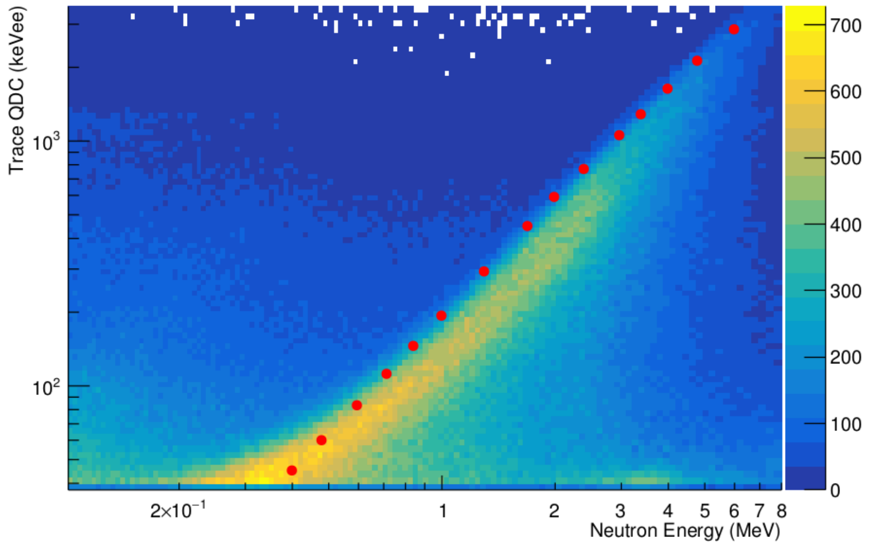
$$\sigma_{d,n} = \frac{N_{det} Q M_{targ}}{\epsilon_{geom} \epsilon_{int} i N_A \tau_{targ} T}$$

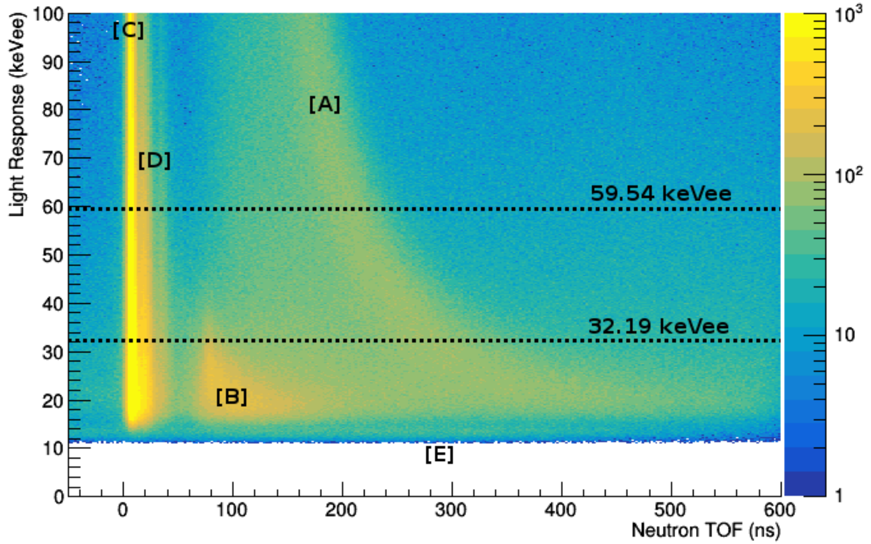


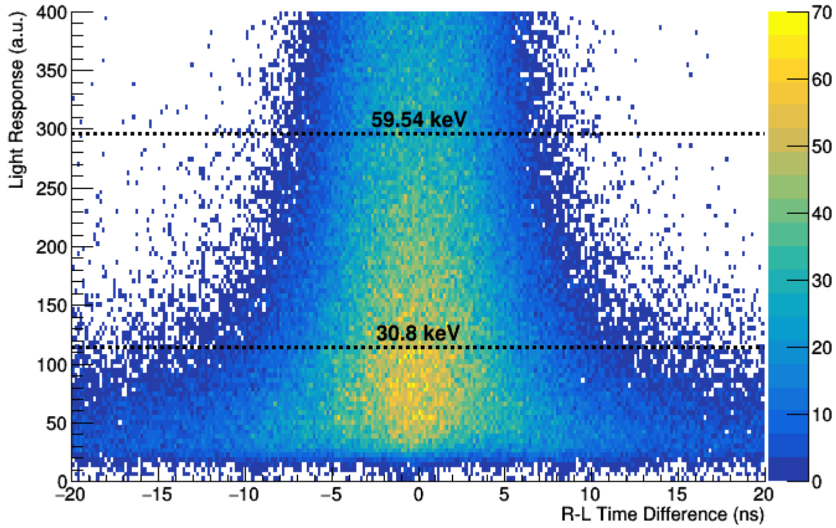


Total geometric efficiency for VANDLE is approx. 9.5%

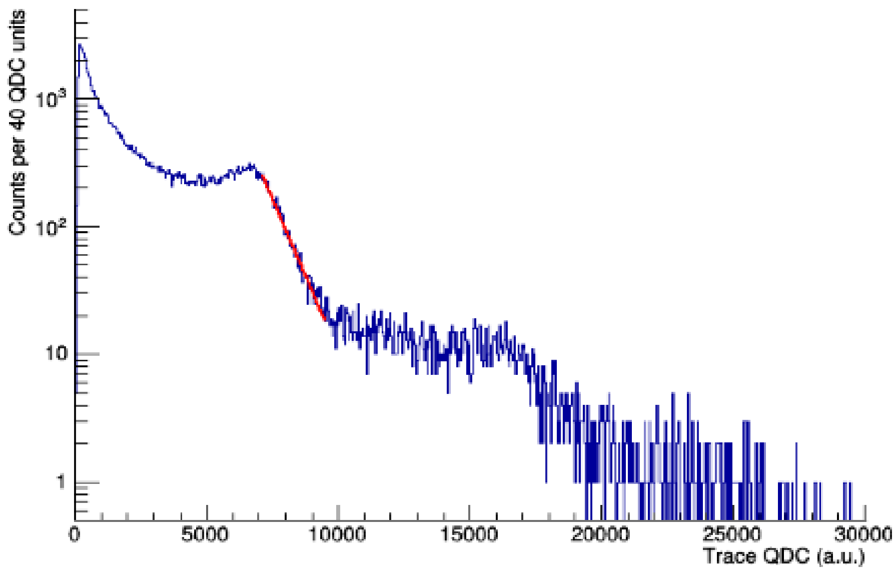
VANDLE Light Response

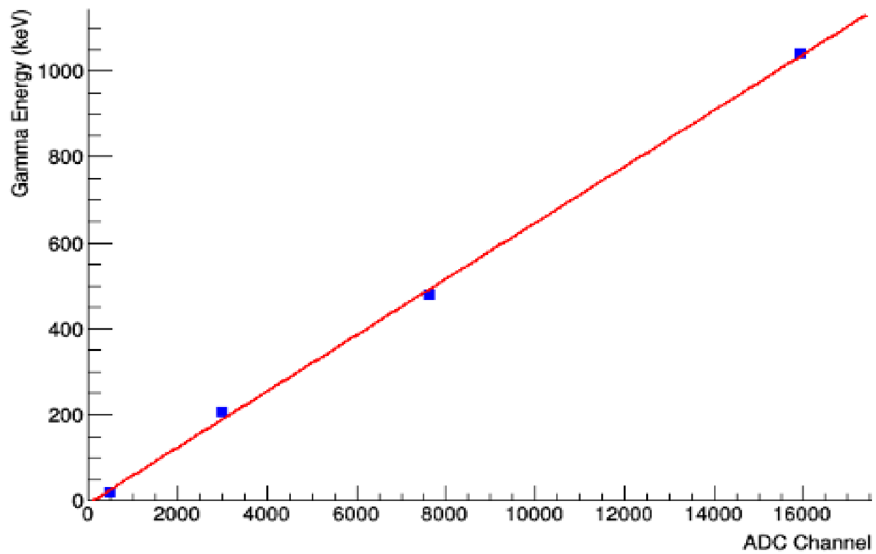






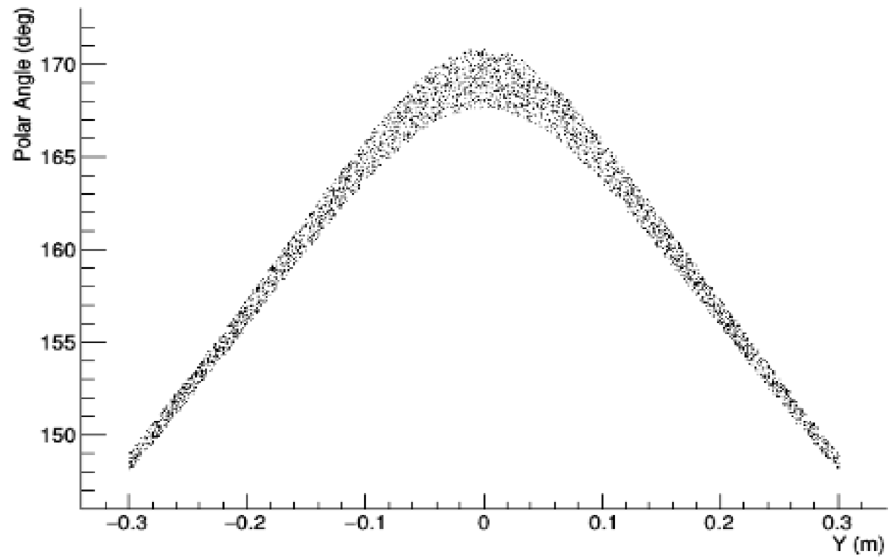
Neutron Detector Calibrations



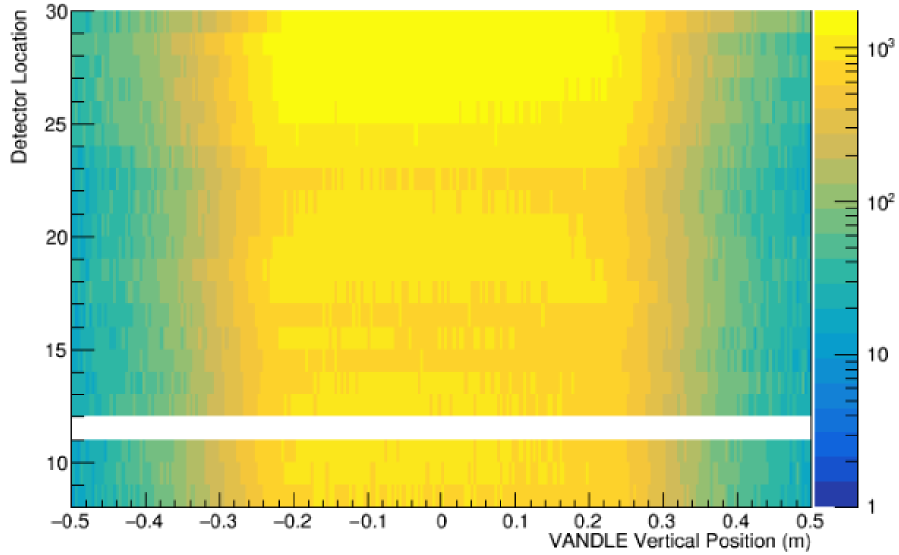


VANDLE Run	NeuDLS Run	Source	γ-Energy (keV)	Edge (keV)
35	36	137Cs	661.657	477.334
38	37	60Co	1252.869 (avg)	1040.648
10	N/A (use 10)	133Ba	80.997, 356.017	19.497, 207.268

Calculating VANDLE Vertical Position

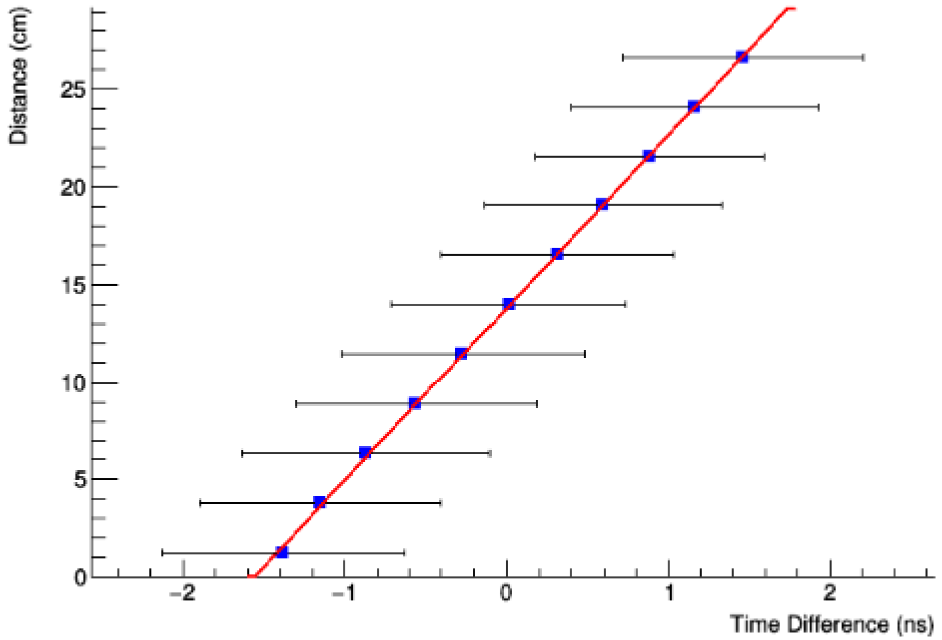


Monte Carlo of lab polar angle versus vertical position for a small VANDLE bar at 169 degrees.



The vertical position in a VANDLE (or SABRE) bar is computed using the time difference between the left and right pmts and the speed of light in the plastic (or liquid scintillator).

Detector Speed of Light Measurements



Measured speed of light for liquid bar no. 001.

8.845 cm/ns

Root fitting results w/ a pol1:

1	p0	1.38137e+01	1.97588e+00	9.64713e-04	3.89390e-05
2	p1	**8.84518e+00**	2.19740e+00	1.06892e-03	-4.94490e-06