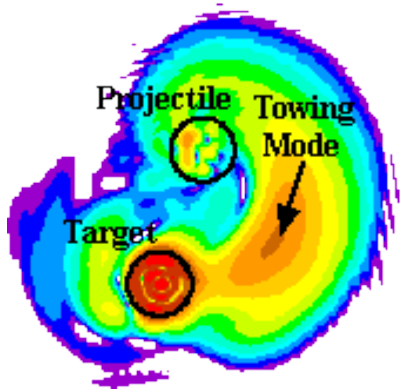
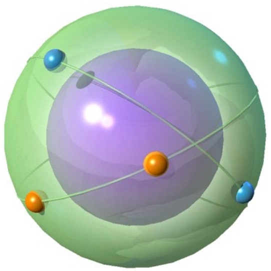


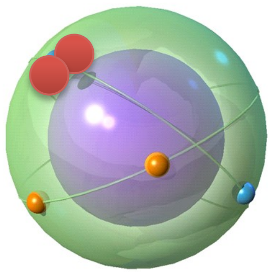
Time-dependent description of break-up

Denis Lacroix

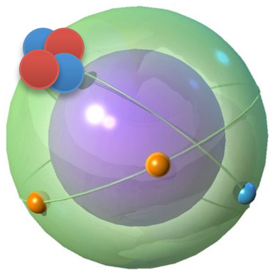
GANIL-Caen



Single Nucleon



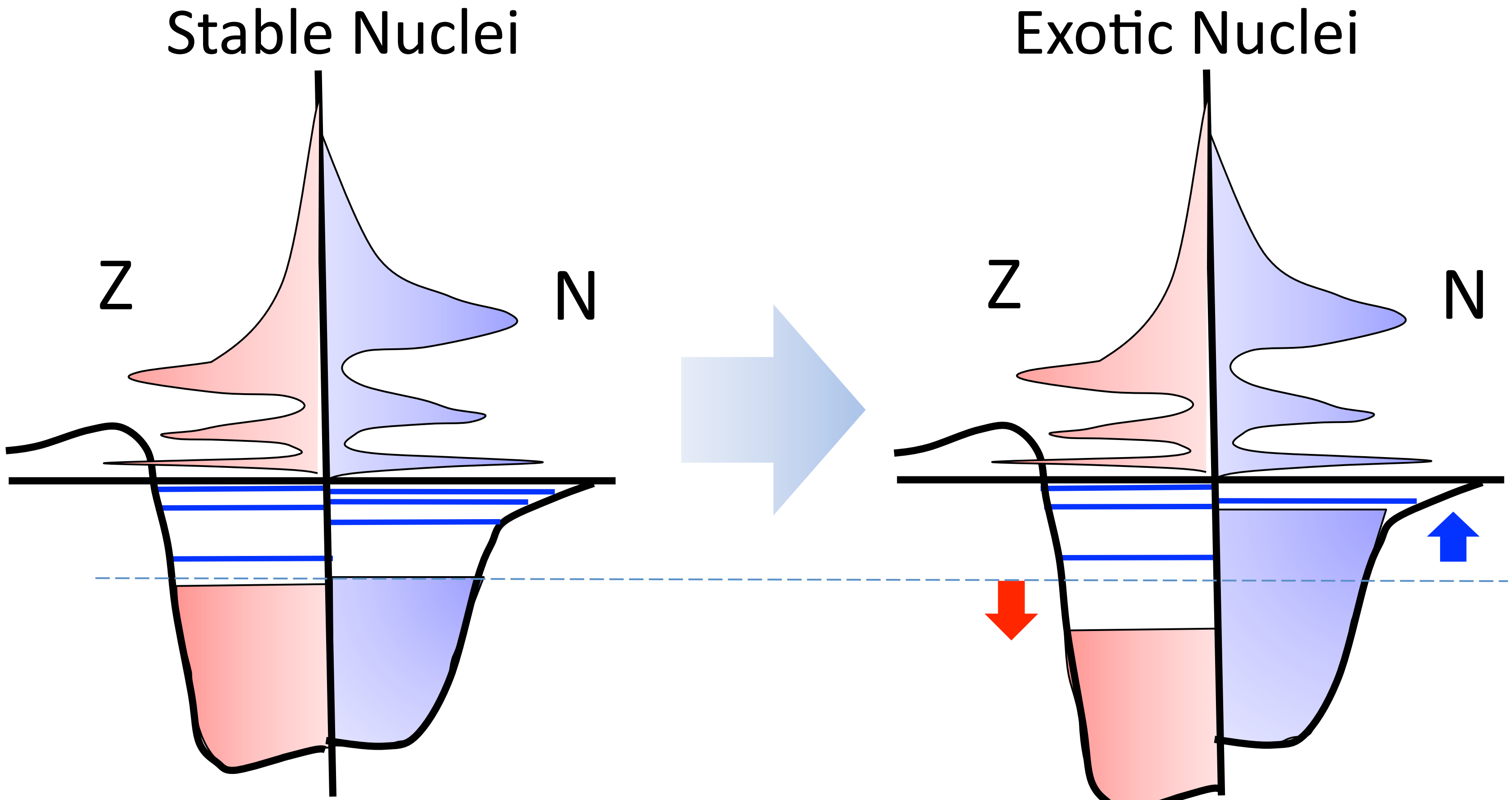
Pairing



Clustering

Coll: M. Assié, J.-A. Scarpaci

Challenges related to continuum effects:
Selected Nuclear structure aspects



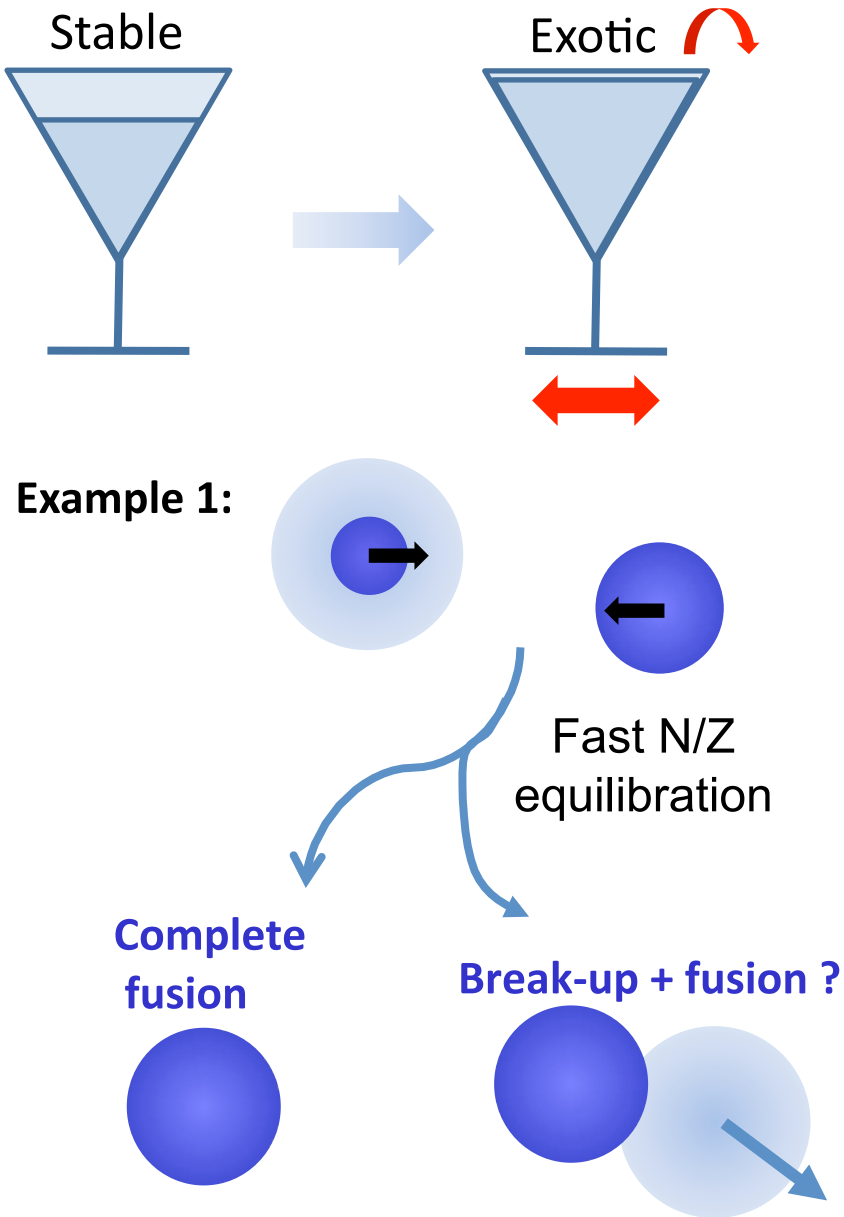
- Weak binding, small shell gaps (halo / anti-halo effect)
- Enhanced Continuum effect (mixing of discrete and continuum states)
- Large influence on nuclear structure and reactions

Importance of the continuum

Beam Energy

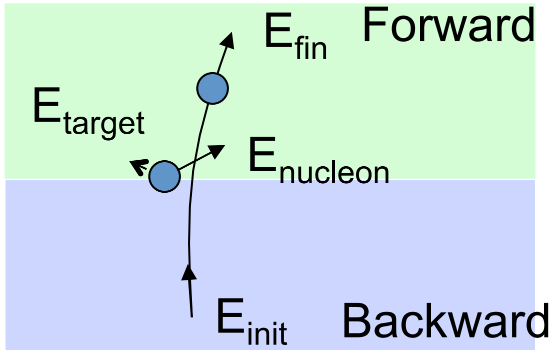
- Fusion
- Transfer★
- Break-up★
  (Nuclear, Coulomb)
- Knock-out★

★ Spectroscopic tools

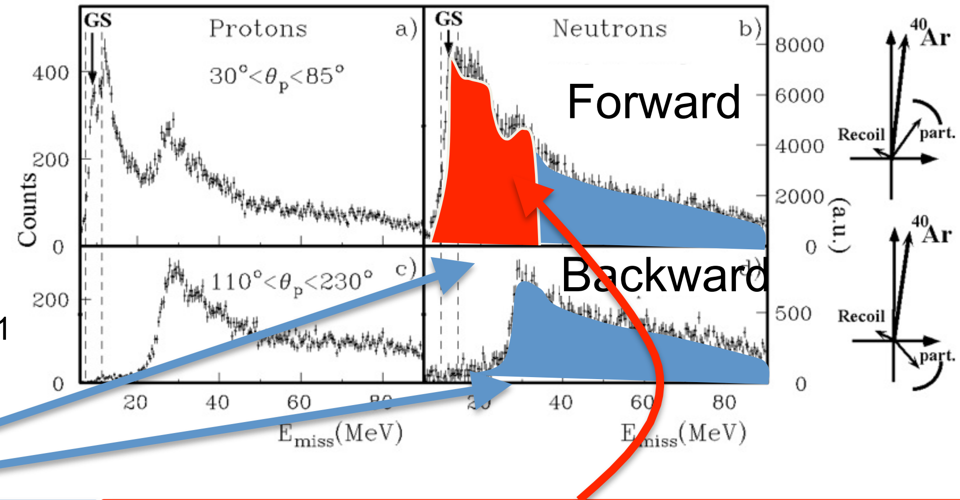


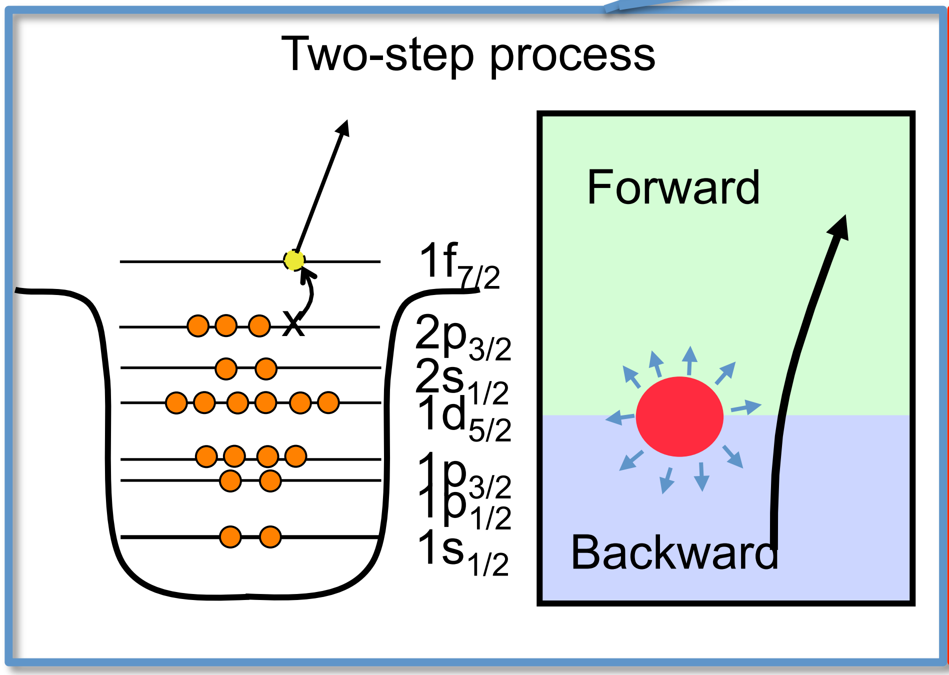
Example of realistic 3D application

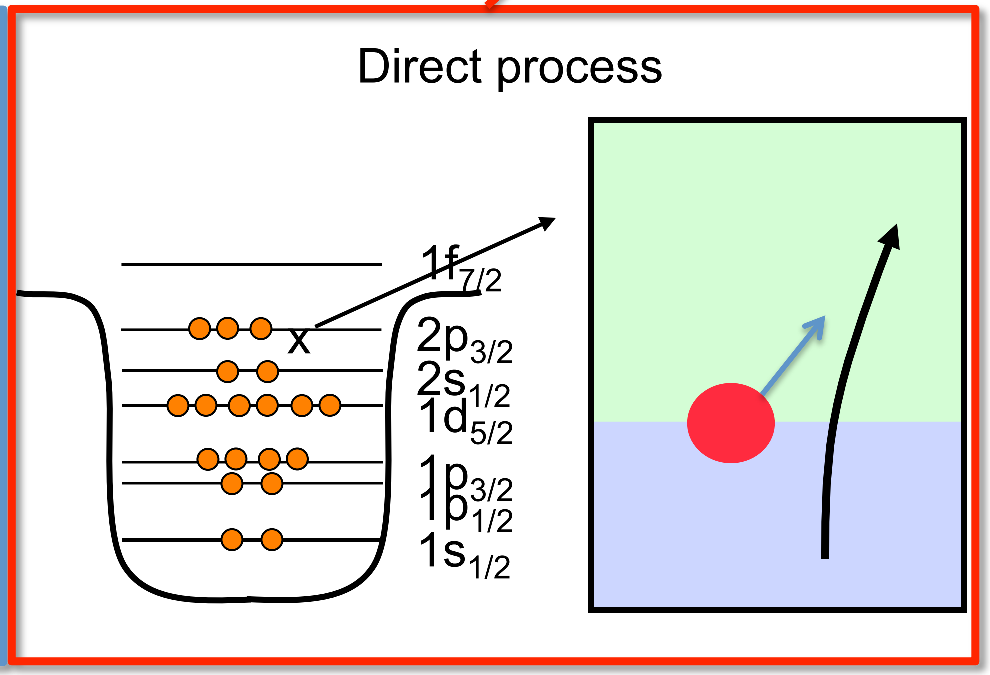
Experimental motivation



J.A.Scarpaci et al., Phys. Lett. B428 (1998) 241

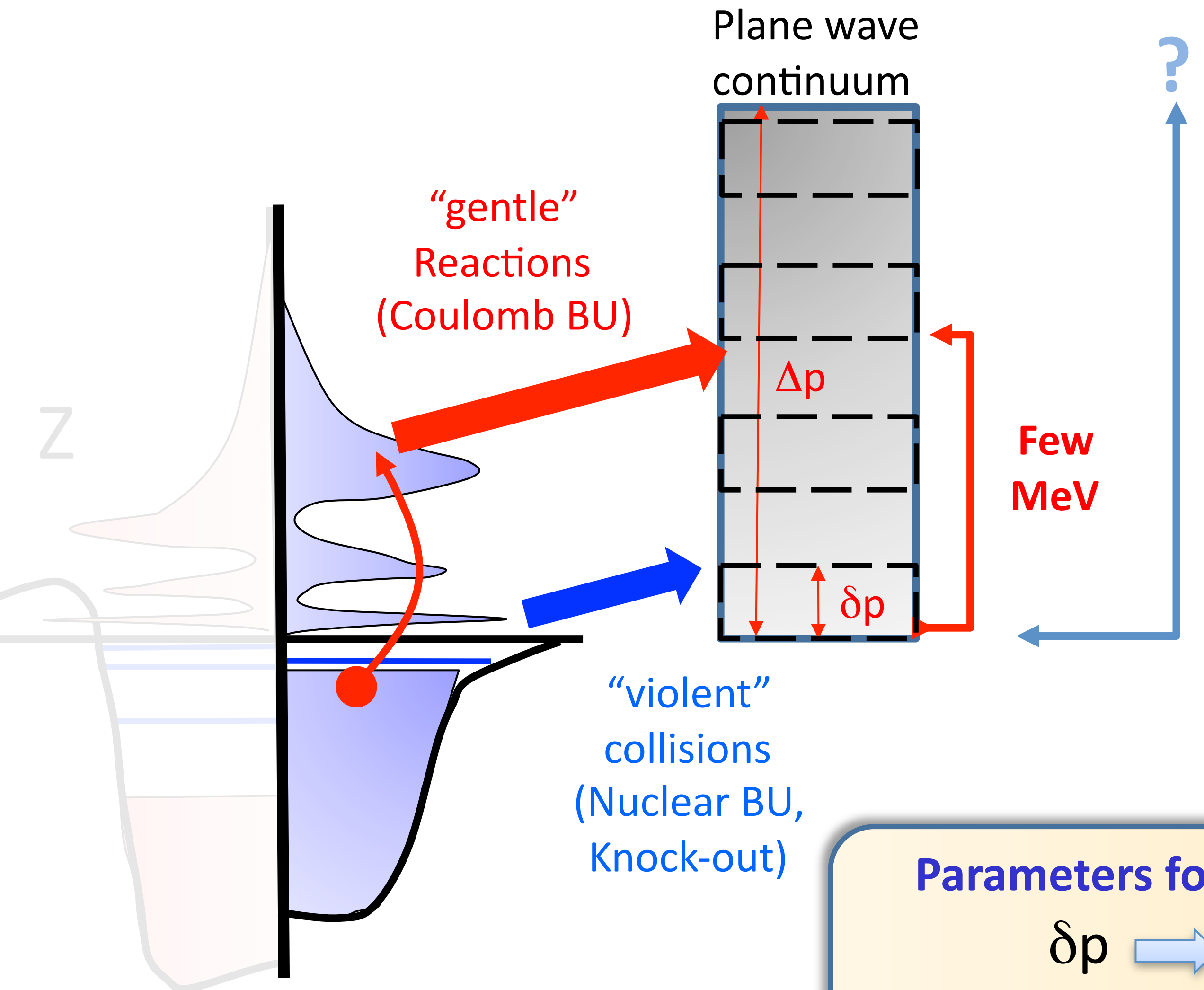




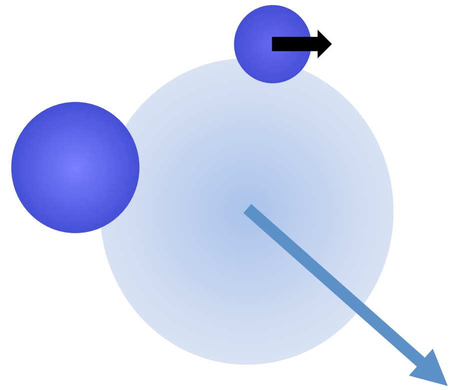


Continuum discretization : some preliminary remarks

Initial State | **Final State**



A small exercise for
Nuclear Break-up:



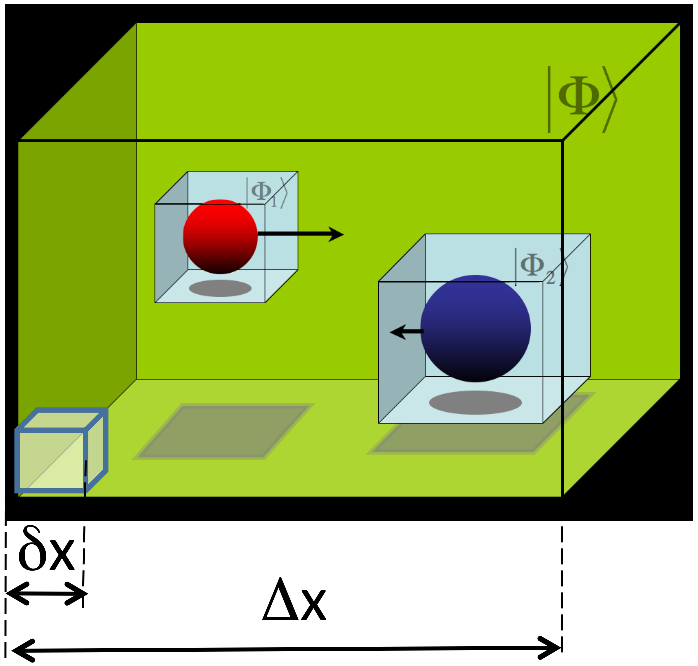
Beam Energy : 60 MeV/A

- ⇨ Beam velocity is 0.36 C
- ⇨ Mid-rapidity emission 0.18 C
- ⇨ Average Kinetic Ener. 15 MeV

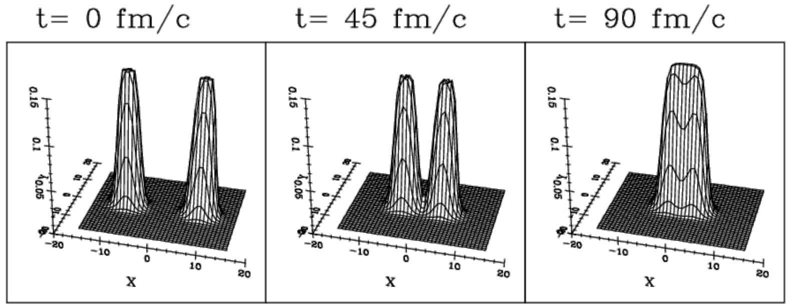
Parameters for Continuum discretization :

- δp ⇨ Resolution of the calculation
- Δp ⇨ Maximal energy for nucleons

One-particle break-up



Full 3D Time-dependent mean-field is now a standard tool



See for instance *Simenel, Avez, Lacroix (2008) arXiv:0806.2614.*

- **Advantage: numerous effects are included**
- **Drawback: numerous effects are included**

Selection of specific channels : Direct resolution in 3D of the nucleon wave in the Core+ Projectile potential

$$i\hbar\frac{\partial}{\partial t}\varphi_n(\mathbf{r}) = \left\{ \frac{\mathbf{p}^2}{2m} + V_T(\mathbf{r}-\mathbf{r}_T) + V_P(\mathbf{r}-\mathbf{r}_P) \right\} \varphi_n(\mathbf{r})$$

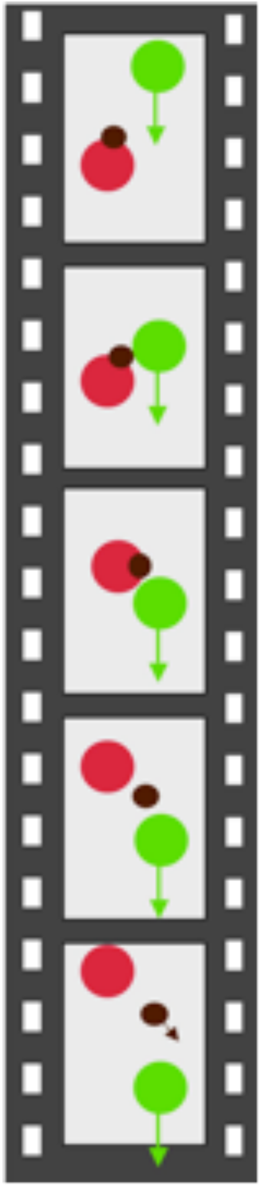
- **Non-perturbative approach**
- **Coulomb+nuclear interference**
- **Continuum is included automatically**

Resolution: DxDp ~$\bar{h}$/2

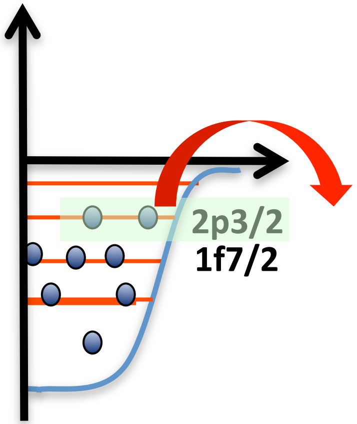
δx=0.5 fm → ΔE_K=20 MeV

Δx=100 fm → δE_K=0.005 MeV

Illustration: time-dependent Schrödinger Eq. for nuclear break-up



^{58}Ni break-up @44 MeV/A



$$i\hbar\partial_t|\Phi_\alpha(t)\rangle = \left\{\frac{\mathbf{p}^2}{2m} + V_P(\vec{\mathbf{r}},t) + V_T(\vec{\mathbf{r}},t)\right\}|\Phi_\alpha(t)\rangle$$

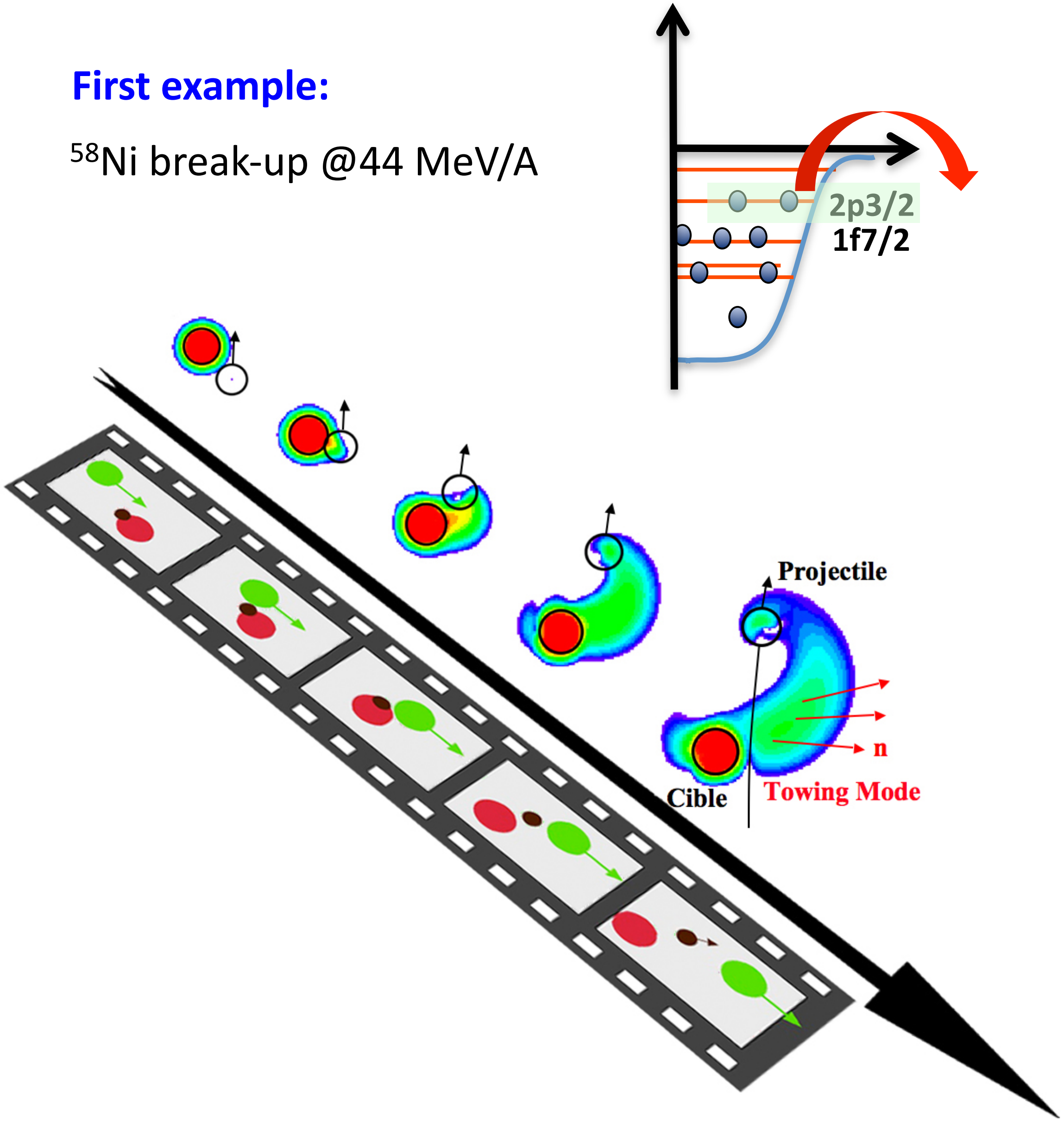
Wood-Saxon potentials

$$V_{P/T}(\vec{r},t) = \frac{V_0}{1+\exp\{|\vec{\mathbf{r}} - \vec{\mathbf{r}}_{T/P}(t)|/a\}}$$

One-particle break-up

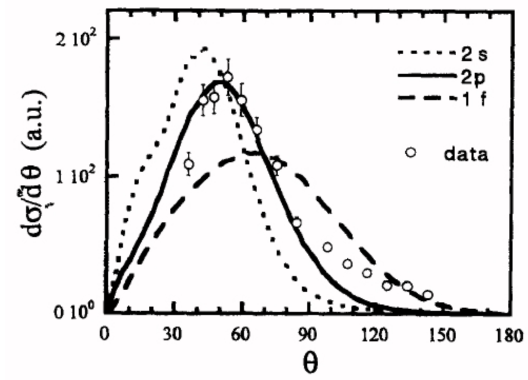
First example:

^{58}Ni break-up @44 MeV/A

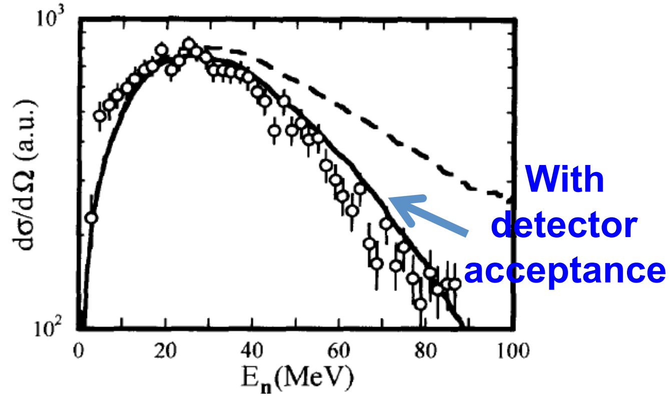


Lacroix, Scarpaci, Chomaz, NPA658 (1999)

Angular distribution:



Kinetic Energy distribution:



Related refs:

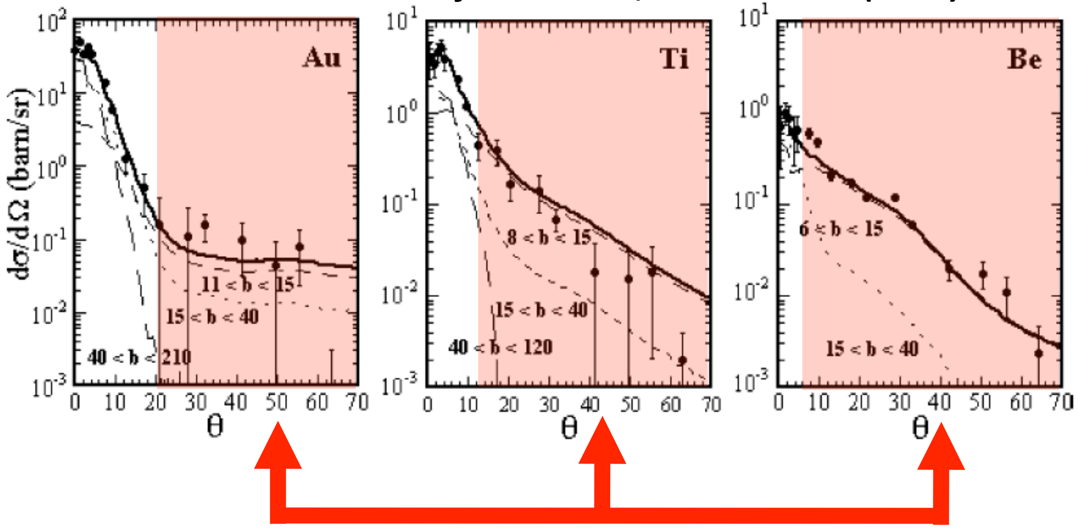
G.F. Bertsch, K. Hencken and H. Esbensen, Phys. Rev. C **57**, 1366 (1998). S. Typel and R. Shyam, Phys. Rev. **64**, 024605 (2001). P. Capel, D. Baye and V.S. Melezhik, Phys. Rev. C **68**, 014612 (2003).

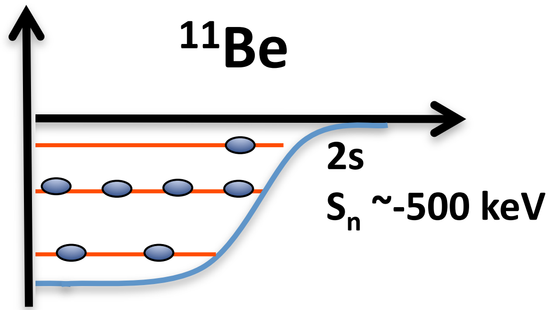
Neutron angular distributions

Au,Ti,Be (^{11}Be, ^{10}Be + n) @ 41 Mev/A

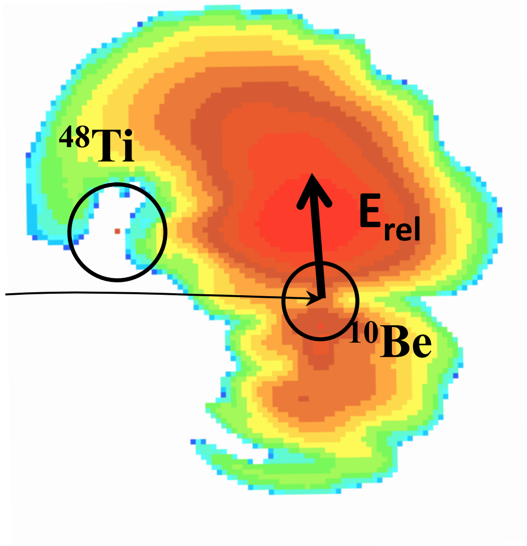
Data from : Anne et al.,Nucl.Phys. A575 (1994).

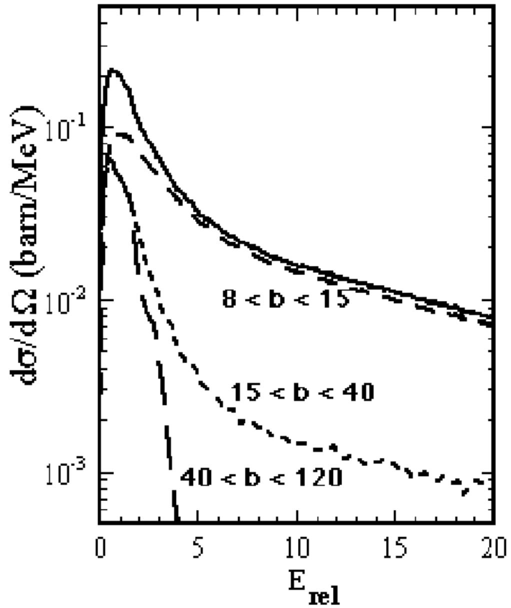
Calc. from: Fallot, et al NPA700 (2002).





Nuclear effects dominates at large angles

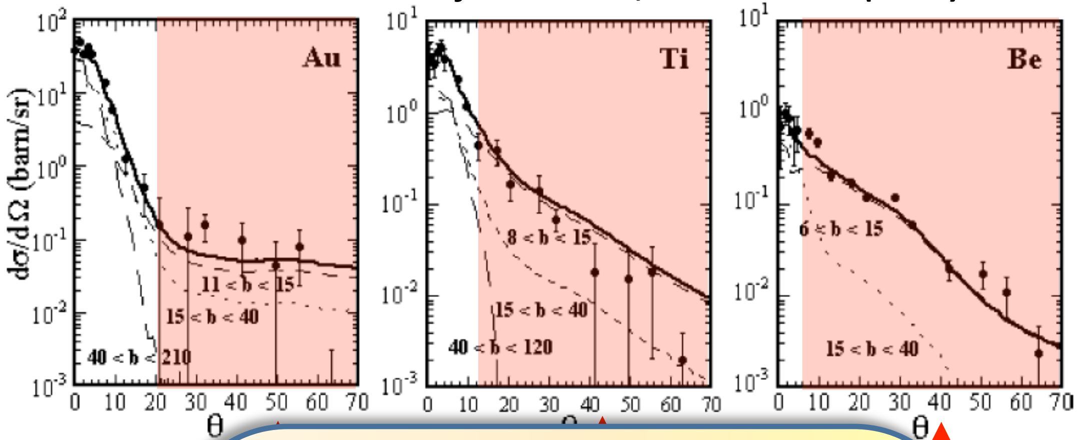


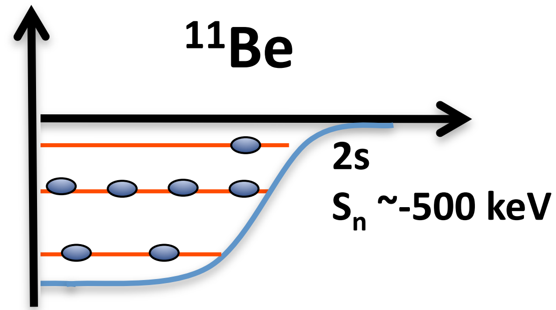


Break-up of weakly bound nuclei: the ^{11}Be case

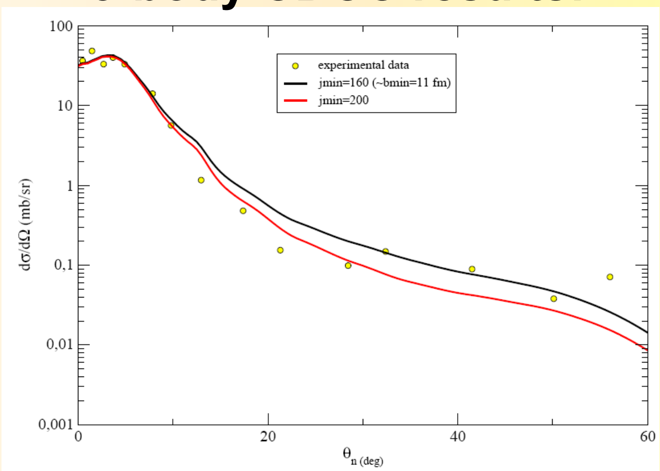
Neutron angular distributions
Au,Ti,Be (^{11}Be, ^{10}Be + n) @ 41 Mev/A

Data from : Anne et al.,Nucl.Phys. A575 (1994).
Calc. from: Fallot, et al NPA700 (2002).



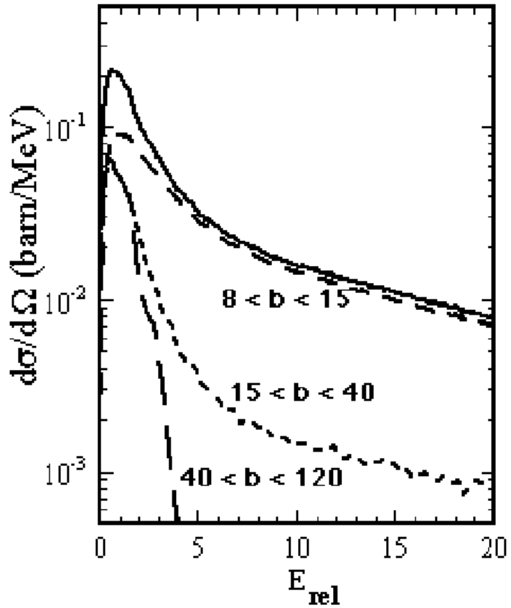


Example of "converged" 3-body CDCC results:

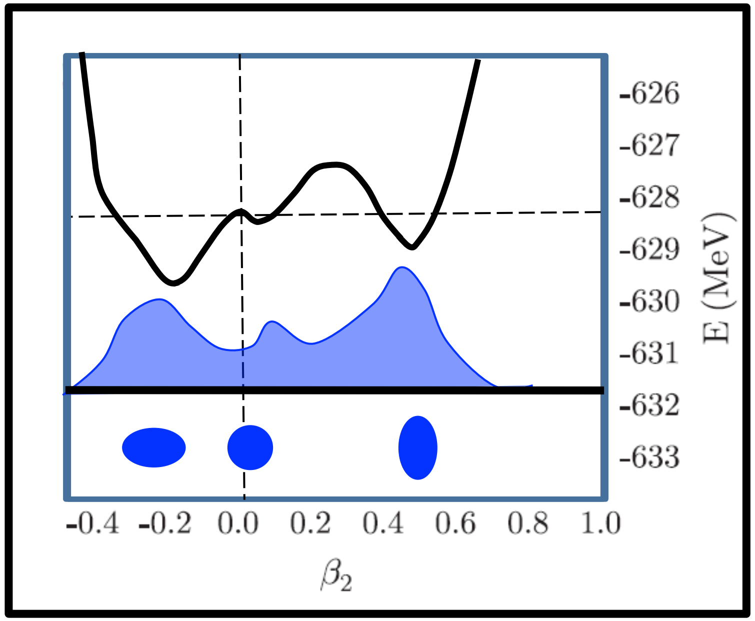


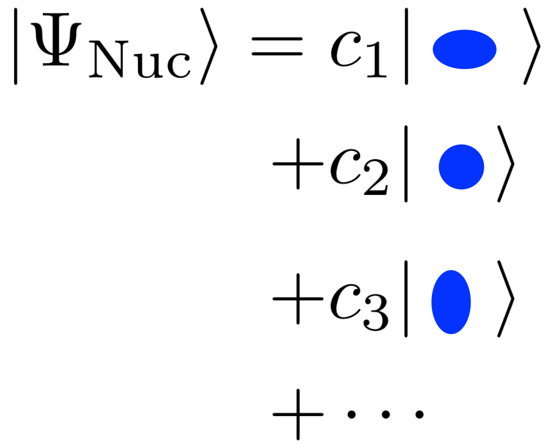
M. Rodriguez Gallardo (private com.)

les

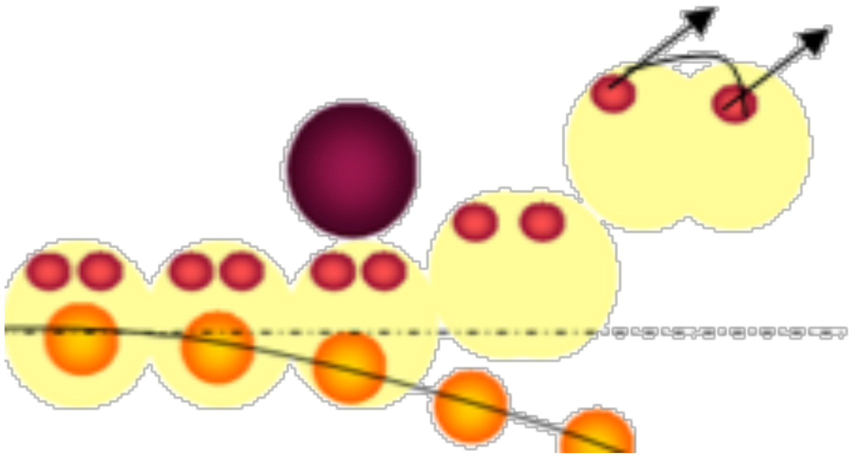


Configuration mixing





Pairing correlation

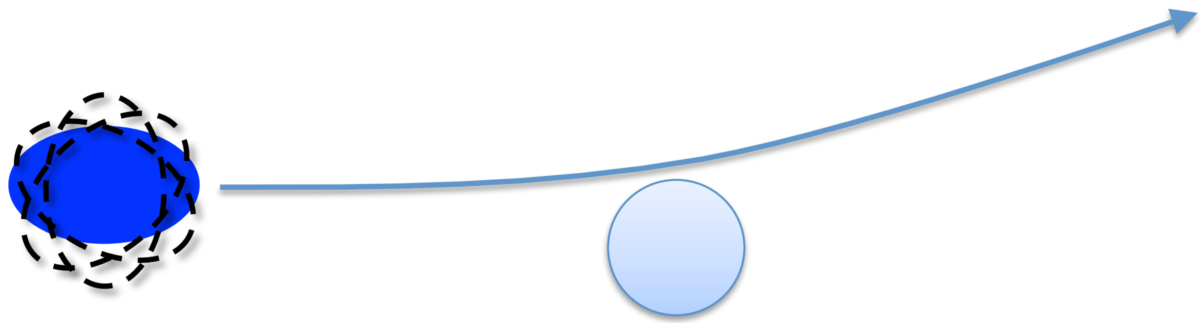


First step beyond the independent particle picture

Configuration mixing in ^{11}Be:

$$|GS\rangle = \alpha\, |2s_{1/2} \otimes 0^{+}\rangle + \beta\, |1d_{5/2} \otimes 2^{+}\rangle$$

Treatment of deformation

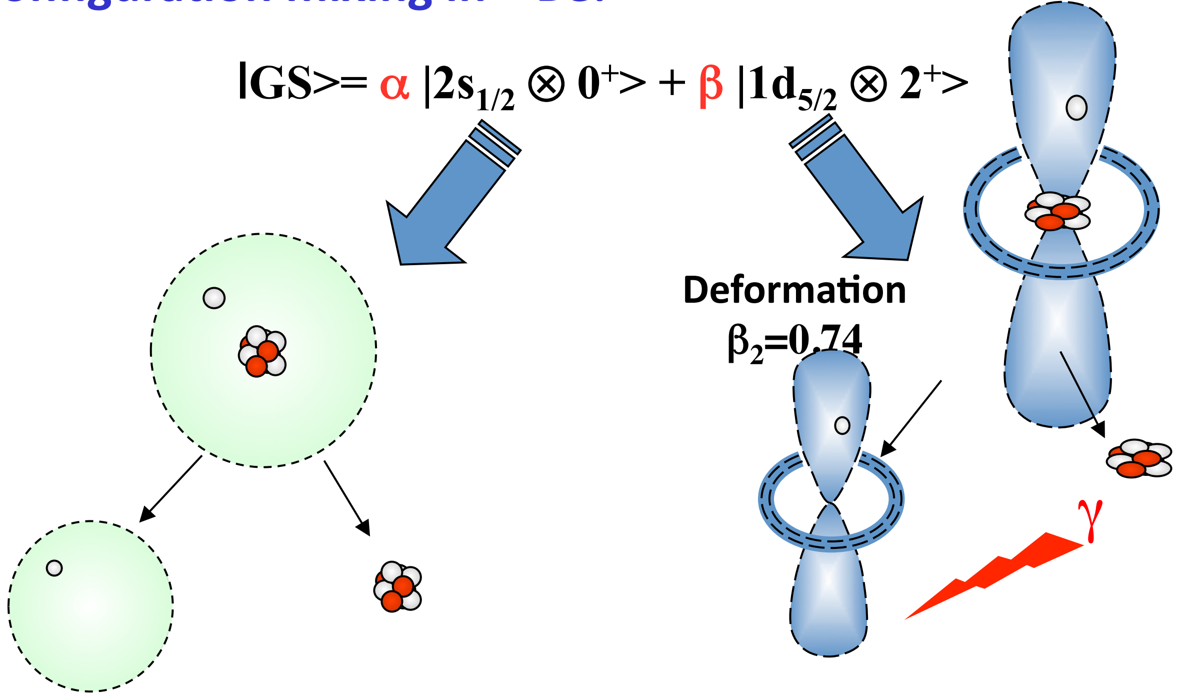


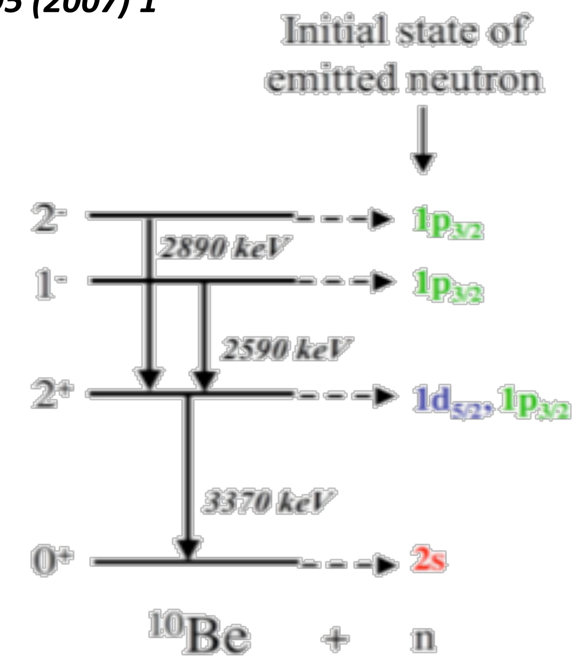
First step beyond the independent particle picture

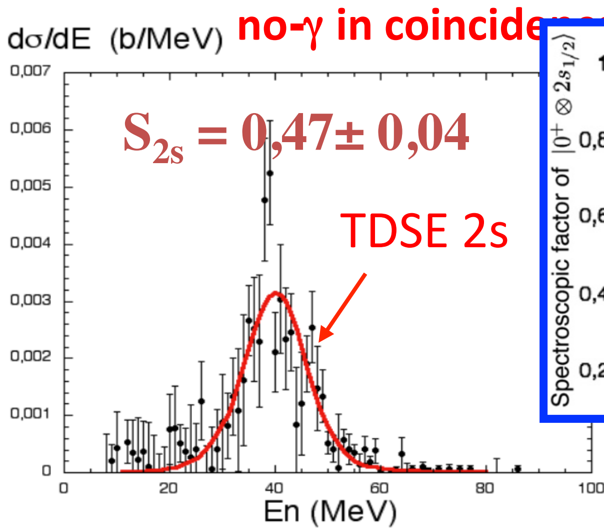
V.Lima et al., Nuclear Physics A795 (2007) 1

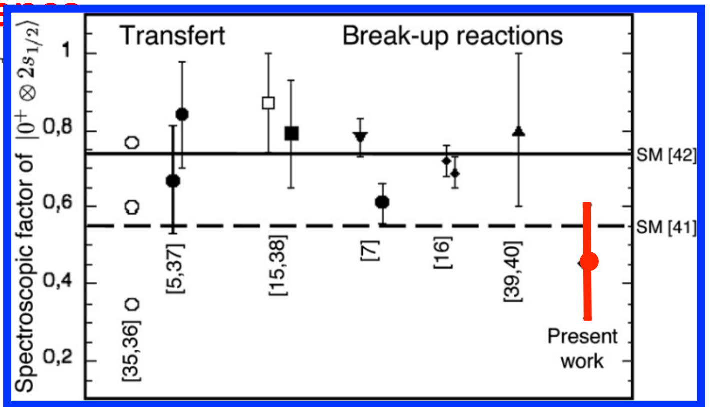
Configuration mixing in ^{11}Be:

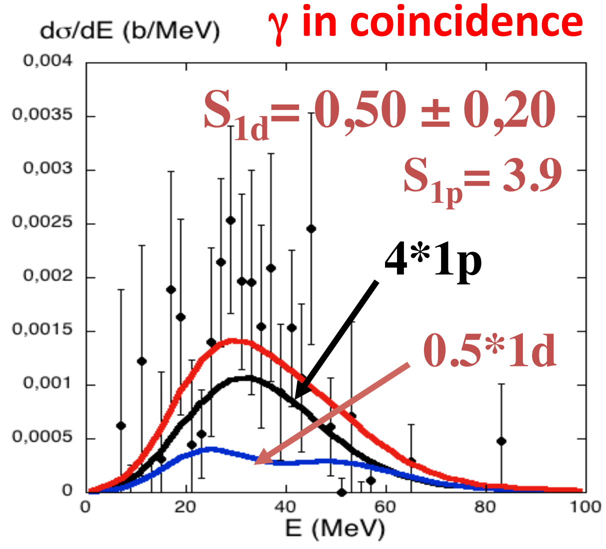
$$|GS\rangle = \alpha\, |2s_{1/2} \otimes 0^+\rangle + \beta\, |1d_{5/2} \otimes 2^+\rangle$$



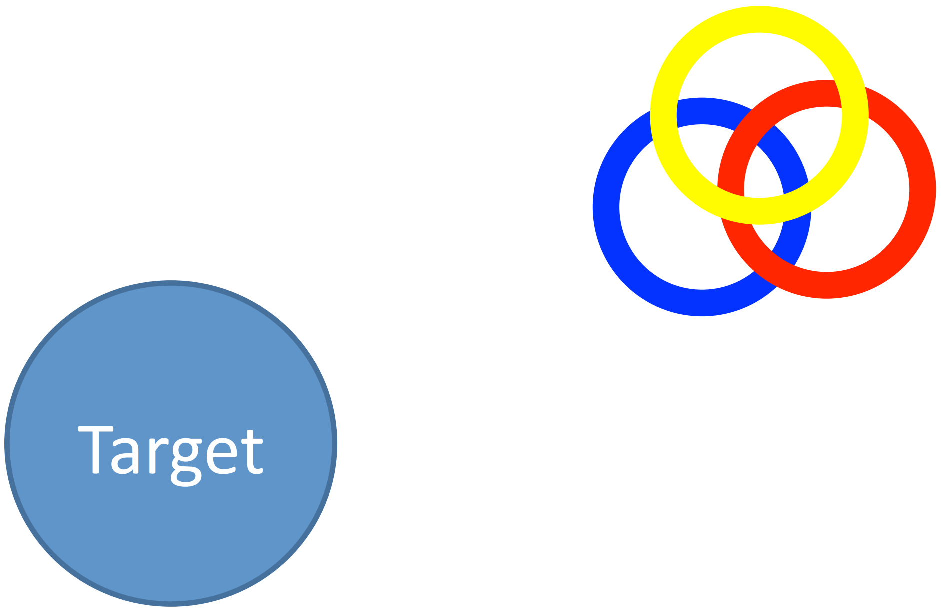






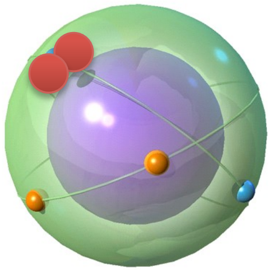


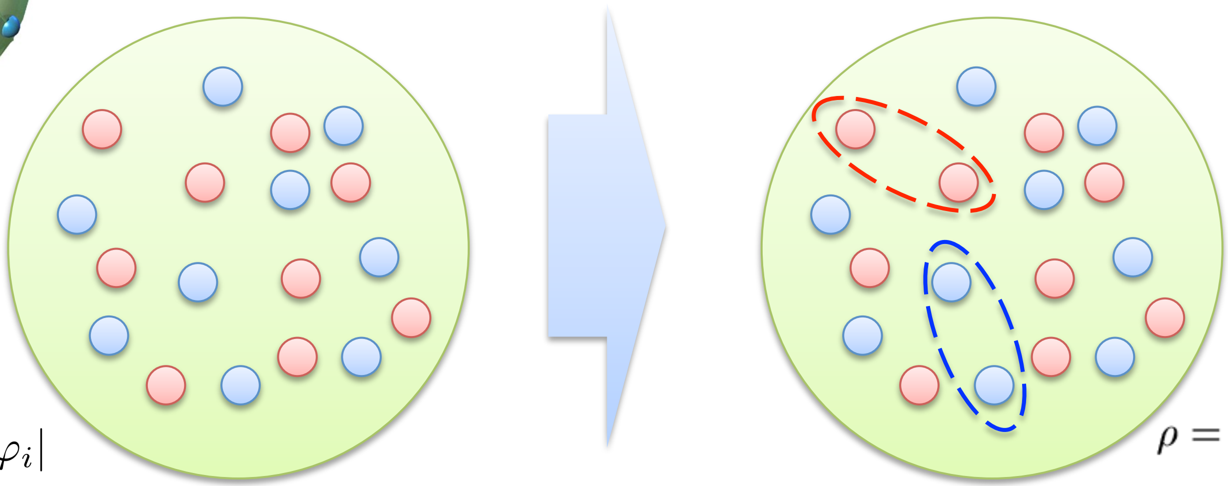
Towards a new generation of
time-dependent calculation:
4-body calculations



Static and dynamical properties of correlated system

Beyond the independent particle picture: pairing effect





$$\rho = \sum_i |\varphi_i\rangle\langle\varphi_i|$$

$$\rho = \sum |\varphi_i\rangle n_i \langle\varphi_i|$$

$$C_{12} = \rho_{12} - \rho_1\rho_2(1 - P_{12})$$

Starting point (BBGKY hierarchy)

$$i\hbar\frac{\partial}{\partial t}\rho_1 = [h_1[\rho], \rho_1] + \frac{1}{2}\mathrm{Tr}_2[\bar{v}_{12}, C_{12}]$$

$$i\hbar\frac{\partial}{\partial t}C_{12} = [h_1[\rho] + h_2[\rho], C_{12}]$$

$$+\frac{1}{2}\left\{(1-\rho_1)(1-\rho_2)\bar{v}_{12}\rho_1\rho_2 - \rho_1\rho_2\bar{v}_{12}(1-\rho_1)(1-\rho_2)\right\} \Longleftrightarrow B_{12}$$

N-N collisions

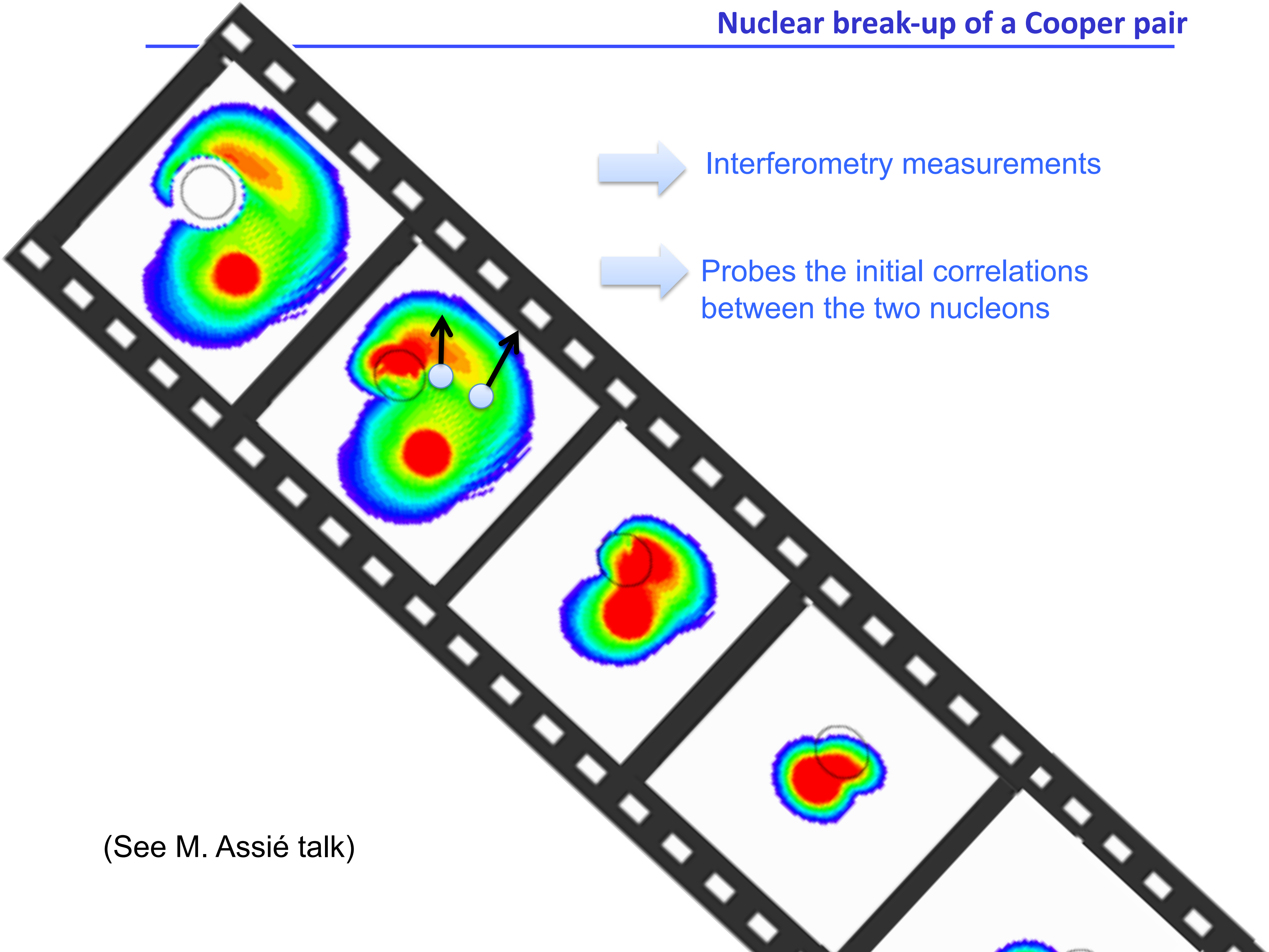
$$+\frac{1}{2}\left\{(1-\rho_1-\rho_2)\,\bar{v}_{12}C_{12} - C_{12}\bar{v}_{12}\,(1-\rho_1-\rho_2)\right\} \Longleftrightarrow P_{12}$$

Pairing

$$+\mathrm{Tr}_3\left[\bar{v}_{13}, (1-P_{13})\,\rho_1 C_{23}\,(1-P_{12})\right]$$
$$+\mathrm{Tr}_3\left[\bar{v}_{23}, (1-P_{23})\,\rho_1 C_{23}\,(1-P_{12})\right]. \Longleftrightarrow H_{12}$$

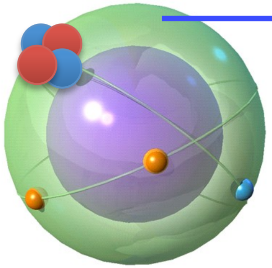
+ 3-body

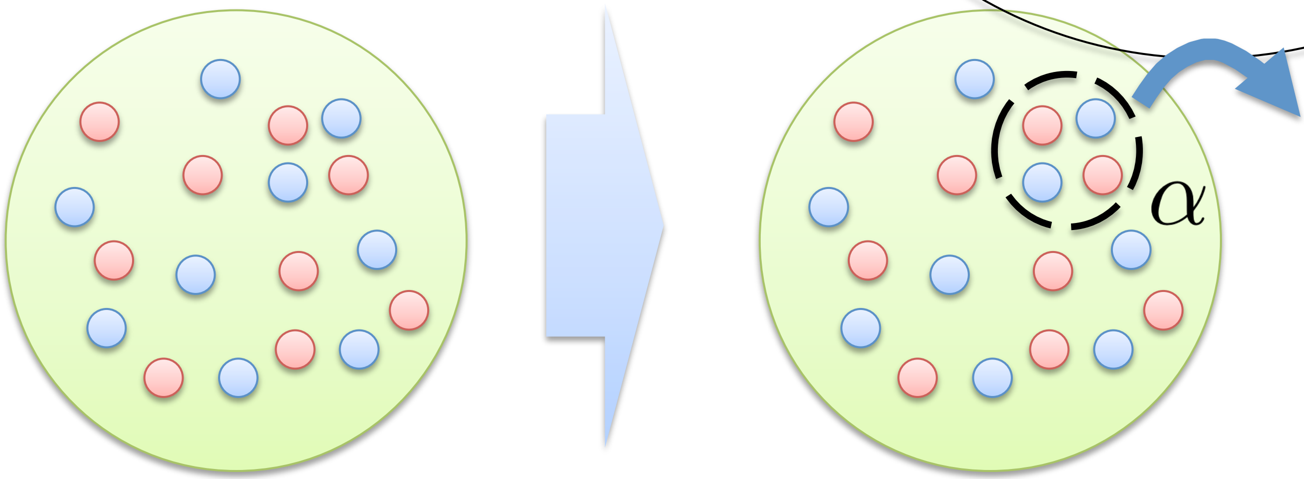
Higher order



- Interferometry measurements
- Probes the initial correlations between the two nucleons

(See M. Assié talk)

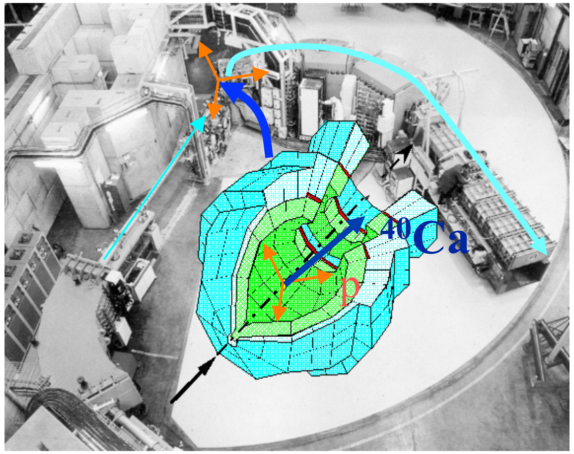




Can we probe clustering with nuclear break-up?

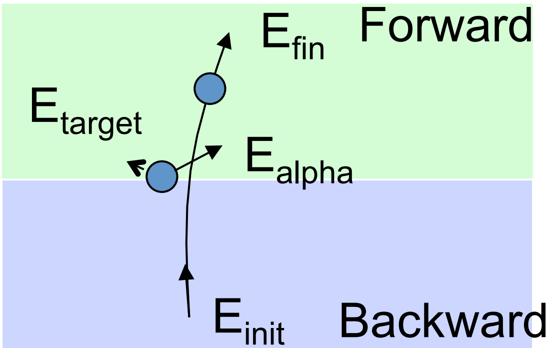
Can we describe alpha composite break-up?

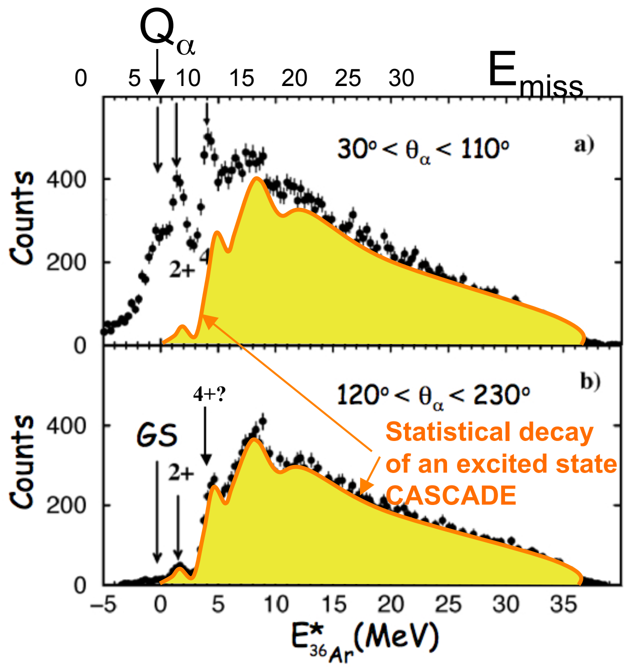
Inelastic scattering of ^{40}Ca to excited GQR and multiphonons in ^{40}Ca target



^{40}Ca(^{40}Ca,^{40}Ca+LCP) @ 50 MeV/A
SPEG + 240 INDRA CsI

Experimental motivation



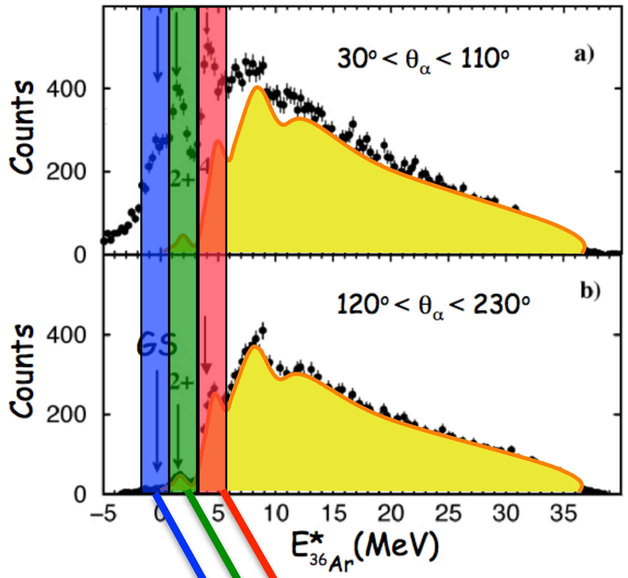


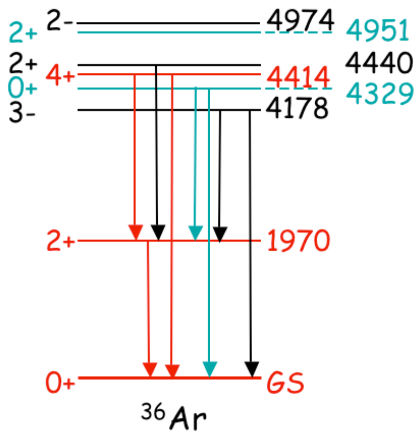
Forward

Backward

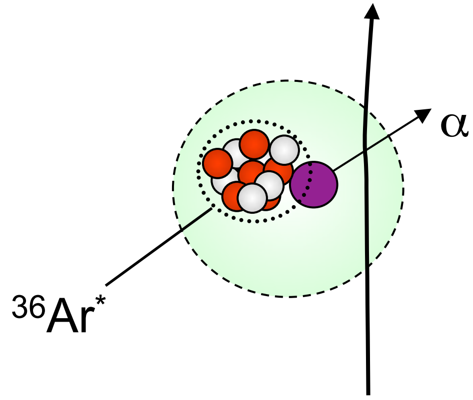
M. Fallot, Ph.D. thesis, 2002, [http://tel.ccsd.cnrs.fr/]

Probing pre-formed alpha particles in the ground state of N=Z nuclei.



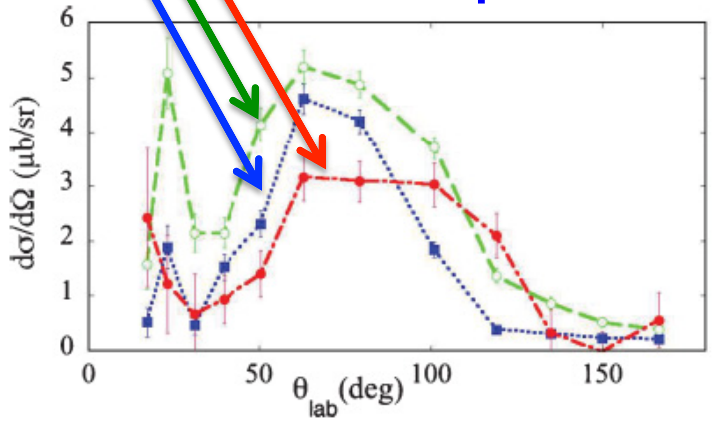


^{36}Ar level scheme

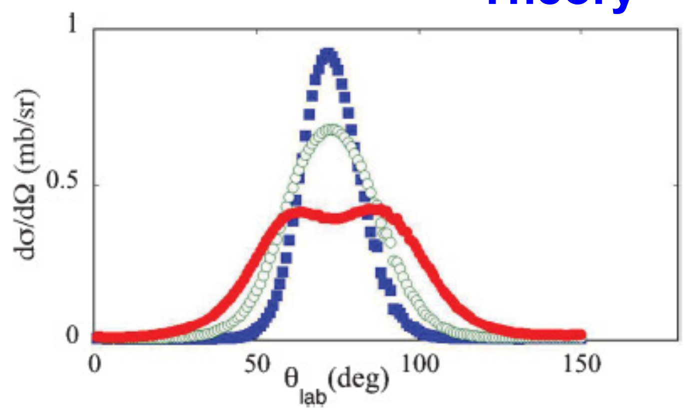


$$|0^+, {}^{40}\mathrm{Ca}\rangle = \cdots + \sum_i C_i \; |(\alpha)_i\rangle \otimes |({}^{36}\mathrm{Ar})^*_i\rangle$$

Experiment



Theory



Scarpaci et al, PRC (2010)

Time-Dependent approaches to break-up reactions

One nucleon removal

- TDSE approaches can provide an appropriate tool to incorporate continuum
- Nuclear break-up can provide important information on structure

Current extensions

- Configuration mixing in weakly bound nuclei
- Extension to treat approximately the dynamics of correlated systems
- First application on alpha particle emission