• Three-body correlations in ^{10}He and ^{13}Li decays

Unbound Nuclei Workshop, Pisa, 3-5 November 2008

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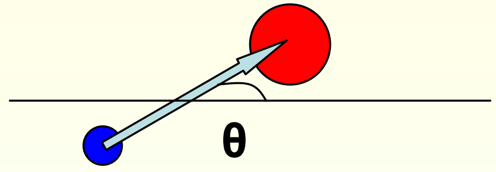
Gesellschaft
für Schwerionenforschung

Angular correlations

Two-body case



$$\hat{l}^2 = -\frac{1}{\sin\theta}\left\{\frac{\partial}{\partial\theta}\left(\sin\theta\,\frac{\partial}{\partial\theta}\right) + \frac{1}{\sin\theta}\,\frac{\partial^2}{\partial^2\varphi}\right\}$$

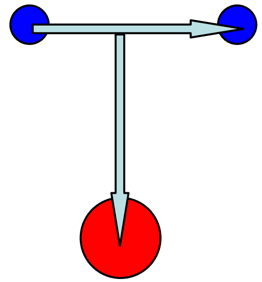
$$\hat{l}^2 Y_{lm}(\theta,\varphi) = l(l+1)\,Y_{lm}(\theta,\varphi)$$

centrifugal barrier

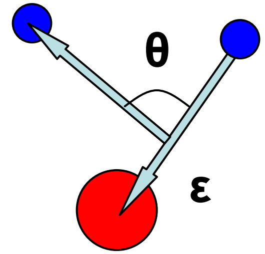
$$\hat{H} = -\frac{\hbar^2}{2}\left[\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} - \frac{1}{r^2}\,l(l+1)\right]$$

$$d\tau = \sqrt{E}\,dE \quad d\Omega$$

Three-body case



T system



Y system

$$\hat{K}^2(\Omega_6) = -\frac{\partial^2}{\partial\alpha^2} - 4\cot 2\alpha\,\frac{\partial}{\partial\alpha} + \frac{1}{\cos^2\alpha}\,\hat{l}^2(\Omega_x) + \frac{1}{\sin^2\alpha}\,\hat{l}^2(\Omega_y)$$

$$\rho^2 = \mathbf{r}_x^2 + \mathbf{r}_y^2 = \rho^2(\sin^2\alpha + \cos^2\alpha); \quad \alpha = \arccos\frac{\mathbf{r}_x}{\rho}$$

$$E = E_x + E_y; \quad \alpha = \arccos\sqrt{\frac{E_x}{E}}; \quad \epsilon = \cos^2\alpha = \frac{E_x}{E}$$

$$\hat{H} = -\frac{\hbar^2}{2}\left[\frac{\partial^2}{\partial\rho^2} + \frac{5}{\rho}\frac{\partial}{\partial\rho} - \frac{1}{\rho^2}K(K+4)\right]$$

α - hyperangle

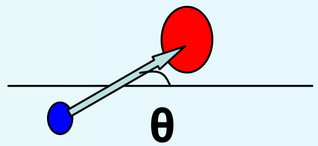
$$\hat{K}^2\mathcal{Y}_K^{l_x,l_y,m_x,m_y}(\Omega_6) = K(K+4)\,\mathcal{Y}_K^{l_x,l_y,m_x,m_y}(\Omega_6)$$

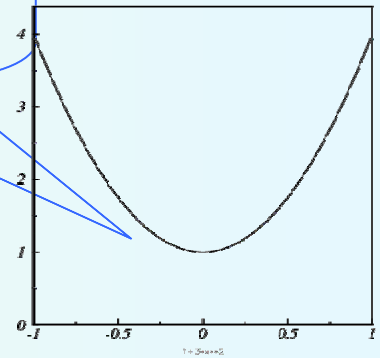
$$d\tau = E^2 dE \;\; \sqrt{\epsilon(1-\epsilon)}\,d\epsilon \;\; d\Omega_x \;\; d\Omega_y$$

three-body barrier

Hyperspherical harmonics

Expansion of a decay amplitude
into the spherical-harmonic series
Requires polarization.





Polarized $p_{3/2}$ shell

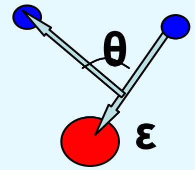
$$\mathcal{Y}_K^{l_x,l_y,m_x,m_y}(\Omega_6) =$$

$$N_K^{l_x,l_y}\cos^{l_x}(\alpha)\sin^{l_y}(\alpha)P_n^{l_x+1/2,l_y+1/2}(\cos 2\alpha)\mathrm{Y}_{l_x m_x}(\Omega_x)\mathrm{Y}_{l_y m_y}(\Omega_y)$$

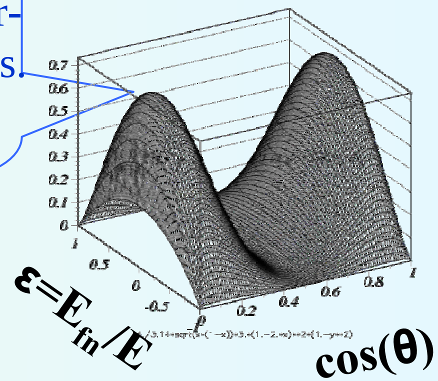
Quantum numbers: J^π, S, L, $\boldsymbol{l_x}$, $\boldsymbol{l_y}$, K - hypermomentum.

$$\mathcal{Y}_K^{l_x,l_y,L,M}(\Omega_6) = \sum_{m_x,m_y} < l_x l_y m_x m_y | LM > \mathcal{Y}_K^{l_x,l_y,m_x,m_y}(\Omega_6)$$

Transformation from T-system to Y-system
Reinal-Revai. coefficients



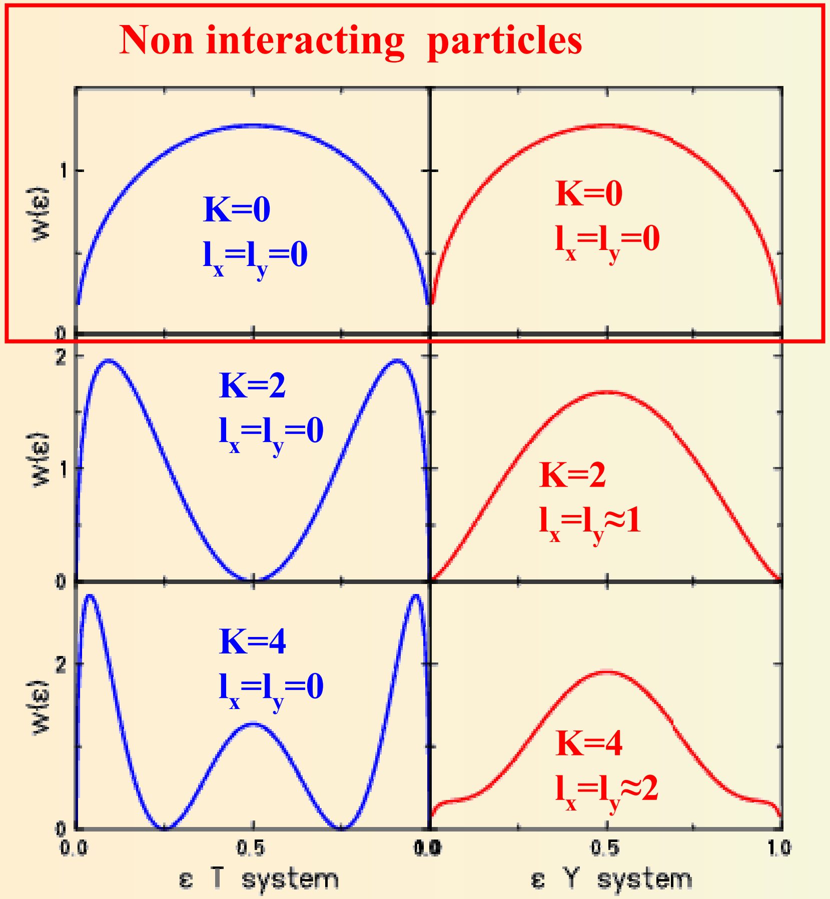
Expansion of a decay
amplitude into the hyper-
spherical-harmonic series.
Internal correlations.



K=4, l_x=1, l_y=1

Two-body correlations:

[5]He - L.V.Chulkov et al., Phys.Rev.Lett. 79, 201 (1997)
[10]Li- H.Simon et al., Phys.Rev.Lett. 83, 496 (1999)



Recoil effect in the 3-body system.

$$\mathcal{Y}_K^{l_x,l_y,L,M}(\Omega_6) = \sum_{m_x,m_y} < l_x l_y m_x m_y | LM > \mathcal{Y}_K^{l_x,l_y,m_x,m_y}(\Omega_6)$$

Harmonic K=4, l_x=0, l_y=0, T-system

S=0, L=0, l_x and l_y	WF components in Y system.
2 and 2	87.0%
1 and 1	2.6%
0 and 0	10.4%

Harmonic K=0, lx=ly=0.
100% in Y and T system when core is very heavy.

Favorite condition for a three-body state: p- or d-resonance in n+core subsystem

3 neutrons, T-system, K=4,lx=ly=0. No AS.

S=0, lx,ly	WF in Y
2 and 2	50%
1 and 1	50%
0 and 0	0%

Assuming strong s-wave interaction between ^{8}He and neutron, intensive resonance at very low energy was predicted for ^{10}He :

S. Aoyama, Phys.Rev.Lett. 89(2002)_052501.
L.V.Grigorenko et al., Phys.Rev. C 77 (2008) 034611

2.A.2 *Nuclear Physics* 9 (1958/59) 391—399; © North-Holland Publishing Co., Amsterdam

TERTIARY AND GENERAL-ORDER COLLISIONS

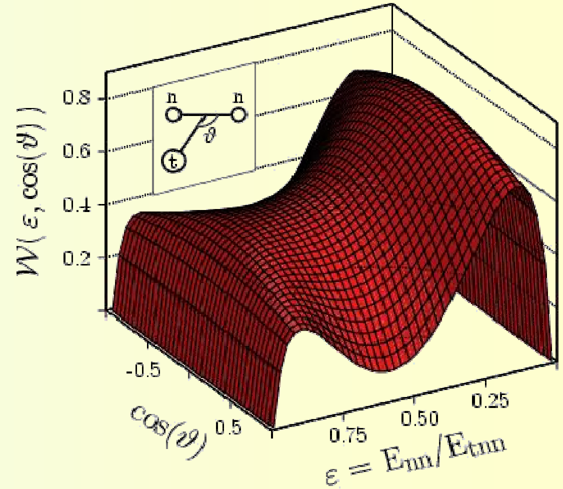
L. M. DELVES
Clarendon Laboratory, Oxford

Received 2 October 1958

Abstract: The general formalism of scattering theory is extended to cover reactions in which more than two particles exist in the entrance or exit channels, and the behaviour of the scattering matrix in this general case is discussed at arbitrary energies, in particular near thresholds. The energy dependence of observable quantities such as cross-sections and polarizations is given, and the occurrence and origin of the Wigner cusps and their counterpart in the general case are clearly seen; such singularities do not arise from the behaviour of the eigenphase-shifts.

Phys.Rev.Lett. 91, 162504 (2003)
M.Meister *et al*

^{5}H



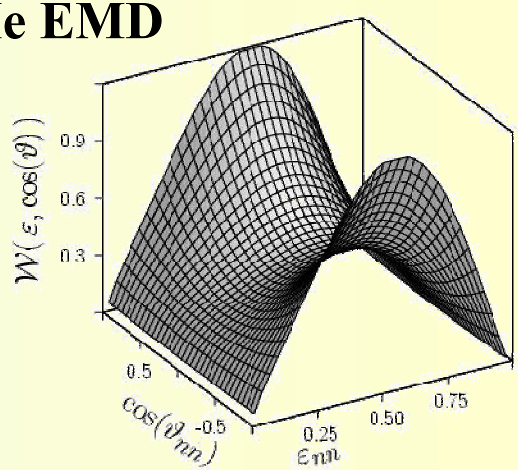
Expansion of a decay amplitude into the hyper-spherical-harmonic series:

$$F_{IM} = \sum_{KLS} \sum_{l_x l_y} A_{l_x l_y}^{KLS}(E) \sum_{m\nu} C_{LmS\nu}^{IM} C_{\frac{1}{2}\nu_1 \frac{1}{2}\nu_2}^{S\nu} \mathcal{Y}_{l_x, l_y}^{KLm}(\mathbf{q}_{12}, \mathbf{q}_{3-12}).$$

Quantum numbers: **K, I^{π}=L+S, L=l_x+ l_y, S=s_1+s_2**

Nucl.Phys. A759, 23 (2005)
L.V.Chulkov *et al.*

^{6}He EMD



Assumptions. Ockham's Razor.

- **Decay amplitude is antisymmetric under permutation of neutrons.**
- **Contribution from the states with the total spin of the two neutrons equal to 0 dominates.**
- **Partial angular momenta are coupled to zero.**
- **The hyperspherical-harmonic series is restricted to K=0, 2, 4**
- **No one more harmonic than necessary (Ockham-razor principle).**

William of Ockham
(1287-1347)

Now we come to the experiment where two unstable nuclides were obtained in proton knock out.

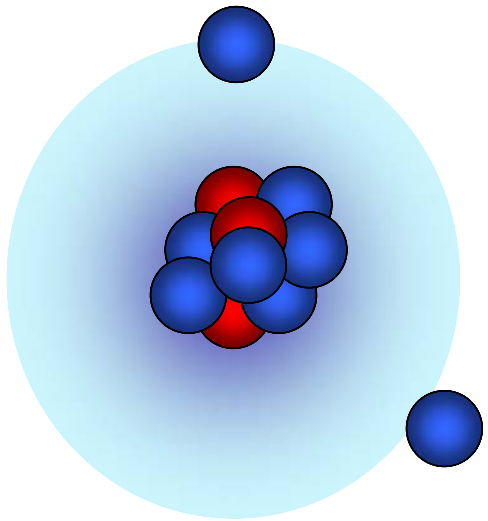
$^{1}H(^{14}Be,^{12}Li+2n) \rightarrow {}^{13}Li$

$^{1}H(^{11}Li,^{8}He+2n) \rightarrow {}^{10}He$

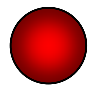
Few words about reaction mechanism:

Quasi free scattering on a nucleon inside halo nucleus (valence nucleon knockout)

Example with ^{11}Li



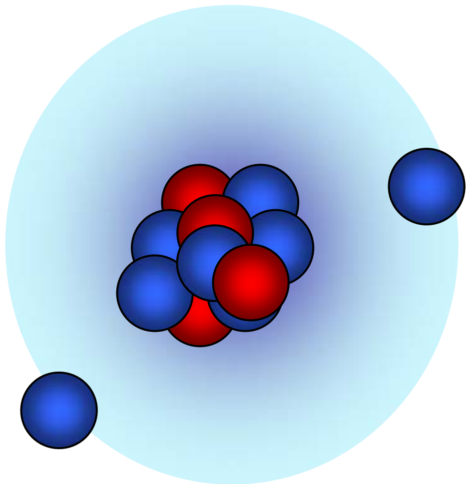
- Valence neutron knockout
- Small binding energy [<1 MeV]
- Remaining system is a spectator
- Momentum is transferred to the whole remaining system (^{10}Li).

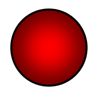


Quasi free scattering on a nucleon inside halo nucleus (nucleon knockout from core)

Example with ^{14}Be

Shake-off mechanism of fragmentation.

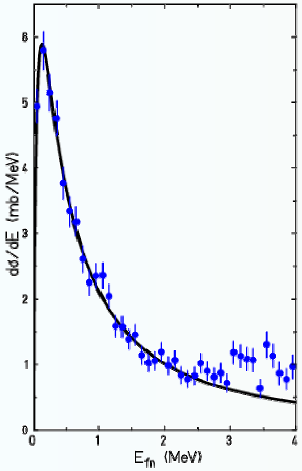




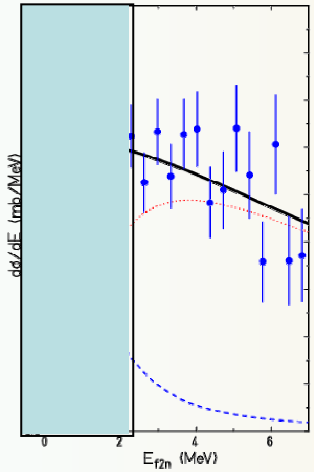
- Proton knockout from the core
- Proton strongly bound [~20 MeV]
- Remaining system can not be considered as spectator.
- Momentum is transferred to the remaining of the core (^{11}Li).

He^{10} and Li^{13}. Twins?

^{12}Li



^{13}Li



Phys. Lett. B 666 (2008) 434, Yu.Aksyutina, H.Johansson *et al.*

^{12}Li

a=−13.7(1.6) fm, ε = 1.47*(19)* MeV
derived in the fit is consistent with the experimental value for the two-neutron separation energy in ^{14}Be of S_{2n} **= 1.26*(13)* MeV**

No other states.

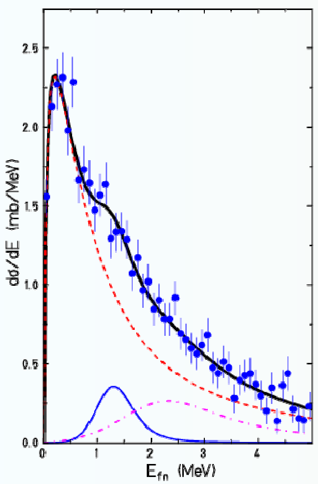
Virtual state

$$\frac{d\sigma}{dE_{fn}} \propto p_{fn}\left[\frac{1}{k^2+p_{fn}^2}\right]^2\left[\cos(\delta)+\frac{k}{p_{fn}}\sin(\delta)\right]^2,$$

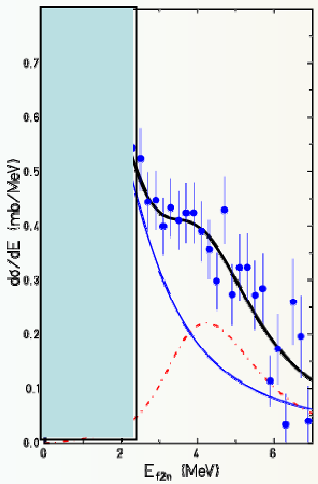
$$p_{fn}\cot(\delta) = -\frac{1}{a}+\frac{1}{2}r_0 p_{fn}^2+\mathcal{O}(p_{fn}^4).$$

G.F.Bertsch *et al.*, Phys.Rev. C57(1998)1356

^{9}He



^{10}He



^{9}He

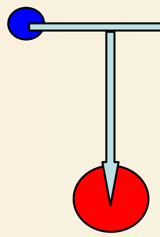
a=−3.3(5) fm, ε = 0.71*(7)* MeV

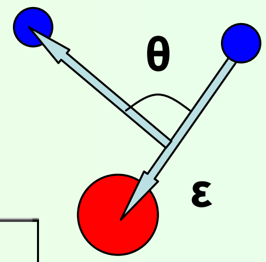
$E_{1=}$1.28(10) MeV Γ=0.15 MeV

E_2=2.4 MeV Γ=2 MeV

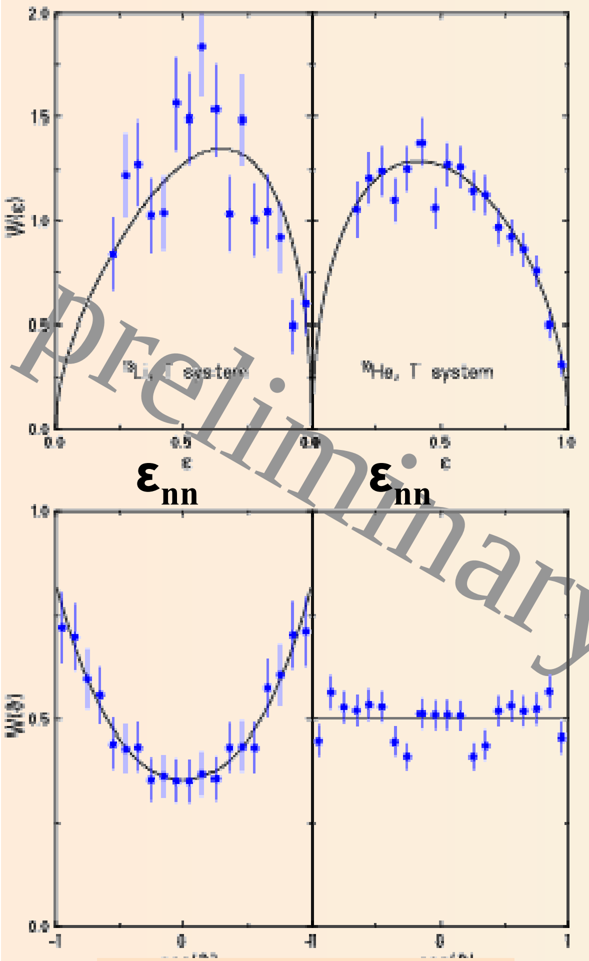
Yu.Aksyutina, H.Johansson *et al.* *to be published*

Ground state region 0-3 MeV.





^{13}Li ^{10}He



Cos(θ) Cos(θ)

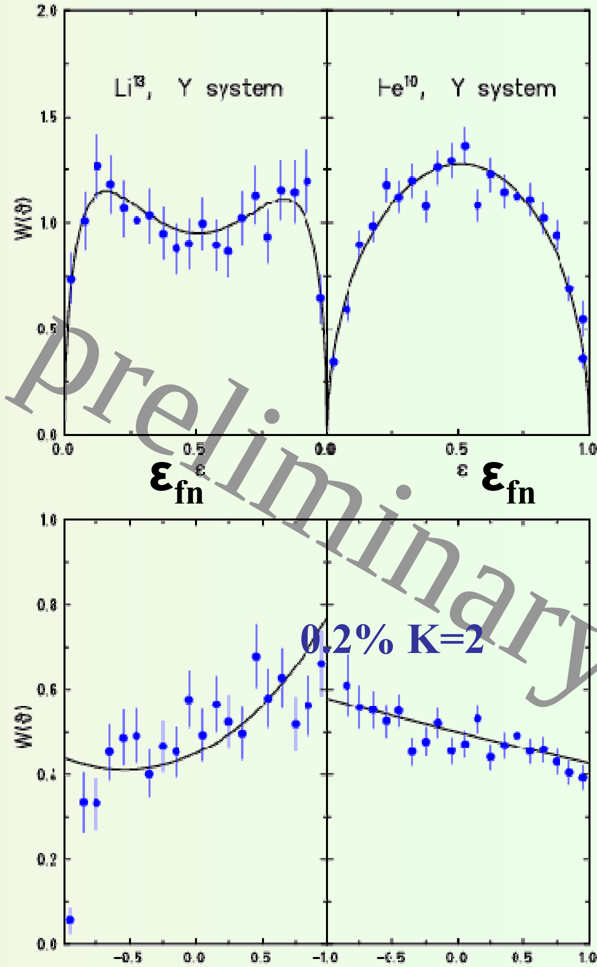
^{13}Li

K=0 ⟶ 97.3%
K=2 lx=ly=0 → 0.8%
K=4 lx=ly=2 →1.9%

^{10}He

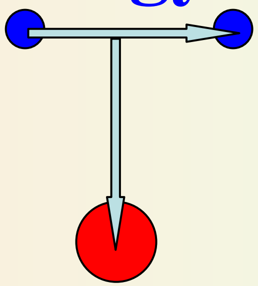
K=0 ⟶ 99.8%
K=2 lx=ly=0 → 0.2%

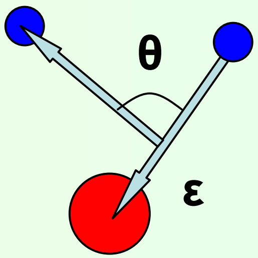
^{13}Li ^{10}He

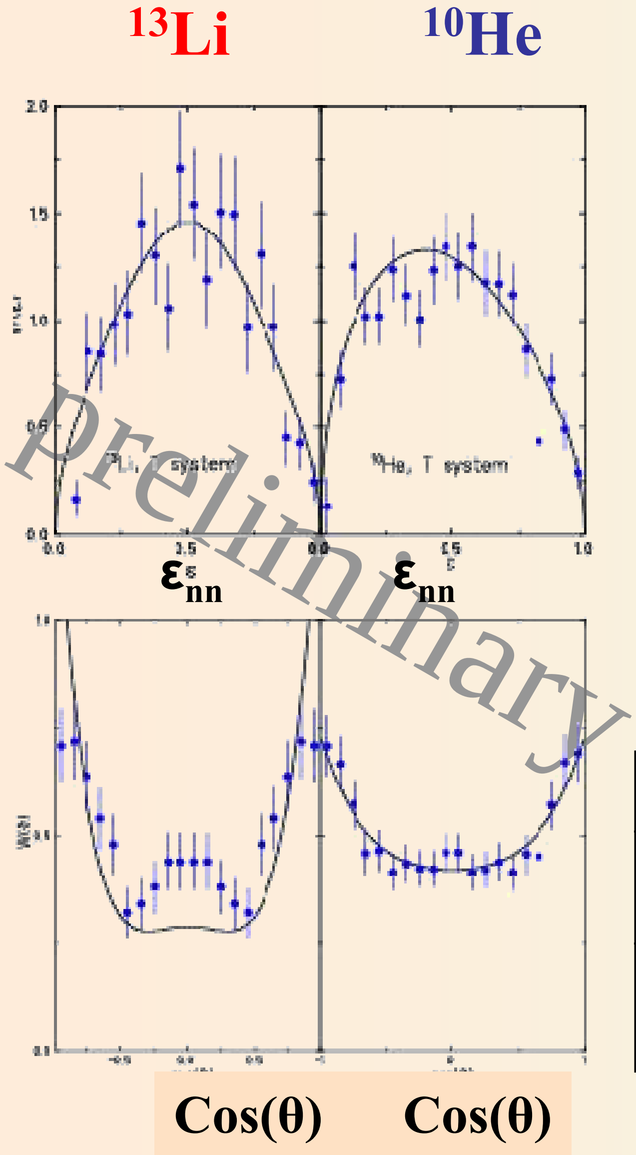


Cos(θ) Cos(θ)

High energy region 3-7 MeV





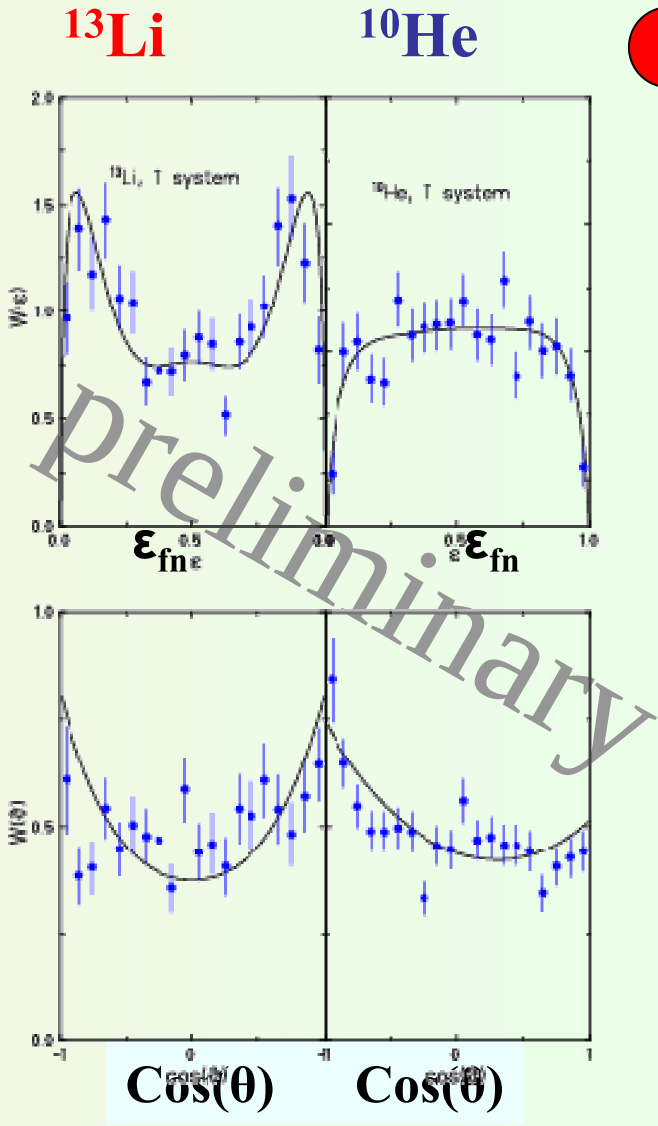


^{13}Li

K=0 → 75.0%	
K=4 lx=ly=2 → 25.0%	

^{10}He

K=0 → 96.3%	
K=2 lx=ly=0 → 0.5%	
K=4 lx=ly=2 → 3.2%	



Résumé

- Expansion of the decay amplitude into a hypersperical-harmonic series allows to feel the presence of alien on a level of 0.1%.
- Essential difference exists between ^{13}Li and ^{10}He nuclides.
- Analysis has shown that a three-body resonance is improbable when only s-wave interactions exists in the binary subsystems.