First experimental test of the ratio method

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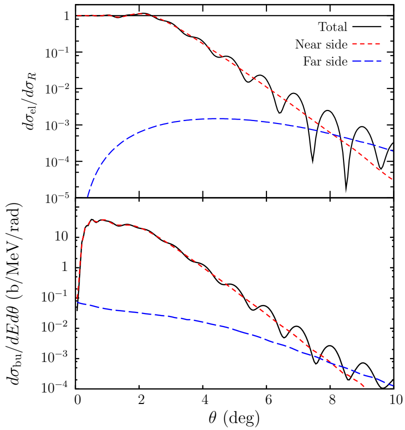
How it all began. . .

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)

⇒ projectile scattered similarly whether bound or broken up

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
- $U_{nT} = 0$

⇒ excitation and breakup due to recoil of the core

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

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

⇒ scattering of compound nucleus ≡

form factor × scattering of pointlike nucleus

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

with $|F_{E0}|^2 = \sum_{ljm} \left| \int \Phi_{ljm}(E)\Phi_0 e^{i\boldsymbol{Q}\cdot\boldsymbol{r}} d\boldsymbol{r} \right|^2$

⇒ explains similarities in angular distributions

provides the idea for the ratio technique. . .

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} ⇒ the same for all targets
- probes only projectile structure
- no need to normalise experimental cross sections

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

$$\mathcal{R}_{\rm sum} = d\sigma_{\rm bu}/d\sigma_{\rm sum} \overset{\rm REB}{=} |F_{E0}|^2$$

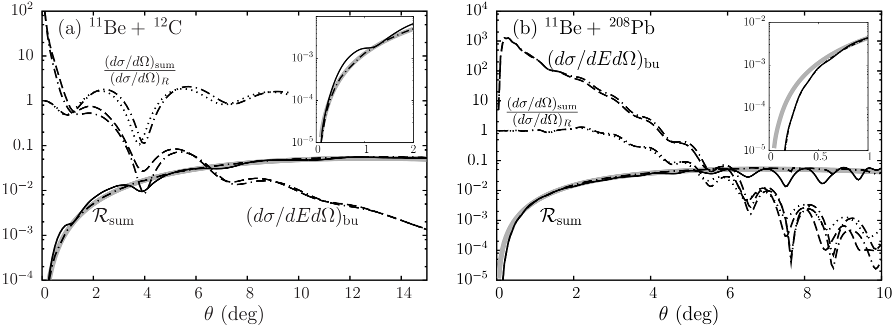
$$\text{with } \frac{d\sigma_{\rm sum}}{d\Omega} = \frac{d\sigma_{\rm el}}{d\Omega} + \frac{d\sigma_{\rm inel}}{d\Omega} + \int \frac{d\sigma_{\rm bu}}{dEd\Omega} dE$$

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

Test this using Dynamical Eikonal Approximation,

- without adiabatic approximation
- including U_{nT}

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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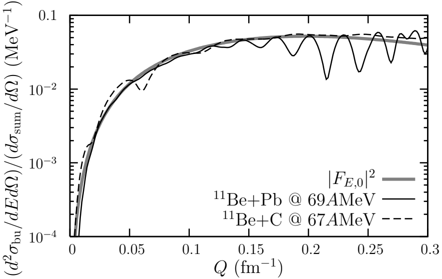

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- In excellent agreement with REB form factor $|F_{E0}|^2$
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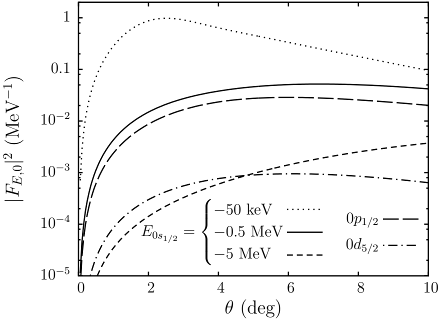
  - U_{nT} (shift of breakup)
  - Dynamics (on Pb at fwd angles)
- Independent of the target

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

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

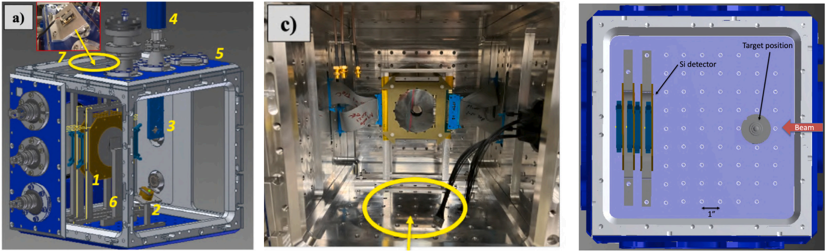
Ratio idea extended to

- 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)]

Blue-STEAl

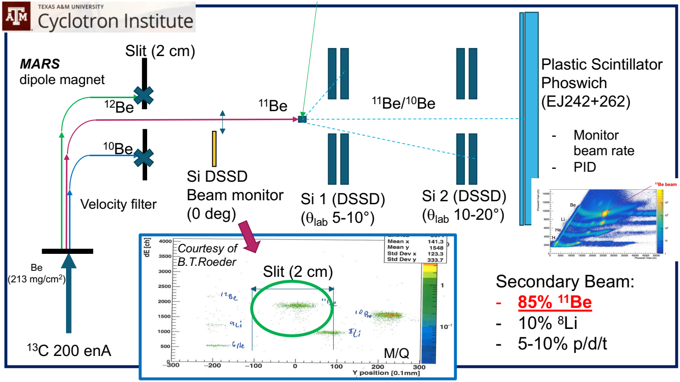
Blue aluminum chamber of Silicon TElescope Arrays for light nuclei



[S. 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 geometries to measure
  - forward $\theta \gtrsim 4^\circ$
  - up to large angles $\theta \lesssim 30^\circ$
- Can be used with RIB

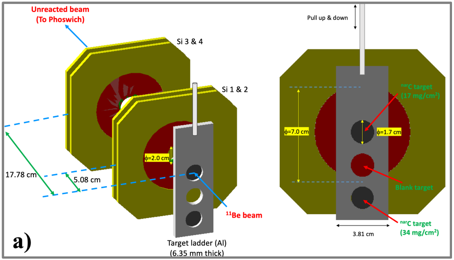
Measurement @ TAMU : ^{11}Be + C @ 22AMeV



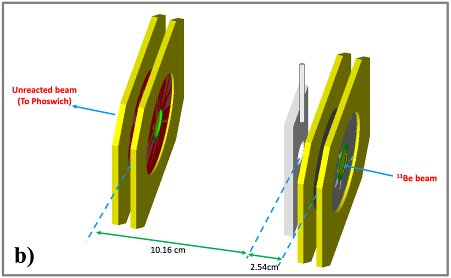
- Use K500 TAMU Cyclotron
- Primary beam of ^{13}C @ 30AMeV on Be target
- Produces a secondary beam of ^{11}Be @ 22.5AMeV
- 10^4 pps with 85% ^{11}Be
- Secondary target : C_{nat} (17 mg/cm^2)

Configurations 1 & 2

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

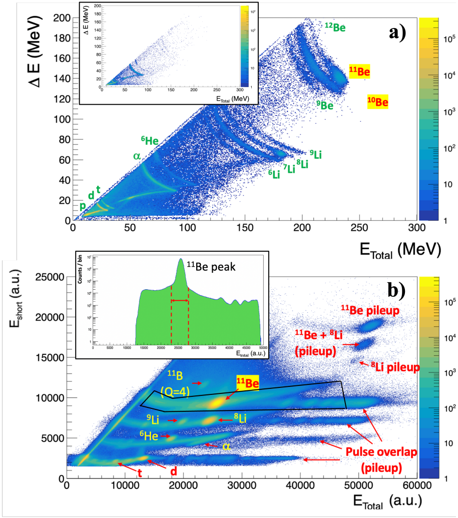


- ❶ Config. 1 :
  - 2 "near" @ 5 cm ($\theta_{\mathrm{lab}} = 17° – 31°$)
  - 2 "far" @ 18 cm ($\theta_{\mathrm{lab}} = 5° – 10°$)



- ❷ Config. 2 :
  - 2 detectors at 10 cm ($\theta_{\mathrm{lab}} = 8° – 18°$)

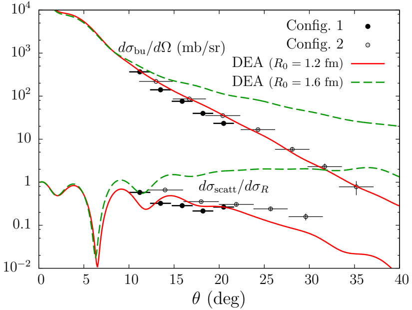
PID



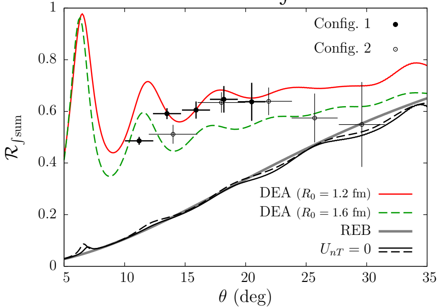
- Very clear PID
  by ΔE-E in the Si telescopes
- Test with empty target (inset) confirms ^{11}Be and ^{10}Be come from reaction with target
  - ^{11}Be : scattering (el. & inel.)
  - ^{10}Be : 1-n removal (incl. bu)
- Clear PID in phoswich plastic scintillator placed 30 cm downstream to measure beam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

^{11}Be + C @ 22AMeV

(inclusive) breakup & scattering



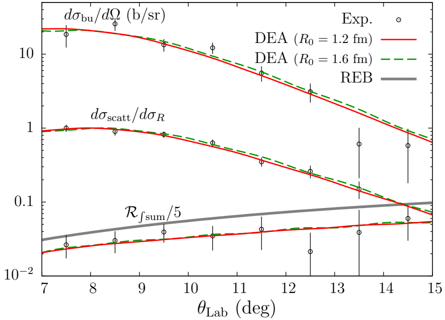
Ratio $\mathcal{R}_{\int \rm sum}$



- Clean data
- Well reproduced with DEA calculations
  with optical potentials from double folding of $\chi_{\rm EFT}$ $V_{\rm NN}$ of cutoff
  - $R_0 = 1.2$ fm excellent agreement with data
  - $R_0 = 1.6$ fm too soft $\Rightarrow$ too large cross sections
- Ratio $\mathcal{R}_{\int \rm sum}$ has smooth angular dependence
  - both cutoffs in agreement with data
  - Difference with REB due to U_{nT} (inclusive breakup)

^{11}Be + Pb @ 19AMeV

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



- DEA calculations in excellent agreement with data
- Little influence of optical potentials (Coulomb dominated)
- Ratio
  - removes the angular dependence
  - reproduced by DEA
  - underestimates REB : dynamical effects

Summary and outlook

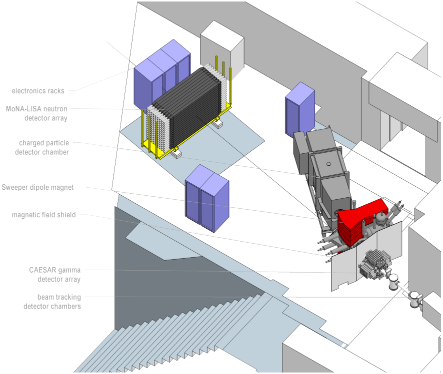
- The ratio method is new reaction observable to study halo nuclei, predicted to be
  - independent of reaction process (and optical potentials)
  - very sensitive to structure observables

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

- Confirmed this with first measurement @ TAMU ^{11}Be+C @ $22A$MeV (and re-analysis of Lanzhou data ^{11}Be+Pb @ $19A$MeV) but inclusive breakup ⇒ limitted 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. . .

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

⇒ kill two birds with one stone

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

Thanks to our collaborators

Mahir Hussein† — Universidade de São Paulo

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Experimental team — Texas A&M University Cyclotron Institute