Recent progress in the Gamow Shell Model

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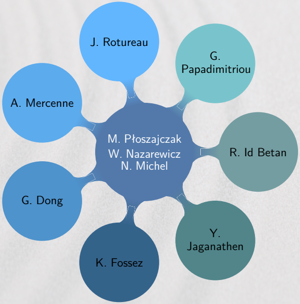
NSCL/MSU

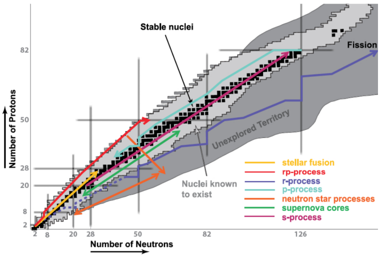
ICNT. May 19, 2015



The Big Picture

Next generation of RIB facilities:

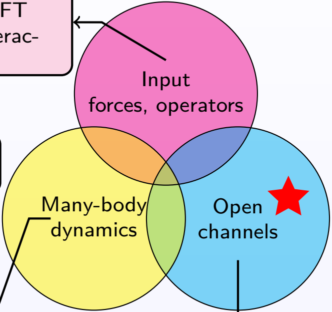
FRIB FAIR GANIL RIKEN



https://people.nscl.msu.edu/~zegers/HRS_draft.pdf

- rooted in QCD
- insights from EFT
- many-body interactions

Renewal of Nuclear Physics!



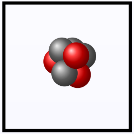
- many-body techniques
- high-performance computing
- interdisciplinary connections

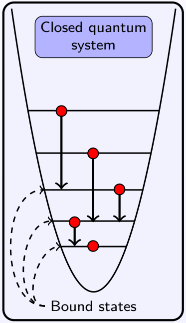
- continuum shell model, *ab initio* reaction theory
- unified picture of structure, reactions, and decays

(Figure modified from Forssén *et al.*, Phys. Scripta T **152**, 014022 (2013))

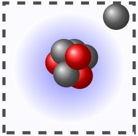
Open Quantum Systems (OQSs): What are they?

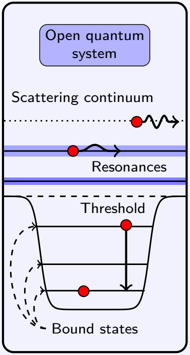
→ Quantum systems coupled to the environment of scattering states and decay channels.





- Examples of OQSs in many domains of physics: hadrons, nuclei, atoms, molecules, quantum dots, microwave cavities.
- Exotic phenomena in OQSs: superradiance phenomena, spontaneous two-proton radioactivity, near-threshold clustering phenomena...
- General properties of OQSs (resonances, halos, exceptional points) are common to all mesoscopic systems.



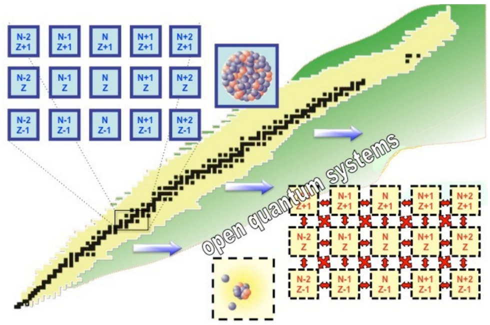


Description of nuclear OQSs

→ Unified description of nuclear structure and reactions.

Nuclear Shell Model (1949):
• Applied successfully to the description of low-lying states in stable nuclei (bound state approximation).
• Fails to describe unstable nuclei.

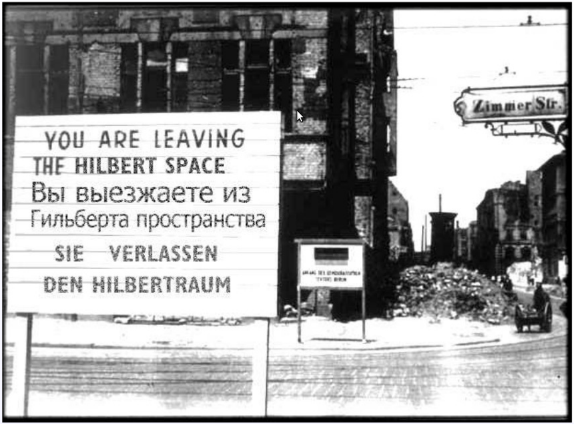
Reaction theory:
• Unable to include the underlying structure of the target and the projectile nuclei microscopically.



- Reconciliation of SM with reaction theory by Feshbach (1958-1962), Fano (1961), Mahaux and Weidenmüller (1969) with the projection operator formalism ⇒ Continuum Shell Model.
- A different approach: Gamow Shell Model (GSM), the SM for OQS in the complex energy plane.

→ Reconciliation of GSM with reaction theory using the coupled-channel formalism: GSM-CC.

Formalism



Picture from `http://arxiv.org/abs/quant-ph/0005024`

Formalism

→ GSM: quasi-stationary open quantum system extension of the SM.

- **Gamow states:** discrete solutions of the quasi-stationary Schrödinger equation that are regular at the origin and with outgoing boundary conditions.
  G. Gamow, Z. Physik **51**, 204 (1928)

$$\frac{\partial^2 u_l(k,r)}{\partial r^2} = \left(\frac{l(l+1)}{r^2} + \frac{2m}{\hbar^2} V(r) - k^2 \right) u_l(k,r)$$

$$E = \frac{\hbar^2 k^2}{2m} \qquad u_l(k,r) \underset{r\sim 0}{\sim} C_0(k) r^{l+1}$$

$$u_l(k,r) \underset{r\to\infty}{\sim} C_+(k) H^+_{l,\eta}(kr) + C_-(k) H^-_{l,\eta}(kr)$$

$$u_l(k,r) \underset{r\to\infty}{\sim} C_+(k) H^+_{l,\eta}(kr) \Leftarrow \text{outgoing solution}$$

- Complex eigenenergies $E_n = e_n - i\Gamma_n/2$ corresponding to poles of the S-matrix:

$$k_n = \sqrt{\frac{2\mu E_n}{\hbar^2}} = \kappa_n - i\gamma_n .$$

- Rigged Hilbert space (RHS): construction designed to link the distribution and square-integrable aspects of functional analysis (Gel'fand, Vilenkin *et al.* (1964), Maurin (1968)).
- Rigorous framework for quantum mechanics (Böhm (1964), Roberts (1966), Antoine (1969) and Melsheimer (1974)).
- Unified formalism for bound states, resonances and scattering states.
- RHS inner product:

$$\langle \tilde{u}_n | u_n \rangle = \int_0^\infty dr\, \tilde{u}_n^*(r) u_n(r).$$

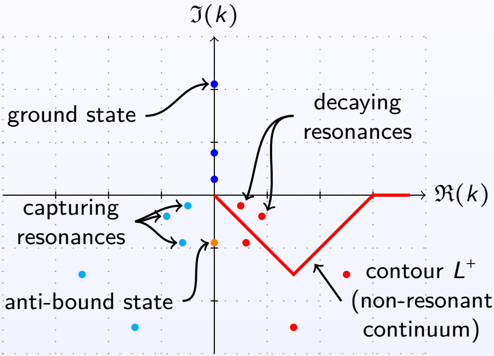
Formalism

→ **Berggren completeness relation:**

$$\sum_{n\in(b,d)} |u_l(k_n)\rangle\langle\tilde{u}_l(k_n)| + \int_{L^+_{l,j}} dk\, |u_l(k)\rangle\langle\tilde{u}_l(k)| = \hat{\mathbb{1}}.$$

T. Berggren, Nucl. Phys. A **109**, 265 (1968)

→ Discretization: $\sum_{n\in(b,d,c)} |u_l(k_n)\rangle\langle u_l(k_n)| \approx \hat{\mathbb{1}}.$



Normalization in practice:

- Scattering states:

$$C_+(k)C_-(k) = \frac{1}{2\pi}.$$

  (holds also with Coulomb)

- Resonant states:

$$C_-(k) = 0.$$

- Resonances:

  → Exterior complex-scaling:

  $\hat{U}_a(\theta)\chi(r) = \chi(r_a + |r - r_a|e^{i\theta})$

  if $|r| > r_a$.

  B. Gyarmati and T. Vertse (1971), B. Simon (1979)

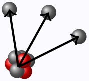
- Differentiability: $\mathcal{J}^+(k) = 0$.
- The RHS inner product gives $C_0(k)$.

The Gamow Shell Model

→ **Gamow Shell Model:**

- Intrinsic nucleon-core coordinates of the Cluster-Orbital Shell Model.

  Y. Suzuki *et al.*, Phys. Rev. C **38**, 410 (1988)



- SM Hamiltonian:

$$\hat{H} = \hat{H}_c + \sum_{i=1}^{N_{\rm val}} \hat{t}_i + \sum_{i<j}^{N_{\rm val}} \hat{V}_{ij}.$$

- N-body basis of Slater determinants:

$$\sum_n |\Psi_n\rangle \langle\Psi_n| \approx \hat{\mathbb{1}}$$

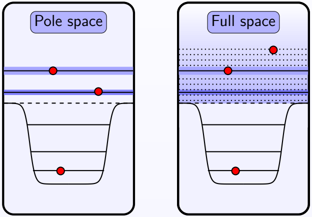
  from the 1-body Berggren basis.

- Hermitian Hamiltonian but complex-symmetric matrix $A = A^{\rm T}$.

  → Davidson diagonalization.

- Eigenenergies: $\tilde{E}_n = E_n + i\Gamma_n 2$.

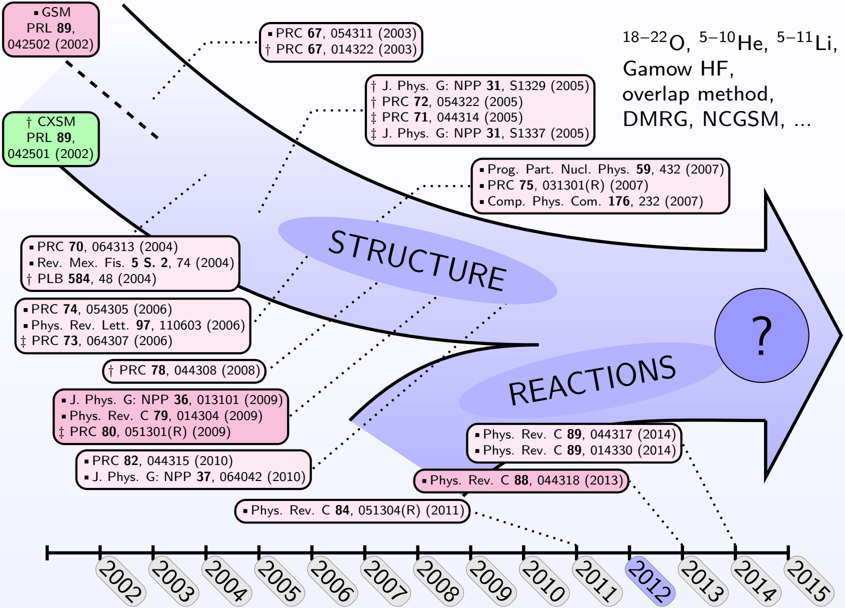
- Overlap method to identify N-body resonances.



$$\langle\Psi_n^{(\rm pole)}|\Psi_n^{(\rm full)}\rangle \approx 70\% - 90\%$$

- Schematic interactions: proof of applicability of GSM.
- Spectroscopy of stable and unstable nuclei.

The Gamow Shell Model

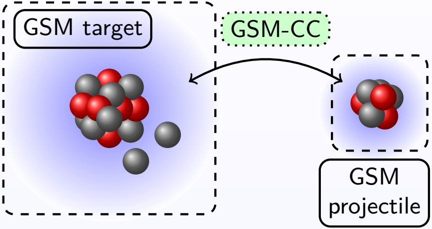


$^{18-22}$O, $^{5-10}$He, $^{5-11}$Li, ...
Gamow HF,
overlap method,
DMRG, NCGSM, ...

FORMALISM

→ **Unification of nuclear structure and reactions based on GSM.**

- Coupled-channel (CC) formalism.
- Channel: $|r, c\rangle = |r\rangle \otimes |c_{\text{proj}}\rangle \otimes |c_{\text{targ}}\rangle$.
- Target:
  - bound state or resonance.
    → Resonant channel.
  - scattering state.
    → Nonresonant channel.
- Fully antisymmetrized calculation.

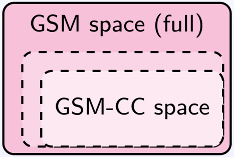


$$\sum\!\!\!\!\!\!\int_c \int_0^\infty dr\, r^2 \left(H_{c',c}(r',r) - E\, N_{c',c}(r',r)\right) \frac{u_c(r)}{r} = 0.$$

$H_{c',c}(r',r) = \langle r', c'|\hat{H}|r, c\rangle$, $N_{c',c}(r',r) = \langle r', c'|r, c\rangle$
→ Direct integration method (Bulirsch-Stoer).

Orthogonalization: $\langle r', c'|r, c\rangle = {}_o\langle r', c'|\hat{O}|r, c\rangle_o$,
Moore-Penrose pseudo inverse, equivalent potential method, ...

- Unified approach:
  GSM-CC$(A-a, a) \approx$ GSM(A).

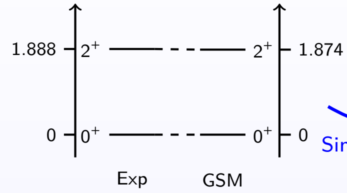


Elastic and inelastic scattering reactions

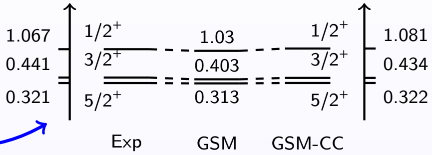
→ **First application of GSM-CC: (p,p') reactions.**

Y. J. *et al.*, J. Phys.: Conf. Series **403**, 012022 (2012)
Y. Jaganathen, PhD. thesis (2012)
Y. Jaganathen *et al.*, Phys. Rev. C **89**, 034624 (2014)

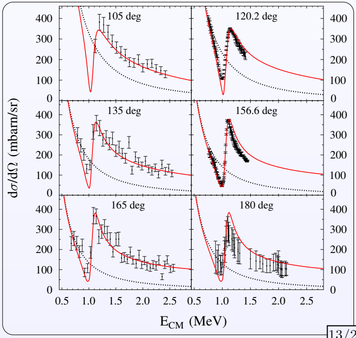
- The ^{18}Ne(p,p') reaction.



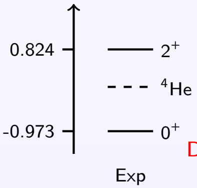
Similar structures



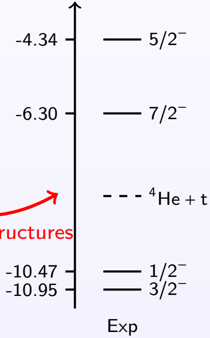
GSM-CC ≈ GSM
without nonresonant channels



- The ^{6}He(p,p') reaction.



Different structures

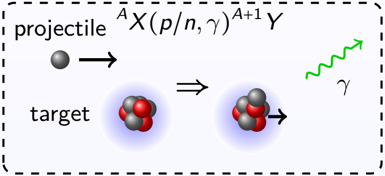


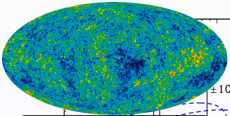
→ GSM-CC ≠ GSM
without nonresonant channels

Proton and neutron radiative capture reactions

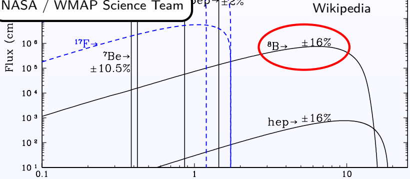
→ **Extension of GSM-CC to (p,γ) and (n,γ) reactions.**

- Big Bang nucleosynthesis, (H)CNO cycles, solar neutrinos, *pp* chains...

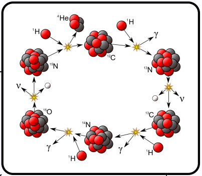




NASA / WMAP Science Team



The Astrophysical Journal **621**, L85 (2005)



Wikipedia

- Cross section:

$$\sigma = f\left(\langle \Psi_f(J_f) || \hat{O}^L || \Psi_i(J_i, c_e)\rangle\right).$$

- **Method:**

$$\langle \Psi_f || \hat{O}^L || \Psi_i \rangle = \langle \Psi_f || \hat{O}^L || \Psi_i \rangle_{\text{nas}} + \langle \Psi_f || \hat{O}^L_< || \Psi_i \rangle^{\text{HO}} - \langle \Psi_f || \hat{O}^L_< || \Psi_i \rangle^{\text{HO}}_{\text{nas}}.$$

- Important quantities:

$$S_{p/n} = E_0^{(A)}[\text{GSM}] - E_0^{(A+1)}[\text{GSM-CC}].$$

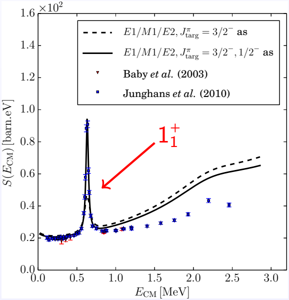
K. Fossez, PhD. thesis (2014)

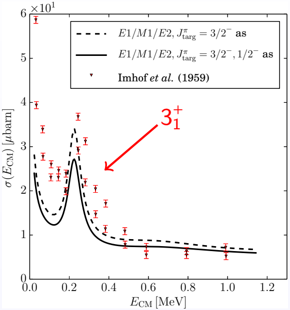
K. Fossez *et al.*, Phys. Rev. C **91**, 034609 (2015)

Proton and neutron radiative capture reactions

The ^{7}Li$(n,\gamma)^8$Li reaction.

The ^{7}Be$(p,\gamma)^8$B reaction.





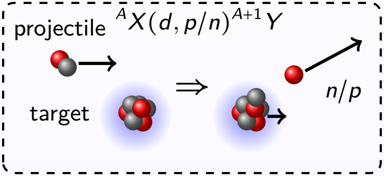
- Study of mirror reactions.
- $\hat{\mathcal{A}}\left(\langle \Psi_f(J_f) || \hat{O}^L || \Psi_i(J_i, c_e)\rangle\right)$.
- Role of the long wave length approximation.
- Corrective factors in $\tilde{V}_{c,c'} = c(J^\pi)V_{c,c'}$ with $c(J^\pi) < 5\%$.

→ Nonresonant channels missing.

Nucleon transfer reactions

→ **Extension of GSM-CC to (d,p) and (d,n) reactions.**

A. Mercenne, PhD. thesis (2013 – 2016)
N. Michel, private communication



- Probe of the single-particle structure.
- Many-body projectile.
- Channels definition:

$$|R^{\mathrm{CM}}, c\rangle = |R^{\mathrm{CM}}\rangle \otimes |c_{\mathrm{proj}}\rangle \otimes |c_{\mathrm{targ}}\rangle$$

with (GSM):

$$|c_{\mathrm{proj}}\rangle = |J_c^{\mathrm{CM}}(L_c^{\mathrm{CM}}, S_c^{\mathrm{CM}})\rangle_{\mathrm{proj}}.$$

- Momentum space expansion:

$$\{|R_{\mathrm{CM}}, c_{\mathrm{proj}}\rangle\} \Rightarrow \{|K_{\mathrm{CM}}, c_{\mathrm{proj}}\rangle\}.$$

- Naive approach: Direct expansion in the many-body Berggren basis.

$$|K_{\mathrm{CM}}, c_{\mathrm{proj}}\rangle \approx \sum_i c_i\, |\mathrm{SD}_i\rangle$$

$$\langle K_{\mathrm{CM}}|K'_{\mathrm{CM}}\rangle \overset{?}{=} \delta(K_{\mathrm{CM}} - K'_{\mathrm{CM}})$$

but drawbacks:
  - Contours discretization and truncations:
  - Normalization cannot be tested accurately.
- Solution: focus on the short-range part of $\hat{H}$:

$$|K_{\mathrm{CM}}, c_{\mathrm{proj}}\rangle^{\mathrm{HO}} = \sum_{N_{\mathrm{CM}}} U^{\mathrm{HO}}_{N_{\mathrm{CM}}, c_{\mathrm{proj}}}(K_{\mathrm{CM}})\, |N_{\mathrm{CM}}, c_{\mathrm{proj}}\rangle^{\mathrm{HO}}$$

$$= \sum_i c_i\, |\mathrm{SD}_i\rangle\,.$$

where $U^{\mathrm{HO}}_{N_{\mathrm{CM}}, c_{\mathrm{proj}}}(K_{\mathrm{CM}})$ comes from:

$$\hat{H}_{\mathrm{CM}} = \frac{\hat{P}^2_{\mathrm{CM}}}{2M_p} + U_{\mathrm{CM}}(\hat{R}_{\mathrm{CM}}).$$

EFFECTIVE INTERACTION FOR GSM/GSM-CC

→ **Development of an effective interaction.**

Y. Jaganathen, R. Id Betan *et al.*, In preparation.

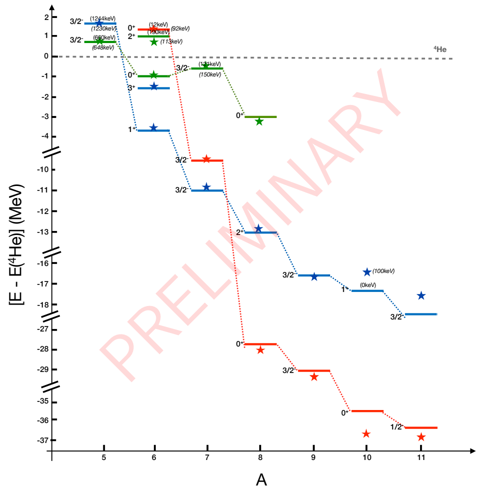
- Derived from the FHT interaction.
  H. Furutani *et al.*, Prog. Theor. Phys. **60**, 307 (1978)
  H. Furutani *et al.*, Prog. Theor. Phys. **62**, 981 (1979)
- Terms: V_c, V_{so}, V_T and V_C.
- Short-range (Gaussian).
- POUNDerS algorithm.
  http://www.mcs.anl.gov/tao
- Chi-squared minimization:

$$\chi^2(p) = \sum_{i=1}^{N_{\text{data}}} \frac{[\mathcal{O}_i(p) - \mathcal{O}_i^{\text{exp}}]^2}{\Delta\mathcal{O}_i^2}, \quad \frac{\chi^2(p_0)}{N_{\text{d.o.f.}}} = 1.$$

and removing of the arbitrariness in the adopted errors at the minimum.

J. Phys. G: Nucl. Part. Phys. **41**, 074001 (2014)

- Woods-Saxon ^{4}He core.
  - $n/p - \alpha$ phase shifts up to 20 MeV.
  - s.p. energies and widths.



- 2p, 3n with 3 nucleons max in the continuum.

Additional applications: NCGSM

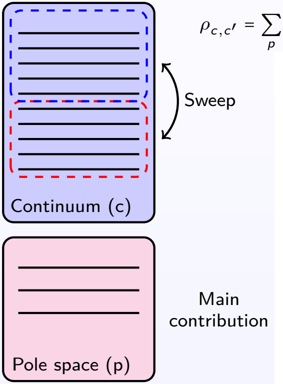
→ **First application of the *ab initio* GSM: The NCGSM.**

- Dimensional explosion: Density Matrix Renormalization Group (DMRG) method.

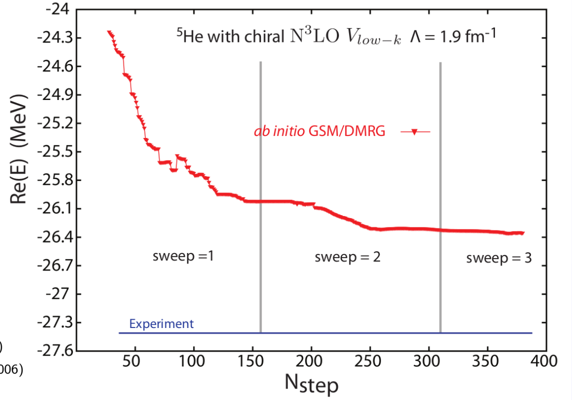
Truncation among states with nucleons in the continuum.

S. R. White, Phys. Rev. Lett. **69**, 2863 (1992)
T. Papenbrock *et al.*, J. Phys. G: NPP. **31**, S 1377 (2005)
S. Pittel *et al.*, Phys. Rev. C **73**, 014301 (2006)

$$\rho_{c,c'} = \sum_p \Psi_{c,p}\Psi_{c',p}$$



G. Papadimitriou *et al.*, Phys. Rev. C **88**, 044318 (2013)



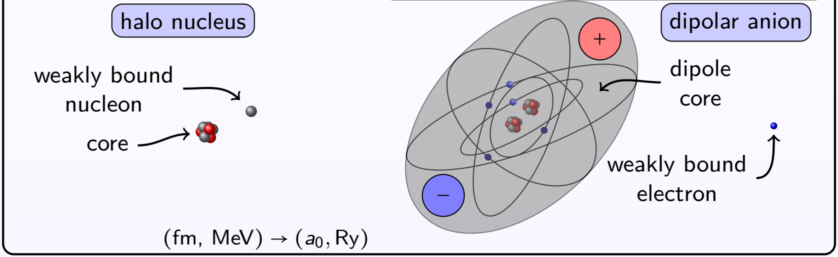
J. Rotureau *et al.*, Phys. Rev. C **79**, 014304 (2009)
J. Rotureau *et al.*, Phys. Rev. Lett. **97**, 110603 (2006)

Select the most important
continuum configurations by retaining only the "largest" eigenvalues of the density matrix at each iteration

Additional applications: Dipolar anions

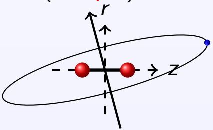
→ **Study of a molecular open quantum system using the Gamow Shell Model.**

Calculation of resonances in dipolar anions.
Bound dipolar anions as extreme halo systems.
Competition between threshold effects and rotation.



$\hat{\vec{l}}$: electronic orbital momentum (no spin)

$\hat{\vec{J}} = \hat{\vec{l}} + \hat{\vec{j}}$



$\hat{\vec{j}}$: rotation of the dipole

- Effective Hamiltonian of multipolar anions : $$\hat{H} = \frac{\hat{\vec{p}}_e^{\,2}}{2m_e} + \frac{\hat{\vec{j}}^{\,2}}{2I} + \hat{V}.$$
- $V(r,\theta) = V_\mu + V_\alpha + V_{Q_{zz}} + V_{SR}$.
- At large distances: no analytical asymptotic solution for finite I with $V_{cc'} \propto 1/r^2$.

W. R. Garrett, *J. Chem. Phys.* **77**, 3666 (1982)
W. R. Garrett, *J. Chem. Phys.* **133**, 224103 (2010)

Additional applications: Dipolar anions

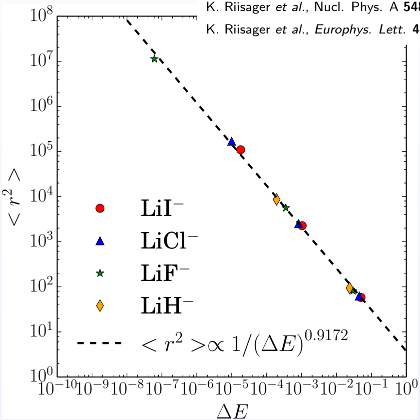
→ **Extreme halo systems and density in the rotor frame.**

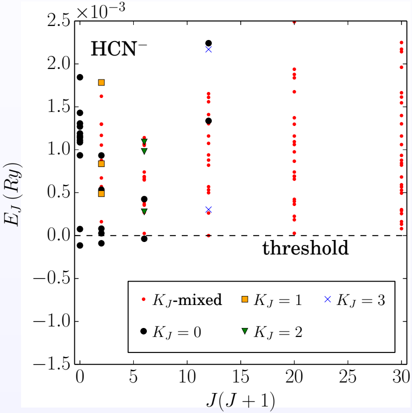
For a relative angular momentum:

- $l = 0 : < r^2 >$ diverges as $1/\Delta E$.
- $l = 1 : < r^2 >$ diverges as $1/\sqrt{\Delta E}$.
- $l > 1 : < r^2 >=$ constant.

$$\rho_J(r,\theta) = \sum_{K_J} \rho_{J,K_J}(r,\theta)$$

K. Riisager *et al.*, Nucl. Phys. A **548**, 393 (1992)
K. Riisager *et al.*, *Europhys. Lett.* **49**, 547 (2000)





Intrinsic density: all K_J-components except one vanish.

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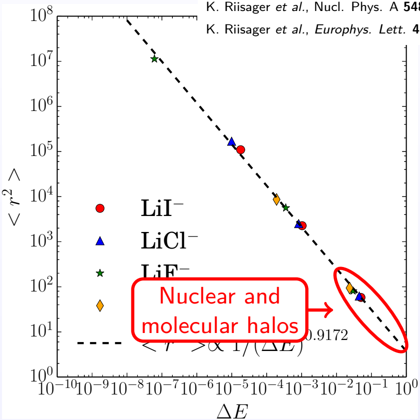
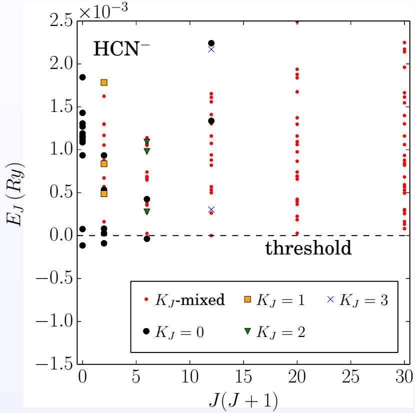
K. Riisager *et al.*, Nucl. Phys. A **548**, 393 (1992)

K. Riisager *et al.*, *Europhys. Lett.* **49**, 547 (2000)





Intrinsic density: all K_J-components except one vanish.

Additional applications: Dipolar anions

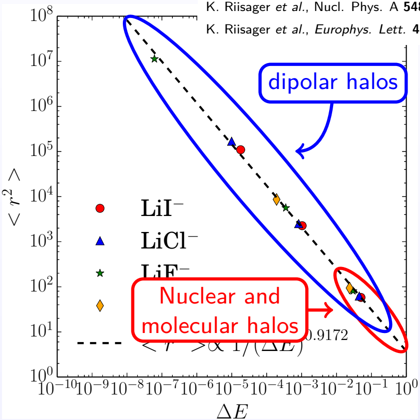
→ **Extreme halo systems and density in the rotor frame.**

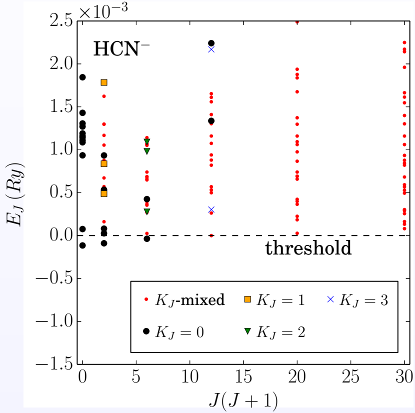
For a relative angular momentum:

- $l = 0 : < r^2 >$ diverges as $1/\Delta E$.
- $l = 1 : < r^2 >$ diverges as $1/\sqrt{\Delta E}$.
- $l > 1 : < r^2 > =$ constant.

$$\rho_J(r,\theta) = \sum_{K_J} \rho_{J,K_J}(r,\theta)$$

K. Riisager *et al.*, Nucl. Phys. A **548**, 393 (1992)
K. Riisager *et al.*, *Europhys. Lett.* **49**, 547 (2000)





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→ **Extreme halo systems and density in the rotor frame.**

Problem

No resonant states (poles)
in the Berggren basis.
⇔ no overlap method.

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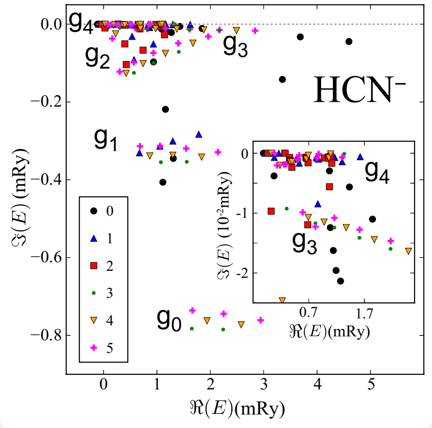
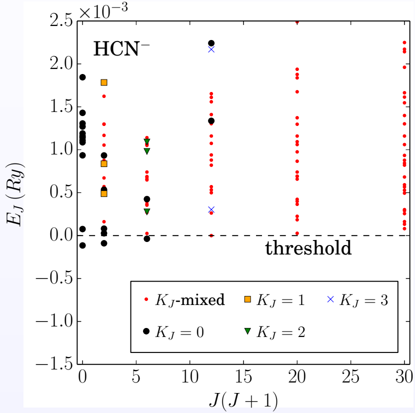


, 393 (1992)
, 547 (2000)



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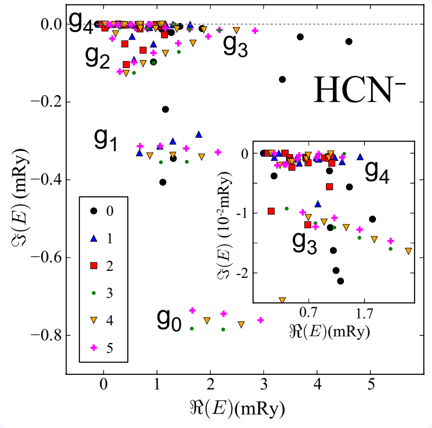

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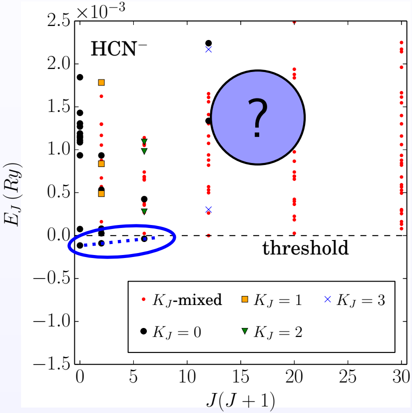
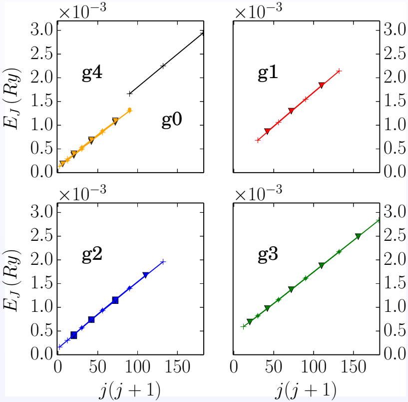


Intrinsic density: all K_J-components except one vanish.

Additional applications: Dipolar anions

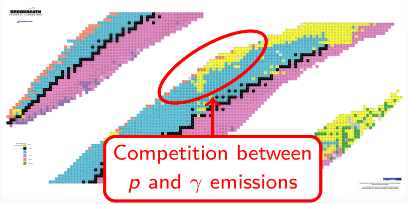
→ **Competition between threshold effects and rotation.**

- Above the threshold: weak coupling of the rotational motion of the dipole and the valence electron.

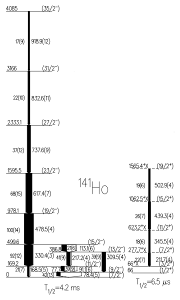


- Collective bands: $E_{J,l_c=6-8}(j)$.

→ Study of quadrupolar anions.



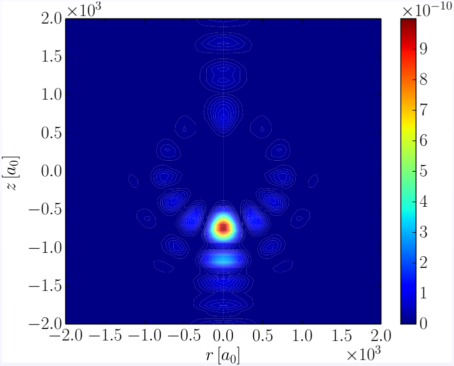
- ^{141}Ho = ^{140}Dy + p
- Important Coulomb barrier.
- Quadrupole moment.
- Collective bands in heavy p-rich nuclei?
- What about heavy n-rich nuclei?
- (centrifugal barrier)

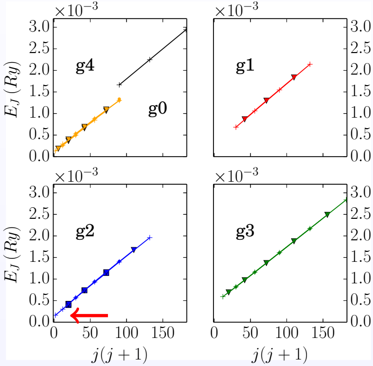


→ Under investigation.

Additional applications: Dipolar anions

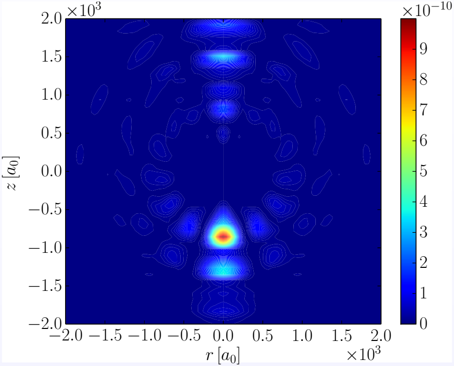
g_2: $J = 5(l_c = 6, j_c = 1)$.

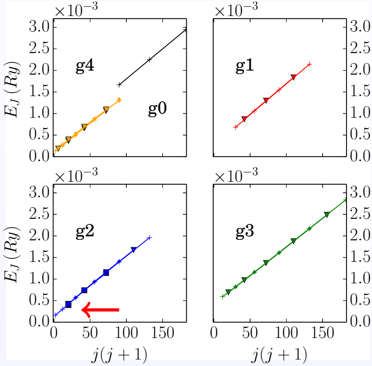




Additional applications: Dipolar anions

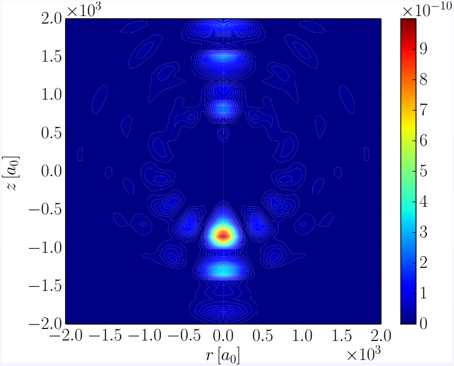
g_2: $J = 5(l_c = 6, j_c = 3)$.

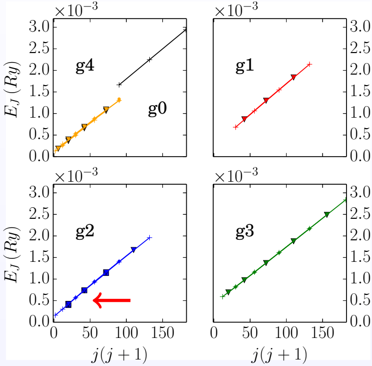




Additional applications: Dipolar anions

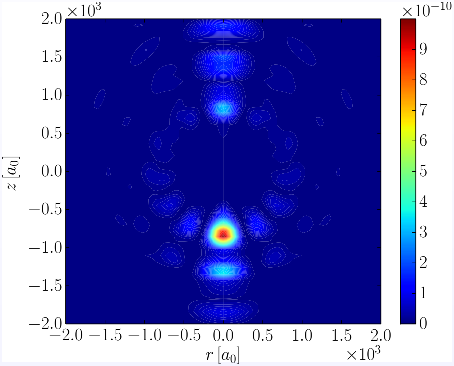
g_2: $J = 5(l_c = 6, j_c = 5)$.

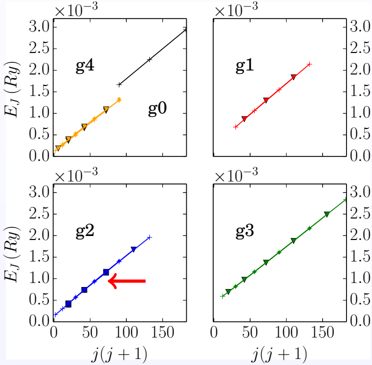




Additional applications: Dipolar anions

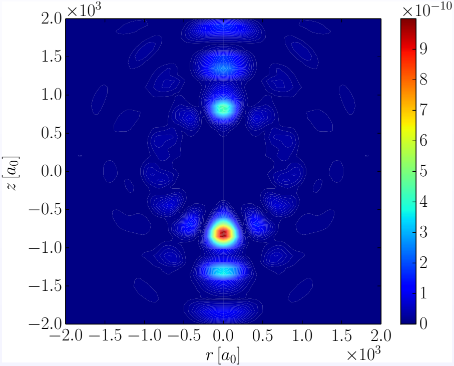
g_2: $J = 5(l_c = 6, j_c = 7)$.

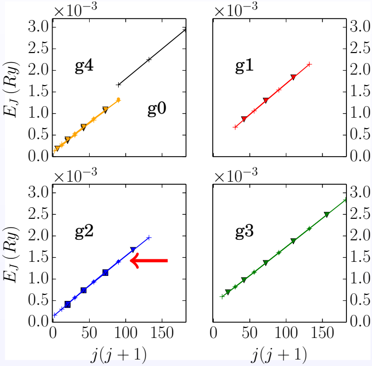




Additional applications: Dipolar anions

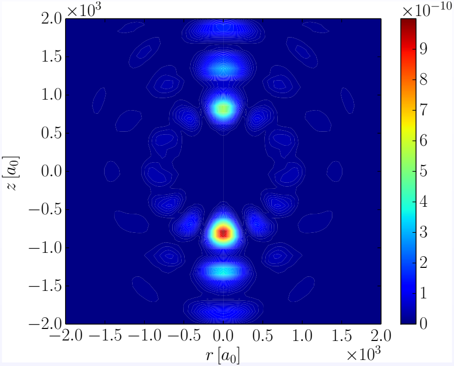
g_2: $J = 5(l_c = 6, j_c = 9)$.

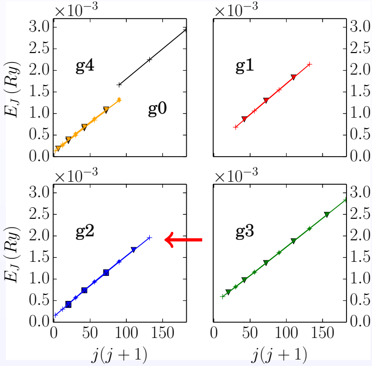




Additional applications: Dipolar anions

g_2: $J = 5(l_c = 6, j_c = 11)$.





Additional applications: Richardson model

J. von Delft *et al.*, Proceeding of the NATO ASI (1999)
R. W. Richardson, Phys. Lett. 3, 277 (1963)
R. W. Richardson *et al.*, Nucl. Phys. 52, 221 (1964)

- **Pairing Hamiltonian in the Berggren basis:**

$$H = \oint\!\!\!\!\!\!\int 2\epsilon_k b_k^\dagger b_k dk - G \oint\!\!\!\!\!\!\int b_k^\dagger b_{k'} dk dk'$$

$$(d): \left[b_k, b_{k'}^\dagger\right] = 2\delta_{kk'}(\Omega_k - 2n_k)$$

$$(c): \left[b_k, b_{k'}^\dagger\right] = 2\delta(k-k')\Omega_k - 2\delta_{kk'} n_k$$

- **Discretization:**

$$H = \sum_a^L 2\epsilon_a \tilde{b}_a^\dagger \tilde{b}_a - G \sum_{a,a'} \tilde{b}_a^\dagger \tilde{b}_{a'} \sqrt{w_a}\sqrt{w_{a'}} \quad \text{with} \quad \tilde{b}_a^\dagger = \tilde{b}_{k_a}\sqrt{w_a}$$

$$\Rightarrow \left[\tilde{b}_a, \tilde{b}_{a'}^\dagger\right] = 2\delta_{aa'}(\Omega_a - 2\tilde{n}_a)$$

- **Problem:** $G_{aa'} = G\sqrt{w_a}\sqrt{w_{a'}} \Rightarrow$ No analytical solution

- **Approximate solution of the pairing problem:**

$$(d): \left[b_k, b_{k'}^\dagger\right] = 2\delta_{kk'}(\Omega_k - 2n_k)$$

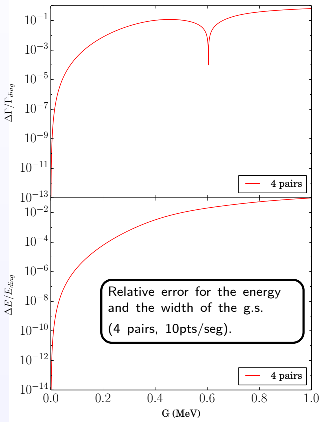
$$(c): \left[b_k, b_{k'}^\dagger\right] = 2\delta(k-k')\Omega_k - 2\delta(k-k') n_k$$

- **Discretization:**

$$\Rightarrow \left[\tilde{b}_a, \tilde{b}_{a'}^\dagger\right] = 2\delta_{aa'}\left(\Omega_a - \frac{2}{w_a}\tilde{n}_a\right)$$

- **Ansatz:**

$$|\Psi\rangle = \prod_{i=1}^{N_{\text{pair}}} \mathcal{N}_i^{-1} \left(\sum_a^L \frac{\tilde{b}_a^\dagger}{2\epsilon_a - E_i}\right)|\rangle \quad \text{with } \mathcal{N}_i = \sqrt{\sum_a \frac{w_a}{(2\epsilon_a - E_i)^2}}$$



$$1 - 2G\sum_a^L \frac{\Omega_a/4 - \nu_a/2}{2\epsilon_a - E_i} + 2G\sum_{j\neq i}^{N_{\text{pair}}} \frac{1}{E_j - E_i} - 2G\sum_c^{\ell_{max}, j_{max}} \int_{L_c^+} \frac{\Omega_c/4 - \nu_c/2}{\hbar^2 k_c^2/m - E_i} = 0$$

A. Mercenne *et al.*, In preparation.

Summary

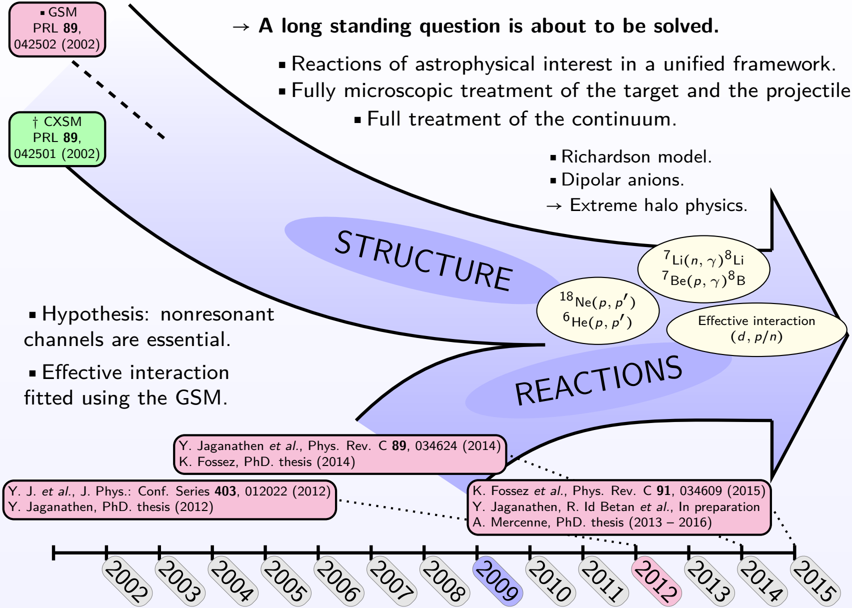
→ **A long standing question is about to be solved.**

- Reactions of astrophysical interest in a unified framework.
- Fully microscopic treatment of the target and the projectile.
- Full treatment of the continuum.

- Richardson model.
- Dipolar anions.

→ Extreme halo physics.

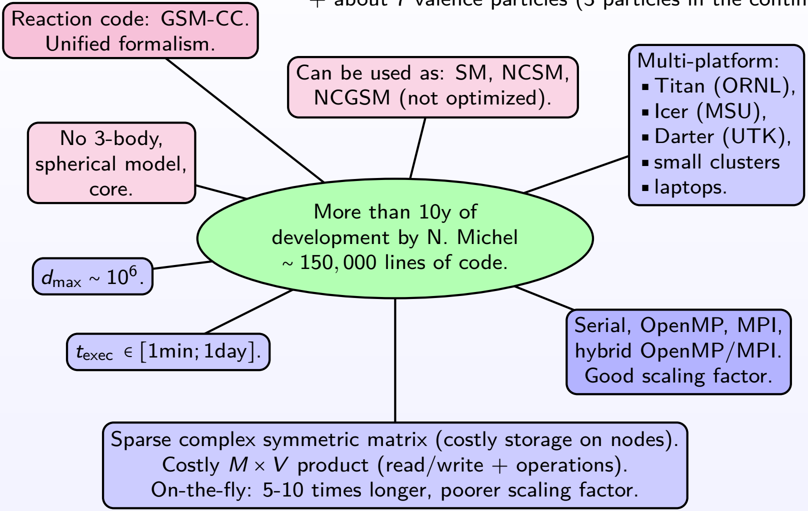
- Hypothesis: nonresonant channels are essential.
- Effective interaction fitted using the GSM.



Limits and possibilities of the code

→ **GSM best for: weakly bound and unbound systems.**

Range of applicability: systems with an inert core
+ about 7 valence particles (3 particles in the continuum).



Perspectives

→ **When computational science, nuclear theory and statistics meet.**

Computational science

- Applied mathematics.
- High performance computing.
- Next supercomputers: more cores but lower frequency and more accelerators (GPUs).

Collaborations with computer scientists.
Optimization.
Typical example: POUNDerS.

GPUs for $M \times V$ in GSM, no conditional statements (IF, WHILE).

Nuclear theory

- Input: nuclear interaction from EFT.
- Many-body dynamics: *ab initio* methods.
- Continuum effects in nuclear structure and reactions.

- ^{6}Li$(p/n, \gamma)$.
- Reactions: $d, t, ^{3}$He$, \alpha$.
- ^{9}C, ^{14}O and ^{24}O, ^{26}Ne.
- Heavy nuclei: r-process, continuum decoupling effect.
- DMRG method.
- EFT and core?

- Reactions with heavy nuclei: ^{132}Sn core.
- $(d, p/n), (n/p, d), (\alpha, \gamma), (n/p, \alpha), (\alpha, \alpha')$.

Statistics

(The end of cargo cult science.)

- Analysis of experiments using model-based extrapolations.
- Statistical and systematic error estimates.
- Predictive power of nuclear models.

Conclusion: We made crucial developments to deal with upcoming experimental measurements.

Thank you for your attention !

Un grand merci
à Eric Olsen !