Large Longitudinal Spin Alignment of Excited Projectiles in Intermediate Energy Inelastic Scattering

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LANL Nuclear Data Seminar

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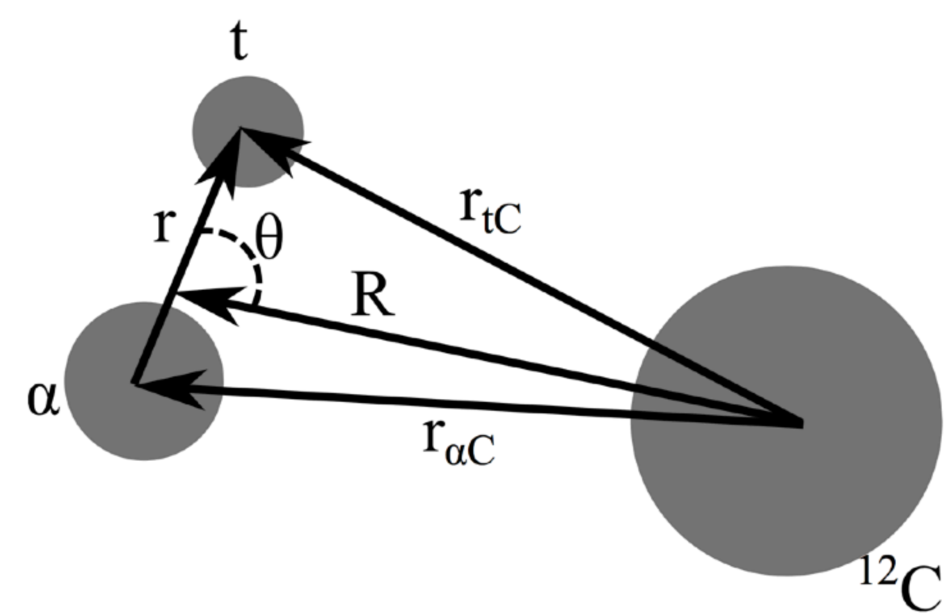
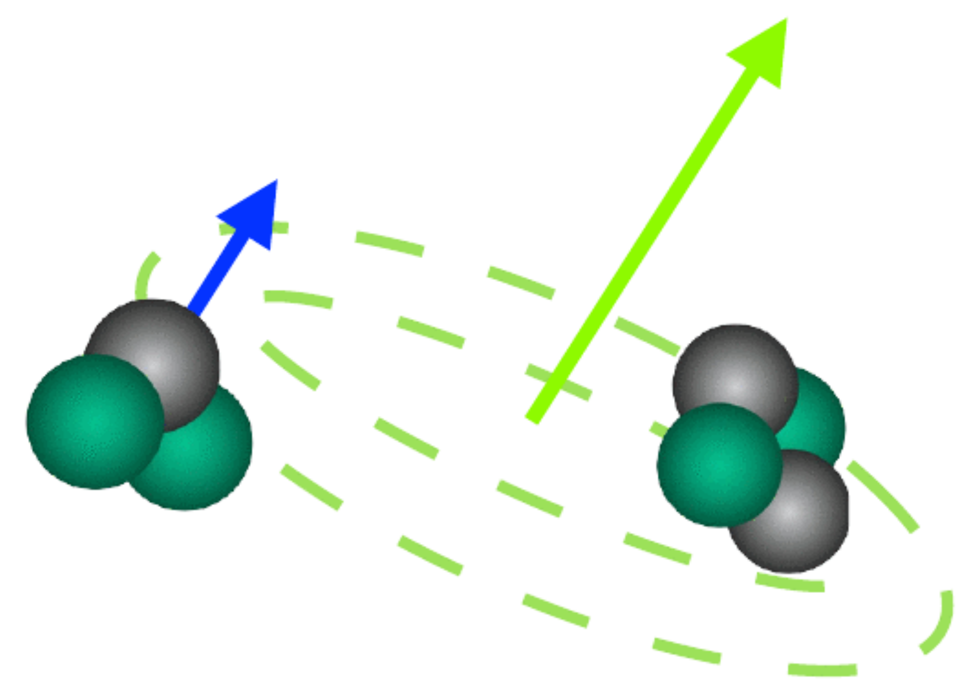
Outline

- Introduction
- Experiment
- Data analysis
- Alignment Mechanism and FRESCO calculations
- Conclusions

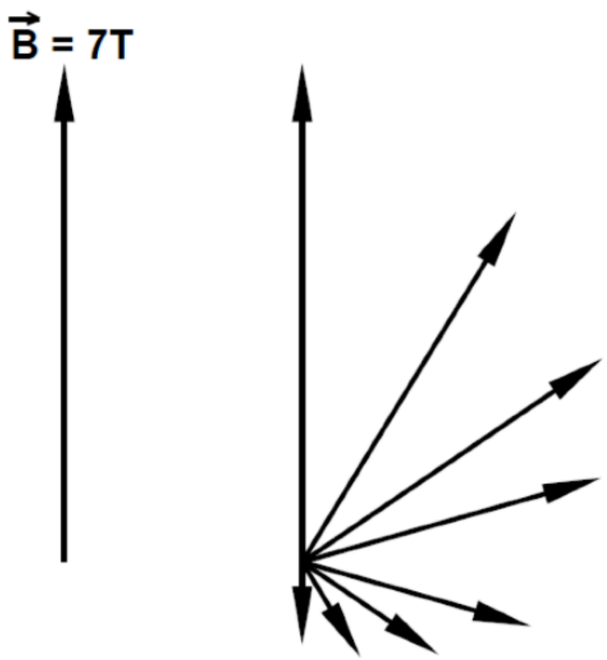




Introduction

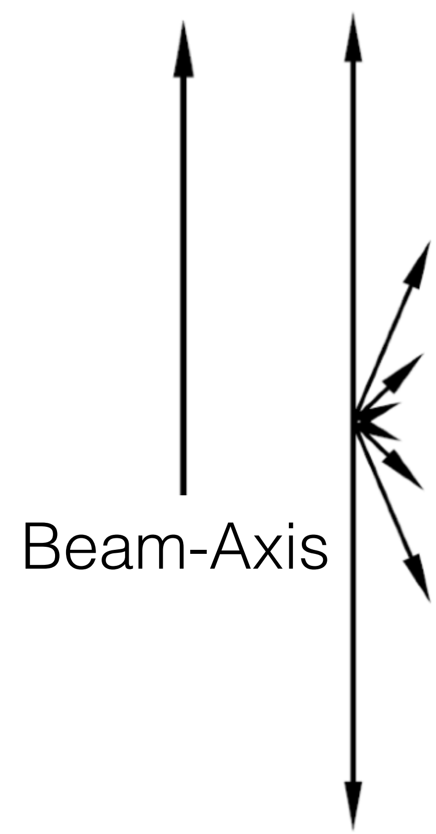
Polarization vs. Alignment

Polarization describes the spin of a particle pointing in mostly one direction
i.e. magnetic substates are lopsided.



Normalized magnetic sub-state populations for $^{7}Li^{*}(J^{\pi} = 7/2^{-})$ in B_0=7T at 20 mK

Alignment describes the spin of a particle pointing along an axis
i.e. magnetic substates are symmetric.



Normalized magnetic sub-state populations given from *PRC **91** 024610 (2015)*

Introduction

- Alignment of nuclear states is useful for g-factor measurements.

- Alignment of molecular states allows for the production of highly polarized hydrogen targets.

- In compound, quasi-elastic, and deep inelastic reactions large alignment ***transverse*** to the beam-axis is common.

  - Can be used for fragment spin determination

- Large alignments are also seen in relativistic Coulomb excitation.

Introduction

- *Longitudinal* alignment (parallel to th beam-axis) has been seen with projectile fragmentation.

- One can quantify the level of alignment with the scalar A (1 = max alignment, -1 = min alignment),

$$A = \sum_{m_f} \frac{3m_f - J(J+1)}{J(2J-1)} \rho^J_{m_f, m_f}$$

density matrix

- A = 0.35 is largest reported long alignment from projectile fragmentation.

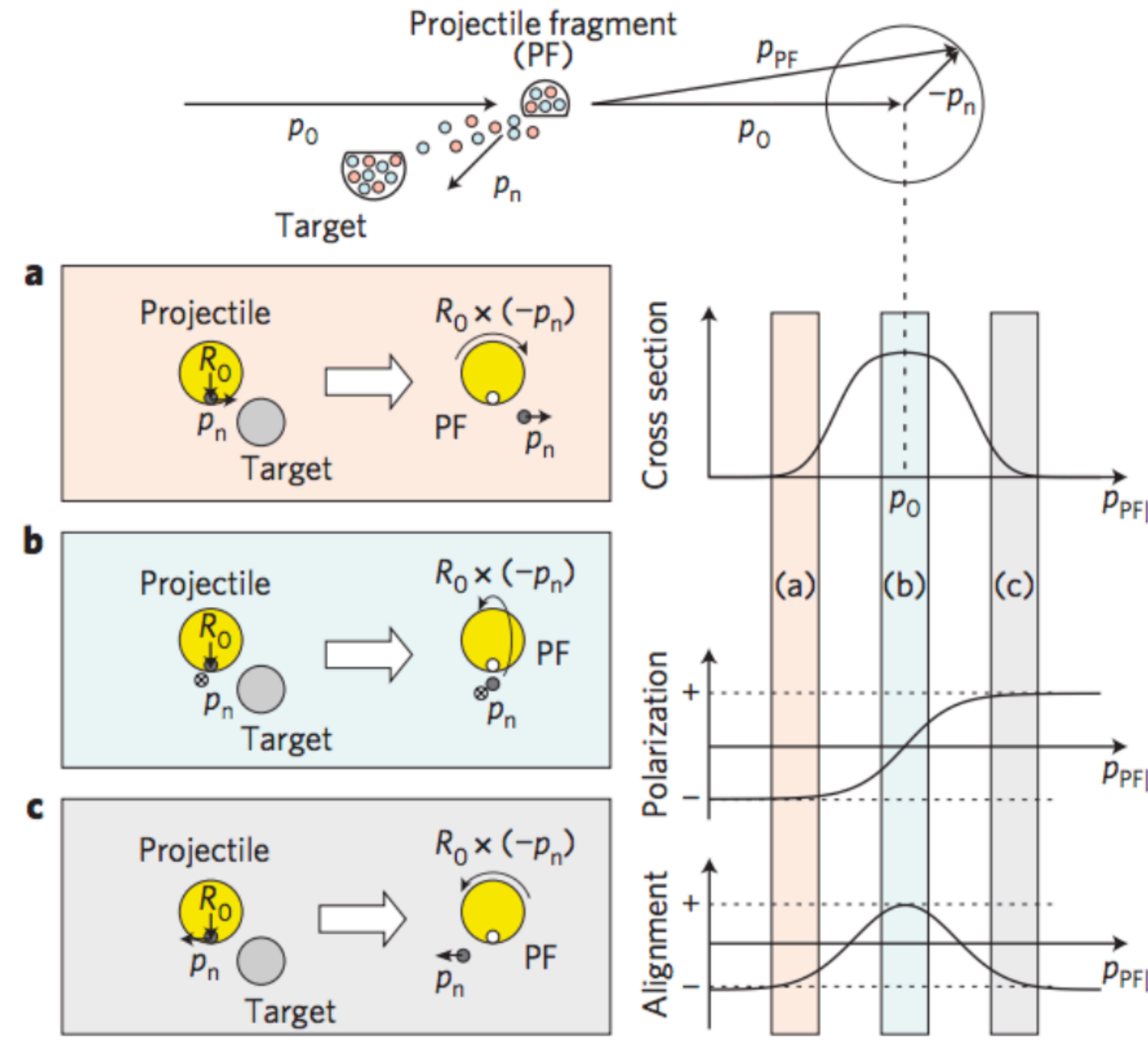


Figure 1. from *Nature Physics* **8**, 918–922 (2012)

Experiment

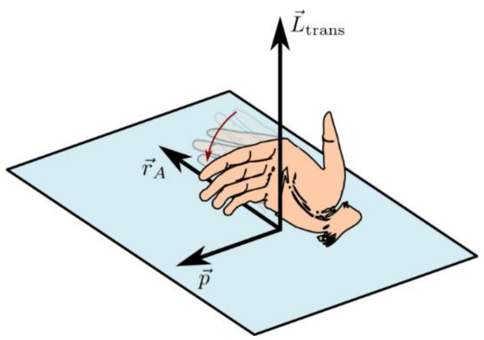
- We studied three ^{7}Li reactions at 24 MeV/A at TAMU:

$$\mathbf{^7Li(J^\pi = 3/2^-) + Be/C/Al \rightarrow {}^7Li^*(J^\pi = 7/2^-) + Be/C/Al}\ \text{(all remaining in GS)}$$

Invariant Mass 2-body kinematics

- We found a ***large*** spin alignment (A = 0.49) of ^{7}Li* *longitudinal* to the beam axis for all three targets.
- Largest reported longitudinal alignment generated from nuclear reactions.
- This is not relativistic Coulomb excitation.
  - 24 MeV/A ^{7}Li is only slightly relativistic.
  - We only used low Z targets.

Experiment



Collisional A.M. $= \mathbf{L} = \mathbf{r} \times \mathbf{p}$

-Known
-Unknown

$\mathbf{p}$

^{7}Li ($J^{\pi} = 3/2^{-}$)

~500 fm

^{7}Li* ($J^{\pi} = 7/2^{-}$)

^{3}H ($J^{\pi} = 1/2^{+}$)

α ($J^{\pi} = 0^{+}$)

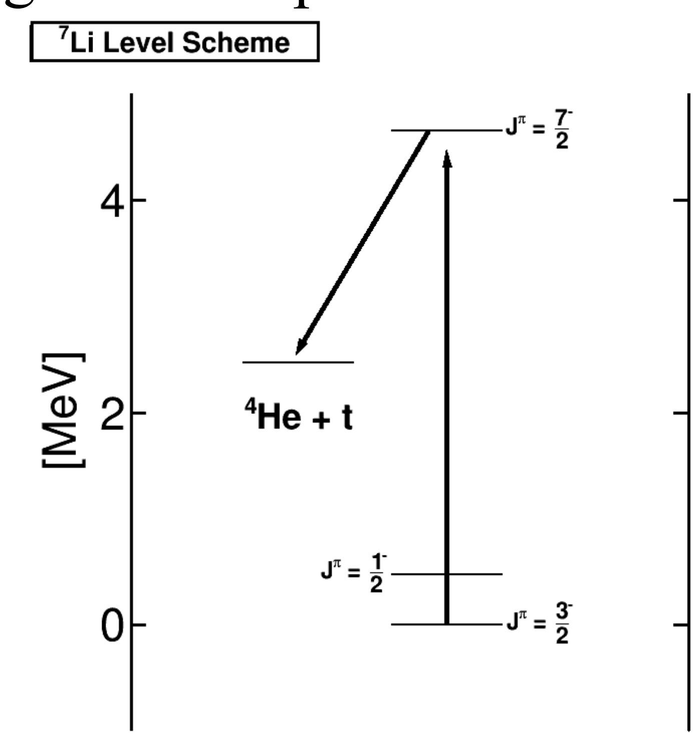
Decay fragments carry orbital A.M depending on fragments' total spin

^{12}C(^{7}Li,^{7}Li*)^{12}C @ 24 MeV/A generates up to 36ħ collisional A.M.

$\mathbf{r}$

The largest reservoir of A.M. is the collisional orbital A.M. (*transverse* to **p** i.e. ⊥to beam)

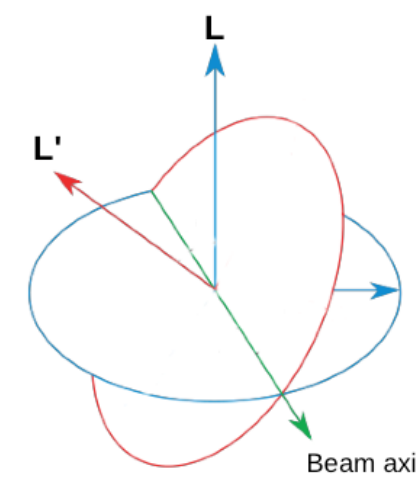
L→spin preferentially aligns spins ⊥to beam axis



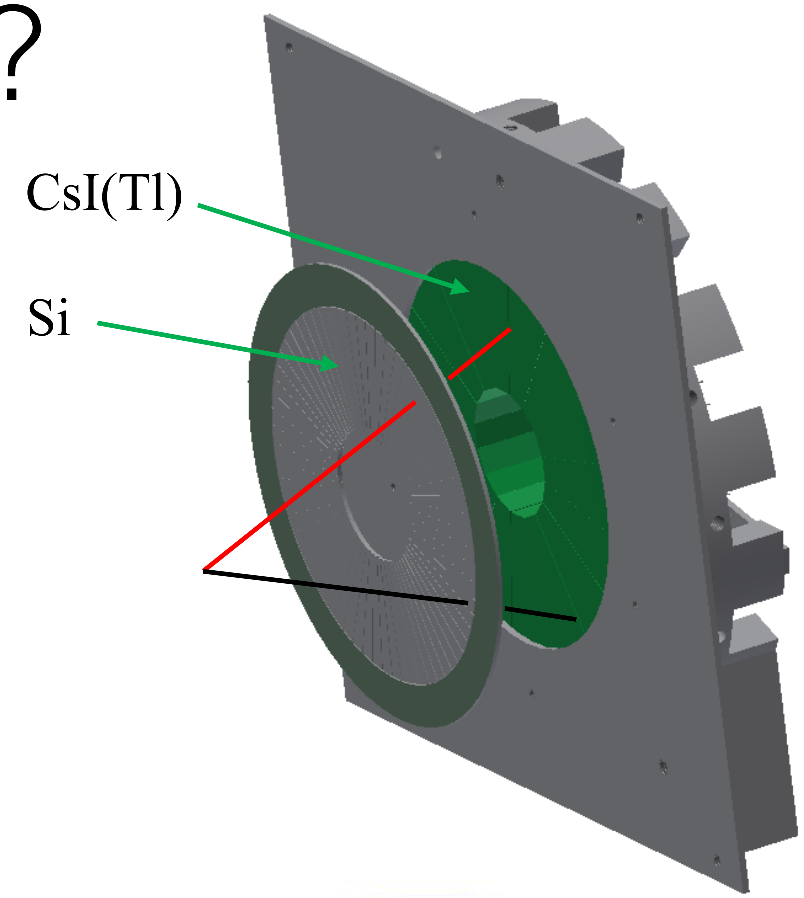
^{12}C ($J^{\pi} = 3/2^{-}$)

^{12}C ($J^{\pi} = 3/2^{-}$)

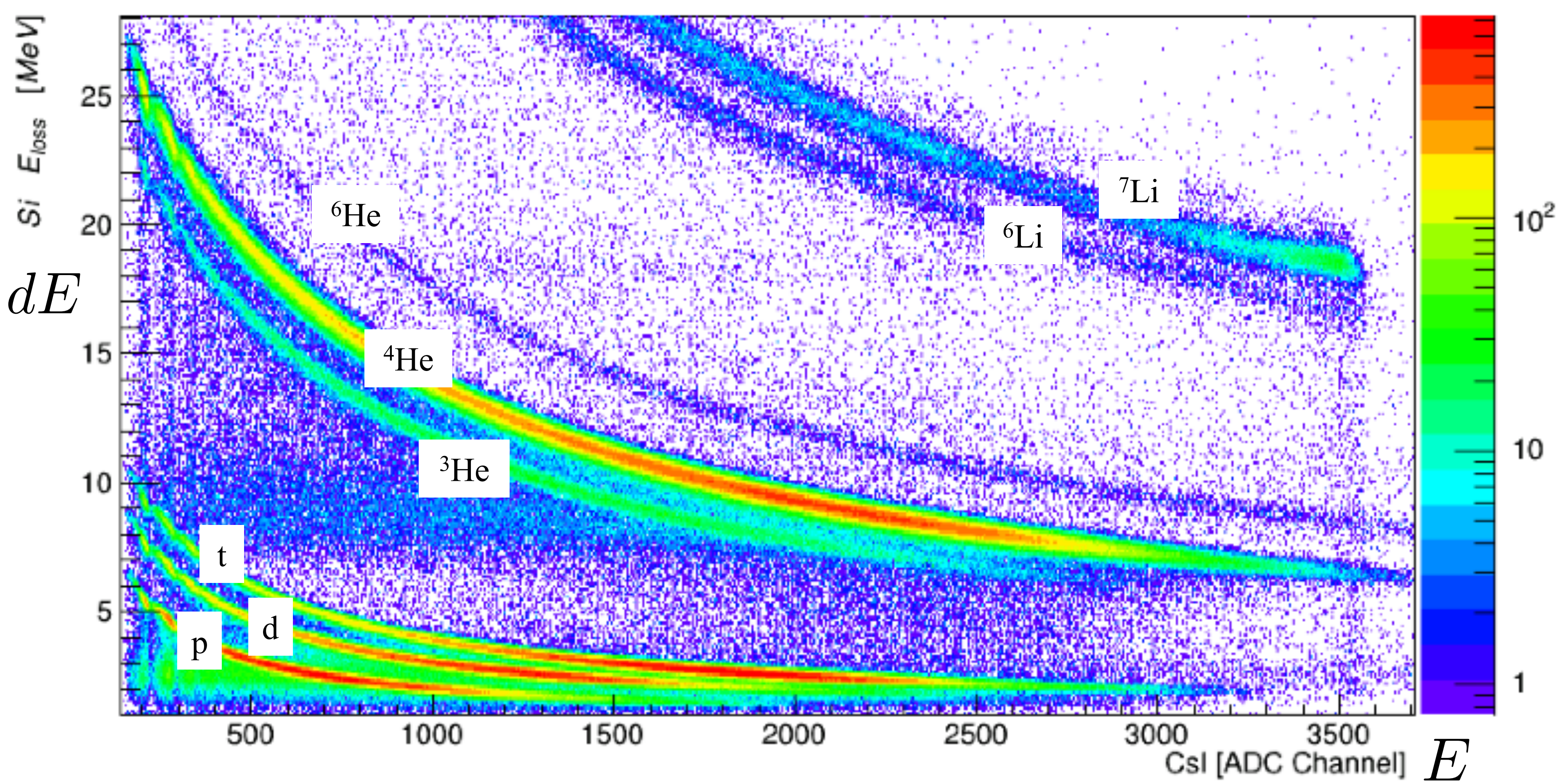
$\mathbf{r}$ ~ fermi



How do we measure projectile fragments (α+t)?

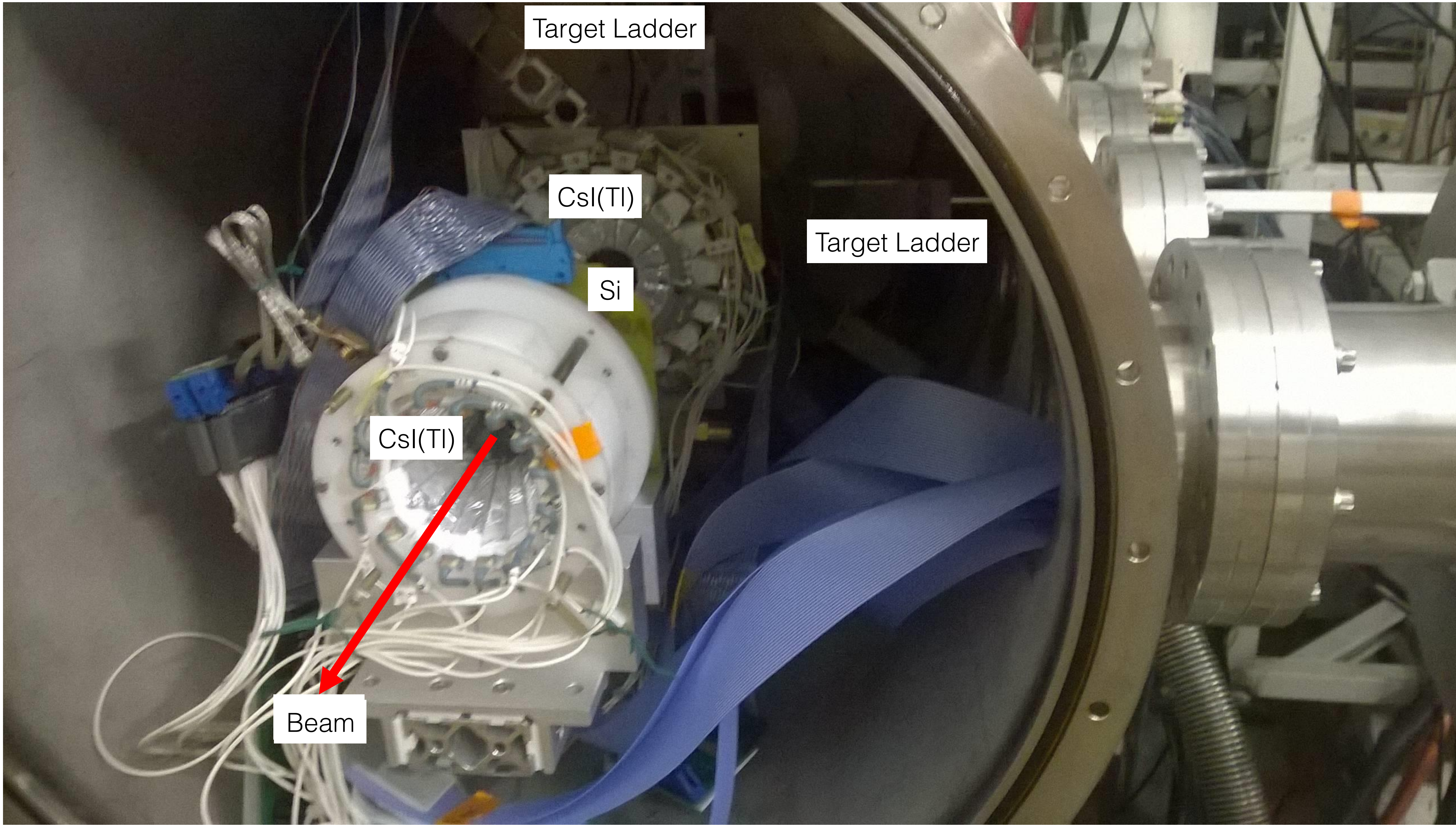


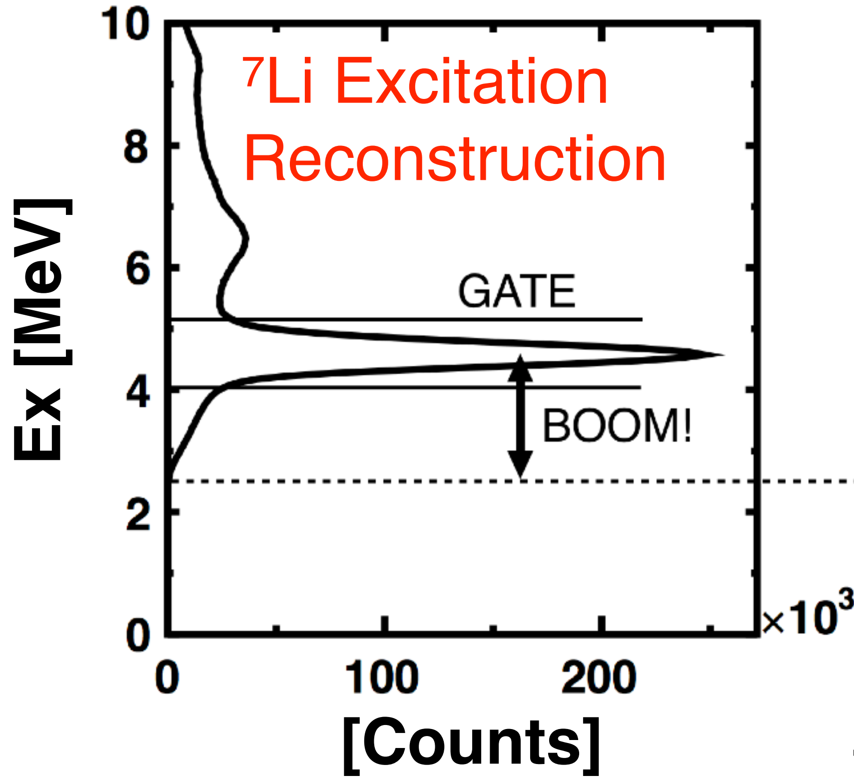
- We used two annular Si-CsI(Tl) telescopes, one looking through the hole of the other ➔
- These allow us measure E, $\vec{p}$, and Particle ID of the projectile fragments.



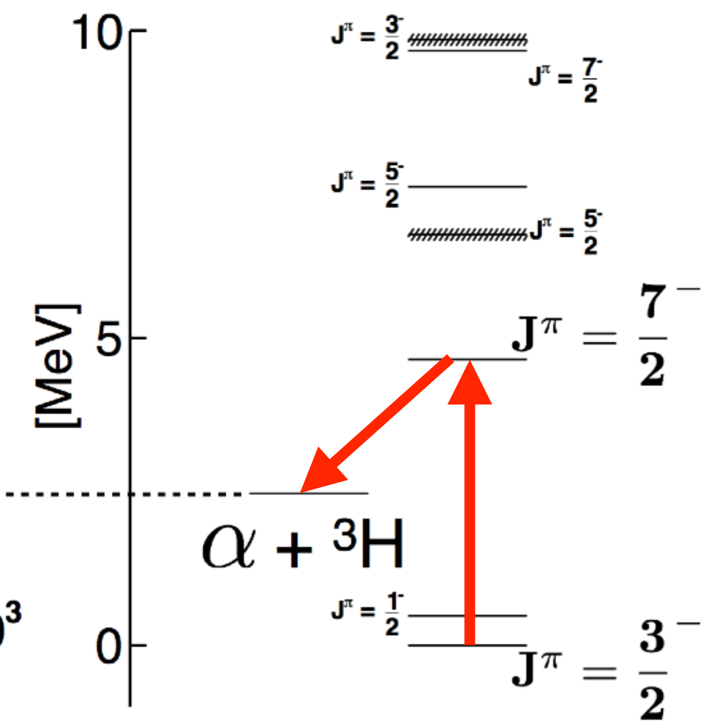
$$dE \propto \frac{Z^2 A}{E}$$

Setup at TAMU MARS line

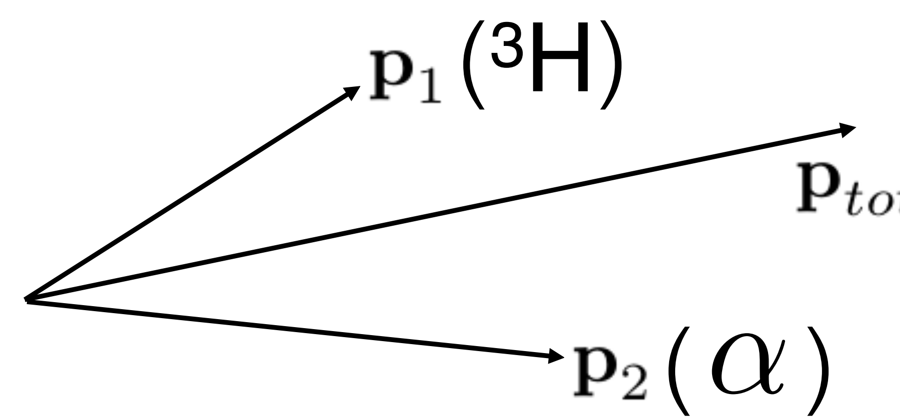




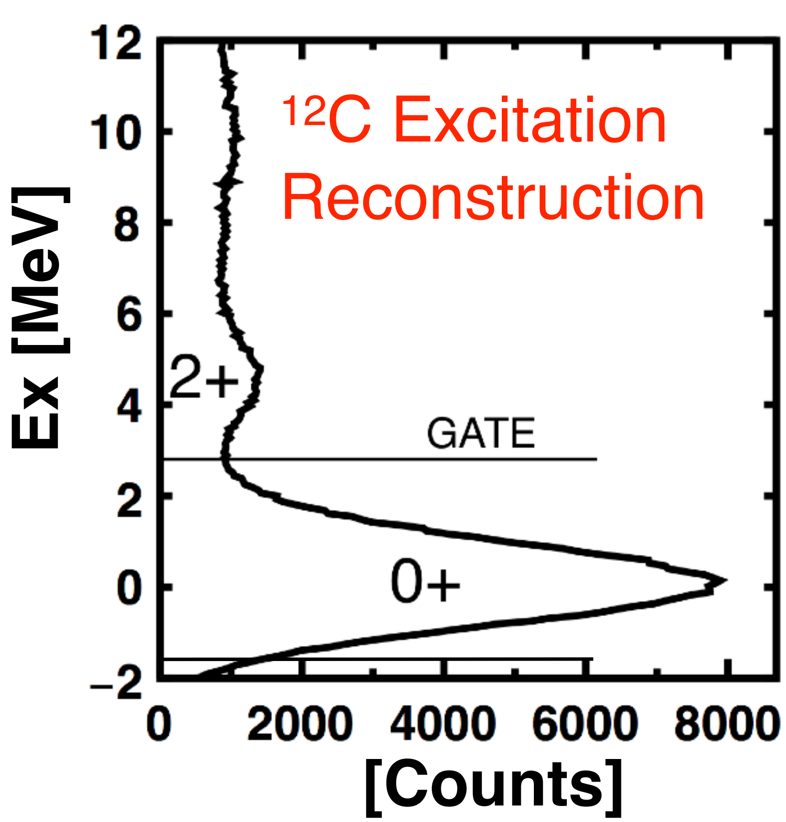
^{7}Li Level Scheme

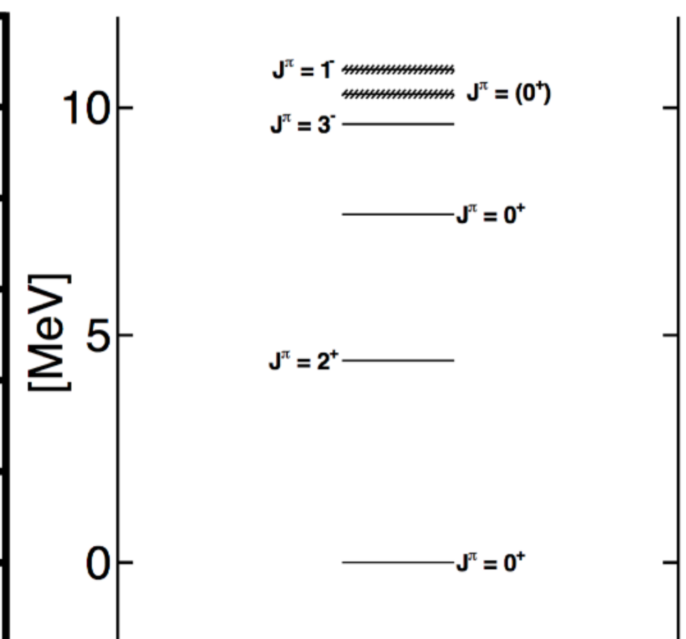


We reconstruct events by adding momentum back together.



^{12}C Level Scheme





We know 3/4 parts of the Kinematics for
^{7}Li + ^{12}C → ^{7}Li* + ^{12}C(GS)
so we can
deduce the target's
excitation energy as well.

Cluster Model

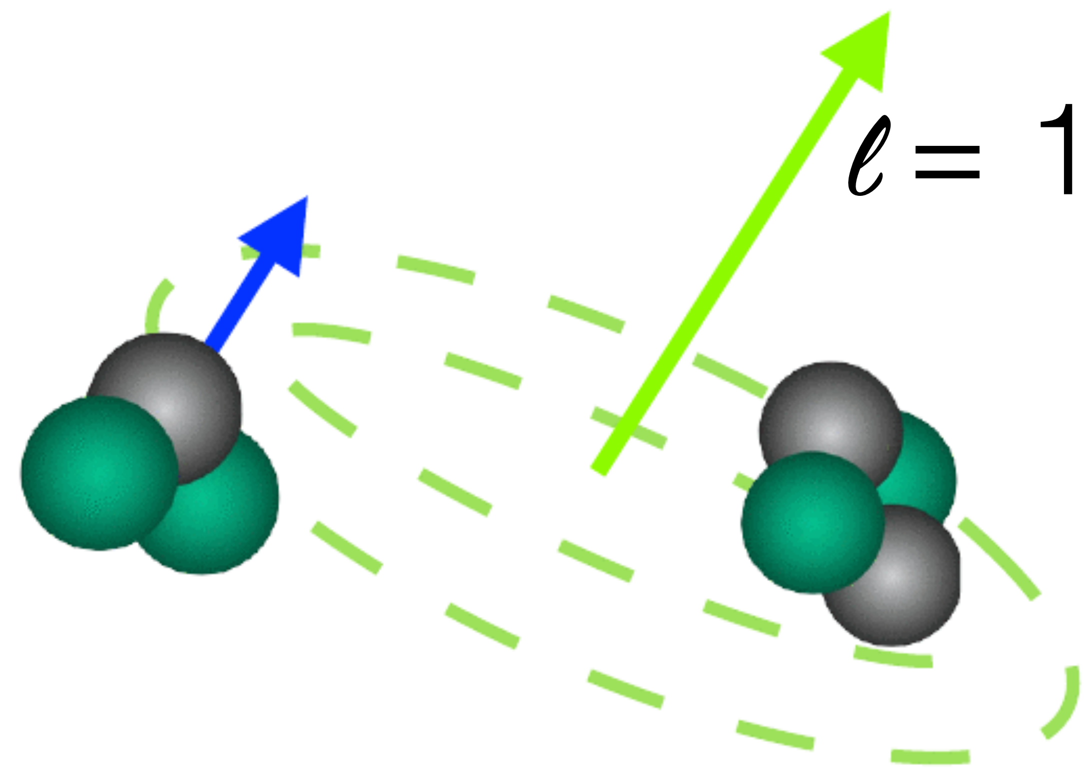
- We treat ^{7}Li as a "cluster" of an α and ^{3}H orbiting each other with angular momentum, ℓ, with projection, μ.

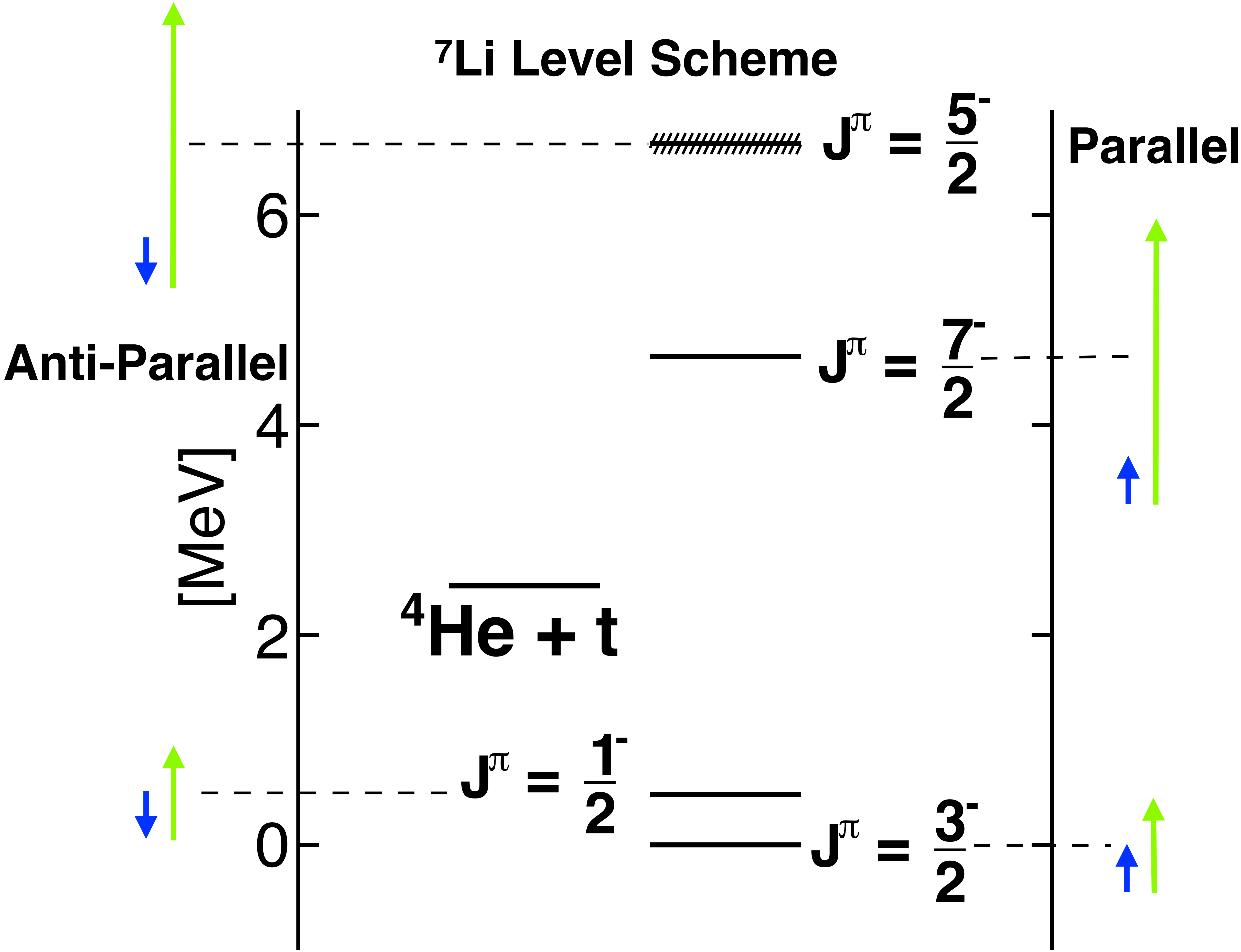
- We describe the g.s. (J^π = 3/2-) with ℓ = 1 and the triton spin *parallel* to the internal angular momentum.

- The 1st excited state (J^π = 1/2-) has ℓ = 1 with the triton spin *anti-parallel*.

- The 2nd excited state (J^π = 7/2-) has ℓ = 3 with the triton spin *parallel*.

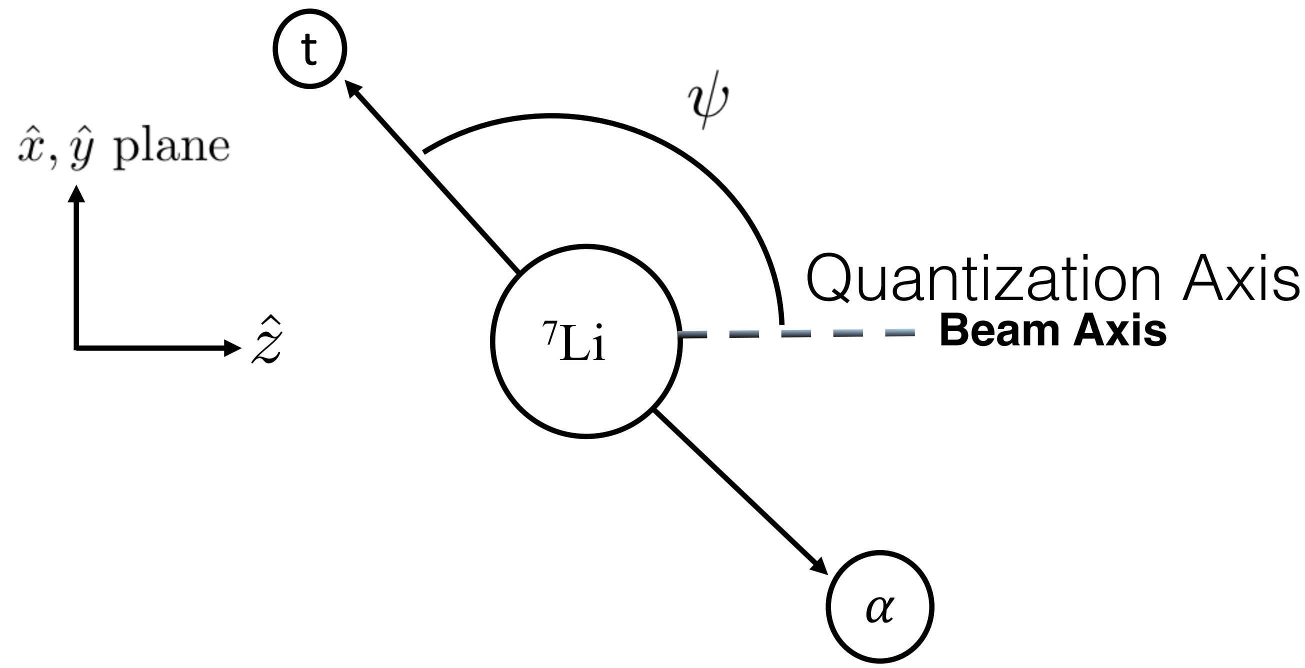
- The 3rd excited state (J^π= 5/2-) has ℓ = 3 with the triton spin *anti-parallel*.

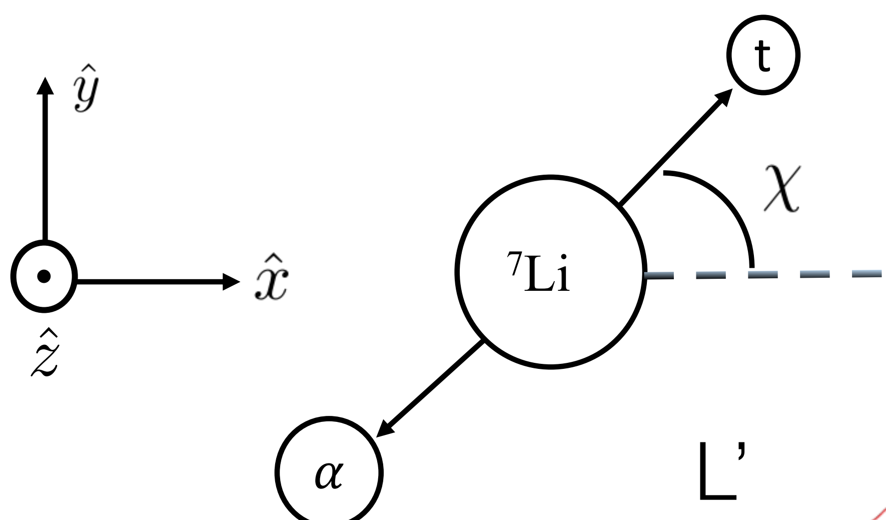


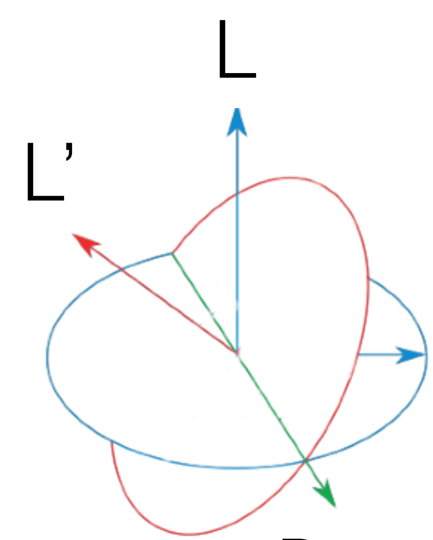


^{7}Li Level Scheme
$J^\pi = \frac{5}{2}^-$
Parallel
6
Anti-Parallel
$J^\pi = \frac{7}{2}^-$
4
[MeV]
2
^{4}He + t
$J^\pi = \frac{1}{2}^-$
0
$J^\pi = \frac{3}{2}^-$

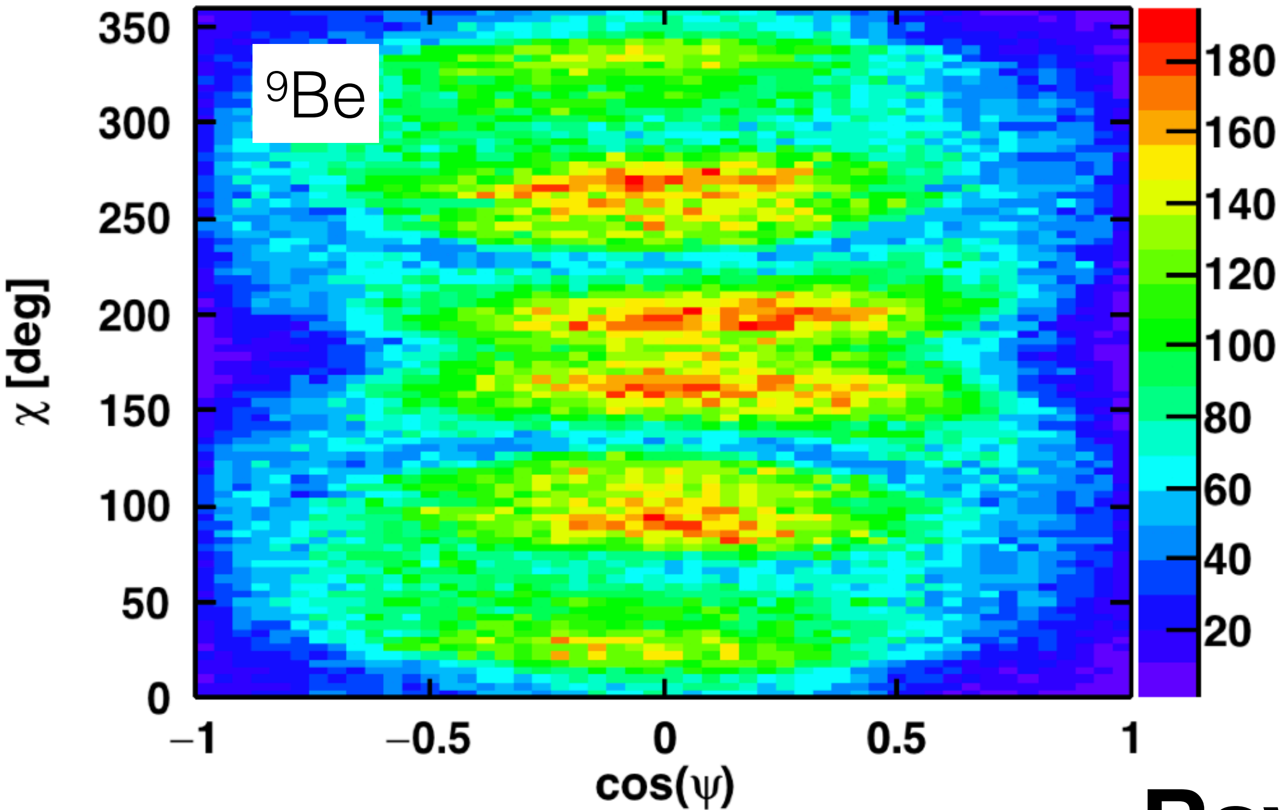
How do we determine spin alignment?



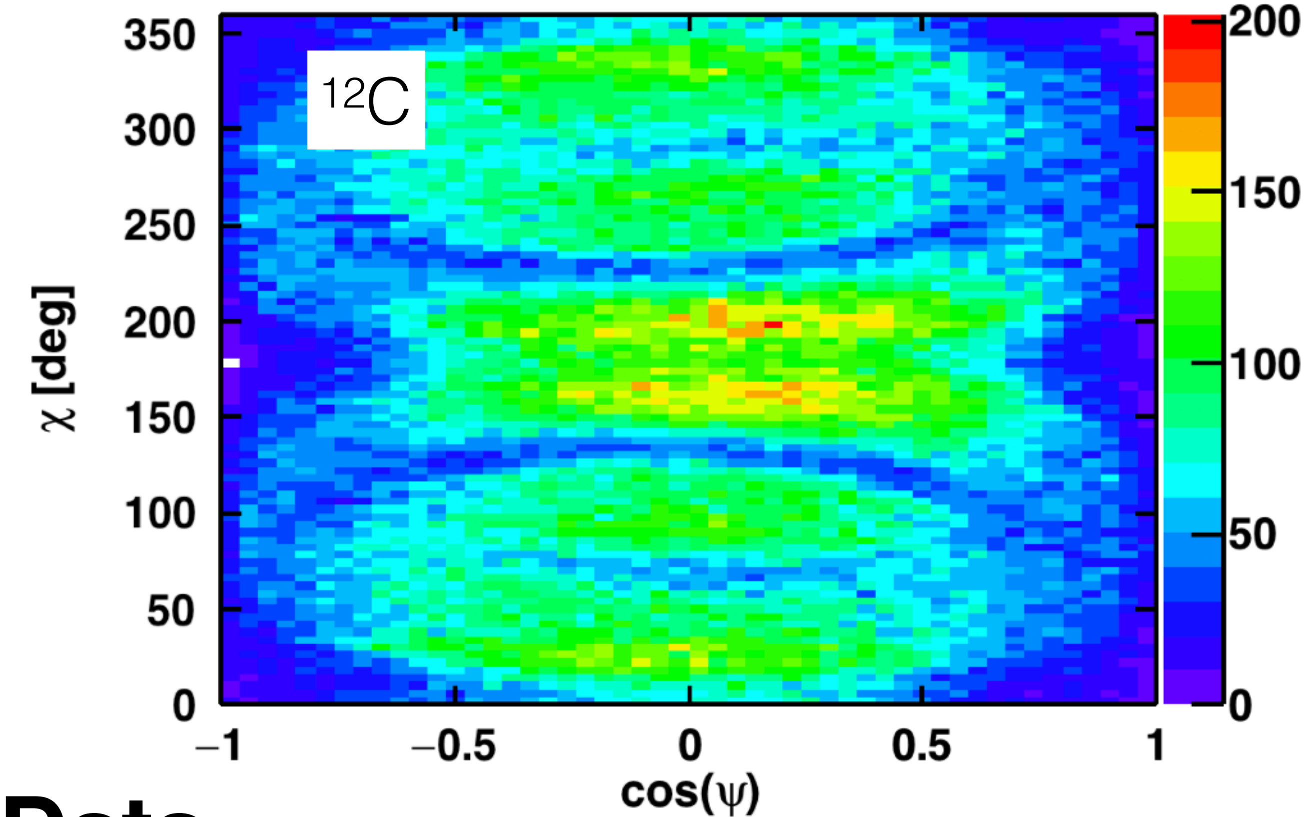




- Decay of 7/2- state has ℓ_{final} = 3 (α+t internal A.M.)
- If A.M. is ***perpendicular*** to the beam-axis fragments of decay will be preferentially emitted in a plane containing the beam axis (ψ = 0^o).
- If A.M is ***parallel*** to the beam-axis fragments of decay will be preferentially emitted in the x-y plane (ψ = 90^o).

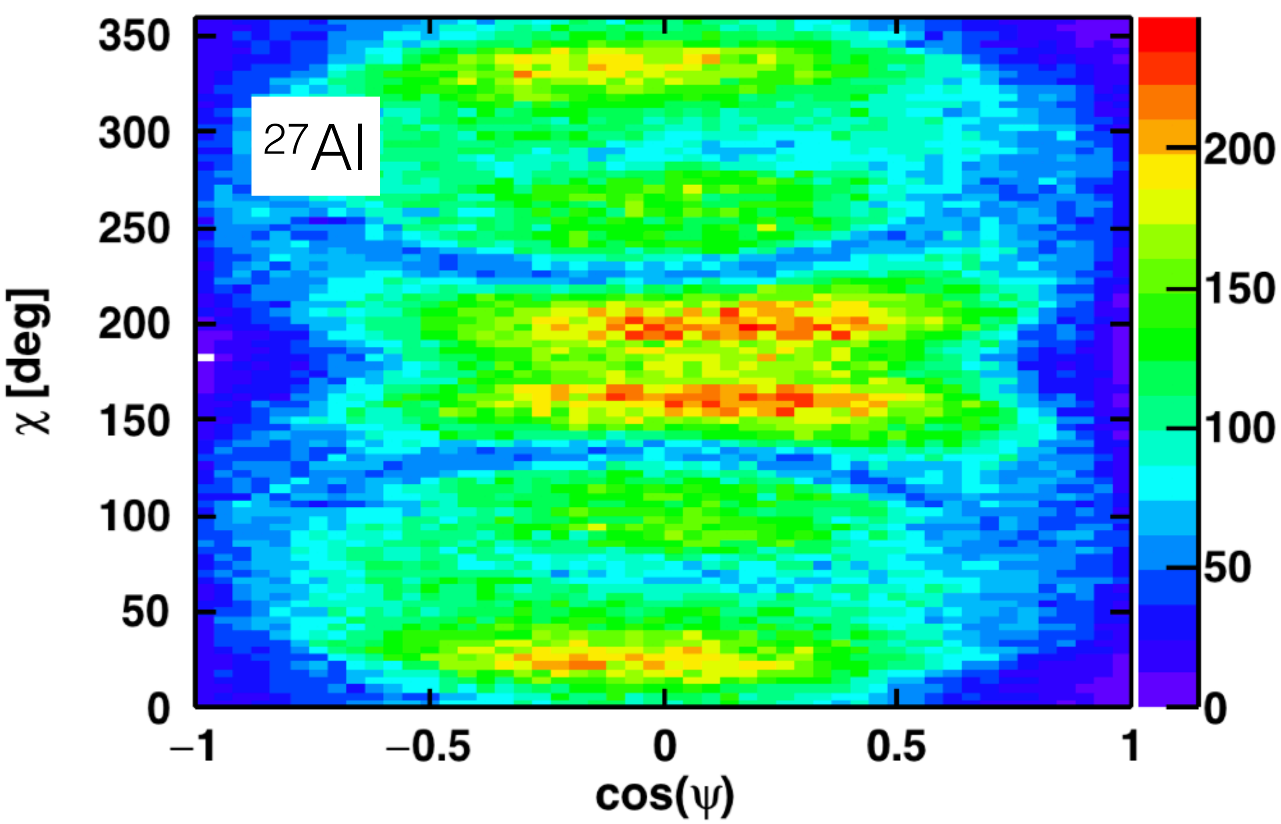


⁹Be
χ [deg]
cos(ψ)
350
300
250
200
150
100
50
0
−1
−0.5
0
0.5
1
180
160
140
120
100
80
60
40
20

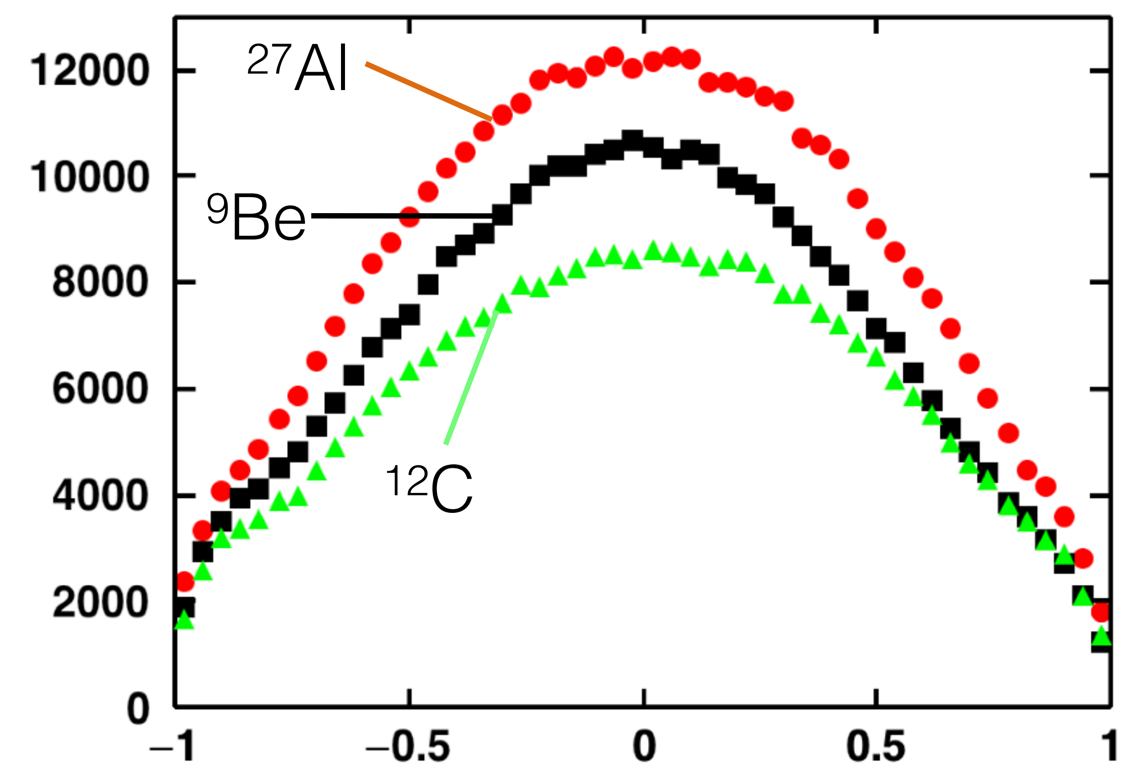


¹²C
χ [deg]
cos(ψ)
350
300
250
200
150
100
50
0
−1
−0.5
0
0.5
1
200
150
100
50
0

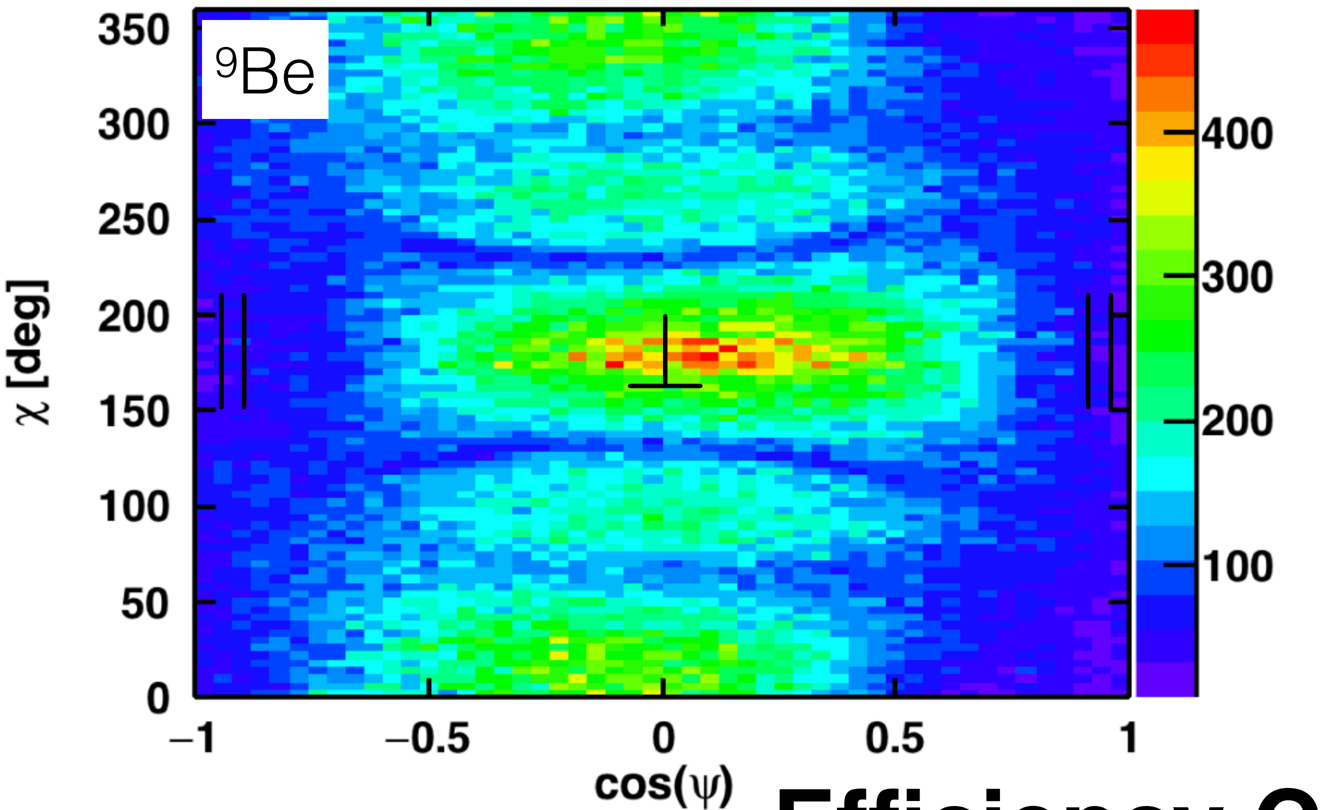
Raw Data

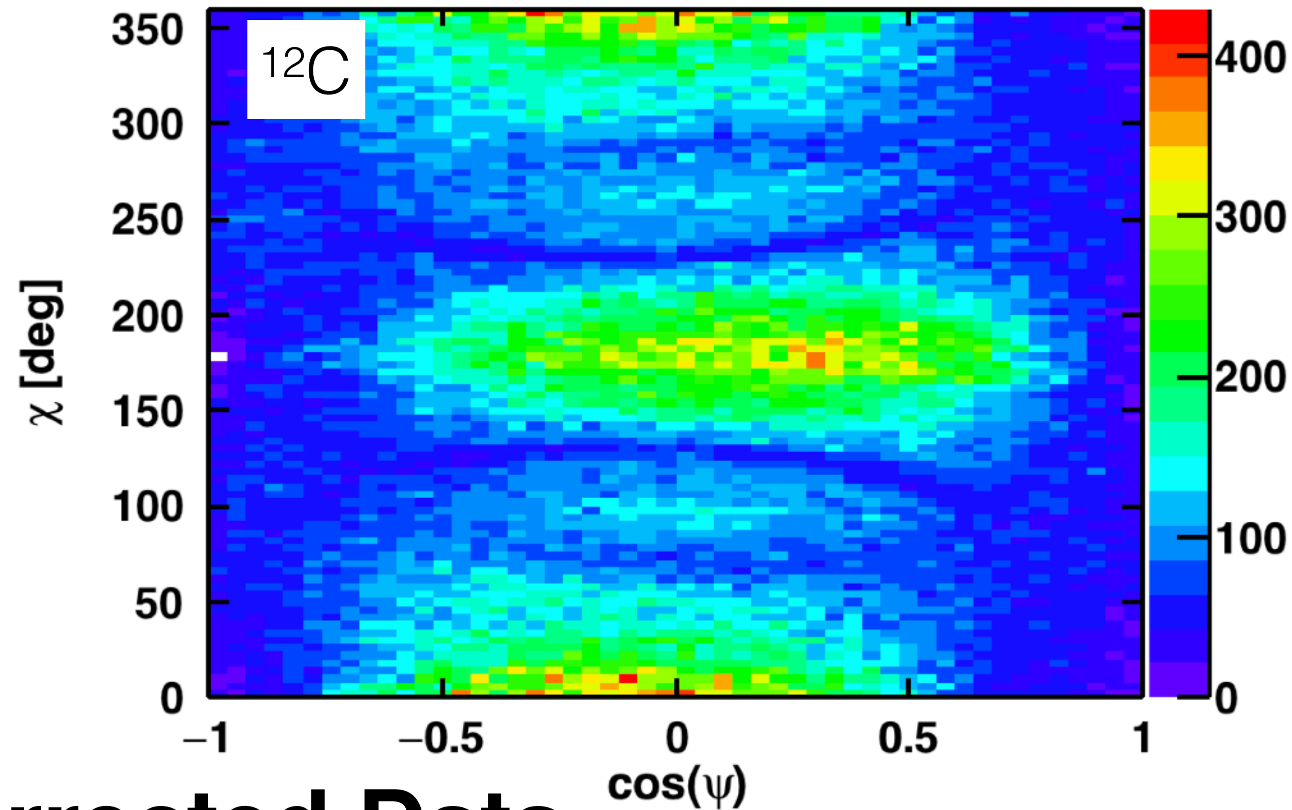


²⁷Al
χ [deg]
cos(ψ)
350
300
250
200
150
100
50
0
−1
−0.5
0
0.5
1
200
150
100
50
0

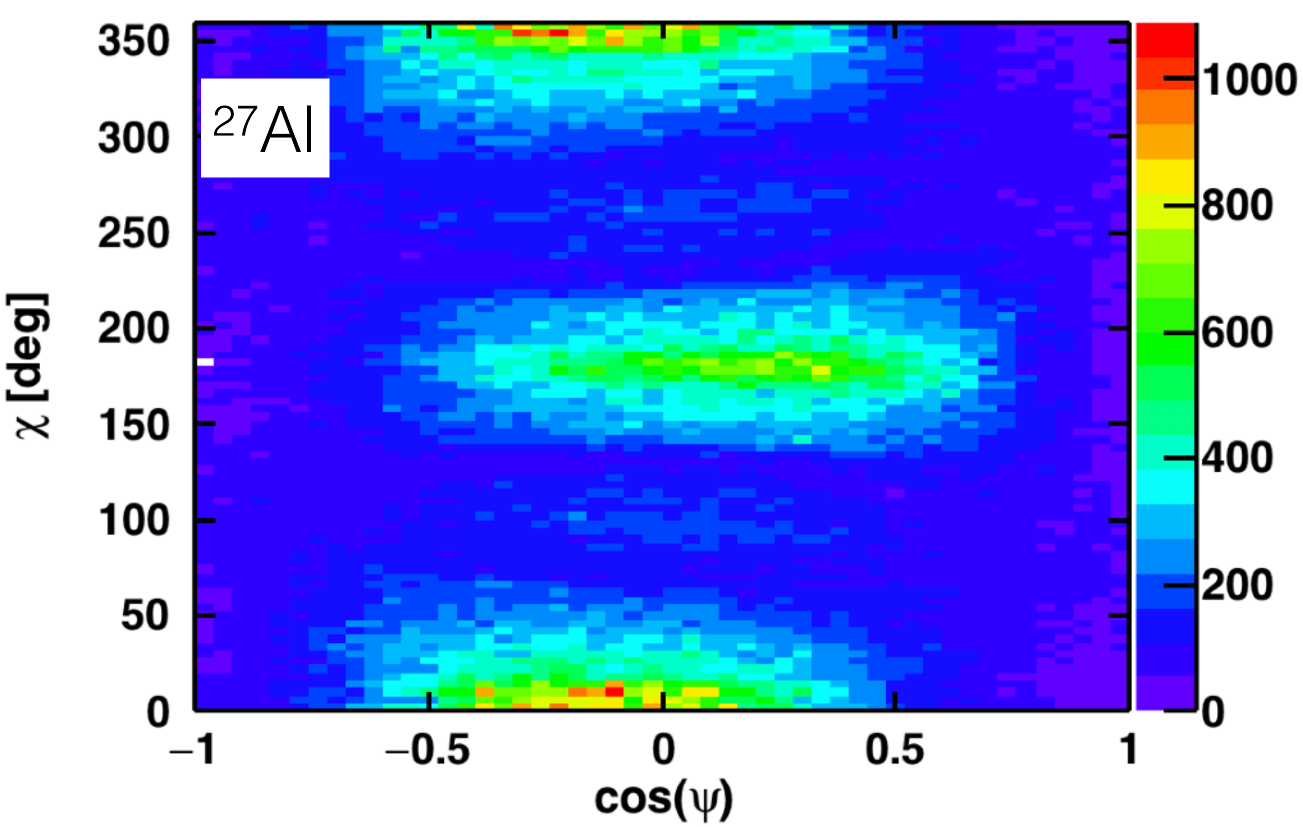


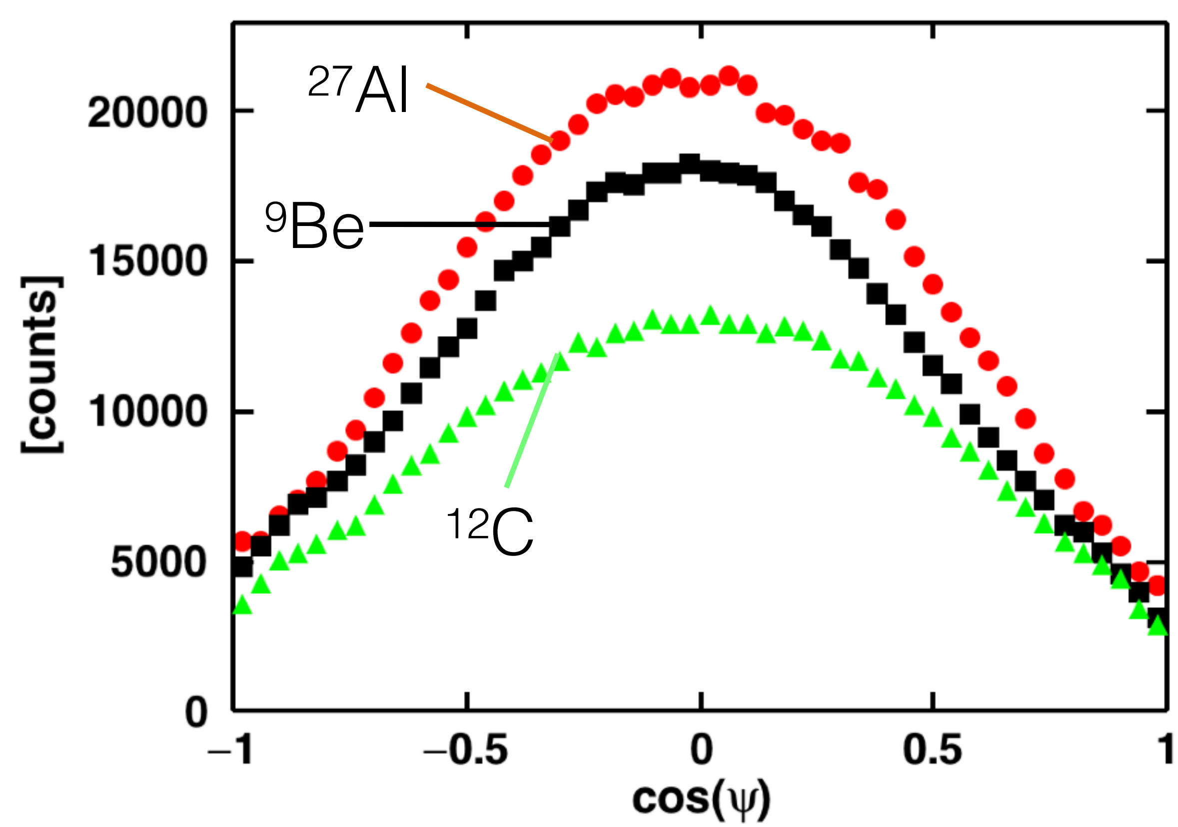
²⁷Al
⁹Be
¹²C
12000
10000
8000
6000
4000
2000
0
−1
−0.5
0
0.5
1





Efficiency Corrected Data

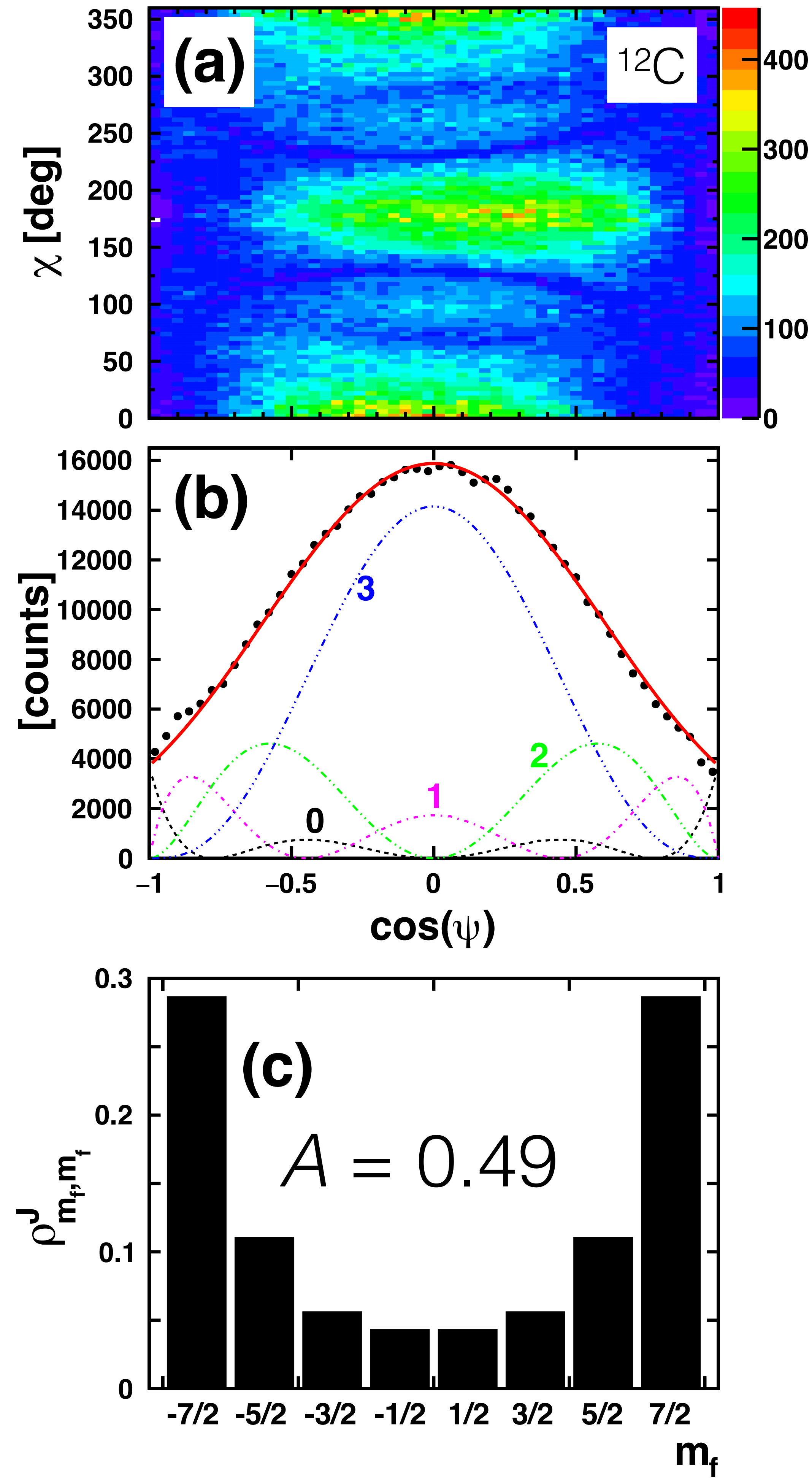




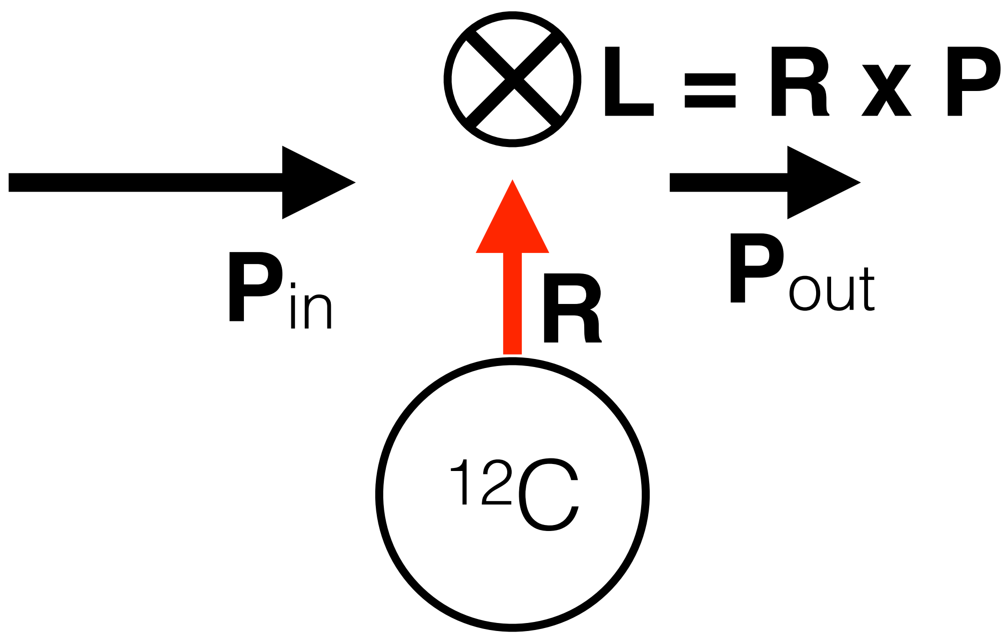
Strong peak at $\cos(\psi) = 0$

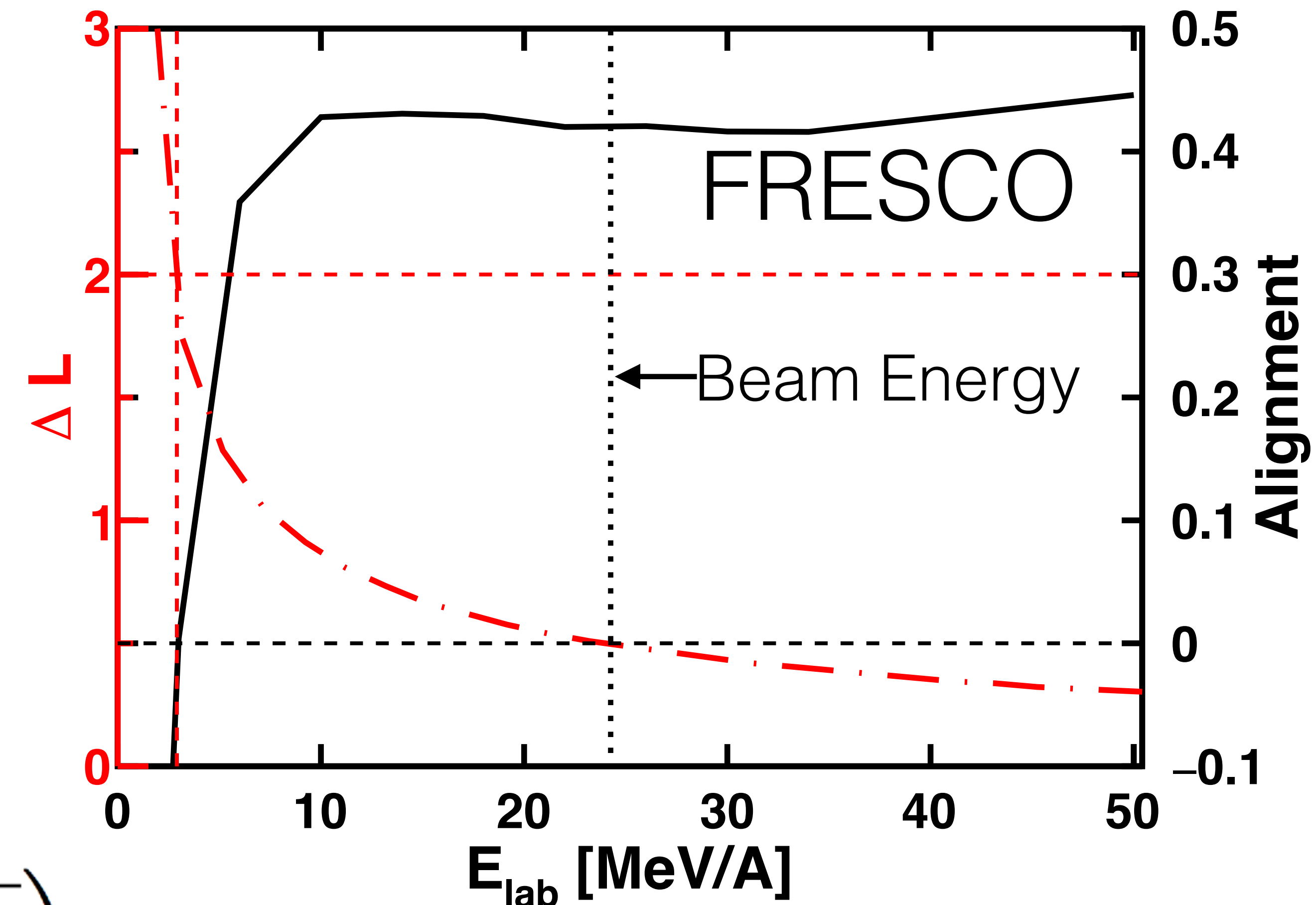
Magnetic Substate Extraction

- For the rest of the talk I'll focus on the reaction with ^{12}C.
- We fit the angular correlations to Legendre Polynomials to extract the magnetic sub-state.
- The weights of the Legendre Polynomials are related to the population of the magnetic substate.
- Extracted magnetic sub-states indicate large *longitudinal* alignment.



Angular Momentum & Excitation Energy Matching





$$\Delta L = \mathbf{R} \times (\mathbf{P}_{in} - \mathbf{P}_{out})$$

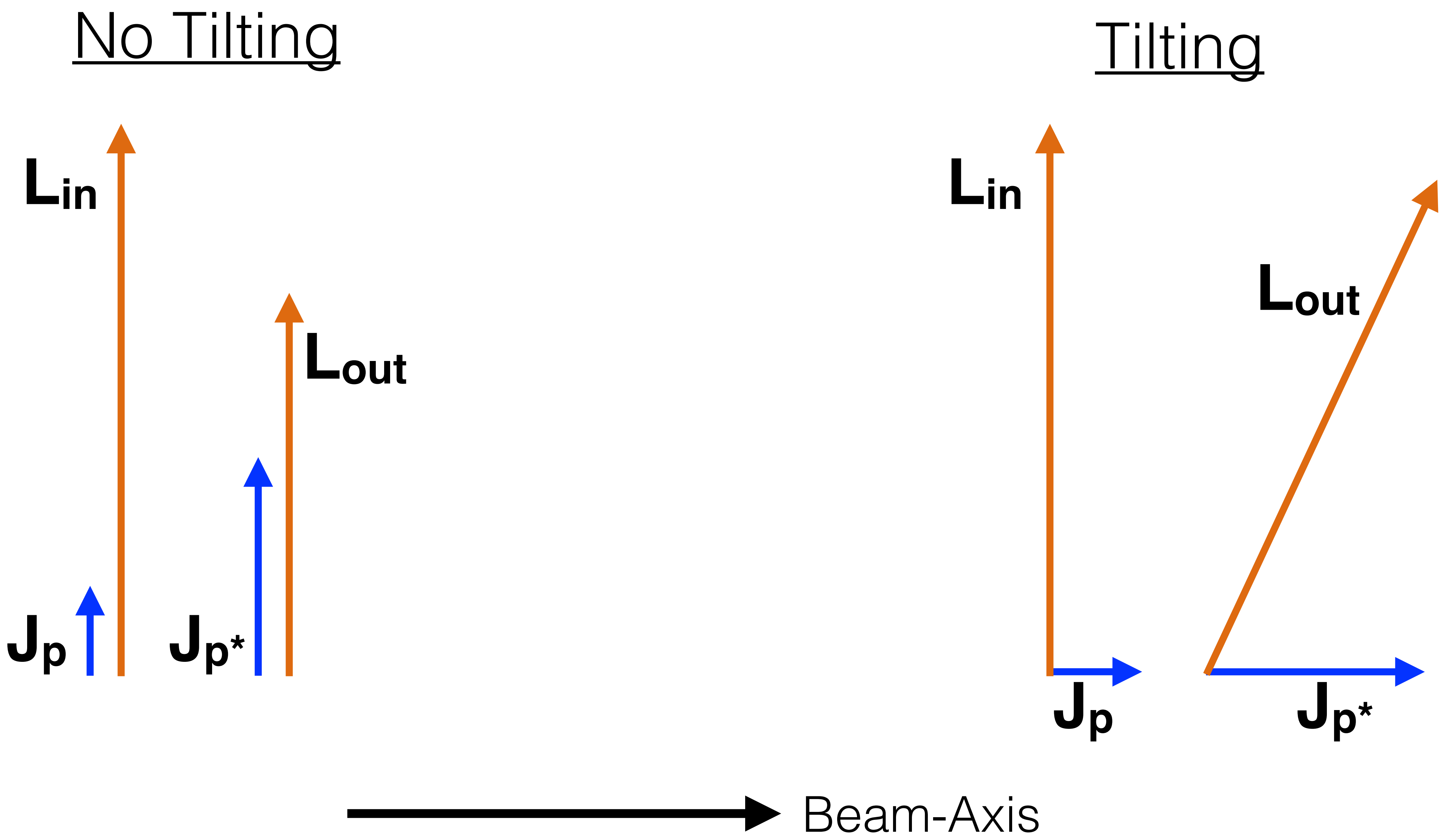
$$= R\sqrt{2\mu E_{CM}}\left(1 - \sqrt{1 - \frac{E^*}{E_{CM}}}\right)$$

R~5 fm, E* = 4.68 MeV

$\Delta\ell = 2$

Reaction-plane must ***TILT*** to conserve A.M. above a certain threshold

Angular Momentum & Excitation Energy Matching



Alignment Mechanism

- We looked at the transfer, or *T*, matrix of the projectile.
- The squared elements of the *T*-Matrix give the probability of going from an initial to final state. The projection onto m_f gives a predicted m-state distribution.
- The last two integrations are directly proportional to Clebsch-Gordan Coefficients.

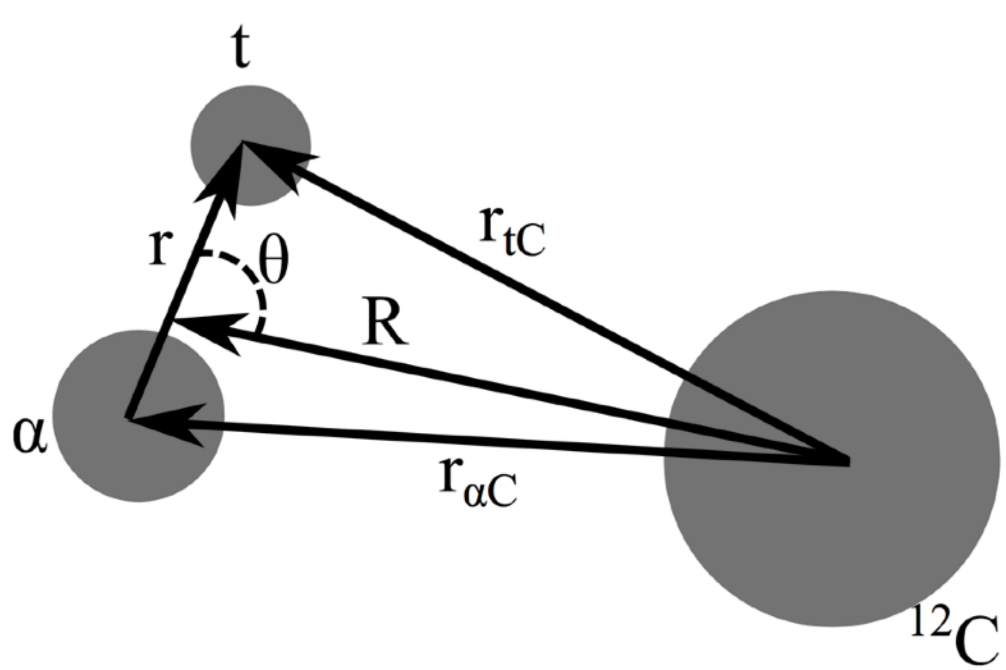
$$T^L_{m_i,m_f} \propto \sum_{\mu_i,\mu_f,m_s} \langle \ell_i, \mu_i; 1/2, m_s | J_i, m_i \rangle$$

$$\times \langle \ell_f, \mu_f; 1/2, m_s | J_f, m_f \rangle$$

Internal $\rightarrow \times \int Y^{\ell_f}_{-\mu_f}(\hat{r}) Y^K_M(\hat{r}) Y^{\ell_i}_{\mu_i}(\hat{r}) d\Omega_r$

External $\rightarrow \times \int Y^L_{-M}(\hat{R}) Y^K_M(\hat{R}) Y^L_0(\hat{R}) d\Omega_R,$

A.M. & E* matching $\rightarrow L_{in} = L_{out}$



$$\mathbf{J} = \ell + 1/2$$

$$\ell_i = 1 \rightarrow J_i = 3/2 \qquad \ell_f = 3 \rightarrow J_i = 7/2$$

$$M = \Delta\mu = \Delta m = m_f - m_i$$

$$K = 2 \text{ (from parity)}$$

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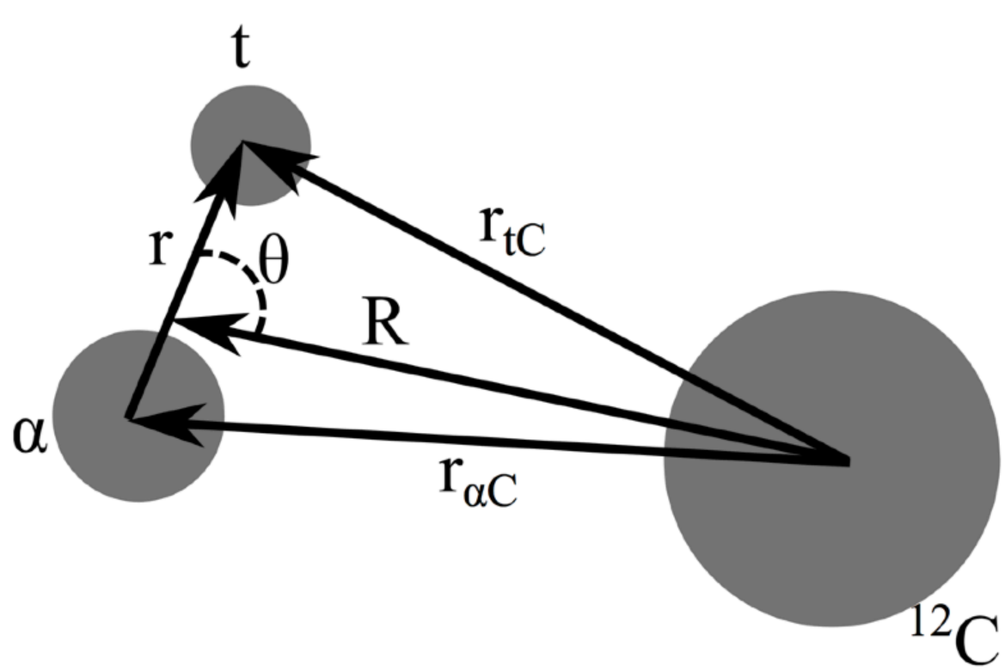
$$T^{L}_{m_i,m_f} \propto \langle J_i, m_i\,;\, K, M \mid J_f, m_f \rangle \times \langle L, 0\,;\, K, M \mid L, M \rangle\,.$$



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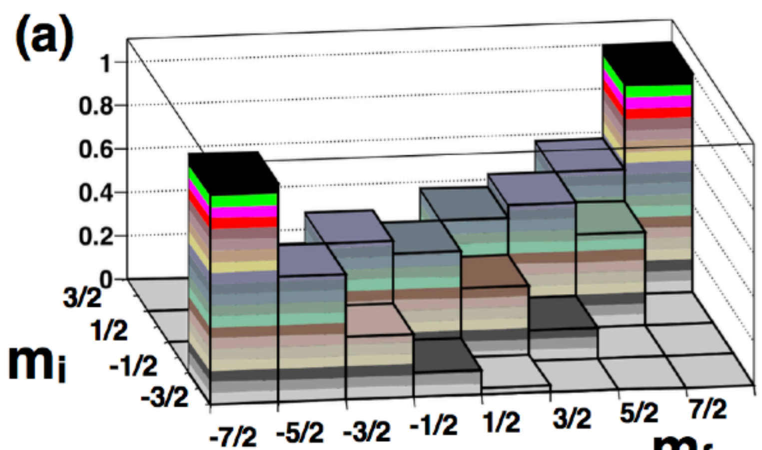
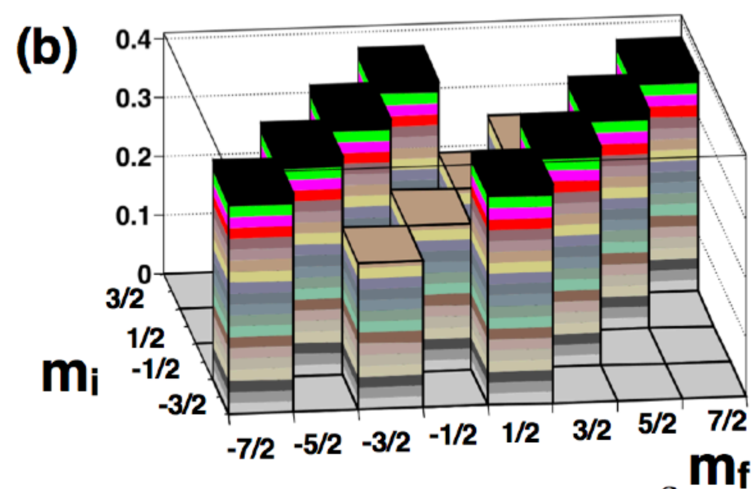
Alignment Mechanism



$\langle 3/2, m_i\,;\,\mathbf{2}, M \mid 7/2, m_f \rangle^2$

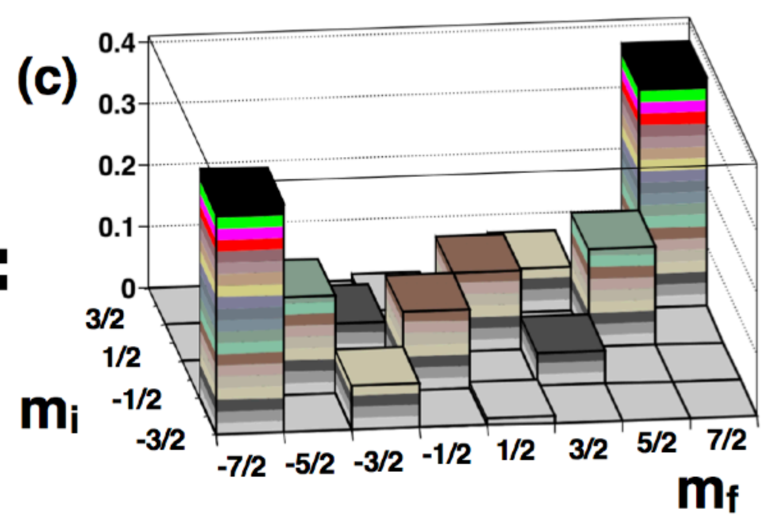
×



$\langle 35, 0\,;\,\mathbf{2}, M \mid 35, M \rangle^2$

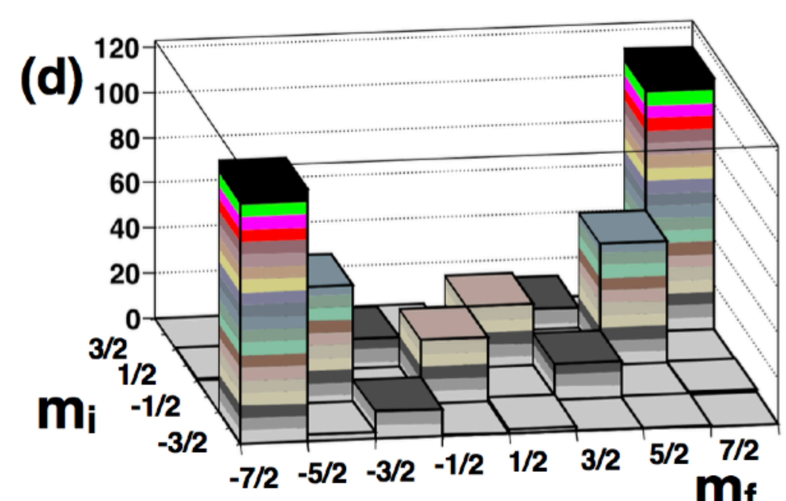
Multiplying together the relevant Clebsch-Gordan coefficients predicts a squared T-Matrix.

=



$\langle 3/2, m_i\,;\,\mathbf{2}, M \mid 7/2, m_f \rangle^2 \, \langle 35, 0\,;\,\mathbf{2}, M \mid 35, M \rangle^2$

$\propto$

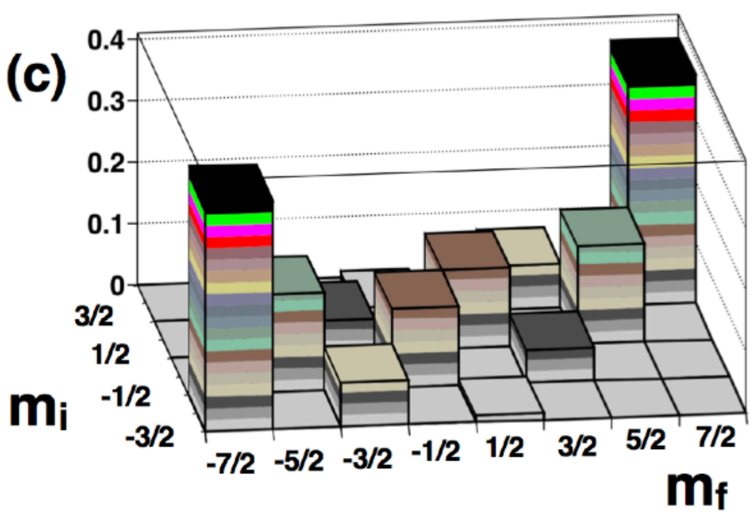


FRESCO

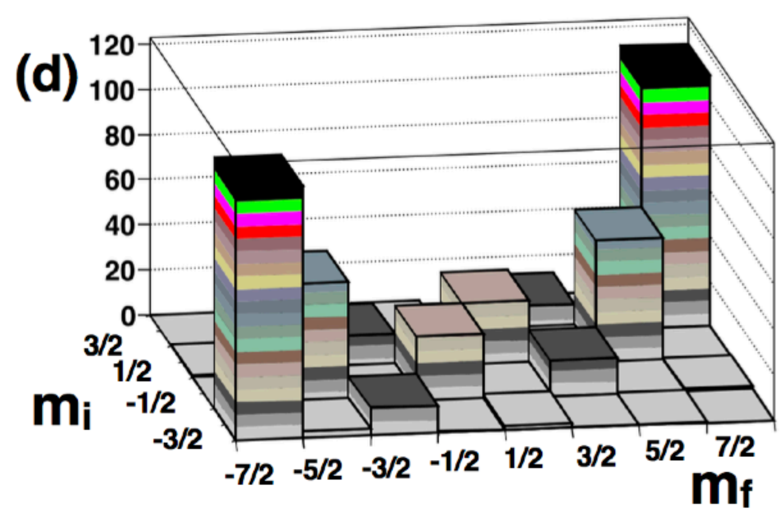
The squared T-Matrix from FRESCO is strikingly similar to the CG prescription.

M = ±1 is completely suppressed

Alignment Mechanism

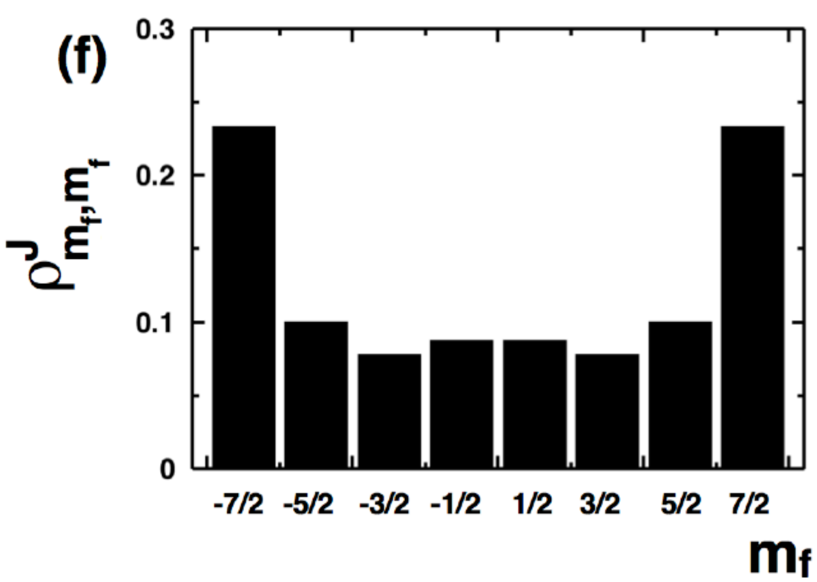


$\propto$

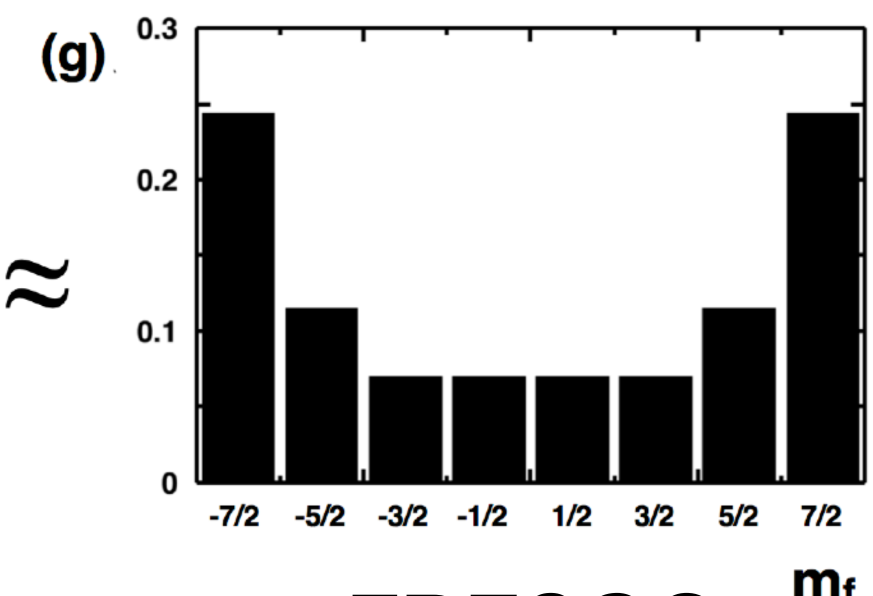


$\langle 3/2, m_i\,;\, \mathbf{2}, M \,|\, 7/2, m_f \rangle^2 \, \langle 35, 0\,;\, \mathbf{2}, M \,|\, 35, M \rangle^2$

Multiplying together the relevant Clebsch-Gordan coefficients predicts a squared T-Matrix.



$\approx$

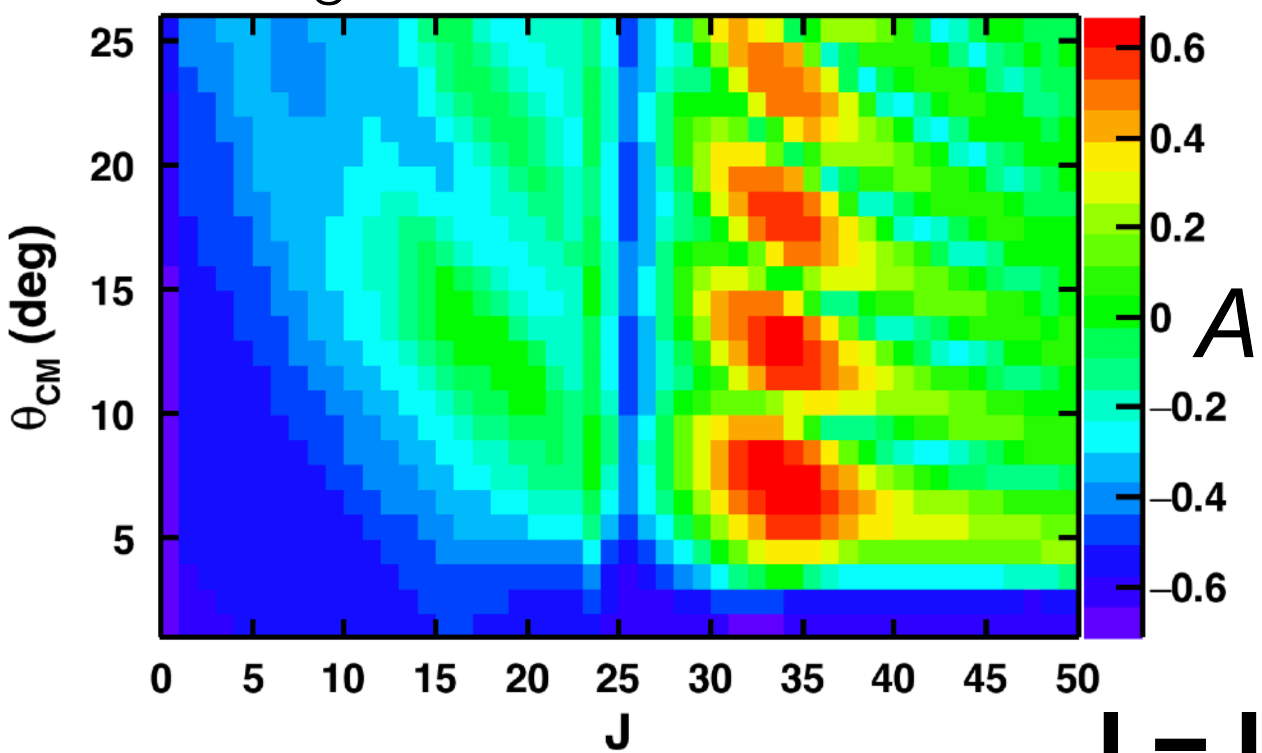


FRESCO

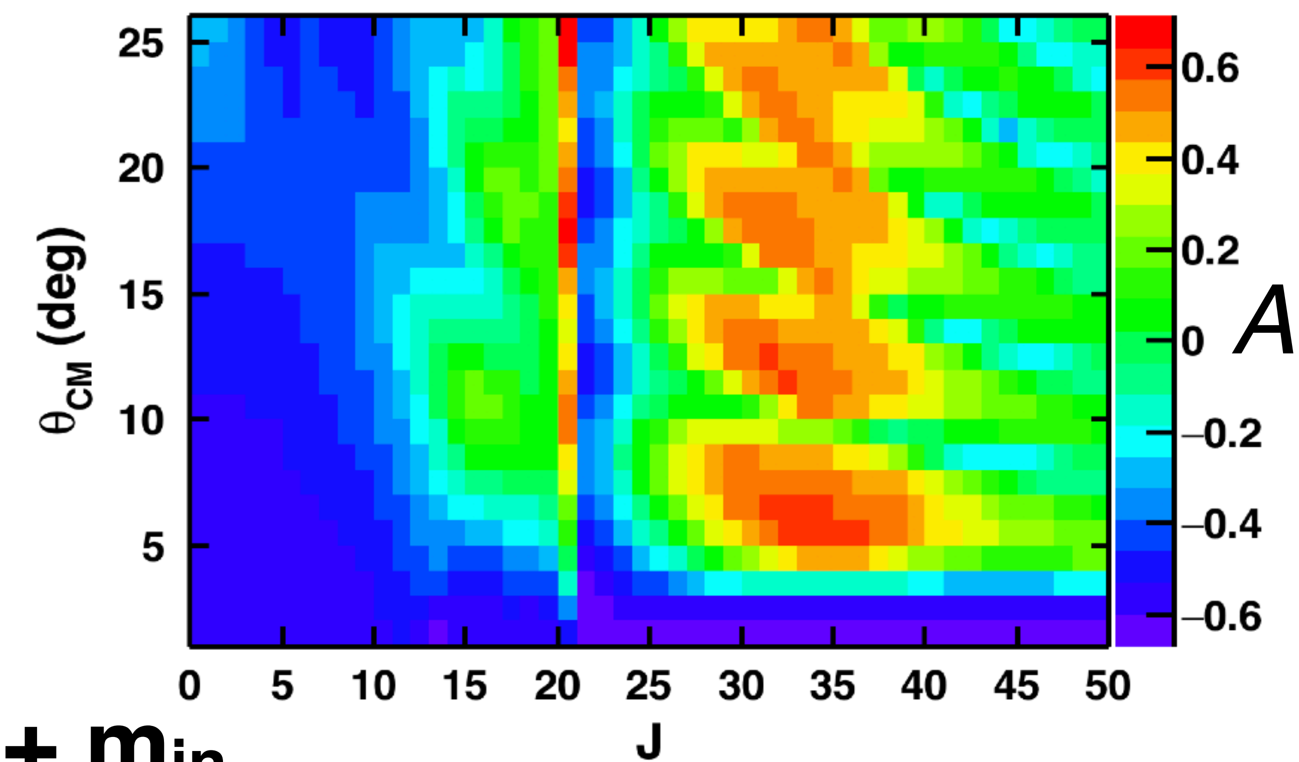
The squared T-Matrix from FRESCO is strikingly similar to the CG prescription.

L-Wave Mixing → Alignment

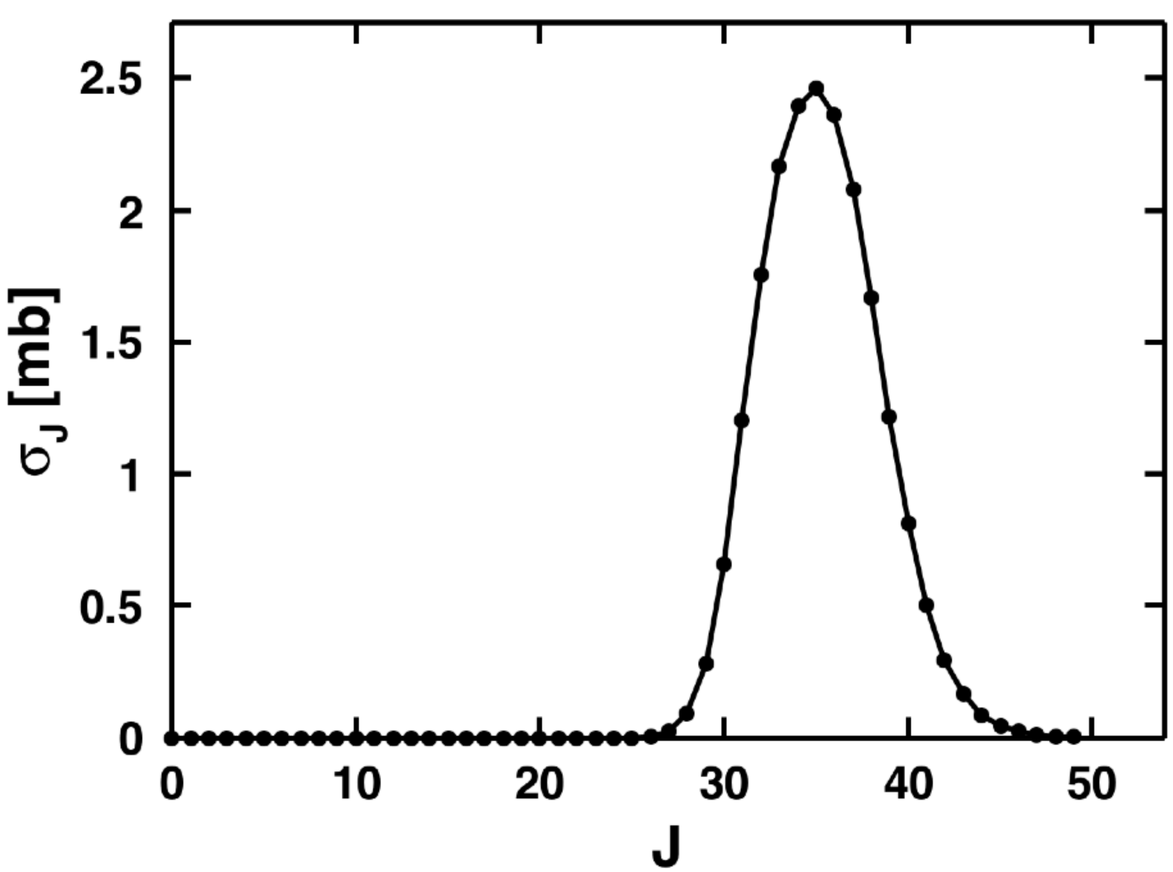
Single J FRESCO calculations

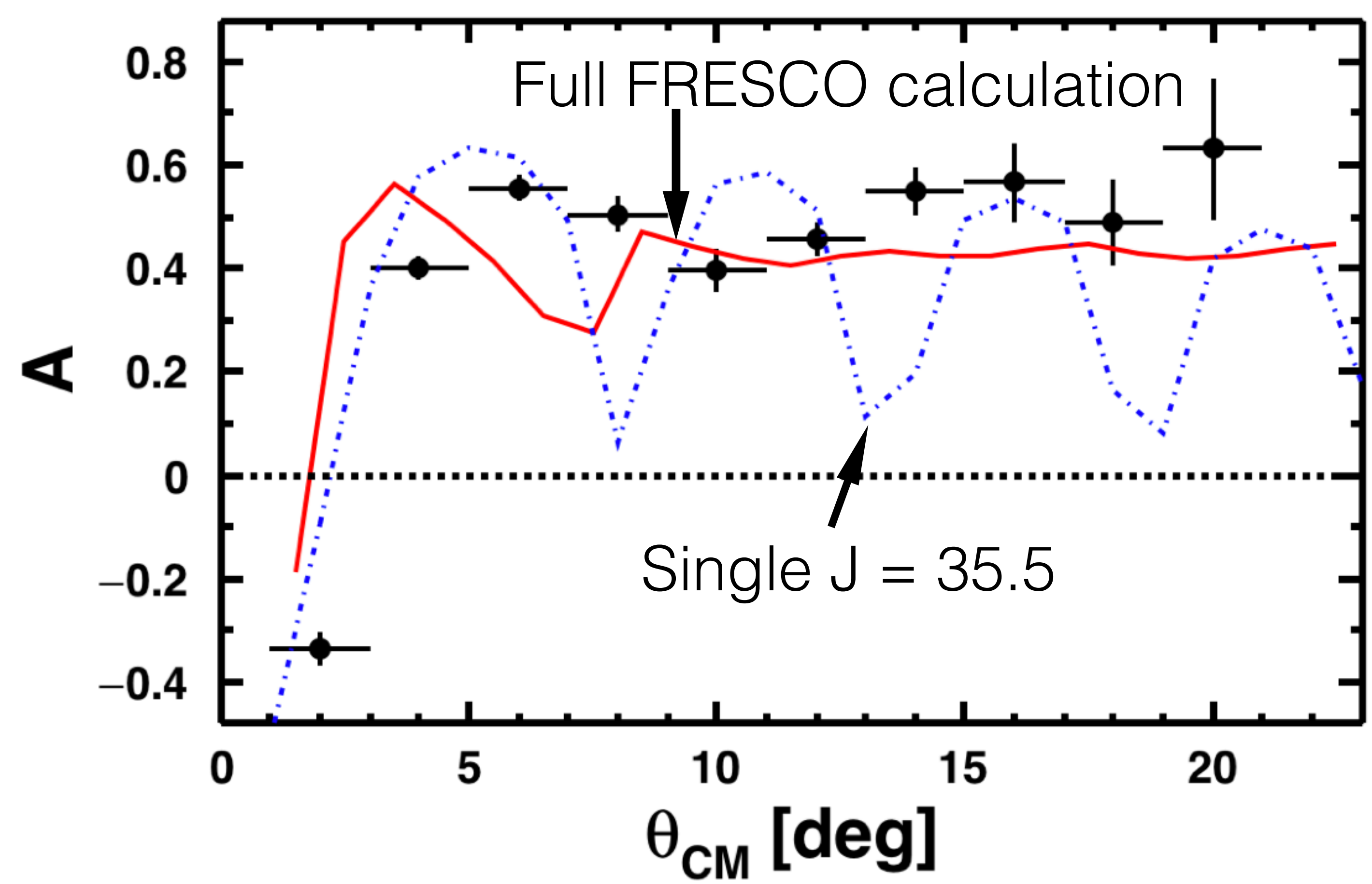


±4 J FRESCO calculations



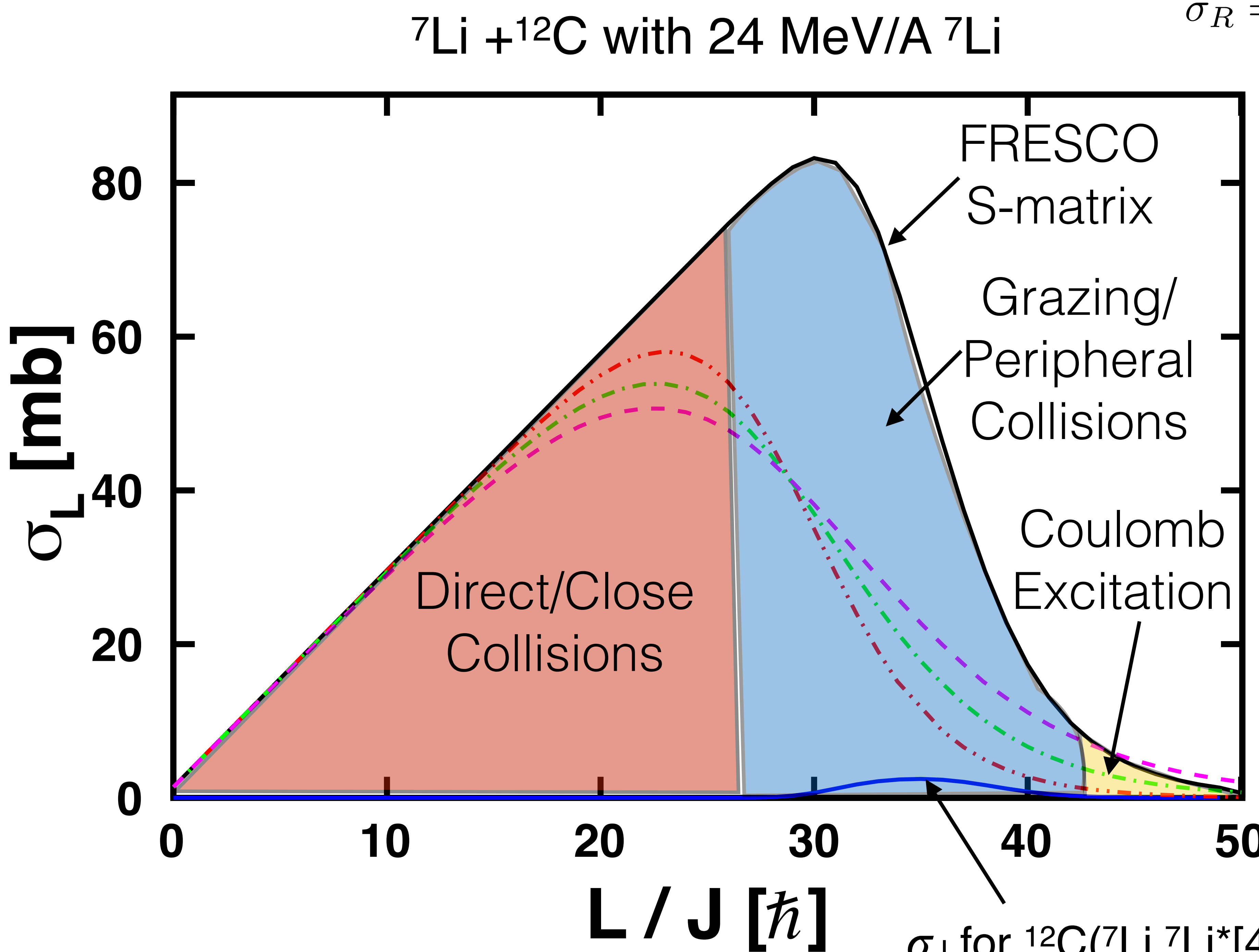
$J = L + m_{in}$





Characterizing the Reaction

$$\sigma_R = \pi \lambda\!\!\!^{-2} \sum_{L=0}^{\infty} (2L+1)(1 - |\mathbf{S}_L|^2)$$



$\lambda\!\!\!^{-}$ ~ 0.212 fm^2

Semi-classical model (dashed-lines) predicts L_g ~28 $\hbar$

FRESCO predicts L_g ~35 $\hbar$

σ_J for ^{12}C(^{7}Li,^{7}Li*[4.6 MeV])^{2}C from FRESCO

Conclusions

- Uncovered alignment mechanism that was buried in standard scattering theory.

- Alignment arises from an angular-momentum-excitation-energy mismatch.

- Many L-waves interfere resulting in the alignment being a smooth function of scattering angle for large angles.

- Alignment mechanism is *<u>independent</u>* of the scattering potential used.

    - Could be found in many scattering experiments.

Partial-Wave Analysis

Separate variables in the Hamiltonian and focus on radial part,

$$\left[\frac{-\hbar^2}{2m}\frac{d^2}{dr^2} + \frac{\hbar^2 L(L+1)}{2mr^2} + V(\mathbf{r})\right]\psi(\mathbf{r}) = E\psi(\mathbf{r})$$

Using the Bohr approximation we treat the incoming particle as a plane-wave,

$$\psi_{\mathbf{k}_{in}}(\mathbf{r}) = e^{-ikz}$$

We can then do a plane-wave expansion giving us,

$$\psi_{\mathbf{k}_{in}}(\mathbf{r}) = e^{-ikz} = \sum_{L=0}^{\infty}(2L+1)i^L j_L(kr)P_L(\cos\theta)$$

Where, $j_L(kr)$, is a spherical Bessel function.

Partial-Wave Analysis

Now we make the ansatz for the full outgoing wavefunction,

$$\psi_{\mathbf{k}_{out}}(\mathbf{r}) = e^{-ikz} + f_k(\theta)\frac{e^{-ikr}}{r}$$

Where, $f_k(\theta)$, is called the “scattering amplitude”. The differential cross section is related to the scattering amplitude by,

$$\frac{d\sigma}{d\Omega} = |f_k(\theta)|^2$$

And with some algebra we have,

$$f_k(\theta) = \frac{1}{k}\sum_{L=0}^{\infty}(2L+1)e^{i\delta_L}\sin(\delta_L)P_L(\cos\theta)$$

where δ_L is called the “phase-shift” and is dependent on the scattering potential used (draw diagram).