Fusion studies at REA

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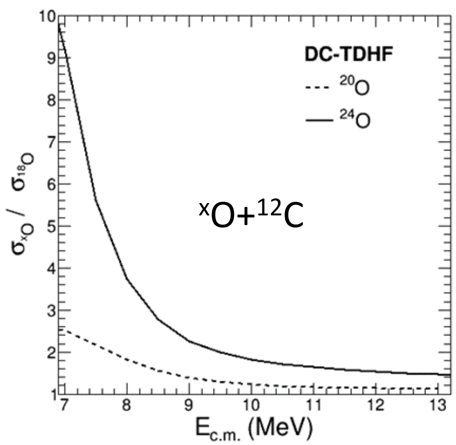
Motivation: understanding the character of neutron-rich nuclear matter is important for a broad range of phenomena:

- Nucleosynthetic r-process
- Neutron-star crusts (X-ray superbursts)
- Neutron star mergers

$^{24}O + ^{24}O$ or $^{28}Ne + ^{28}Ne$ originally proposed as trigger for X-ray superburst.

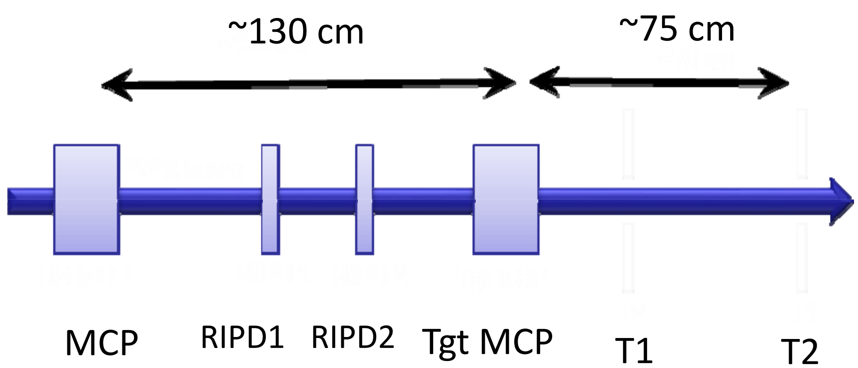
Examination of an isotopic chain allows one to keep the proton density distribution largely unchanged and principally examine the influence of the extended neutron density distribution.

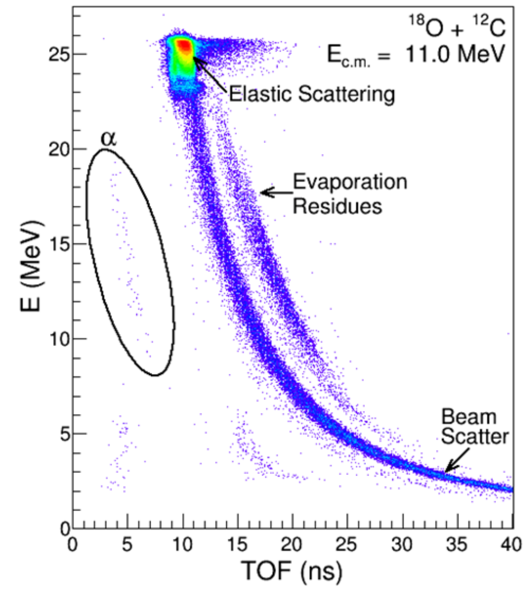
When nuclei collide, if valence neutrons are loosely coupled to the core, then polarization (prelude to transfer) can result and fusion enhancement will occur.



Elimination of pairing greatly enhances the cross section in DC-TDHF: Important sensitivity to structure.

^{13}O	^{14}O	^{15}O	^{16}O	^{17}O	^{18}O	^{19}O	^{20}O	^{21}O	^{22}O	^{23}O	^{24}O
8.58 ms	70.62 s	122.24 s	STABLE	STABLE	STABLE	26.88 s	13.51 s	3.42 s	2.25 s	97 ms	72 ms
1×10^4	7×10^6	6×10^7	← Reaccelerated beam →			3×10^6	2×10^6	7×10^6	1.5×10^5	1×10^4	1×10^3





- $E_{lab} = 2.3 – 3$ MeV/A
- Applicable at intensities of $10^3 – 10^6$ p/s
- Reaction products distinguished by ETOF
- Energy measured in segmented annular silicon detectors
- Fusion product time-of-flight measured between target MCP and silicon detectors
- Efficiency typically 80%

Fusion at the neutron dripline: Theory needs

Understanding fusion dynamics of neutron-rich light nuclei near the dripline at near and sub-barrier energies requires a proper description of:

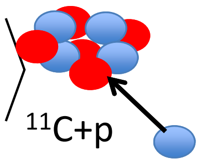
- Pairing as the nuclei deform and fuse (does a BCS approach suffice?)
- Coupling to the continuum
- extended wavefunctions of weakly bound neutrons
- how to consider open systems

The state-of-the-art microscopic model does not at present treat even the first of these topics (pairing) adequately.

A theoretical understanding of weakly bound neutron-rich nuclei near the dripline presents unexplored and fertile territory for the theoretical community.

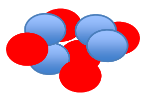
Represents $H\left|\Psi^{J\pi T}\right\rangle = E\left|\Psi^{J\pi T}\right\rangle$ **using the over-complete basis:**

$$\left|\Psi^{J\pi T}\right\rangle = \sum_\lambda c_\lambda \left|E_\lambda\, \lambda\, J^\pi T\right\rangle + \sum_\nu \int dr\, r^2\, \frac{\chi_\nu(r)}{r}\, \hat{A}_\nu \left|\xi^{J\pi T}_{\nu r}\right\rangle$$



^{11}C+p

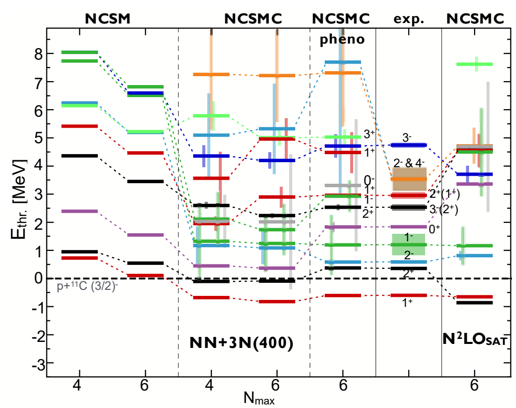
^{12}N

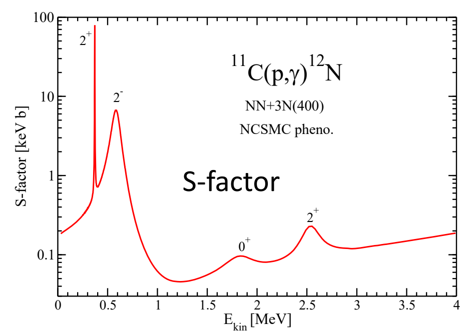


Expansion in A-body NCSM eigenstates

Relative motion of clusters

Example of ongoing application aligned with TRIUMF experimental efforts: ^{11}C(p,p), structure of ^{12}N, & ^{11}C(p,γ)^{12}N FRIB: sd-shell





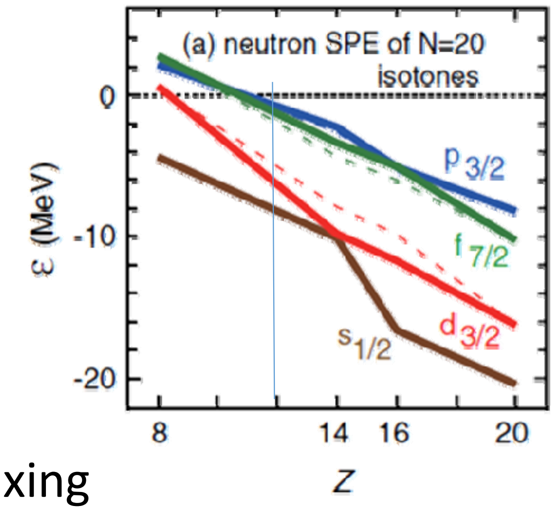
LLNL/TRIUMF collaboration: S. Quaglioni, P. Navratil *et al.*

Currently most suited for reactions with light nuclei

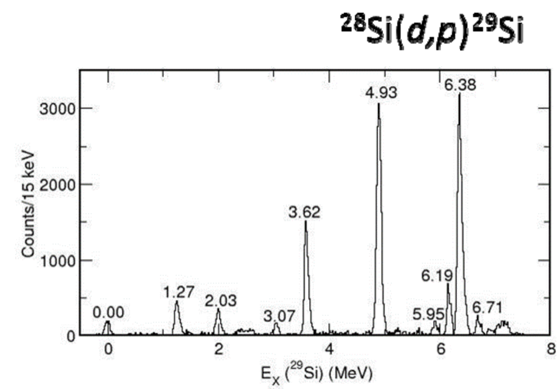
Developments for going to heavier nuclei: use symmetry adapted NCSM (LSU)

Transfer reactions with low-energy Beams (A. Wousmaa)

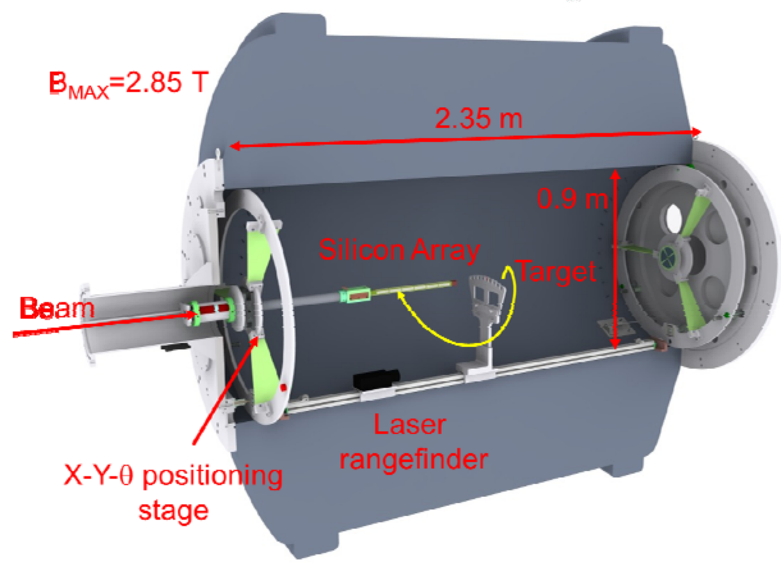
Large program for transfer reactions.
Take the ^{32}Mg region as an example:
Disappearance of N=20
magic number and *sd*-$f_{7/2}$ gap driven
by tensor force and pairing; (*sd*)-(*fp*) mixing



Otsuka et al., PRL 104. 012501 (2010)

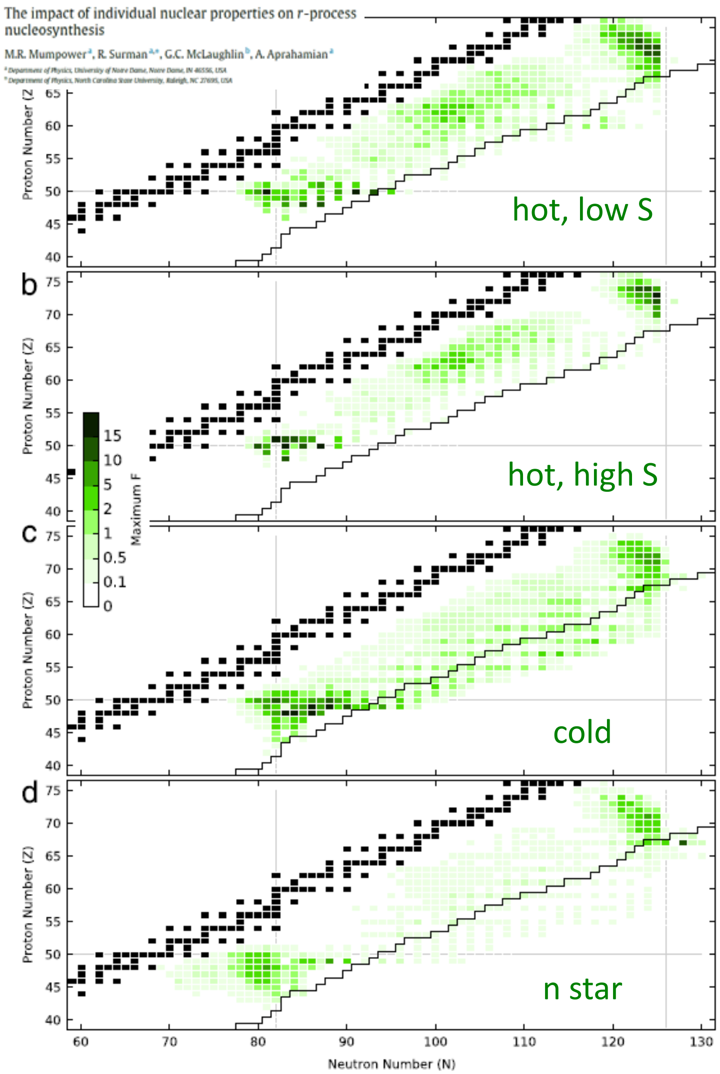


Study evolution of *fp* neutron S.P.E. around ^{32}Mg with (*d,p*) across neutron-rich Mg isotopes
E/A≈5-10 MeV, I>few X10^3/sec
Pairing correlations, multi-p-h states near neutron-rich Mg isotopes with (*t,p*),(*p,t*):
^{32}Mg(*p,t*)^{30}Mg, ^{32}Mg(t,p)^{34}Mg
E/A≈5-10 MeV, I>few X10^4/sec



This and many other transfer reactions can be studied with a solenoid spectrometer like HELIOS@ANL

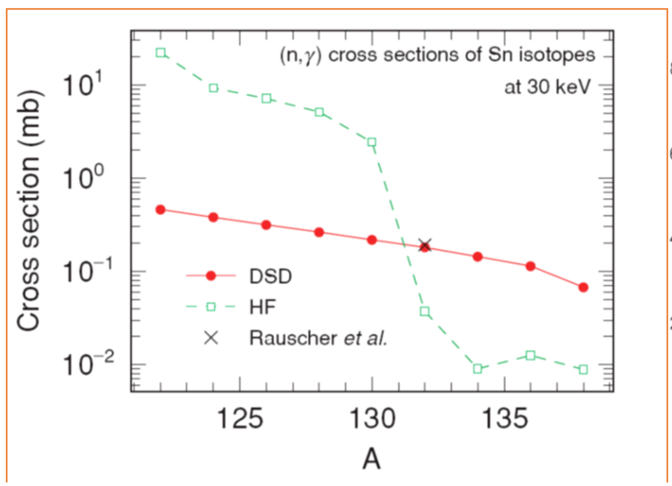
Constraining nucleosynthesis with (d,p) reactions

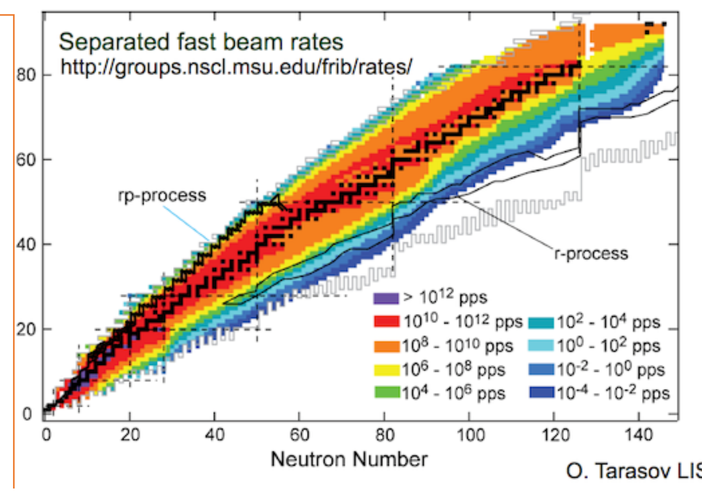


- nucleosythesis sensitive to capture cross sections on specific nuclei (eg proton capture for rp process, neutron capture for r process)
- Constrain nucleosynthesis with transfer reactions
  - •Constrain structure models
  - •Direct-semidirect capture to bound states (esp near shell closures)
  - •Surrogate measurements for compound neutron capture
  - •Mirror studies for proton capture reactions (novae, x-ray bursts)
- Day-1 fast FRIB beams gives access to some important nuclei, e.g.

^{130}Sn(d,pγ) 2e8 pps → **4e6 pps Day 1**
^{80}Ge(d,pγ) 2e9 pps → **5e7 pps Day 1**

^{25}Al(d,pγ) 1e9 pps → **3e6 pps Day 1 ReA**
^{56}Ni(d,pγ) 1e7 pps → **1e6 pps Day 1 ReA**



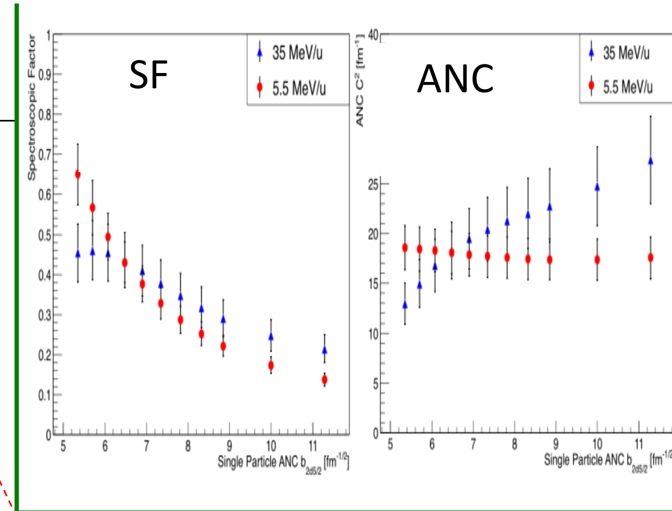


Transfer reactions with ORRUBA+S800+Gammas

- Program currently underway
  - Constraint of SF via SP potential
  - ^{86}Kr(d,p)^{87}Kr completed
  - ^{84}Se(d,p)^{85}Se approved (Dec 2017)

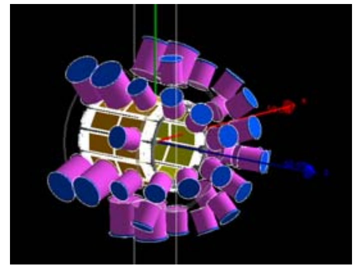
- ORRUBA+GRETINA(GRETA) coupling under development

- ORRUBA + HAGRiD coupling ($LaBr_3$) array under construction

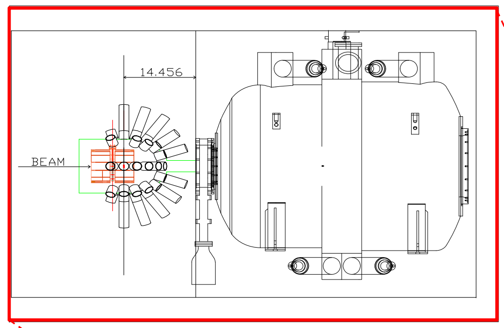


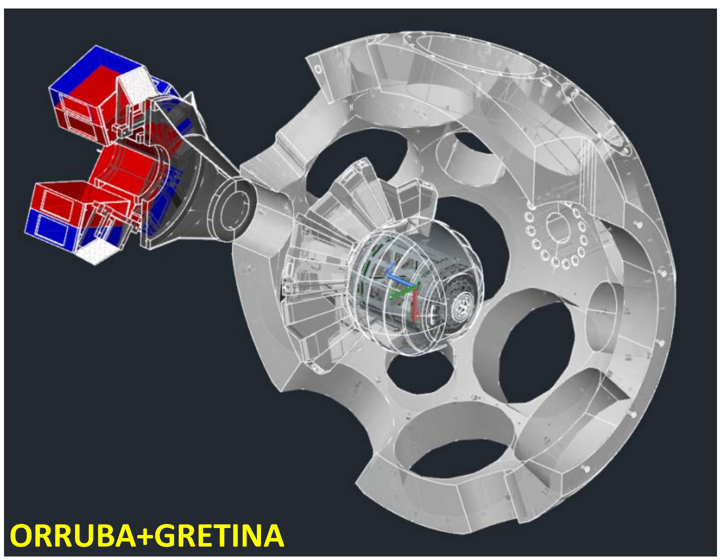
HAGRiD $LaBr_3$ array

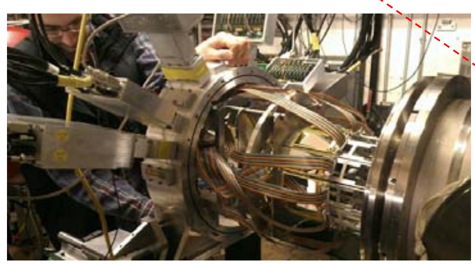
- 27(+) 2” detectors
- 10(+) 3” detectors

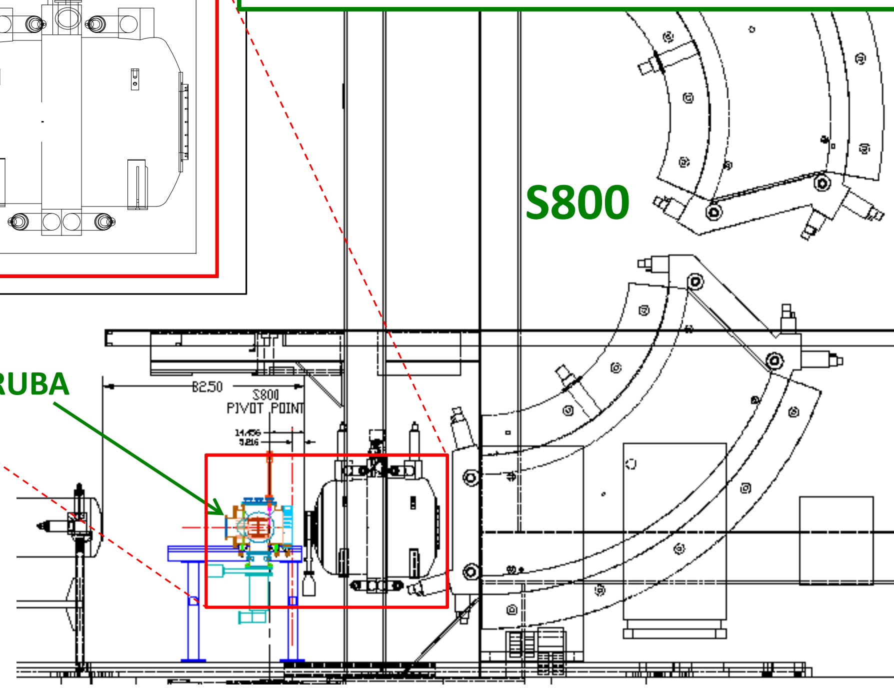


ORRUBA+HAGRiD+S800









FRIB Day-1 Science: challenges for nuclear reactions

Ca Isotopes: Where is the dripline? Are ^{61}Ca or ^{62}Ca bound?

here current mean field and ab-initio approaches show large differences and will help inform the current many-body Hamiltonian.

Theory: will be sorted out in the next 4 years

Exp: How far can FRIB go and are the rates enough for Day 1?

Sn isotopes: Chain is very long – how far in N can be measured?

Exp: Perform interaction cross-section measurements to extract neutron skins consistently all they way from ^{118}Sn to ^{132}Sn?

Theory: predictions for neutron skins
is predicted skin large enough to compete with uncertainties in reaction theory analysis?

Heavier isotopes: (d.p) transfer to probe single particle behavior?

how about ^{238}Th for (d,p)?

F.Nunes, LECM 2107

Nuclear Lattice EFT applied to reaction theory
Collaboration projects ongoing and planned

- **Ab initio calculations of transfer reactions using the adiabatic projection method.**

  approach is suited for e.g. alpha transfer reactions

- **Ab initio calculations of effective interactions:**

  Derivation of a shell model interaction from ab initio nucleon + nucleus elastic scattering and chiral effective field theory.

  Testing new Monte Carlo algorithms for computing ab initio
  - nucleon-nucleus effective interactions
  - alpha-nucleus effective interactions

Lattice sizes and corresponding cpu time limiting factors for heavy nuclei

FRIB science and effective interactions

Current status:

Empirical effective nucleon-nucleus interactions

- only contain E>0 information and do not connect to structure
- are local but should be nonlocal
- should be dispersive, but are not

Ab initio effective nucleon-nucleus interactions

- Currently not adequate to be used in reaction calculations

Further development of

- Nonlocal dispersive optical model
- Multiple scattering approach
- Nuclear lattice approach
- Structure + RGM approach

To effective interactions nucleon-nucleus, deuteron-nucleus, alpha-nucleus needed.

Impact on experiment: Elastic scattering cross sections (inverse kinematics)
Provide essential constrains on effective interactions.

Need to be measured!

W. Dickhoff – augmented CE

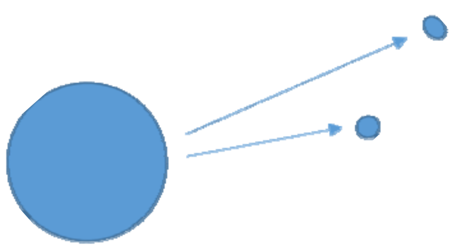
Invariant-mass spectroscopy for two-proton decay (HiRA collaboration)

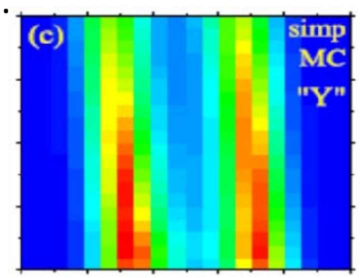
Known prompt two-proton emitting ground states: ^{6}Be, ^{8}C, ^{11}O, ^{12}O, ^{15}Ne, ^{16}Ne (decay in target)
^{19}Mg (ns life time)
gap
^{45}Fe, ^{48}Ni, ^{54}Zn, ^{67}Kr (ms life times)

What about intermediate cases ^{21}Si, ^{26}S(S_p=-0.05, S_{2p}=-1.7 MeV), ^{30}Ar (S_p=-0.5, S_{2p}=-2.28), ^{34}Ca (S_p = 0.48, S_{2p}=-1.47 MeV), ^{38}Ti(S_p = -0.06, S_{2p}=-2.7 MeV) and ^{41}Cr

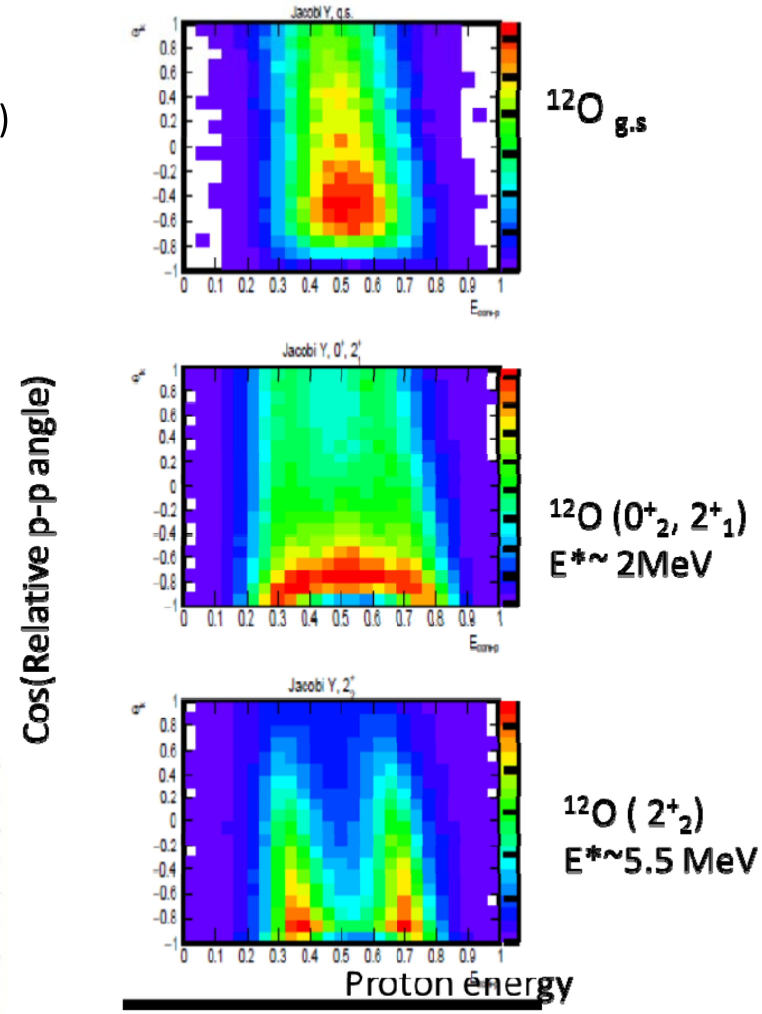
^{34}Ca is a prompt 2p-emitter, but not sure about all the others.

Momentum correlations between the decay fragments give information on the nature of the decay (prompt , sequential) and spectroscopic information (^{45}Fe - sensitivity to amount of p^2 configuration).
Prompt decay persist for excited states (unexpected) where we have a hybrid between "di-proton" emission and sequential.





Sequential simulation

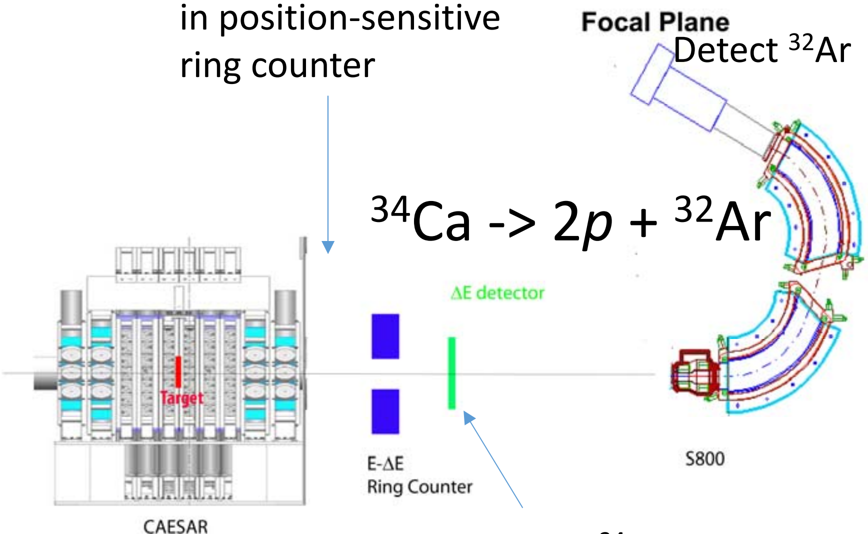


Experimental data

Detect protons
in position-sensitive
ring counter

Detect ^{32}Ar

^{34}Ca -> 2p + ^{32}Ar



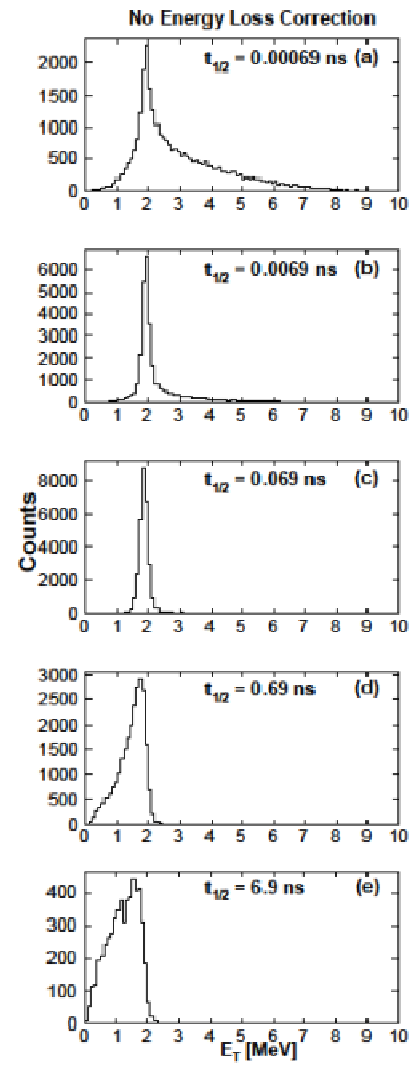
Detect γ-rays from
^{32}Ar

In case ^{34}Ca is
longer-lived and decays in flight

^{35}Ca secondary beam,
^{34}Ca from neutron knockout
Estimates of lifetime range from fs to 10's of ns.

Choice of secondary beam energy?
At E/A=150 MeV, loose ½ of events
as one of the protons undergo a nuclear reaction
in the ring counter before it is stopped.
But intensity is peaked at higher energies.

Invariant-mass
line shape analysis
can tell us about the
lifetime



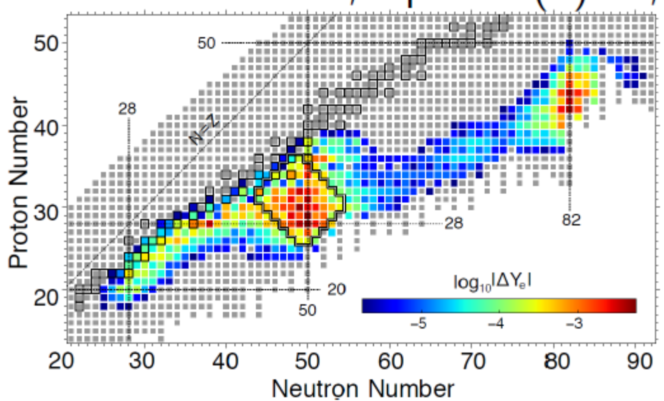
MoNA-LISA for the neutron-rich
invariant-mass spectroscopy.

Study of (d, ^{2}He) charge-exchange reactions in inverse kinematics

R. Zegers, J. Zamora, NSCL CE group, and AT-TPC collaboration

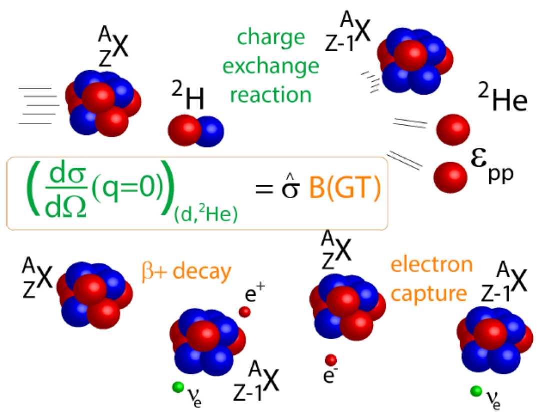
- Electron-capture rates on neutron-rich unstable nuclei are important for simulations of core-collapse supernovae, crustal process in neutron stars, etc.

C. Sullivan et al., ApJ 816(1):44, 2016



- Gamow-Teller (GT) transitions in the β^+ direction are important for benchmarking and guiding theoretical efforts to build an accurate electron-capture rate library for astrophysical simulations.
- Charge-exchange (CE) reactions at intermediate energies are the preferred experimental tool to measure these GT transitions

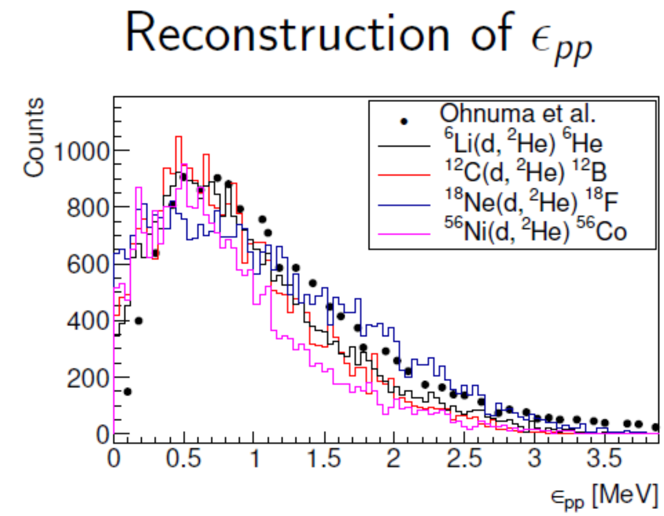
- Stable nuclei: use (n,p), (d,^{2}He), (t, ^{3}He) and heavy-ion CE (forward kinematics) at E/A>100 MeV
- Need to extract E_x and θ_{cm} with good accuracy for E_x up to ~ 10 MeV
- Unstable nuclei: the (d, ^{2}He) reaction in inverse kinematics might be the only viable tool

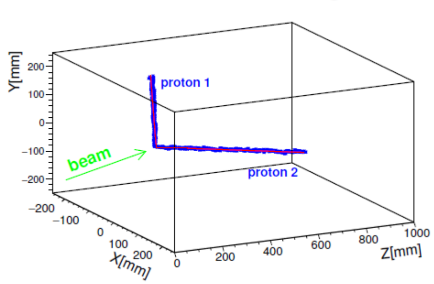


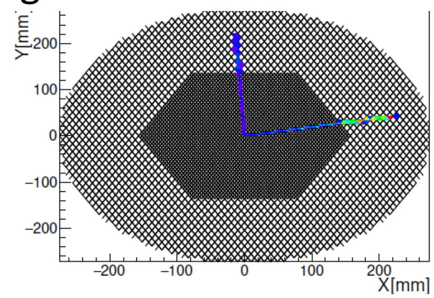
- (d,^{2}He) reaction is a good $\Delta S=1$, $\Delta T=1$ probe. At forward θ_{cm} angles: excellent GT probe.
- ^{2}He decays into 2 protons. Measurements of small *p-p* relative energies (ε_{pp}) ensures a transition to ^{2}He $^1S_0$ "state"

Simulation of (d, ^{2}He) reactions with the AT-TPC

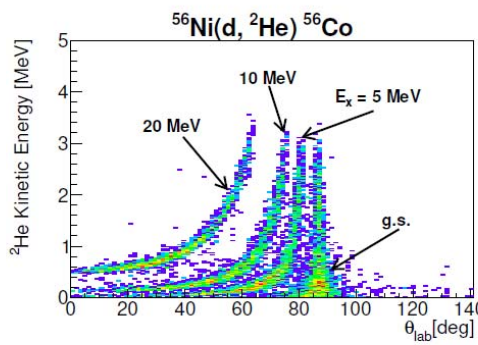
- AT-TPC volume filled with D_2 at 1 atm: $\rho\,\delta x \approx 16$ mg/cm^2
- Heavy ejectile measured in spectrometer (S800, HRS) to tag CE reaction
- Reaction kinematics (E_x and θ_{cm}) are reconstructed from the detection and tracking of low-energy protons from the decay of ^{2}He $^1S_0$ state in the AT-TPC
- Beam energy: 100 MeV/u. An intensity of 10^5 pps is required to achieve the needed luminosity of ~10^{26} cm^{-2}s^{-1}. FRIB beams are crucial to reach nuclei of interest.
- Geant4 simulations show feasibility of method, but challenging!
- Method can be tested with light RI beam at NSCL

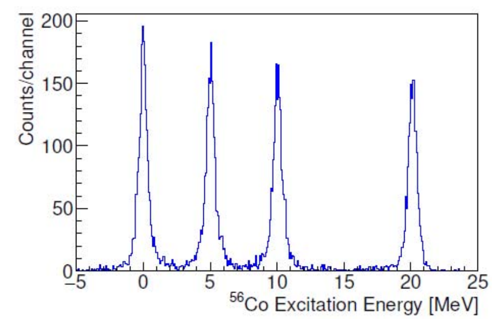






Generation of (d,^{2}He) events in Geant4 simulation. Test tracking and reconstruction with realistic experimental parameters





Reconstruction of ^{2}He, ε_{pp}, E_x, and θ_{cm} feasible with sufficient resolutions for achieving scientific objectives

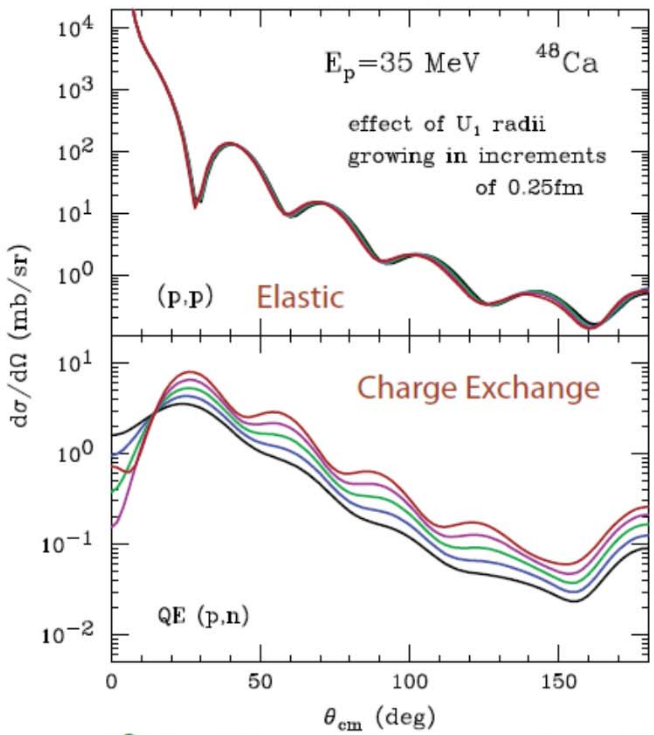
Theory for reactions above 50 MeV/u beam energy

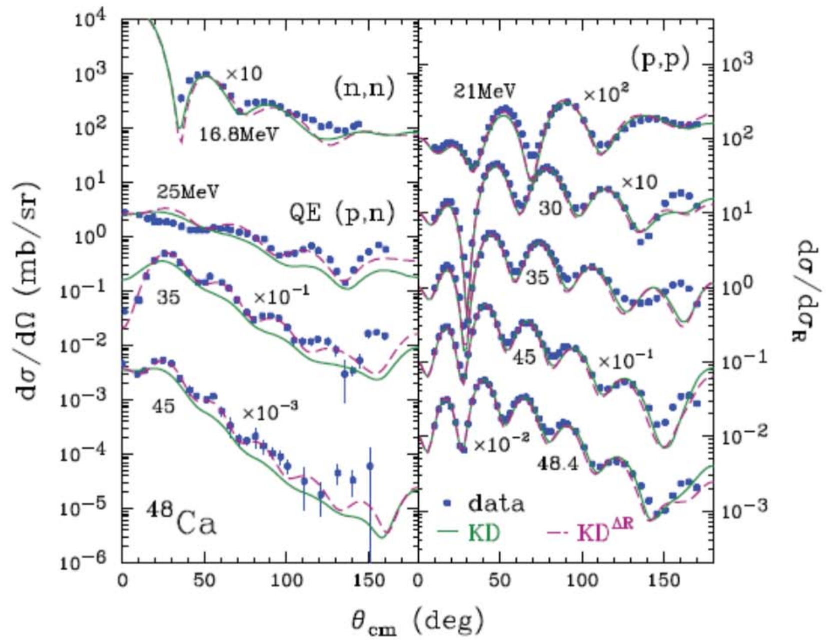
- Priority: Reactions with fast beams (e.g. performed at the S800 and the HRS) have **enormous discovery potential** due to the high luminosity afforded by the use of thick targets and the resulting reach on the nuclear chart. Nuclear structure information is extracted most often in comparison to reaction theory
- Need: The only developments in the corresponding reaction theory have been driven by less than a handful of theorists, mostly based outside of the US, and several of them will be retired by the time FRIB comes online
- Opportunity: Fast-beam reaction theory developments, if started now, would be extremely relevant and are truly needed for FRIB experiments at the frontier of discovery. This is an opportunity for the US theory community to lead

Alexandra Gade and Remco Zegers

Skins/Aura from Charge-Exchange Reactions

Skins more accessible from quasielastic exchange reactions + elastic scattering than electron or nucleon scattering alone





(^{3}He, *t*) could be used and even heavy ions

Danielewicz, Sing & Lee NPA958(17)147

FRIB Day-1 Science: challenges for nuclear reactions

Priorities for FRIB theory

General Goal: Develop many-body theory that will unify nuclear structure and reactions

- Develop quantified microscopic effective interactions as input to describe direct reactions
- Develop exacts methods for solving reactions and test reliability across the nuclear chart
- Develop predictive model of excitation functions/production cross sections
- Explain properties of many-body systems around the reaction threshold. This includes microscopic picture of cluster structures

Ideas/needs for achieving them

- Reaction cross sections based on different approaches
  - Continuum shell models (different realizations) with RGM
  - Green's function approach based on NN and NNN interactions
  - Spectator approach with continuum shell models
- Heavy Ion fusion and quasi-fission reactions from Time-Dependent DFT and DFT
- Advanced statistical tools for uncertainty quantification, model development, data selection, and identification of key experimental data needed
- Development of databases of
  - theoretical results
  - Nuclear matrix elements and codes to process them
  - open-source reaction codes and corresponding user groups

W. Nazarewicz, LECM 2017 – augmented Ch. Elster

FRIB Day-1 Science: nuclear reaction challenges

Impact on/alignment with the experimental effort. Experimental data needed.

- Key measurements:
- reaction mechanism involving neutron-rich projectiles
- Cross sections/excitation functions; angular and energy correlations of light particles (to probe, e.g., di-neutron or di-proton structures);
- Benchmark cross sections for theory approaches
- Pair transfer with exotic projectiles to probe pairing channel

W. Nazarewicz, LECM 2017 -- augmented Ch. Elster