Large Longitudinal Spin Alignment Generated in Inelastic Nuclear Reactions

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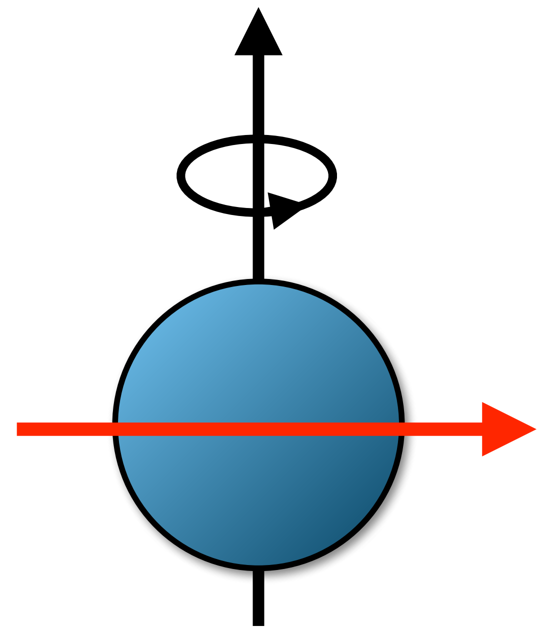
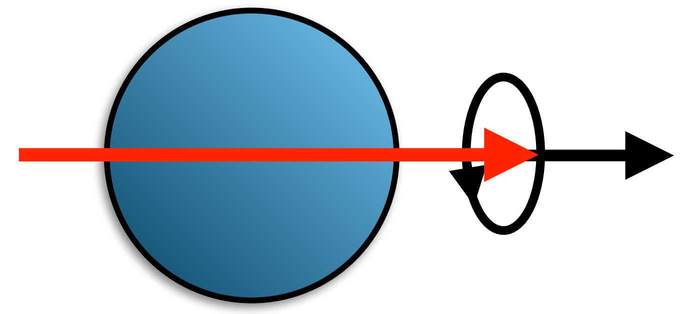
Introduction

- In compound, quasi-elastic, and deep inelastic reactions generate large spin alignments of the excited fragments ***transverse*** to the beam-axis are common.



- *Transverse* alignment typically originates from the transfer of intrinsic spin to the excited fragment from the large reservoir of collision angular momentum generated in the reaction (>100$\hbar$).



- *Longitudinal* spin alignment is rarer but has been observed in relativistic Coulomb excitation and projectile fragmentation.

- *Application*: Spin alignment of nuclear states is useful for *g*-factor measurements.

Introduction

- One can quantify the magnitude of alignment with the scalar *A* (1 = max. longitudinal alignment, -1 = max. transverse alignment),

$$A = \sum_{m_J} \frac{3m_J^2 - J(J+1)}{J(2J+1)} \underbrace{P(m_J)}_{\text{Population}}$$

- A = 0.35 was the largest reported ***longitudinal*** alignment that came from the population of a high-spin isomer in projectile fragmentation.

Experiment

- At the Texas A&M Cyclotron Institute, we studied three ^{7}Li reactions at *E/A* = 24 MeV:

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

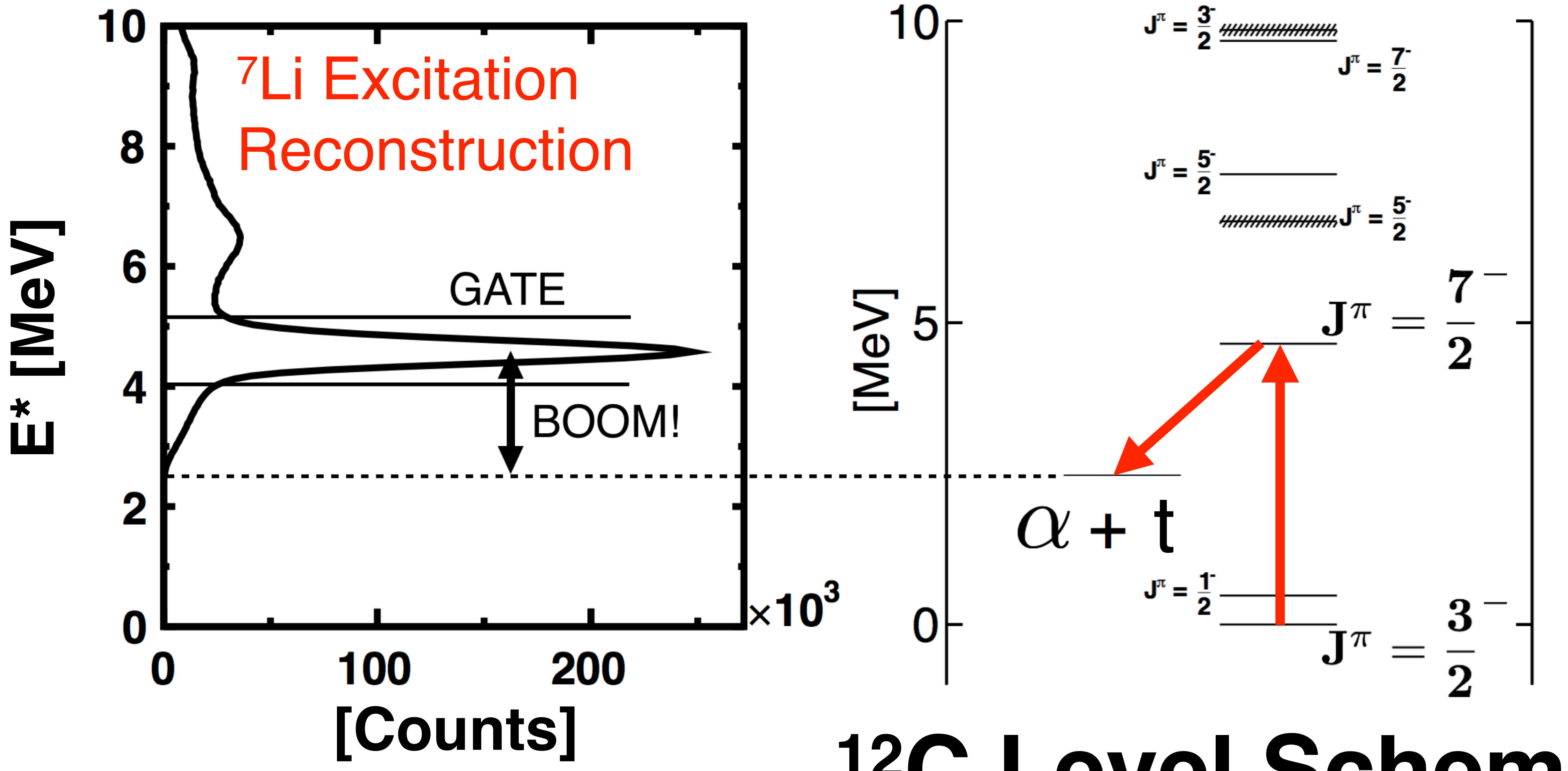
Invariant Mass 2-body kinematics

- **Goal** Measure spin alignment of excited projectile through sequential breakup correlations of ^{7}Li* (α+t).

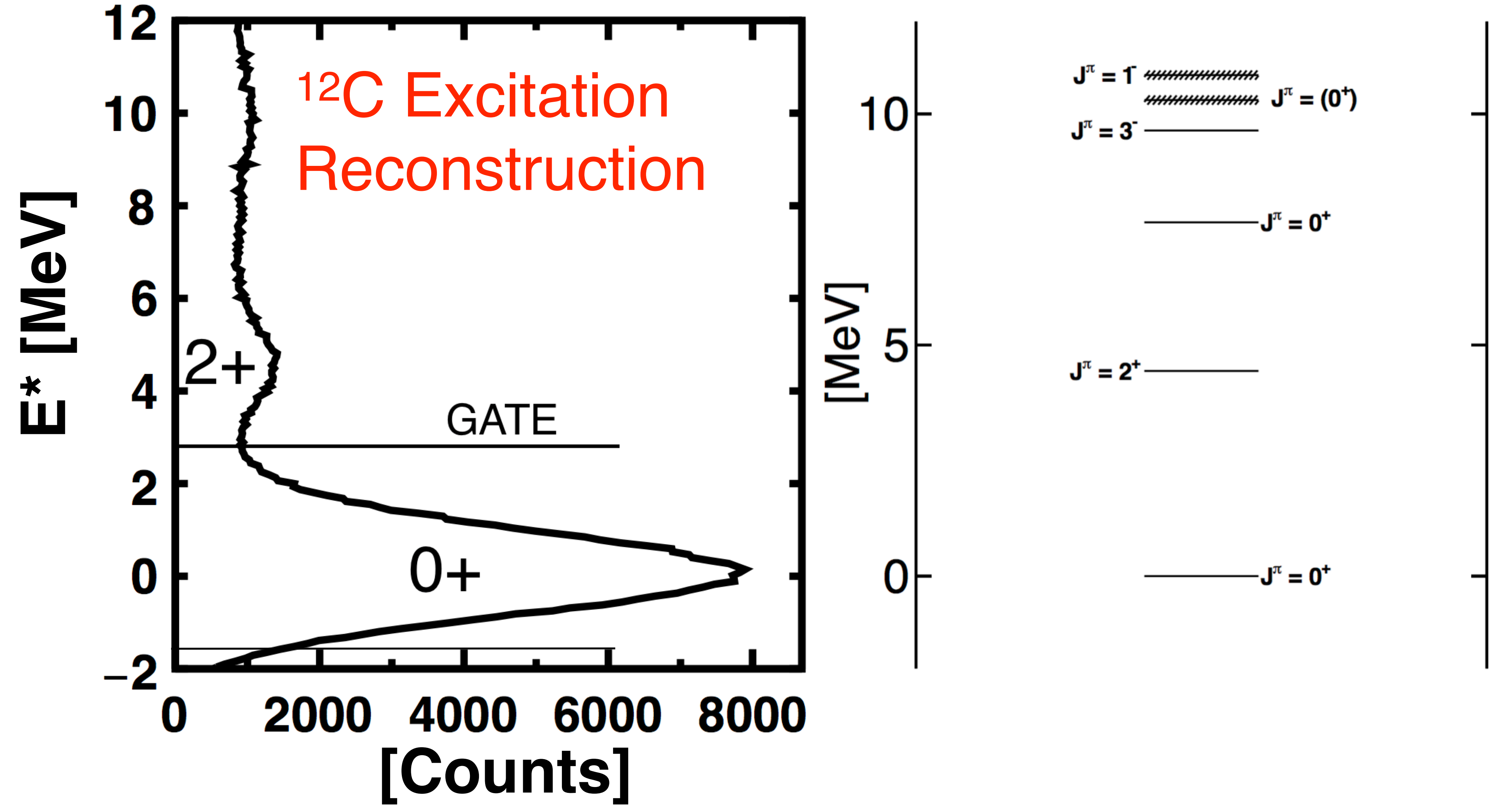
- We found a very *large* spin alignment (A = 0.49) of ^{7}Li* ***longitudinal*** to the beam axis with all three targets.

Search for an alignment mechanism began.

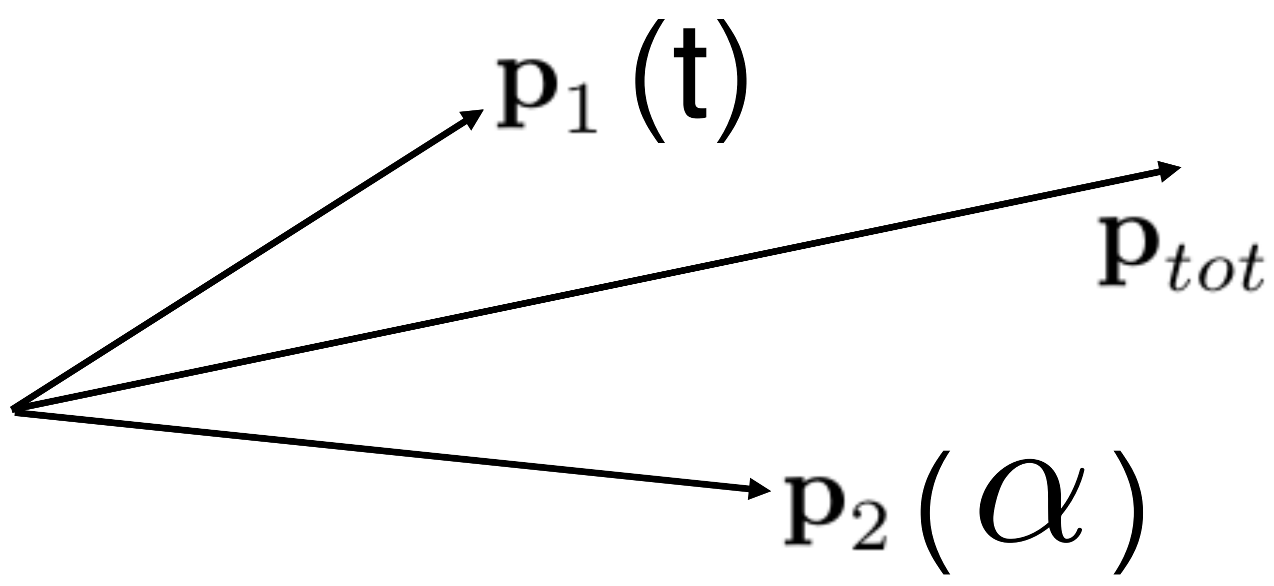
^{7}Li Level Scheme



^{12}C Level Scheme



We reconstruct events by adding momentum back together.

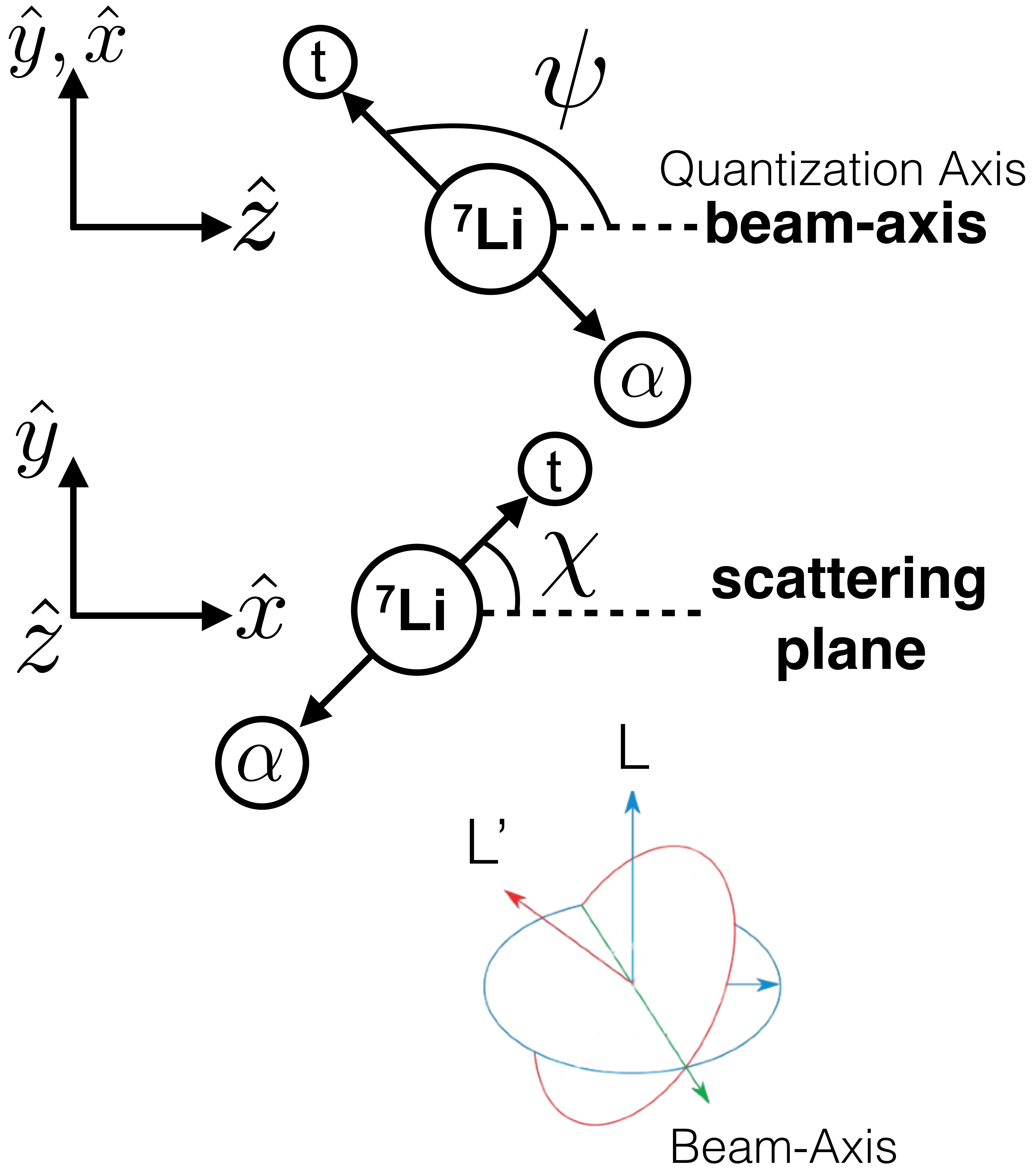


We know 3/4 parts of the Kinematics for

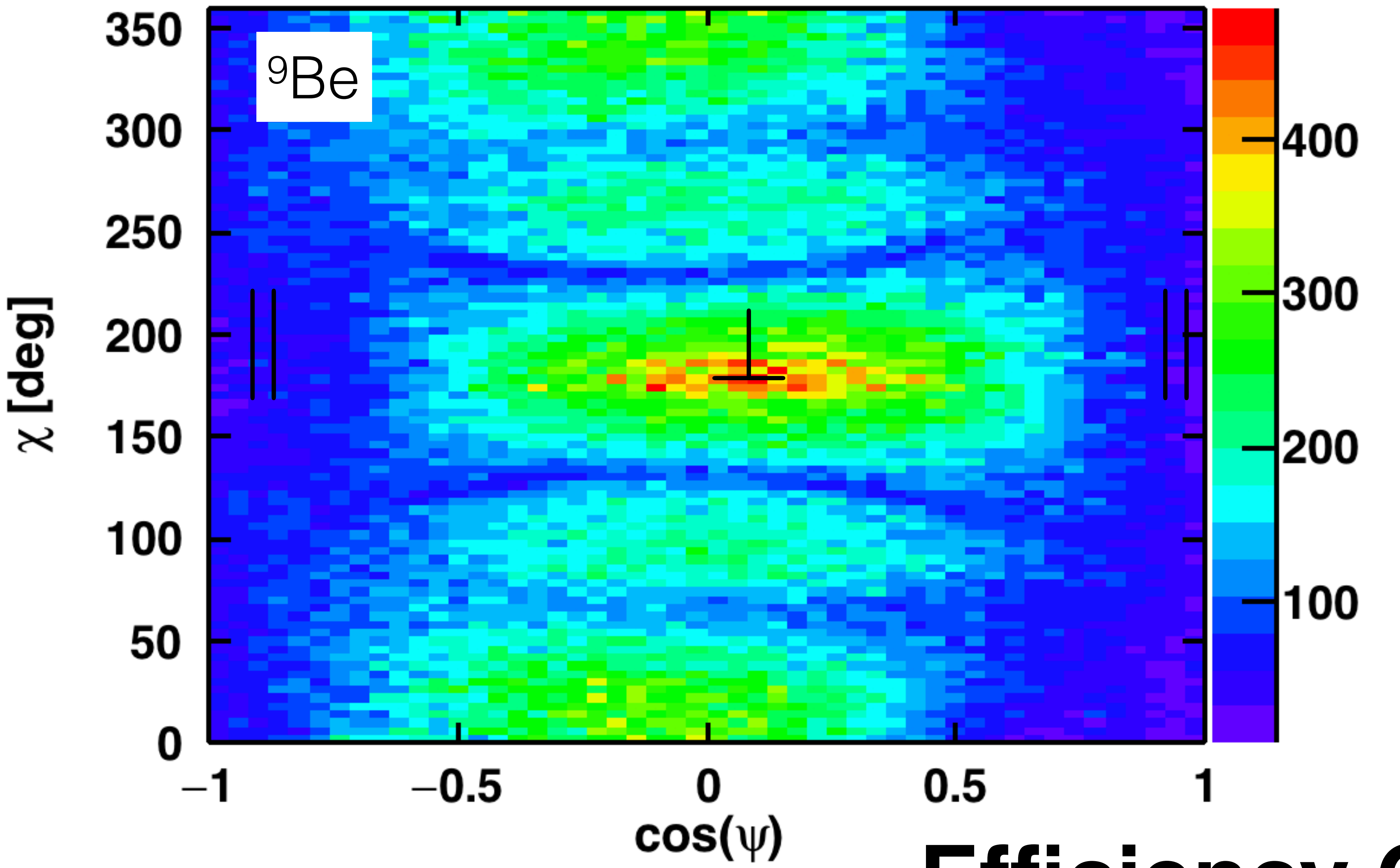
$^{7}\text{Li} + {}^{12}\text{C} \rightarrow {}^{7}\text{Li}^{*} + {}^{12}\text{C}$

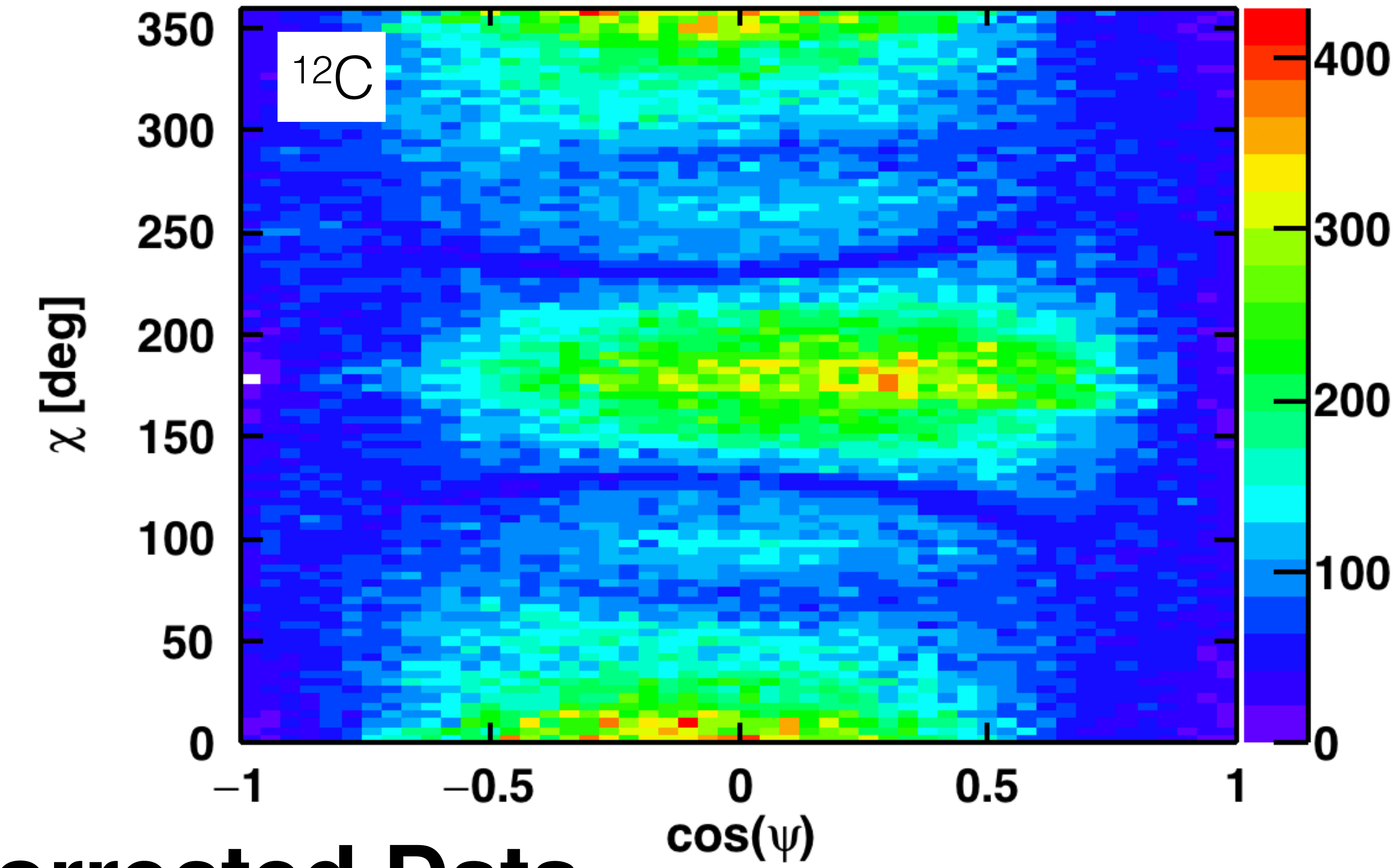
so we can deduce the target’s excitation energy as well.

How do we determine spin alignment?



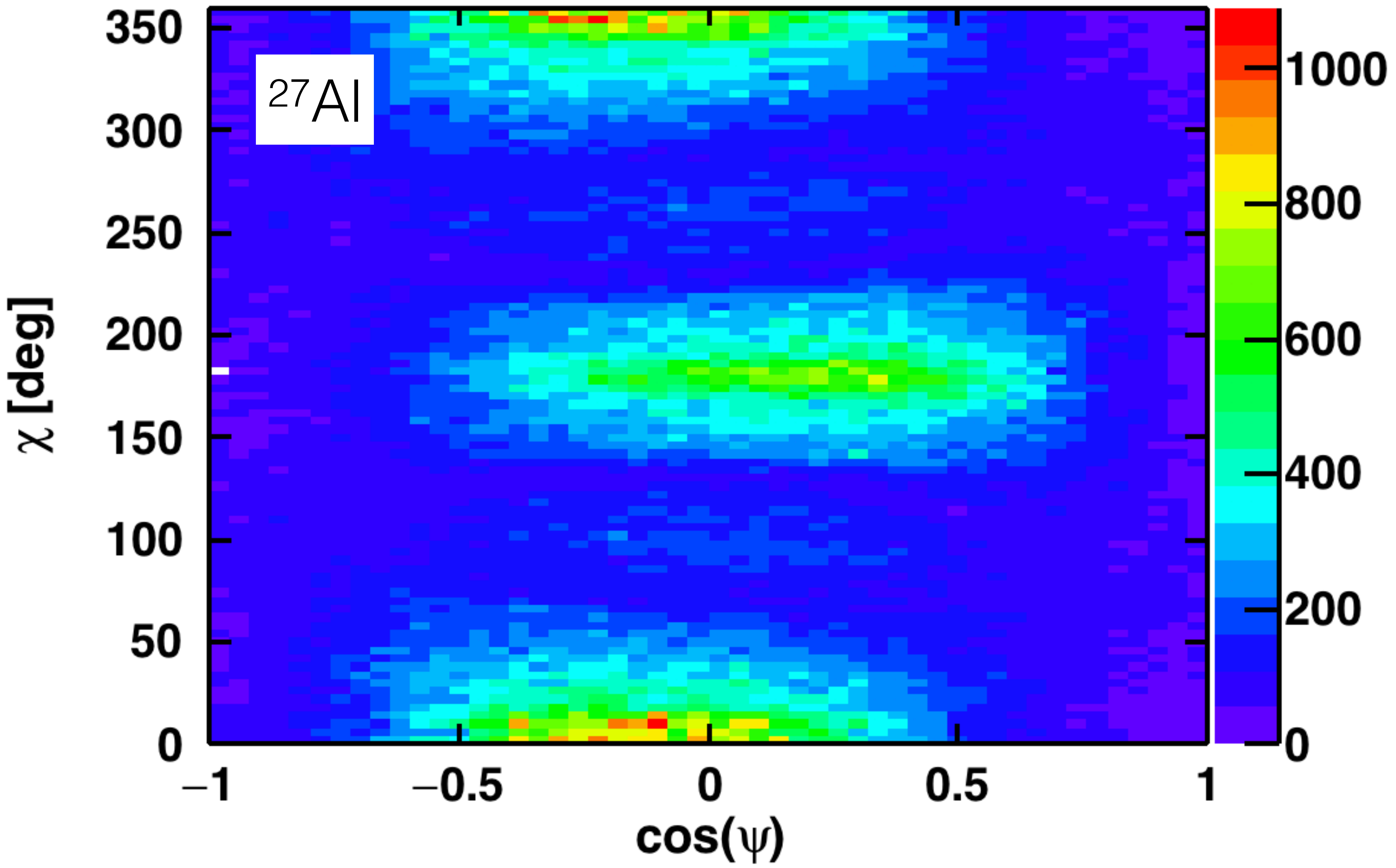
- Decay of 7/2$^-$ state has ℓ_{final} = 3 (α+t internal A.M.)
- If A.M. is ***perpendicular*** to the beam axis, fragments of decay will be preferentially emitted in a plane containing the beam axis (ψ = 0^o,180^o).
- If A.M is ***parallel*** to the beam axis, fragments of decay will be preferentially emitted in the x-y plane (ψ = 90^o).

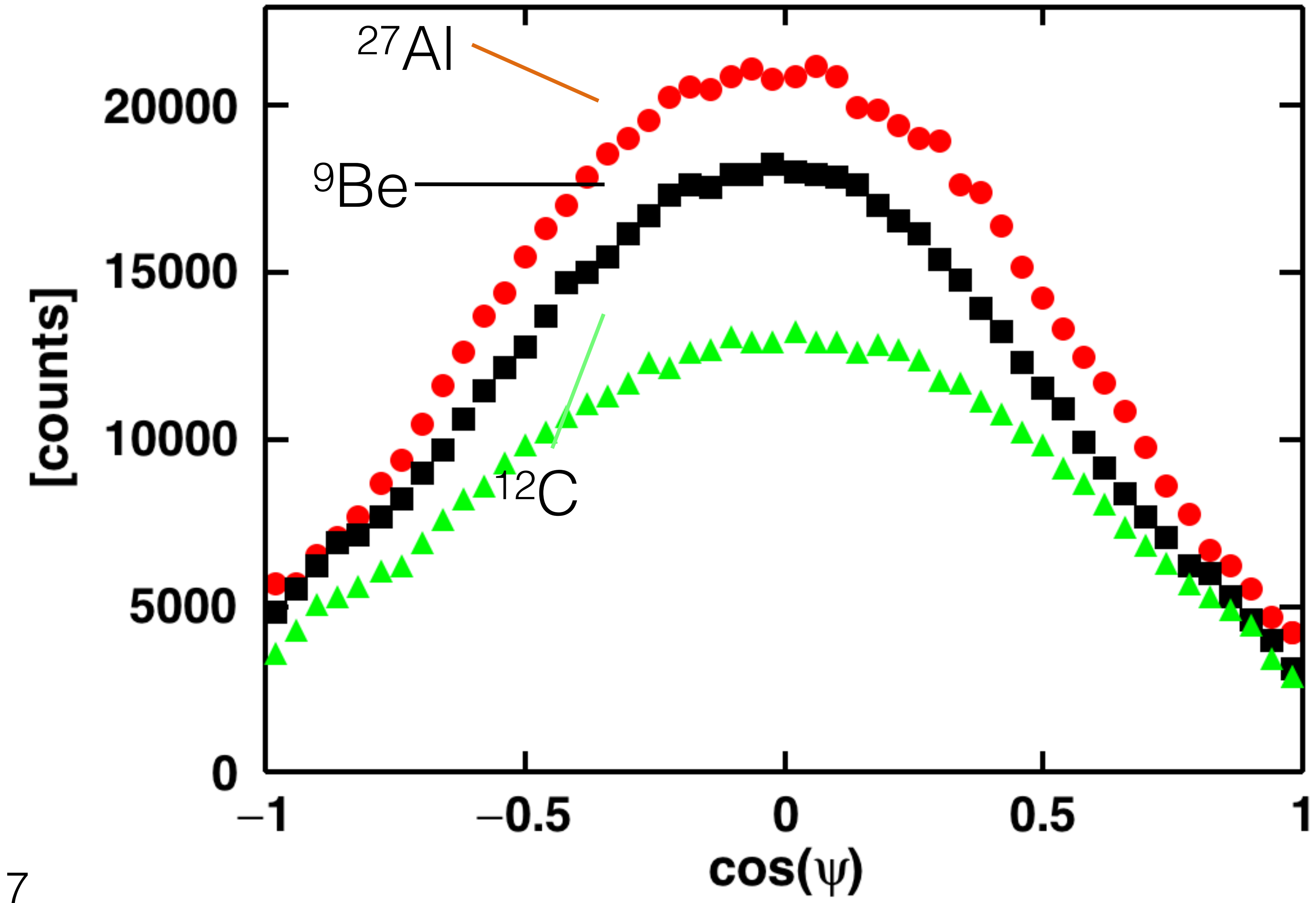




Efficiency Corrected Data

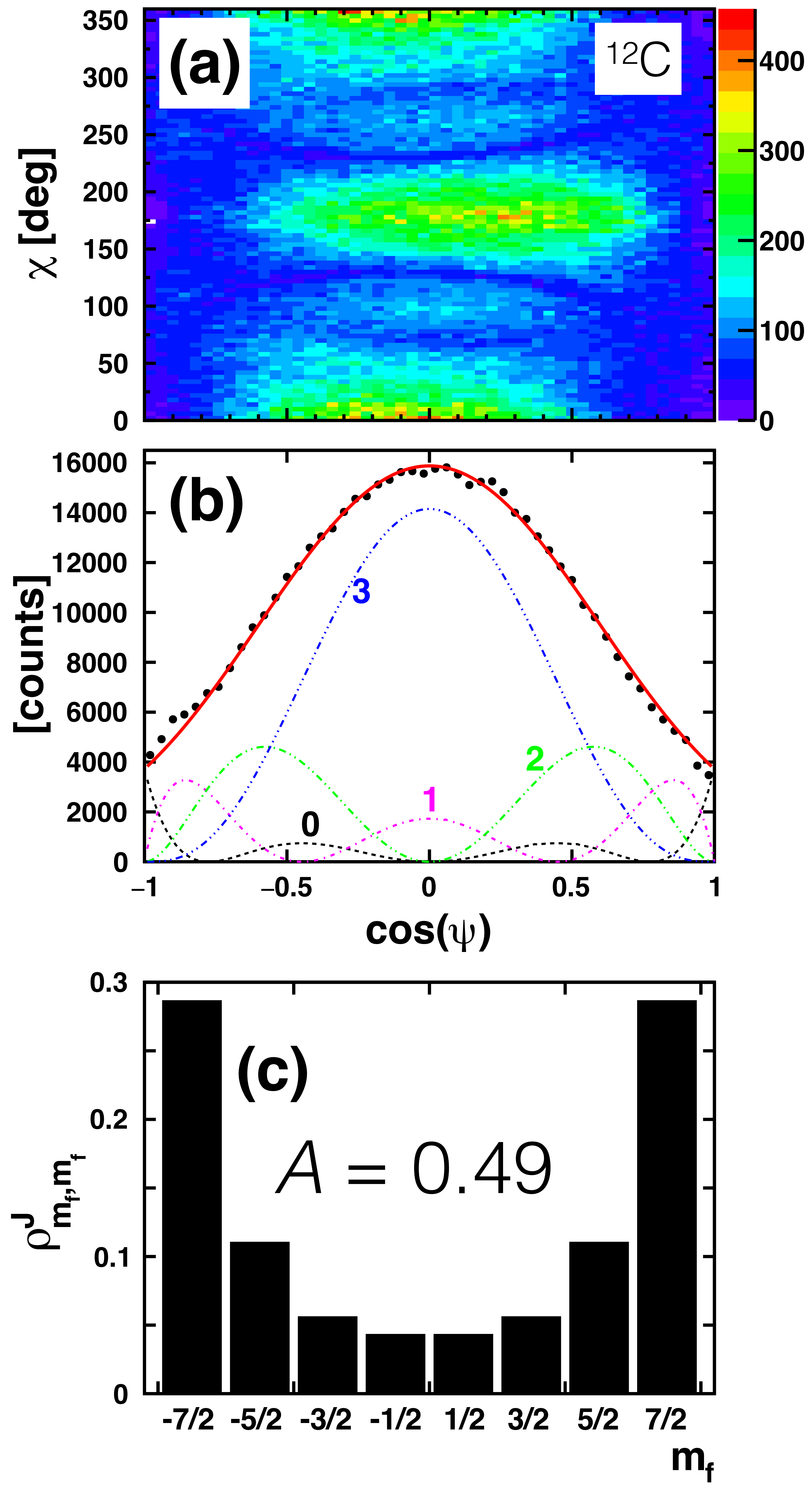
Strong peak at $\cos(\psi) = 0$



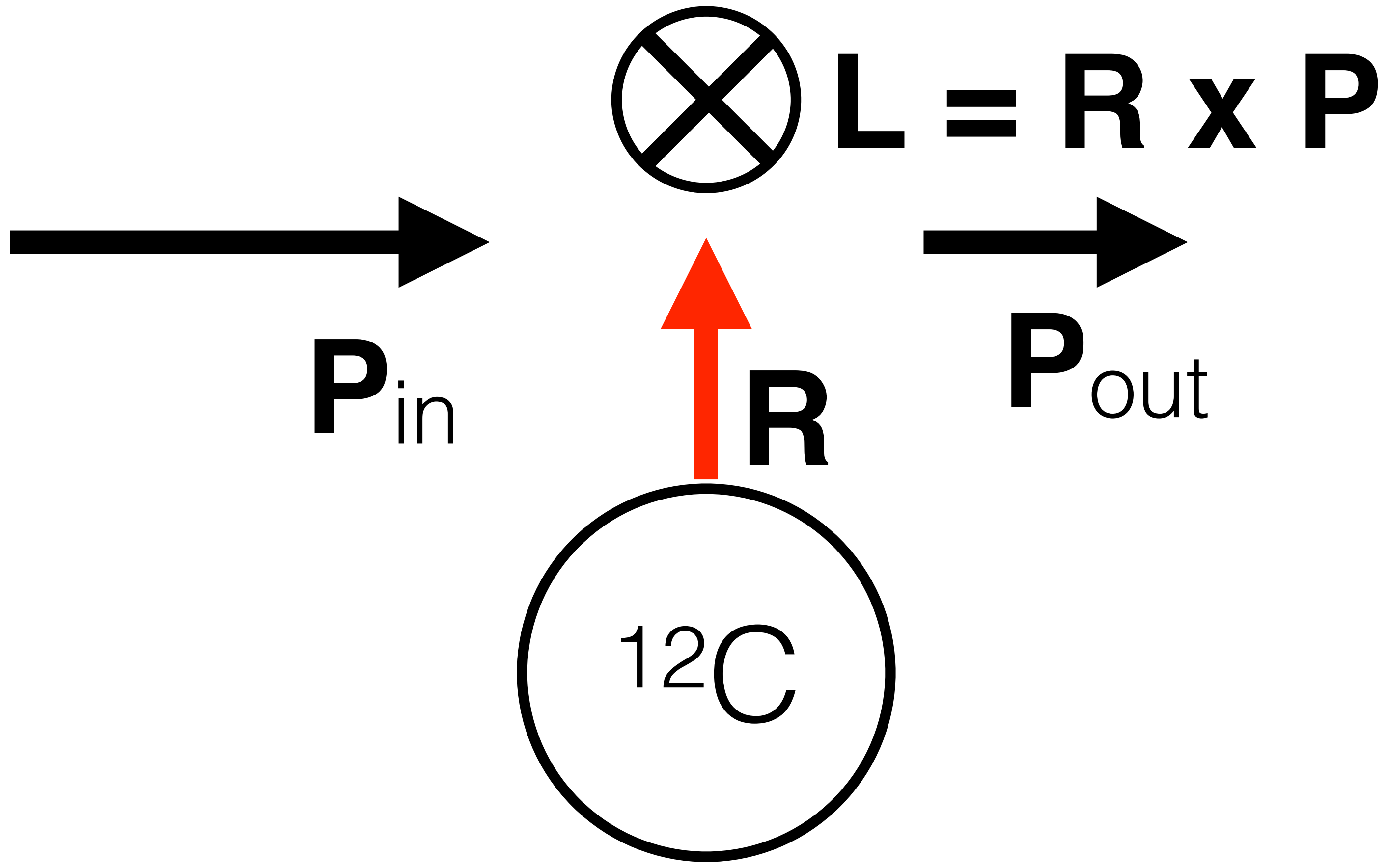


Magnetic-Substate Extraction

- We fit the angular correlations to squared associated Legendre Polynomials to extract the magnetic-substate populations.
- The weights of the squared assoc. Legendre Polynomials are related to the population of magnetic substates of the internal orbital motion.
- We add back the s=1/2 spin of the triton to get preferred orientation of ^{7}Li* spin before decay.
- Extracted magnetic sub-states indicate large ***longitudinal*** alignment.



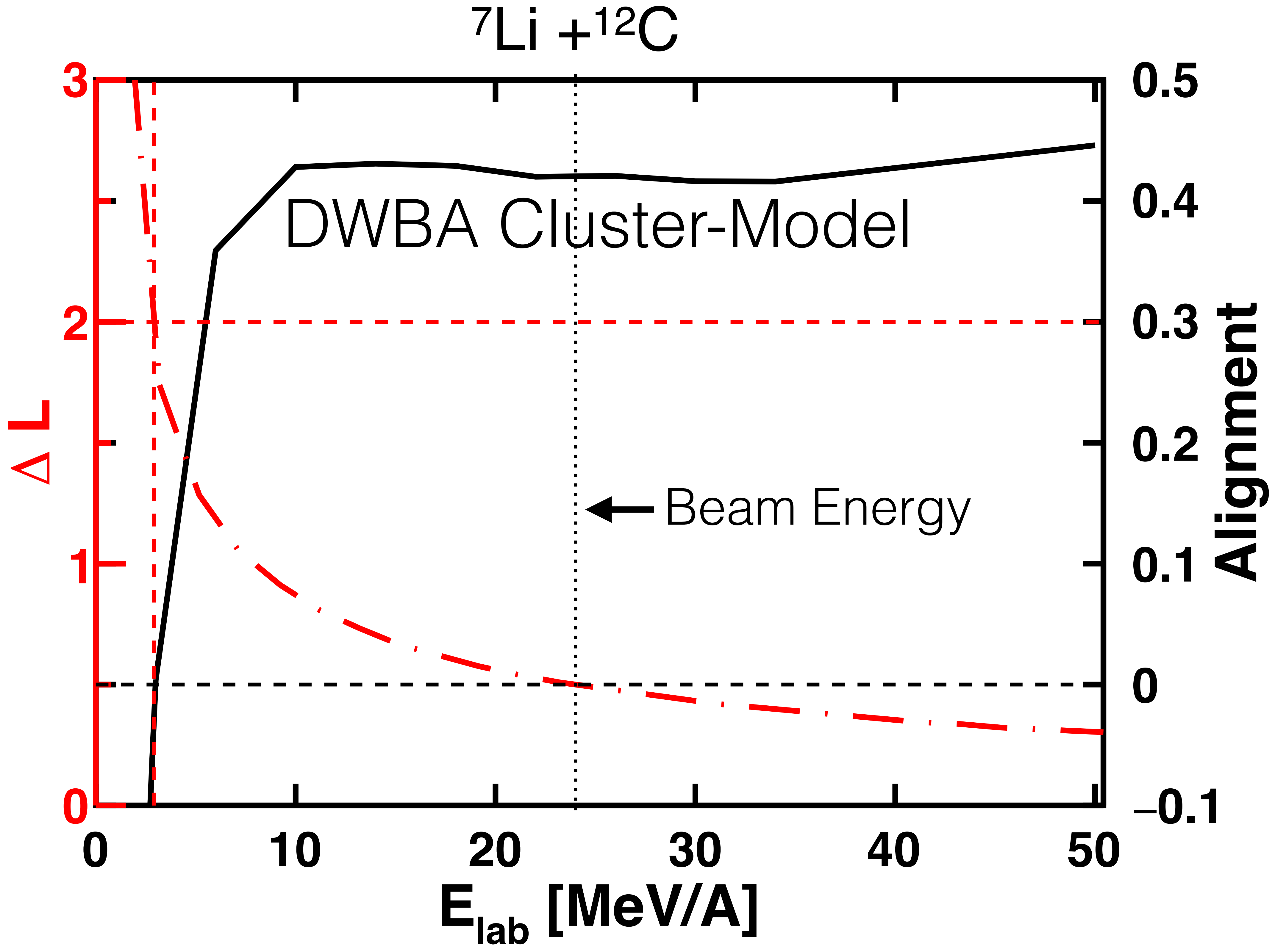
Angular Momentum & Excitation Energy Matching



$$\Delta L = \mathbf{R} \times (\mathbf{P}_{in} - \mathbf{P}_{out})$$
$$= R\sqrt{2\mu E_{CM}}\left(1 - \sqrt{1 - \frac{E^*}{E_{CM}}}\right)$$

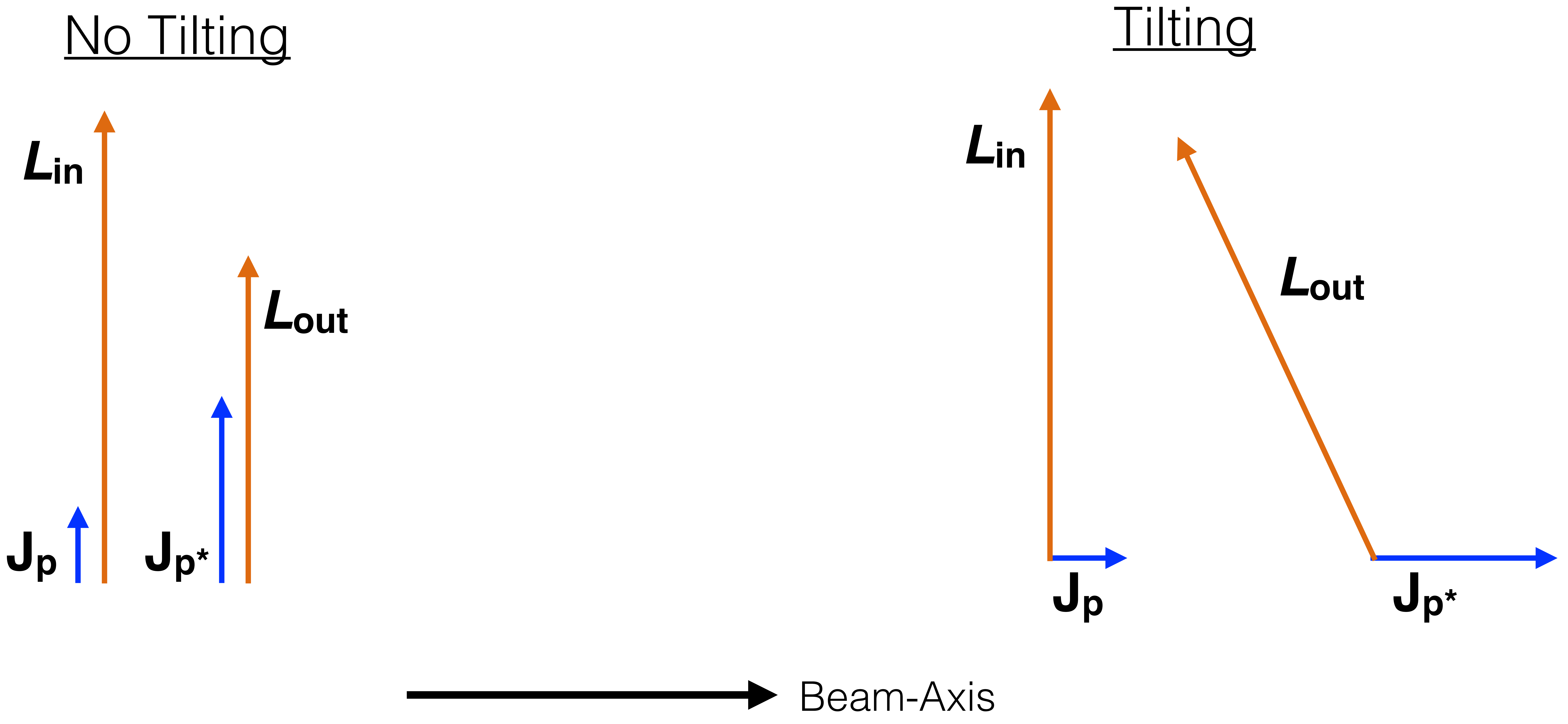
R~5 fm, E^* = 4.63 MeV

$\Delta\ell = 2$



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

Angular Momentum & Excitation Energy Matching



Alignment Mechanism

- We looked at the transition amplitude, or *T*-matrix, of the projectile in the Distorted Wave Born Approximation (DWBA) to understand the generation of alignment.

$$\frac{d\sigma}{d\Omega}(\theta_{CM}; m_i, m_f) = \frac{k_f}{k_i}\frac{\mu^2}{4\pi^2\hbar^2}|T_{m_i,m_f}|^2$$

- 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.

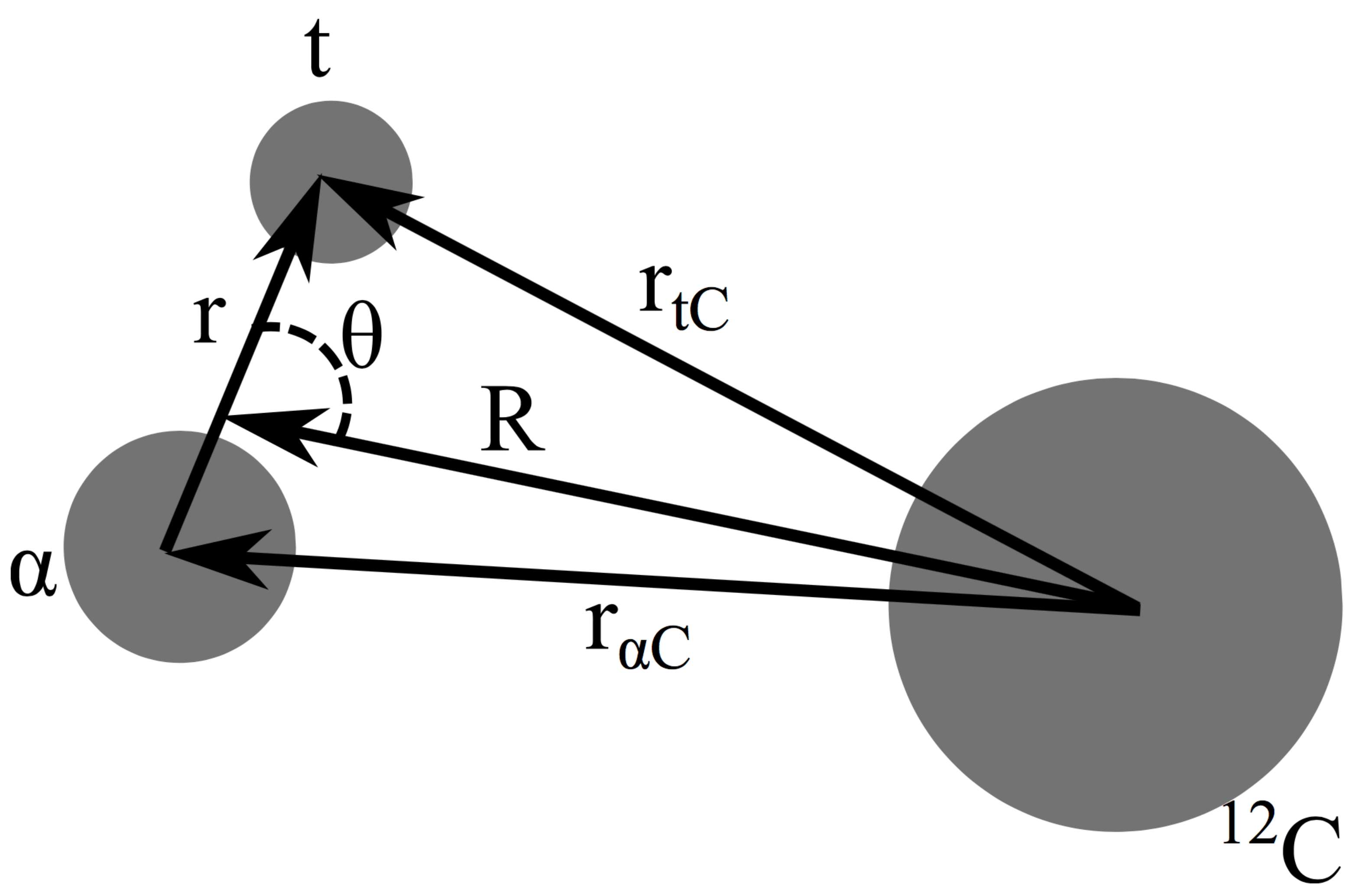
A.M. & E* mismatch → $L_i = L_f$

"external" motion

$$T_{m_i,m_f} = \sum_{K,L_i,L_f} \langle L_i\ 0\ K\ M | L_f\ M\rangle$$
$$\times \langle J_i\ m_i\ K\ M | J_f\ m_f\rangle Y^{L_f}_{-M}(\hat{k}_f) I(K, L_i, L_f)$$

"internal" motion

$$M = m_f - m_i$$



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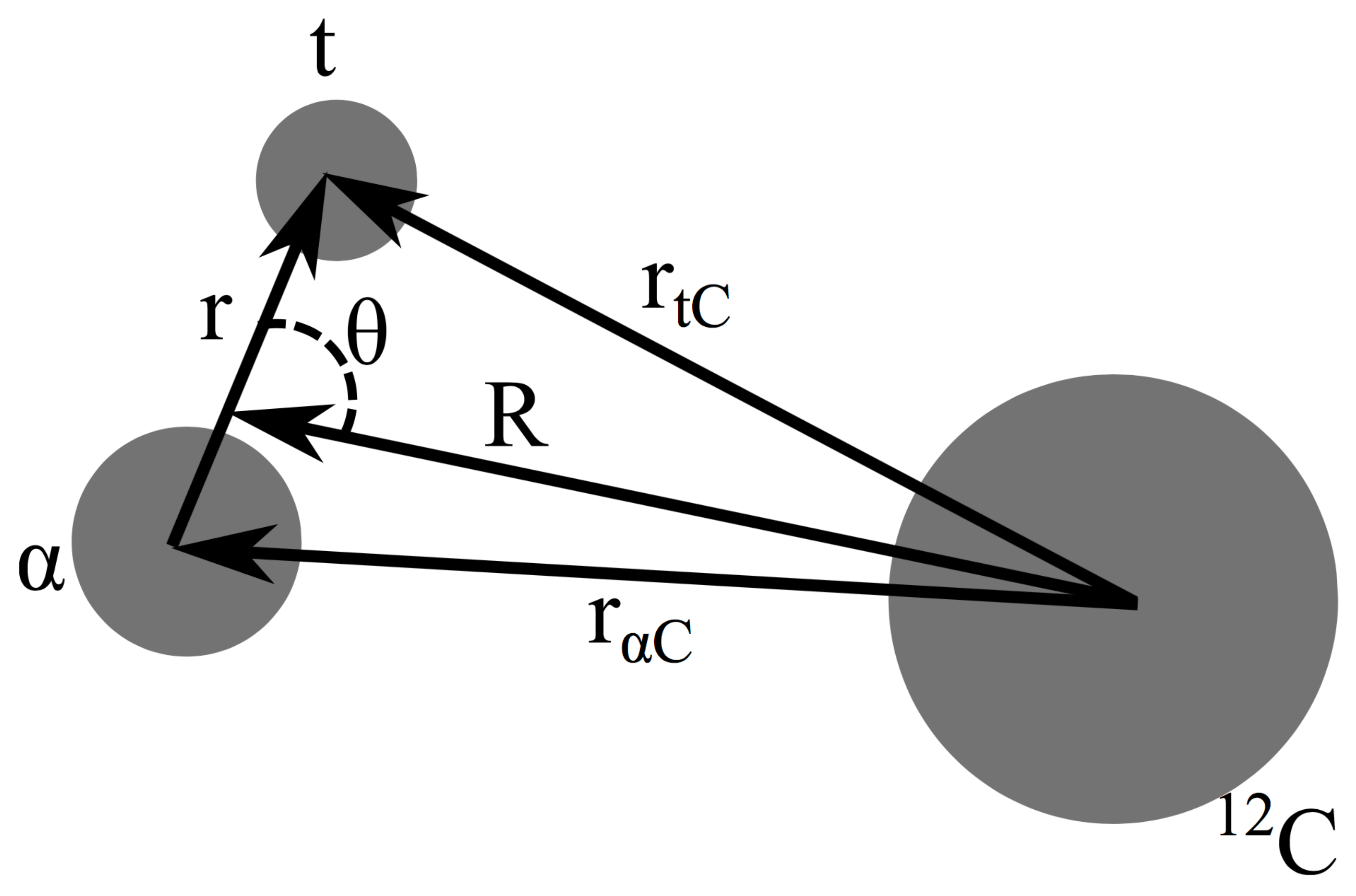
$$M = m_f - m_i$$

$$T_{m_i,m_f} \approx \langle L_{\text{graz}}\ 0\ K'\ M | L_{\text{graz}}\ M\rangle\ \langle J_i\ m_i\ K'\ M | J_f\ m_f\rangle \times \sum_L Y^L_{-M}(\hat{k}_f) I(K', L, L).$$



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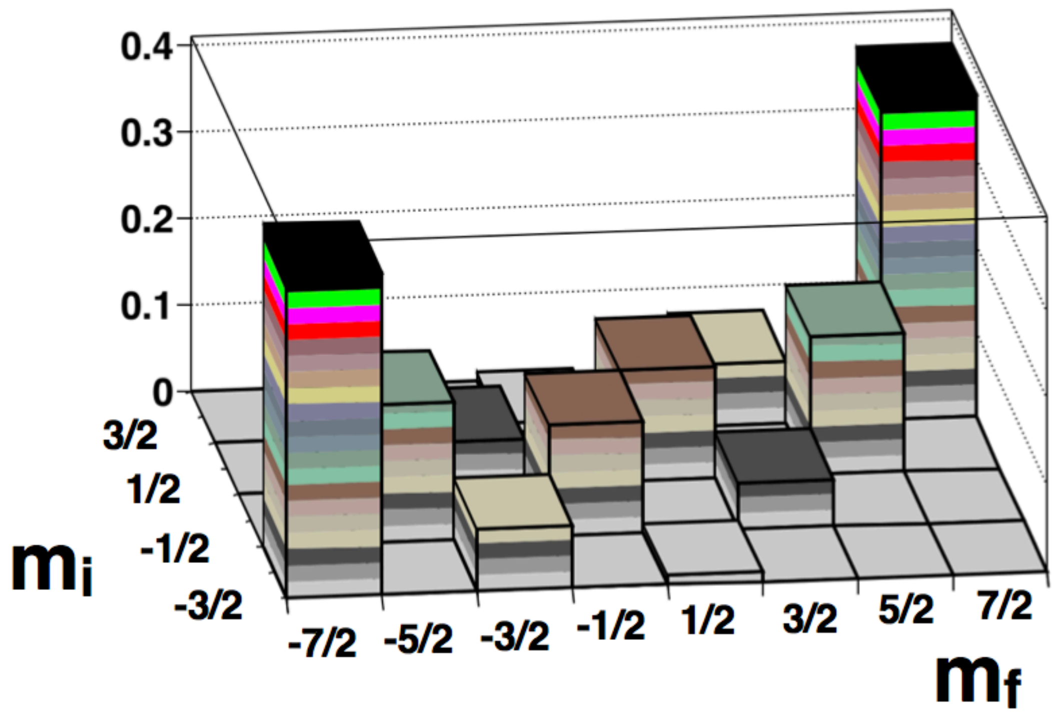

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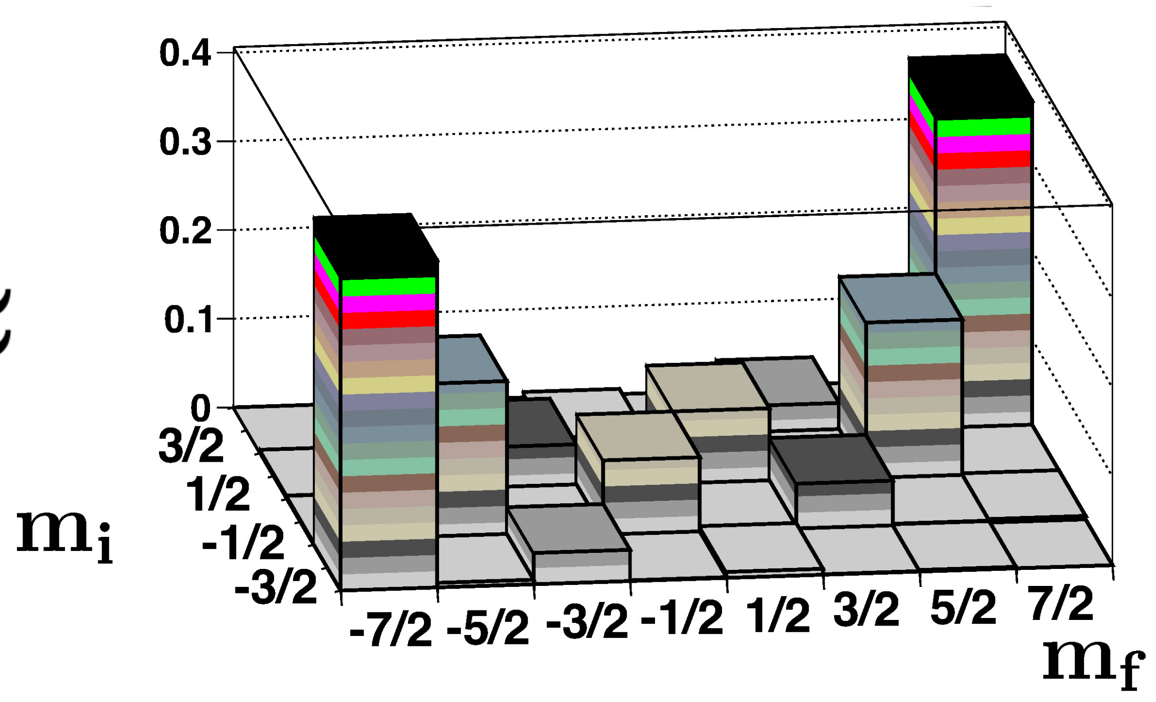
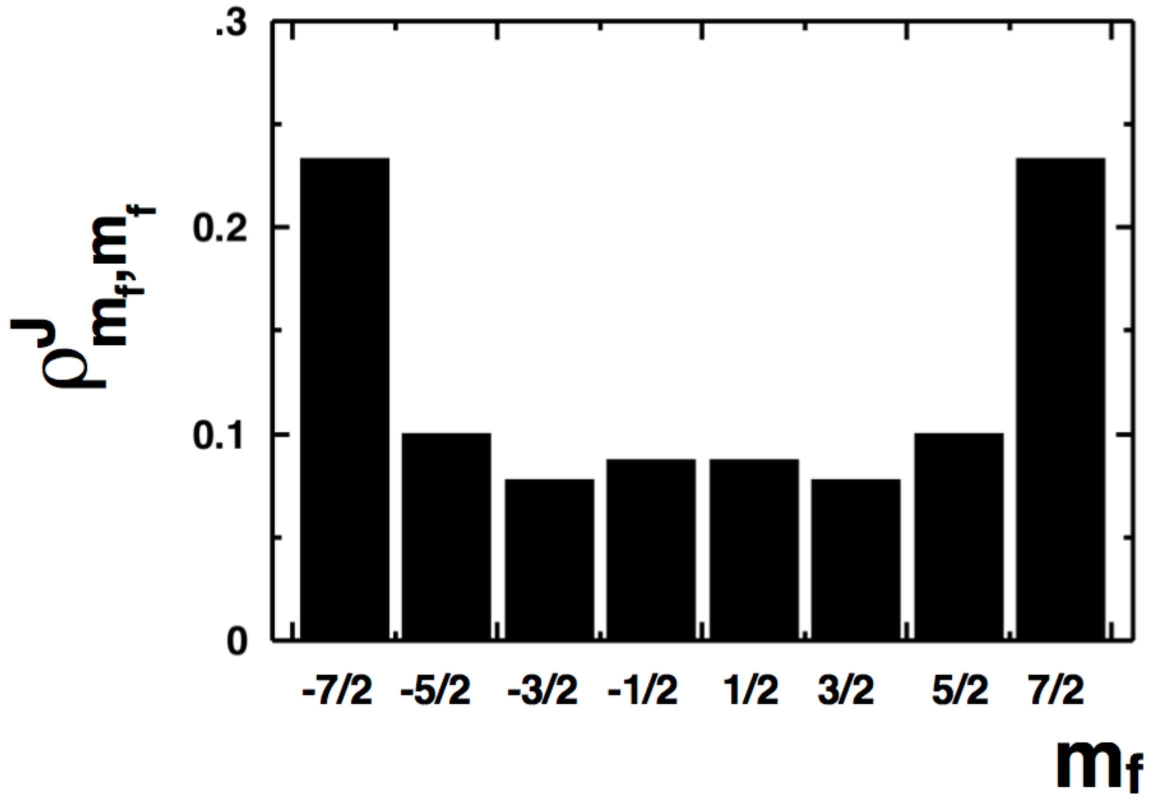


$$\langle 3/2, m_i\,;\,\mathbf{2}, M \,|\, 7/2, m_f\rangle^2 \,\langle 35, 0\,;\,\mathbf{2}, M \,|\, 35, M\rangle^2$$

DWBA



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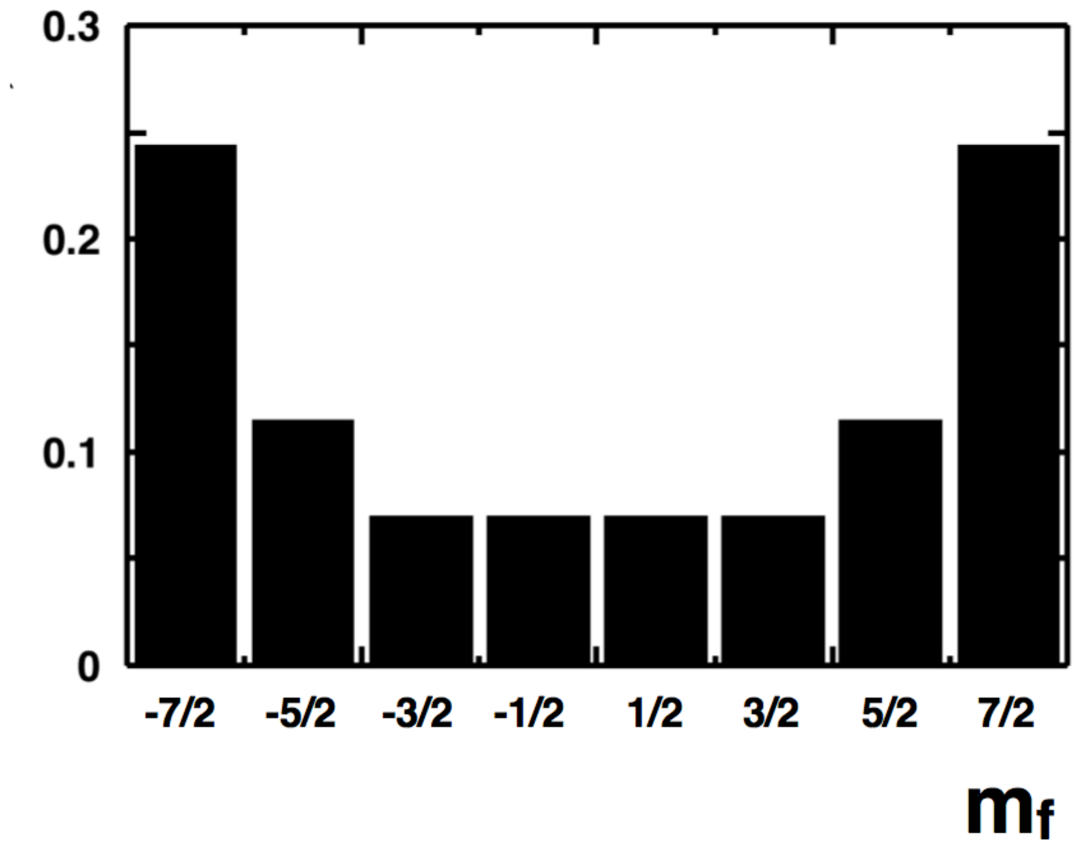
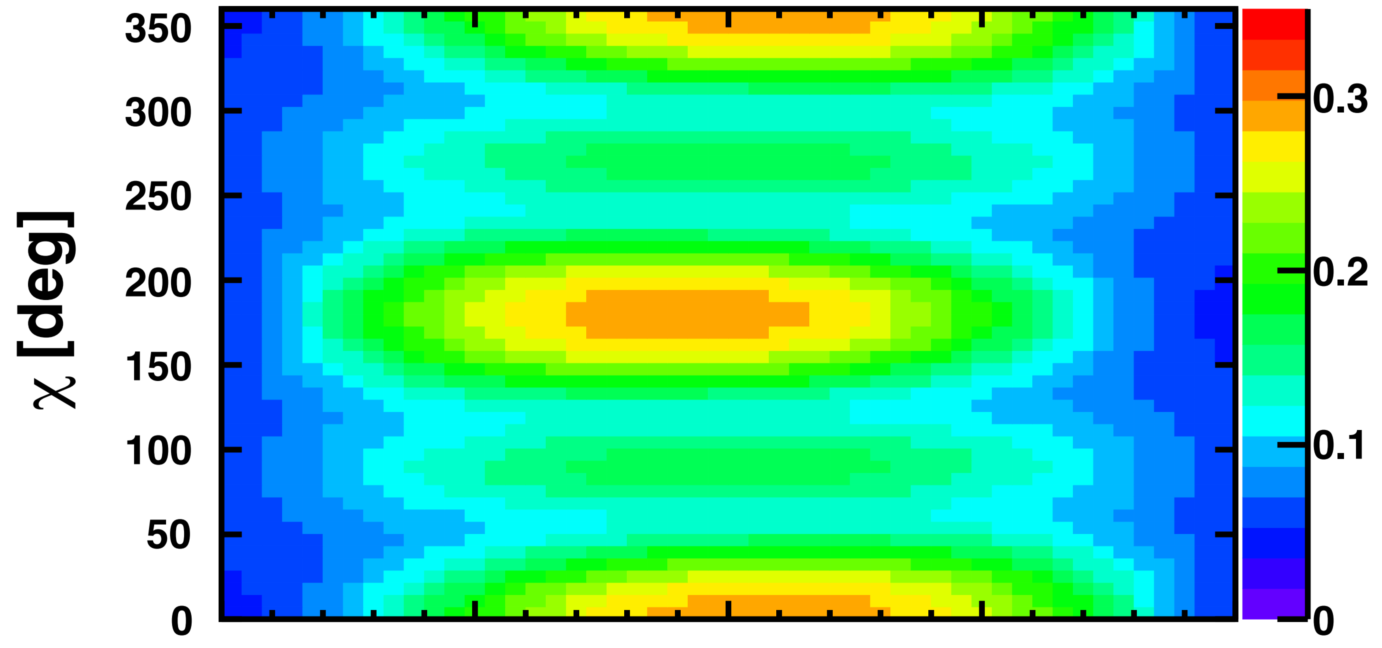


Dominant contributions to *T*-Matrix are tilting solutions!

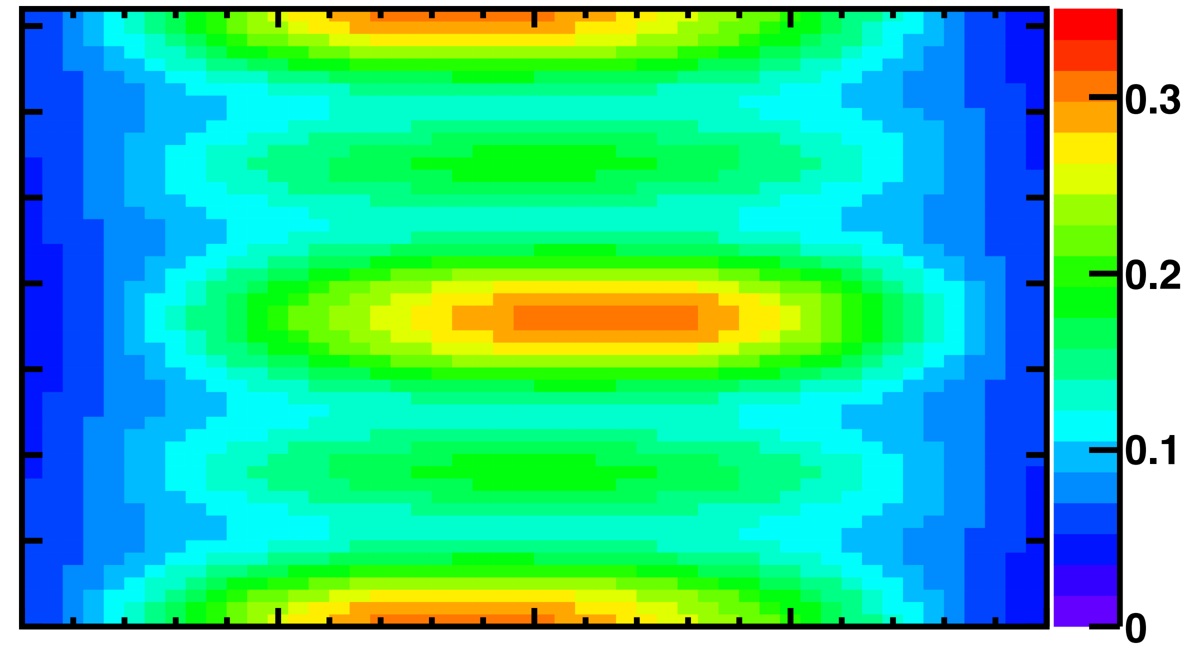
- Multiplying together the relevant Clebsch-Gordan coefficients predicts a “gross” squared T-Matrix.
- The squared T-Matrix from the angle-averaged DWBA cluster-model is strikingly similar to the CG prescription.

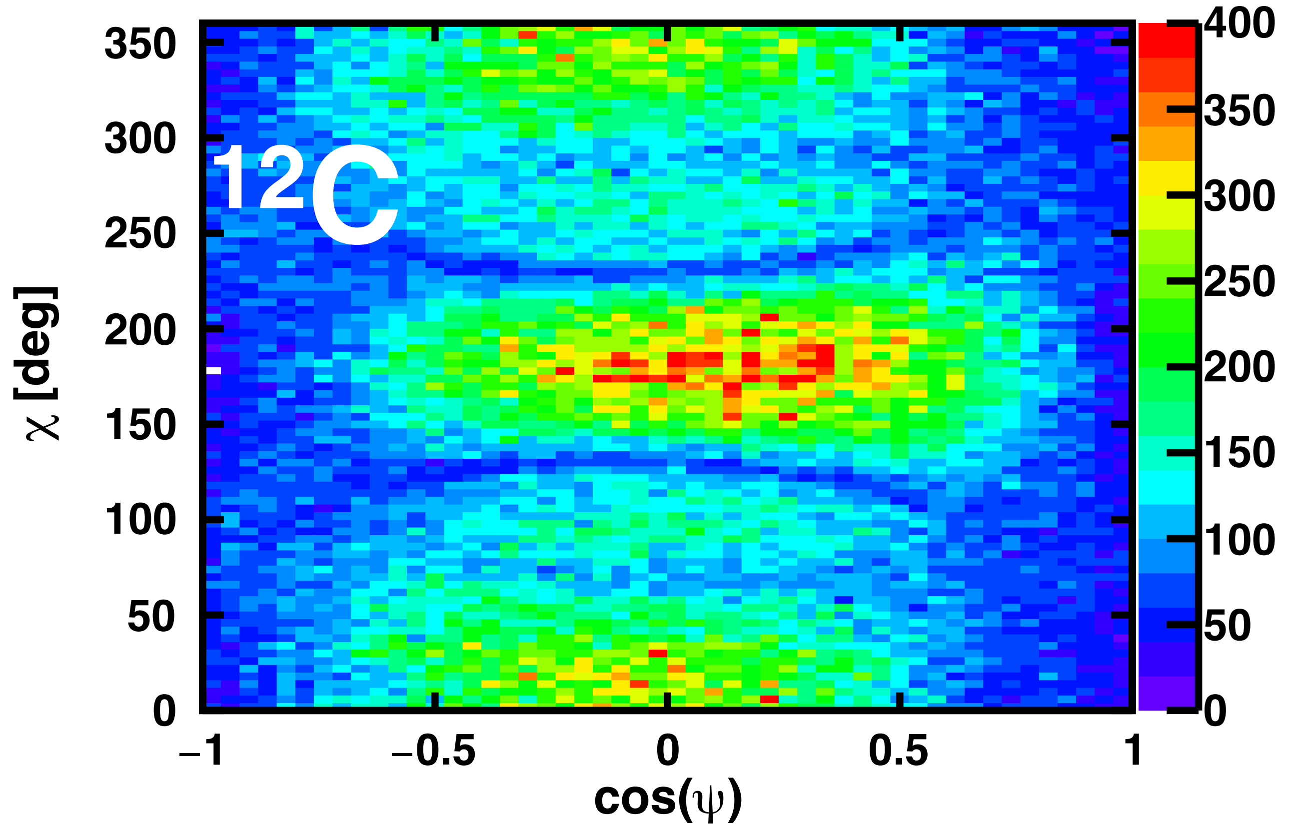
Spin-Orbit Effects on Alignment

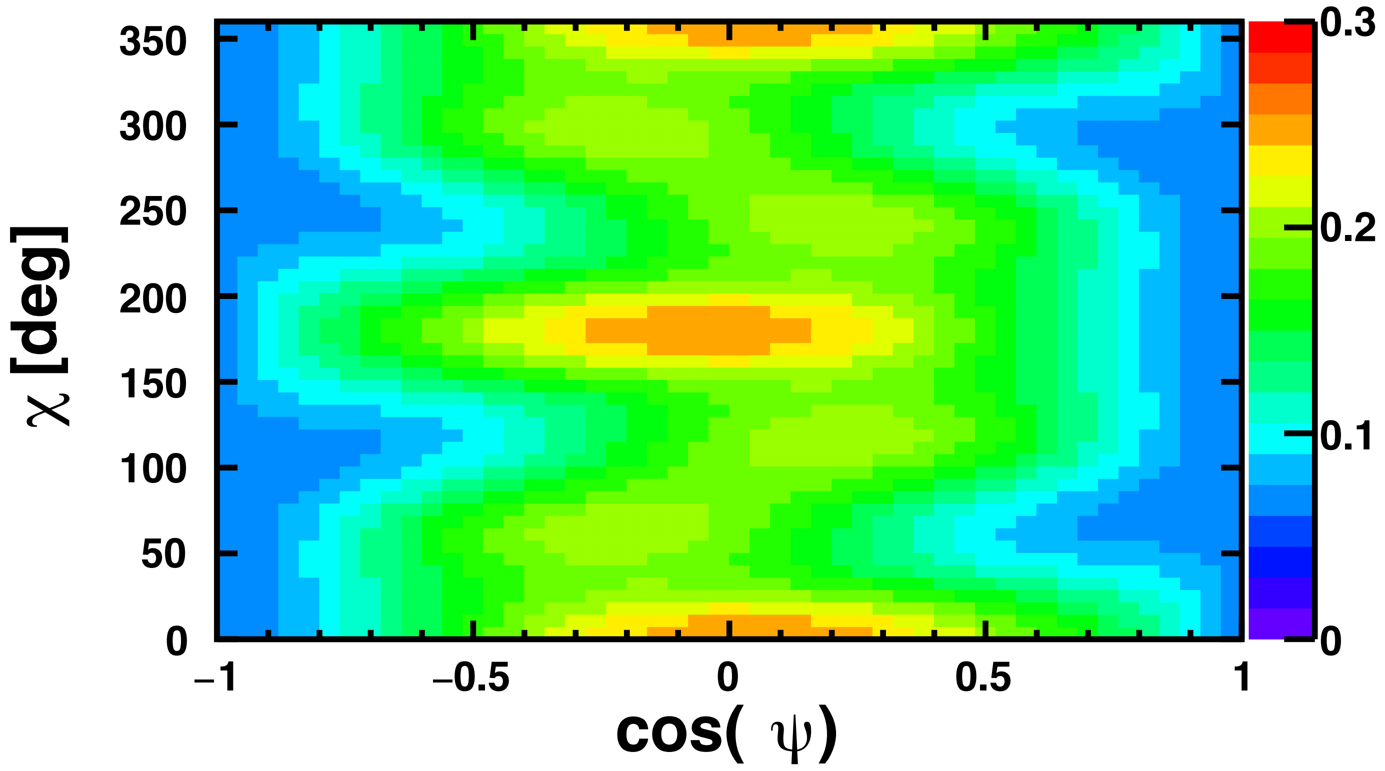
no spin-orbit term



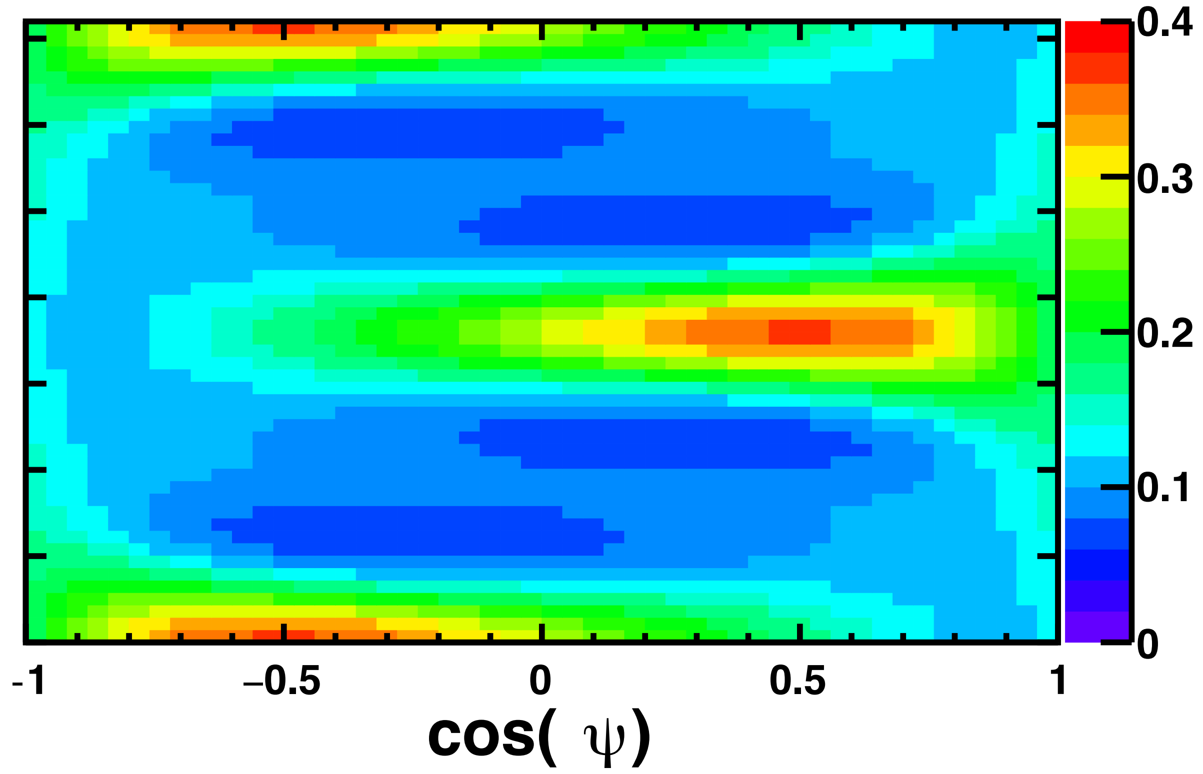
$V_{SO} = 0.55$ & $W_{SO} = 0.72$







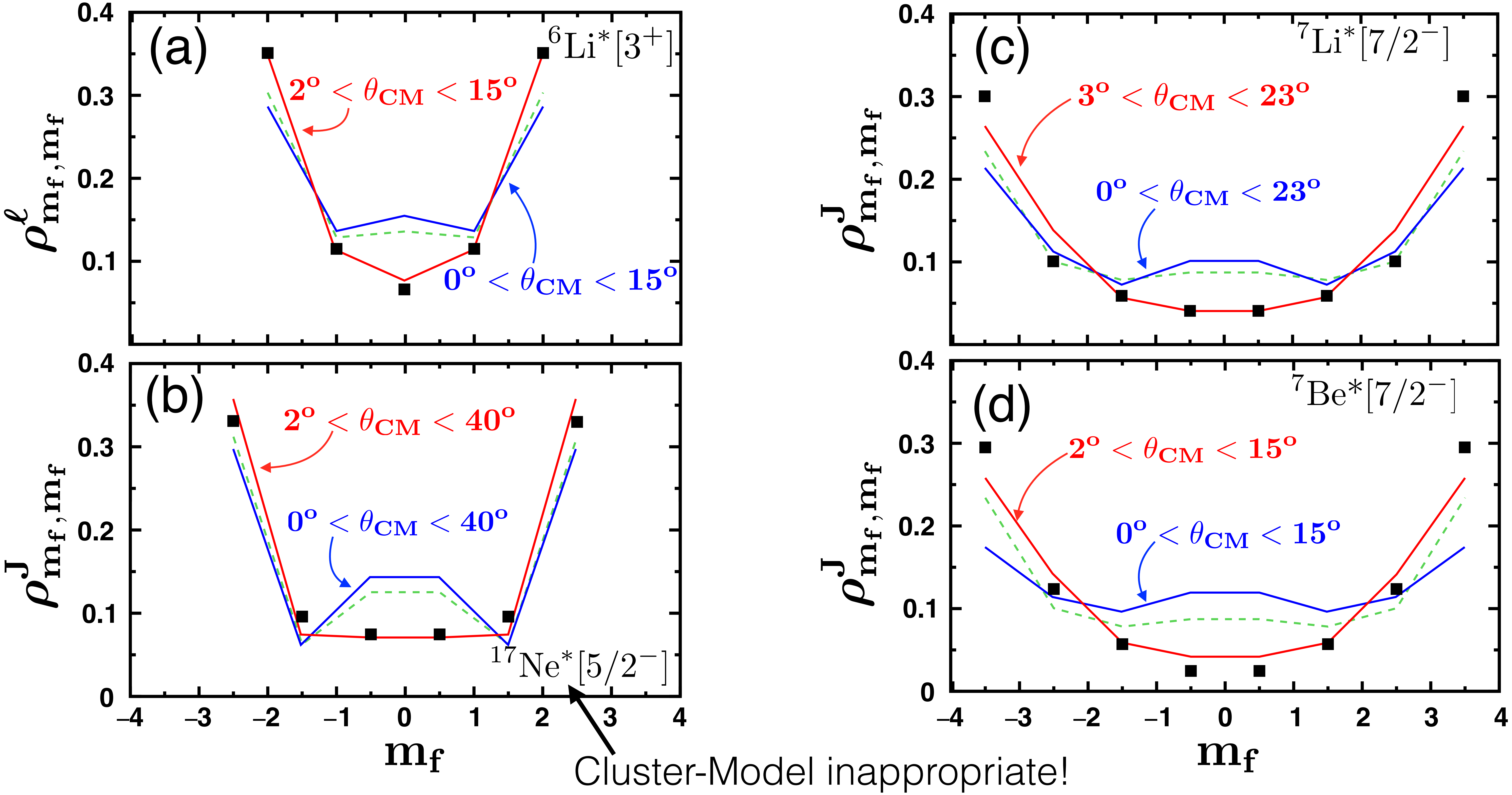
$V_{SO} = 3.0$ & $W_{SO} = 0.72$



$V_{SO} = 0.55$ & $W_{SO} = 1.44$

- Needed small complex spin-orbit potential for the projectile to reproduce data.
- Can put constraint on SO interactions through correlation measurements.

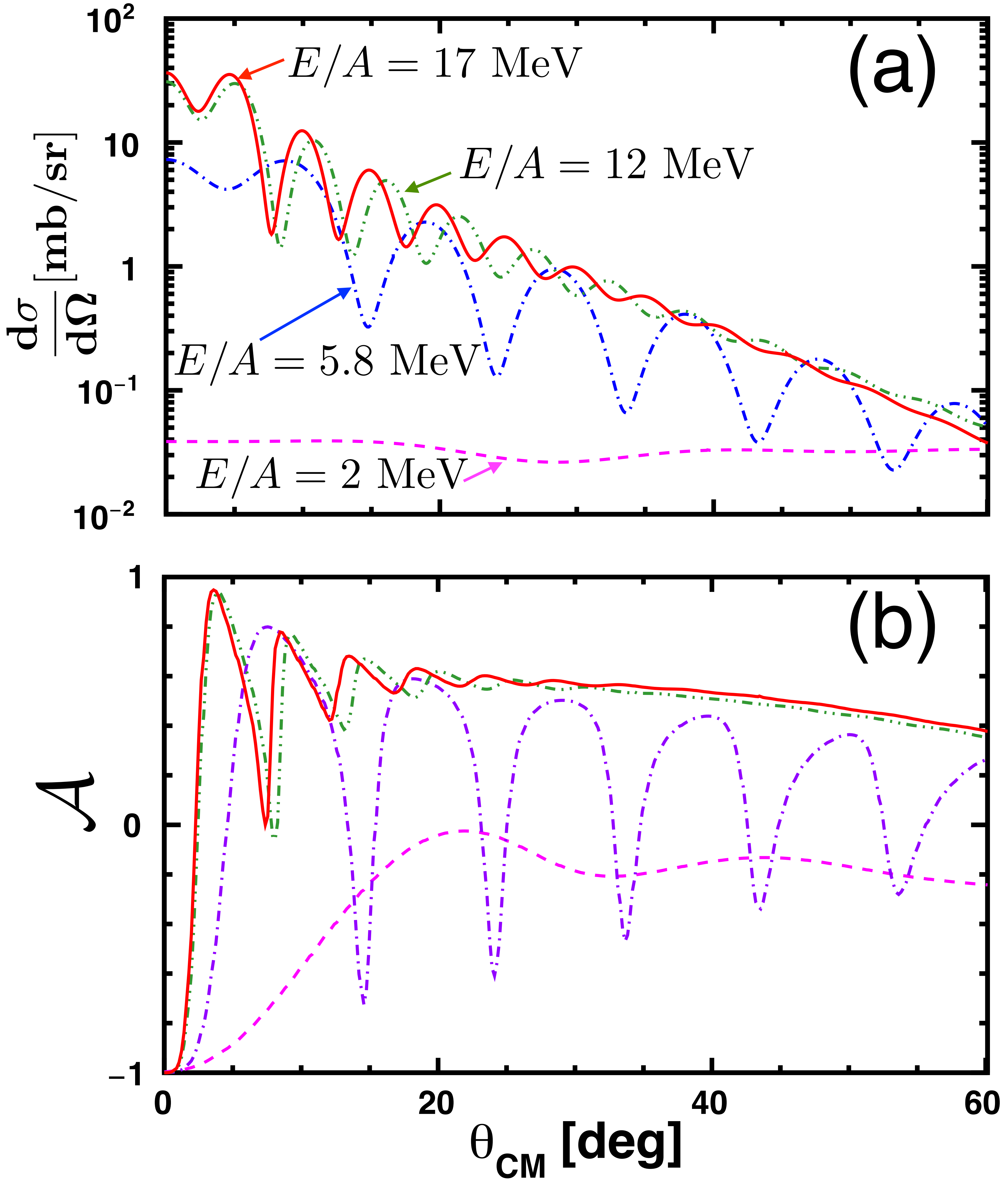
Other Cases of Alignment



Y_0^L is the only contribution to the alignment at small angles (M=0 so no tilting).

Removing small angle scattering enhances alignment.

Predictions for ^{12}C + ^{12}C



- Using a DWBA Soft-Rotator Model we can predict the T-Matrix for:

$$^{12}C(^{12}C,{}^{12}C^*[4.4\ \mathrm{MeV}])^{12}C$$

- Threshold for large alignment is around *E/A* = 5 MeV.

- As the bombarding energy is increased large longitudinal alignment should be observed.

Conclusions

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

- Alignment arises from an angular-momentum-excitation-energy mismatch, which forces $\Delta L = 0$ and so the final reaction plane tilts.

- One can put a constraint on mean-field spin-orbit coupling through correlation measurements (without a polarized beam).

- Alignment mechanism is largely ***independent*** of the scattering potential used.

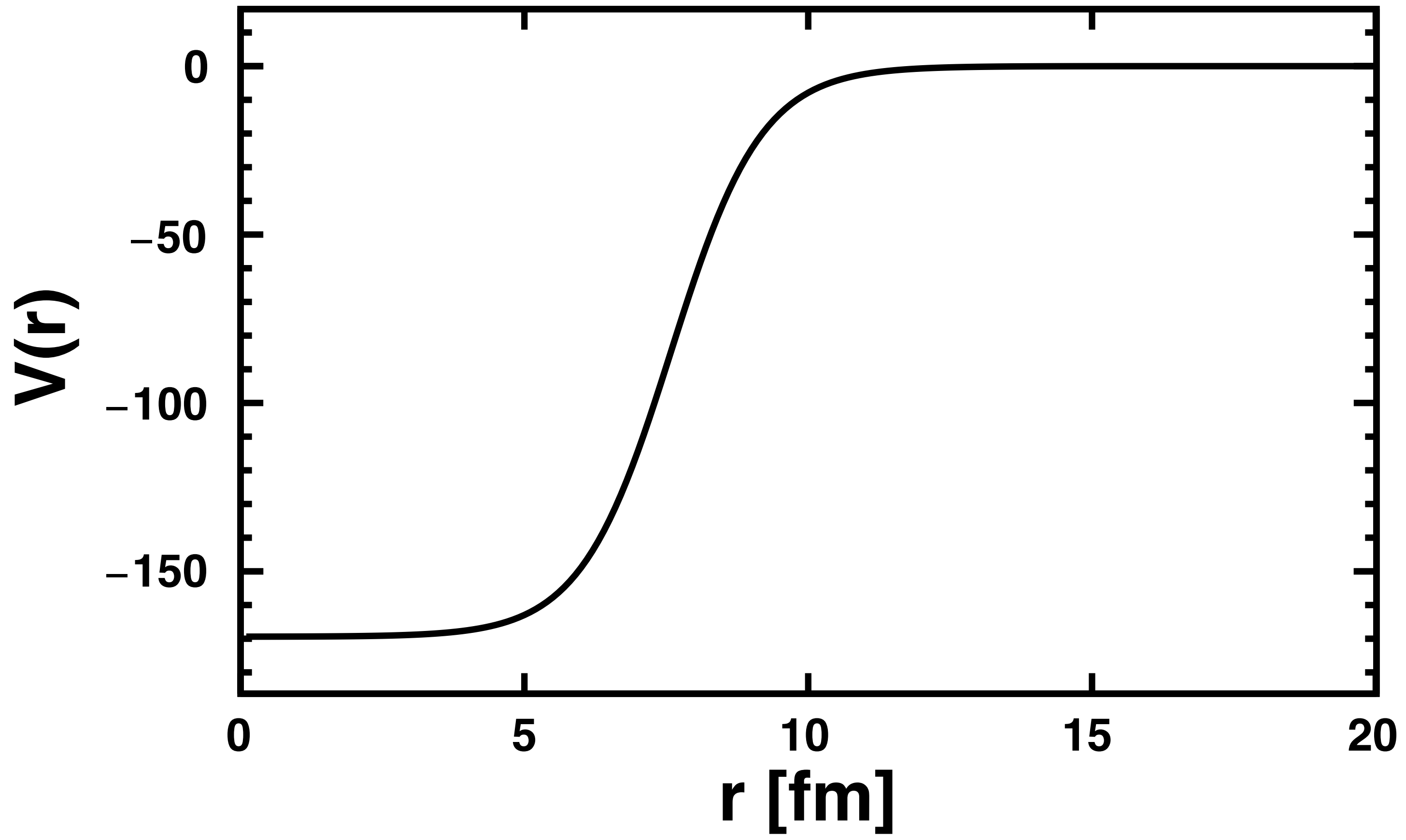
    - Proposed alignment mechanism may be the source of spin alignment in previous *g*-factor measurements performed at “intermediate” energies.

Optical-Model Fits

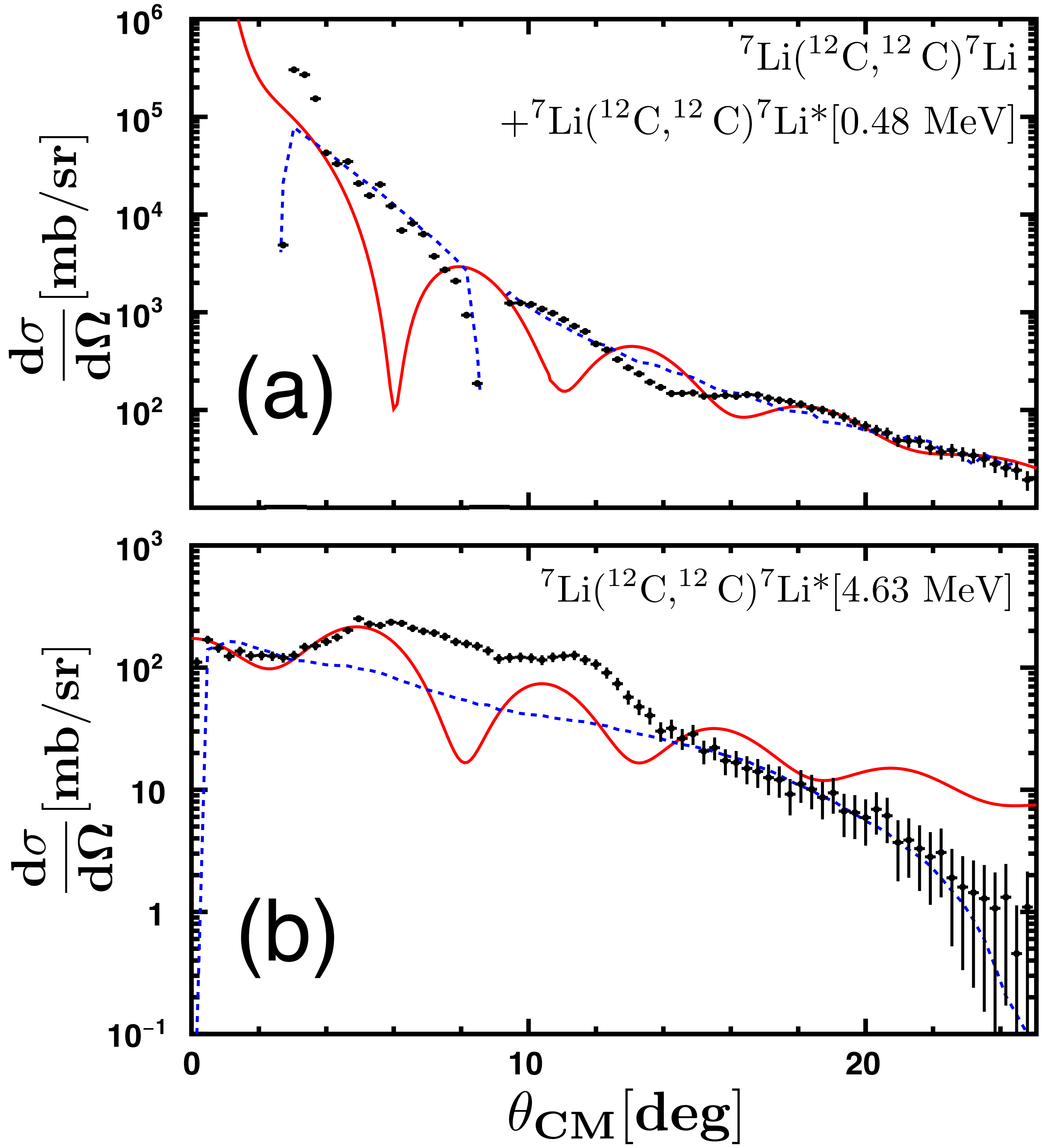
$$V + iW$$

System	Type	V [MeV]	r_{real} [fm]	a_{real} [fm]	W [MeV]	r_{imag} [fm]	a_{imag} [fm]
$^{7}\mathrm{Li}{-}^{12}\mathrm{C}$	Volume	169.4	1.28	0.800	34.8	1.67	0.758
	Spin-Orbit	0.550	1.48	0.727	0.720	1.48	0.485
$\alpha{-}^{12}\mathrm{C}$	Volume	72.0	1.433	0.692	32.0	1.43	0.692
$t{-}^{12}\mathrm{C}$	Volume	65.3	1.15	0.400	30.9	1.35	0.407
$\alpha - t$	Volume	71.6	1.20	0.736			

Volume terms use Woods-Saxon form.



Spin-Orbit term uses differential Woods-Saxon form.



Beam misalignment and divergence limited scattering angle resolution.