First Experimental Test of the Ratio Method

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20 August 2024

Halo Nuclei

Exotic nuclei found far from stability

- Light, n-rich nuclei
- Low S_{n} or $S_{2\mathrm{n}}$

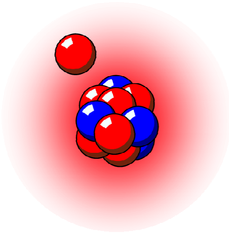


Exhibit large matter radius :

neutrons tunnel far from the core and form a halo

One-neutron halo

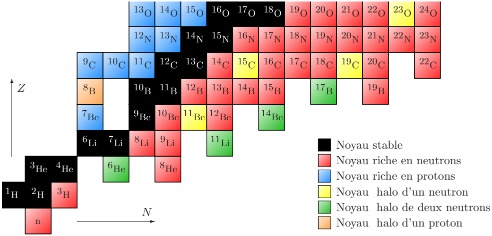
^{11}Be ≡ ^{10}Be + n

^{15}C ≡ ^{14}C + n

Two-neutron halo

^{6}He ≡ ^{4}He + n + n

^{11}Li ≡ ^{9}Li + n + n



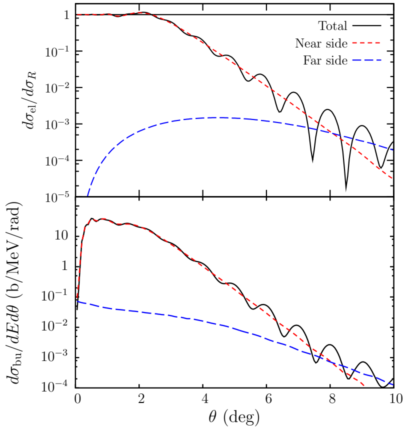
Short lifetime [$t_{1/2}(^{11}\mathrm{Be}) = 13$ s] ⇒ studied mostly through reactions : elastic scattering, breakup, transfer...

We propose a new reaction observable : the Ratio Method

How it all began. . .

With Mahir Hussein, study of angular distributions for scattering and breakup of halo nuclei

^{11}Be + Pb @ $69A$ MeV



Very similar features for scattering and breakup :

- oscillations at fwd angles
- Coulomb rainbow ($\sim 2°$)
- oscillations at large angles (N/F interferences)

$\Rightarrow$ projectile scattered similarly whether bound or broken up

[PC, Hussein, Baye PLB 694, 448 (2010)]

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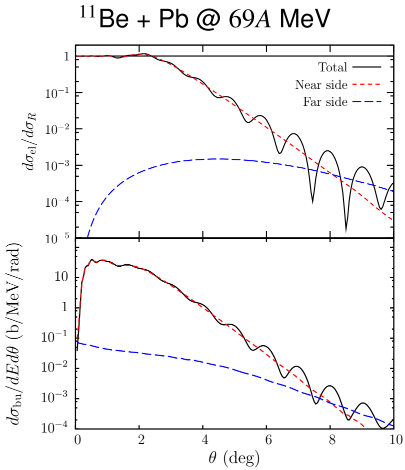

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Then I showed this to Ron Johnson. . .

[PC, Hussein, Baye PLB 694, 448 (2010)]

Recoil Excitation and Breakup

REB assumes [Johnson, Al-Khalili, Tostevin PRL 79, 2771 (1997)]

- adiabatic approximation
- $U_{\mathrm{n}T} = 0$

$\Rightarrow$ excitation and breakup due to recoil of the core

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Elastic scattering : $$\frac{d\sigma_{\rm el}}{d\Omega} = |F_{00}|^2 \left(\frac{d\sigma}{d\Omega}\right)_{\rm pt}$$

with $F_{00} = \int |\Phi_0|^2 e^{i\boldsymbol{Q}\cdot\boldsymbol{r}} d\boldsymbol{r}$ $\quad \boldsymbol{Q} \propto (\boldsymbol{K} - \boldsymbol{K}')$

$\Rightarrow$ scattering of compound nucleus $\equiv$

form factor $\times$ scattering of pointlike nucleus

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Similarly for breakup : $$\frac{d\sigma_{\mathrm{bu}}}{dEd\Omega} = |F_{E0}|^2 \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{pt}}$$

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provides the idea for the Ratio Method. . .

The Ratio Idea

[PC, Johnson, Nunes PLB 705, 112 (2011)]

$$d\sigma_{\rm bu}/d\sigma_{\rm el} = |F_{E0}(\boldsymbol{Q})|^2/|F_{00}(\boldsymbol{Q})|^2$$

- independent of reaction mechanism
  not affected by U_{PT} $\Rightarrow$ the same for all targets
- probes only projectile structure
- no need to normalise experimental cross sections

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Alternative : [PC, Johnson, Nunes PRC 88, 044602 (2013)]

$$\mathcal{R}_{\int \rm sum} = \frac{\int \frac{d\sigma_{\rm bu}}{dE d\Omega}\, dE}{\frac{d\sigma_{\rm el}}{d\Omega} + \frac{d\sigma_{\rm inel}}{d\Omega} + \int \frac{d\sigma_{\rm bu}}{dE d\Omega}\, dE} \overset{\rm REB}{=} 1 - |F_{00}|^2$$

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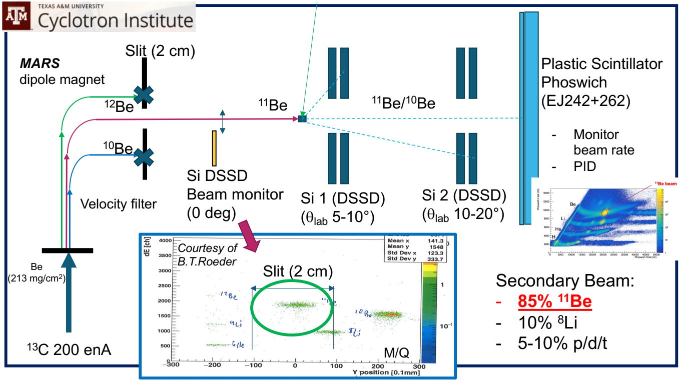
Test this experimentally @ TAMU

$$^{11}\text{Be+C} \rightarrow {}^{10,11}\text{Be+C @ } 22.5A \text{ MeV}$$

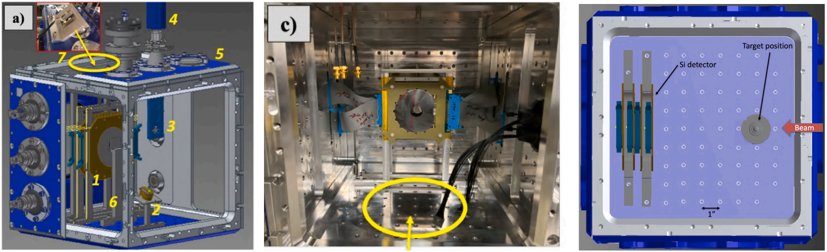
Measurement @ TAMU : ^{11}Be + C @ $22.5A$ MeV



- Use K500 TAMU Cyclotron
- Primary beam of ^{13}C @ $30A$ MeV on Be target
- Produces a secondary beam of ^{11}Be @ $22.5A$ MeV
- 10^4 pps with 85% ^{11}Be on secondary target [C_{nat} (17 mg/cm^2)]
- Products ^{10,11}Be detected with BlueSTEAI

Blue-STEAl

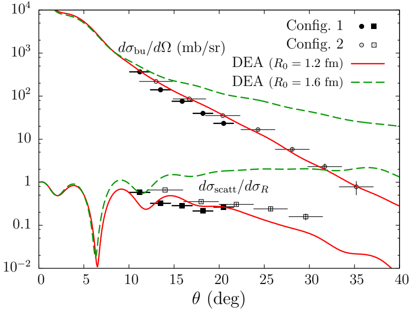
Blue aluminum chamber of Silicon TElescope Arrays for light nuclei



[Ota *et al.* NIM A 1059, 168946 (2024)]

- Scattering chamber to study direct reactions in inverse kin.
- 4 Si stripped detectors can be used as ΔE-E telescope arrays
- Different possible configurations to measure
  - forward $\theta \gtrsim 4^\circ$
  - up to large angles $\theta \lesssim 30^\circ$

^{11}Be + C @ $22.5A$ MeV
(inclusive) breakup & scattering



- Clean data [Ota, PC *et al.* arXiv:2407.15535]
- Well reproduced with accurate reaction calculations with optical potentials from double folding of χ_{EFT} V_{NN} of cutoff
  - $R_0 = 1.2$ fm excellent agreement with data
  - $R_0 = 1.6$ fm too soft $\Rightarrow$ too large cross sections

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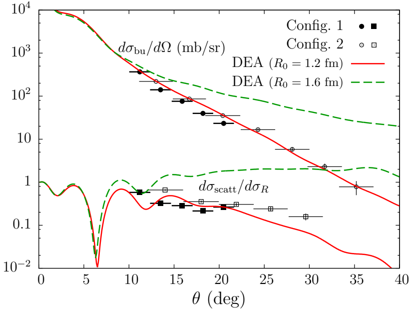
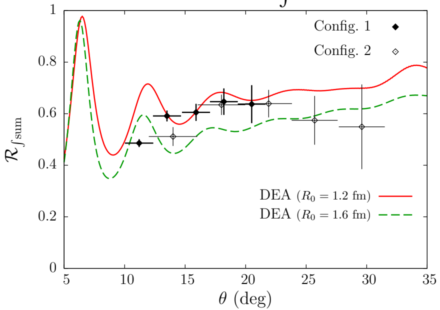


Ratio $\mathcal{R}_{\int \text{sum}}$



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  - $R_0 = 1.2$ fm excellent agreement with data
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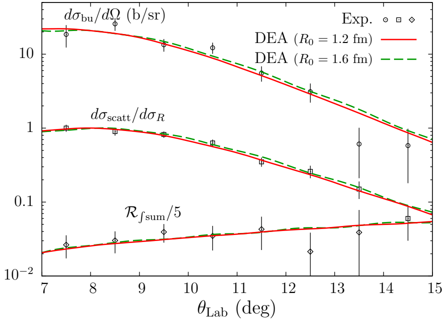
- Ratio $\mathcal{R}_{\int \text{sum}}$ has smooth angular dependence
  - both cutoffs in agreement with data

^{11}Be + Pb @ 19A MeV

Similar data on Pb from Lanzhou [Duan *et al.* PRC 105, 034602 (2022)]



- Calculations in excellent agreement with data
  [Ota, PC *et al.* arXiv:2407.15535]
- Little influence of optical potentials (Coulomb dominated)
- Ratio
  - removes the angular dependence
  - reproduced by theory

Summary and outlook

- The ratio method is new reaction observable to study halo nuclei, predicted to be
  - independent of reaction process (and optical potentials)
  - very sensitive to structure observables

[PC, Johnson, Nunes PLB 705, 112 (2011)]

- Confirmed this with first measurement @ TAMU
  ^{11}Be+C @ $22.5A$ MeV [Ota, PC *et al.* arXiv:2407.15535]
  (and re-analysis of Lanzhou data ^{11}Be+Pb @ $19A$ MeV)
  but inclusive breakup ⇒ limited accuracy
- We need to measure the ratio
  - with exclusive breakup (n in coincidence)
  - at higher beam energy

  will enable a direct comparison to form factor $|F_{E0}|^2$
- Plan to do that @ FRIB for ^{19}C…

Thanks to my collaborators

Shuya Ota

Experimental team

Mahir Hussein†

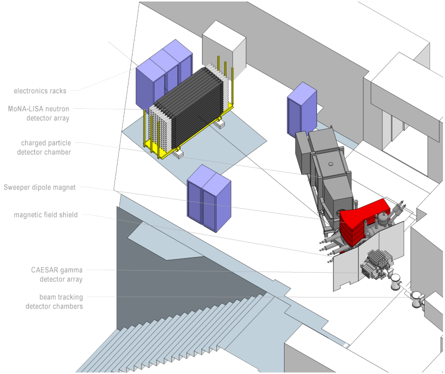
Ron Johnson

Filomena Nunes

Victoria Durant

...and to you for your attention!

Future @ FRIB (MoNA) : breakup and scattering of ^{19}C



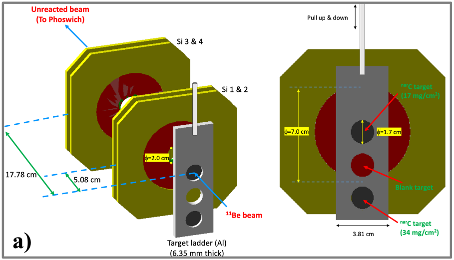
- at larger beam energy
  viz. $100A$ MeV
- C and/or Pb targets
- use MoNA
  to detect n in coincidence

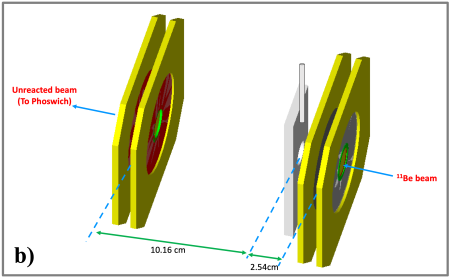
$\Rightarrow$ kill two birds with one stone

- Test the full ratio method
- Study accurately ^{19}C :
  - S_n
  - ANC
  - Resonance structure

Configurations 1 & 2

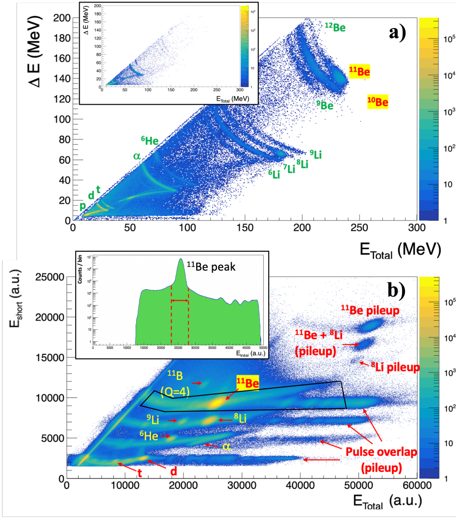
We used two configurations of the Si detectors used in pairs for ΔE-E PID





1. Config. 1 :
   - 2 "near" @ 5 cm
     $(\theta_{\text{lab}} = 17° - 31°)$
   - 2 "far" @ 18 cm
     $(\theta_{\text{lab}} = 5° - 10°)$
2. Config. 2 :
   - 2 detectors at 10 cm
     $(\theta_{\text{lab}} = 8° - 18°)$

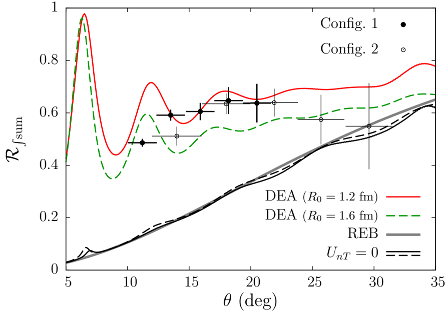
PID

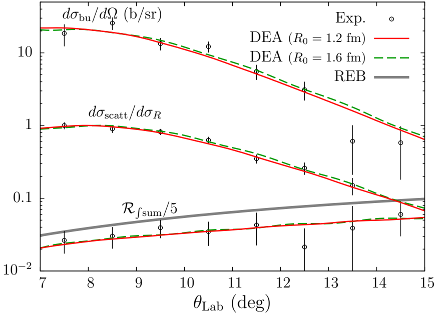


- Very clear PID
  by ΔE-E in the Si telescopes
- Test with empty target (inset) confirms ^{11}Be and ^{10}Be come from reaction with target
  - ^{11}Be : scattering (el. & inel.)
  - ^{10}Be : 1-n removal (incl. bu)
- Clear PID in phoswich plastic scintillator placed 30 cm downstream to measure beam rate

Comparison to REB form factor

^{11}Be + C @ $22.5A$ MeV ^{11}Be + Pb @ $19A$ MeV





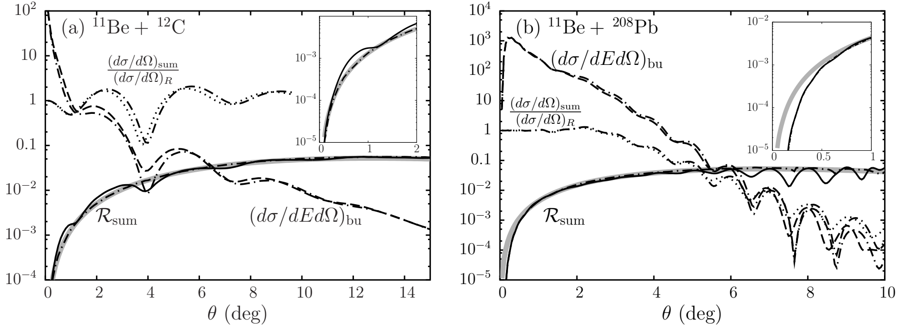
REB form factor disagrees with data

- On C : U_{nT} not negligible
- On Pb : adiabatic approximation not fully valid

$\Rightarrow$ need to measure

- n in coincidence
- consider low ^{10}Be-n energies

DEA calculation of the ratio @ $70A$ MeV



[PC, Johnson, Nunes PLB 705, 112 (2011), PRC 88, 044602 (2013)]

Dynamical calculations confirm the idea :

- Same pattern for scattering and breakup
- Ratio is smooth ⇒ removes sensitivity to reaction mechanism
- In excellent agreement with REB form factor $|F_{E0}|^2$
- Small influence of
  - U_{nT} (shift of breakup)
  - Dynamics (on Pb at fwd angles)

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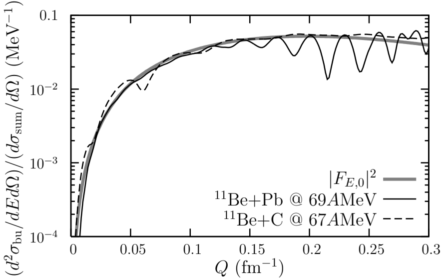

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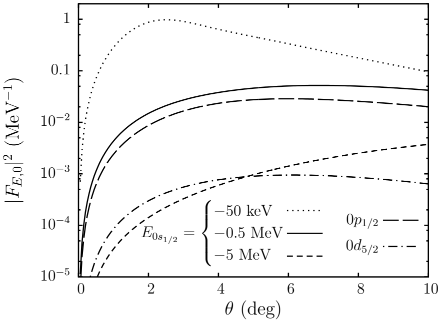
- Small influence of
  - U_{nT} (shift of breakup)
  - Dynamics (on Pb at fwd angles)
- Independent of the target

Sensitivity to the projectile structure

Because insensitive to U_{PT} and reaction dynamics
very sensitive to projectile structure

Angular dependence and magnitude of form factor F_{E0} change with



- neutron binding energy E_0
- orbital angular momentum ℓ

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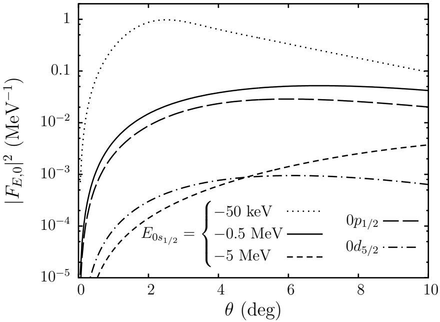

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[PC, Johnson, Nunes
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Ratio idea extended to

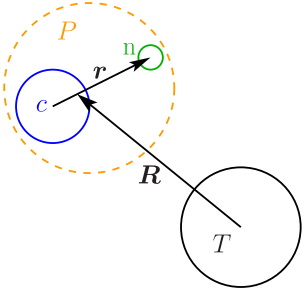
- low beam energy ($20A$ MeV) [Colomer *et al.* PRC 93, 054621 (2016)]
- proton halos [Yun, Colomer *et al.* JPG 46, 105111 (2019)]

Short review : [PC, Johnson, Nunes EPJA 56, 300 (2020)]

Framework

Projectile (P) modelled as a two-body system :
core (c)+loosely bound neutron (n) described by

$$H_0 = T_r + V_{c\mathrm{n}}(\boldsymbol{r})$$



$V_{c\mathrm{n}}$ adjusted to reproduce P spectrum

Target T seen as structureless particle

P-T interaction simulated by optical potentials

$\Rightarrow$ breakup reduces to three-body scattering problem :

$$[T_R + H_0 + U_{cT} + U_{\mathrm{n}T}]\,\Psi(\boldsymbol{r},\boldsymbol{R}) = E_T\Psi(\boldsymbol{r},\boldsymbol{R})$$

with initial condition $\Psi(\boldsymbol{r},\boldsymbol{R}) \underset{Z\to-\infty}{\longrightarrow} e^{iKZ+\cdots}\,\phi_0(\boldsymbol{r})$