Structure and reaction observables of drip-line nuclei with the Gamow Shell Model

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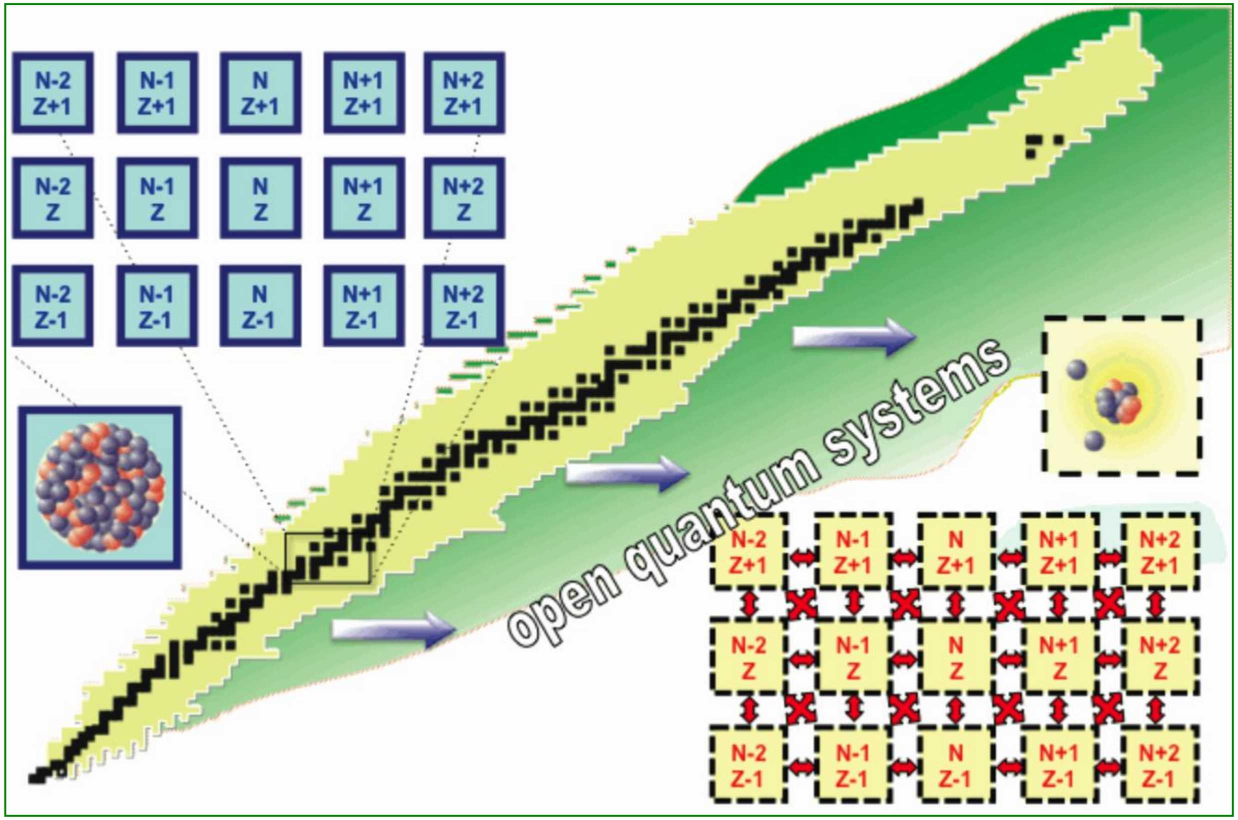
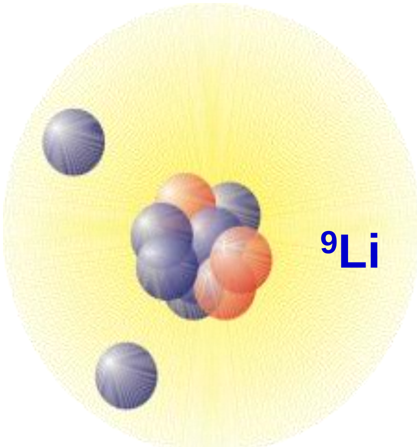
Scientific context



<u>Experimental interest</u>
Study of nuclei far from the valley of stability
Many efforts made to study drip-line nuclei

N. Michel, W. Nazarewicz, J. Okołowicz, M. Płoszajczak, J. Phys. G: Nucl. Part. Phys., **37** 064042 (2010)

Borromean nuclei



^{11}Li: Borromean halo nucleus

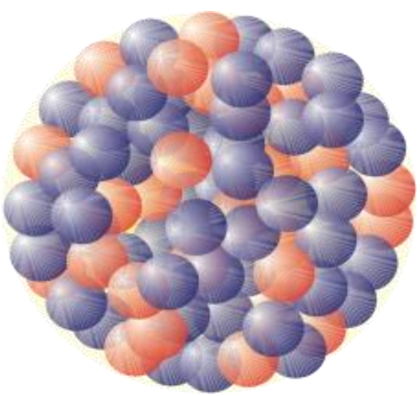
Z=3, N=8

n+n is unbound

n+ ^{9}Li is unbound

but n+n+ ^{9}Li is bound !

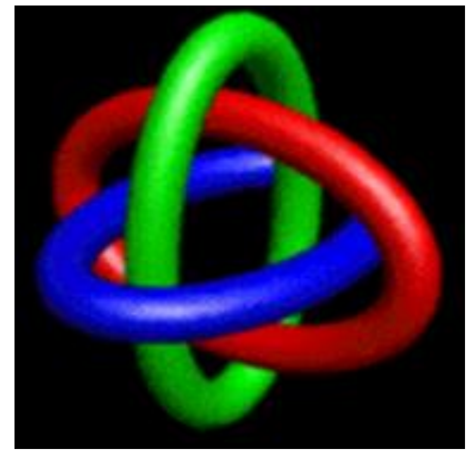
← 0.0000000000014 cm →



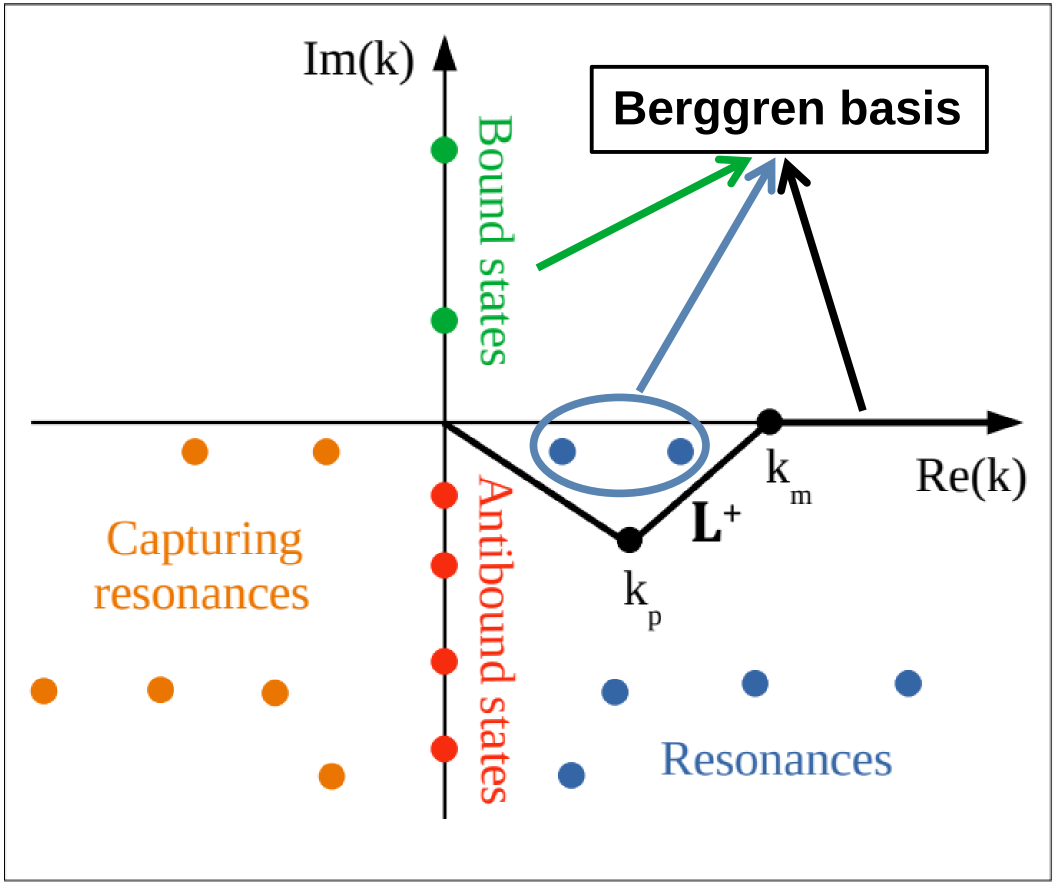
^{208}Pb: well bound

heavy nucleus Z=82, N=126

The Borromean Rings



The Berggren basis



Berggren basis : bound, resonance and scattering states

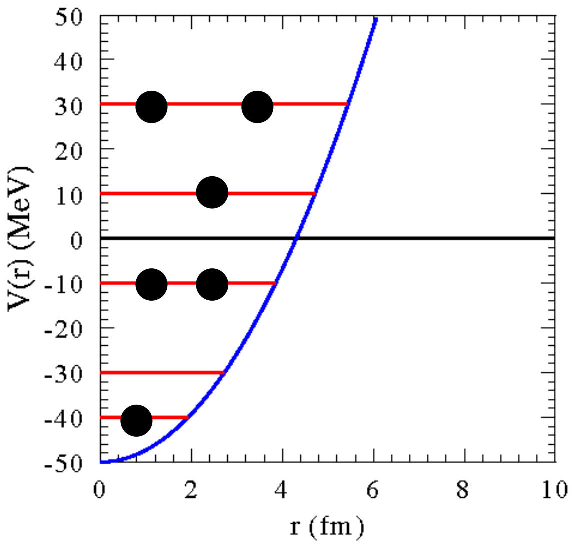
Efficient discretization of the L^+ contour with Gauss-Legendre quadrature

N. Michel, M. Płoszajczak,
The Gamow Shell Model:
the unified theory of nuclear structure and reactions,
Lecture Notes in Physics, Springer (2021)

Gamow Shell Model (GSM)

Standard shell model

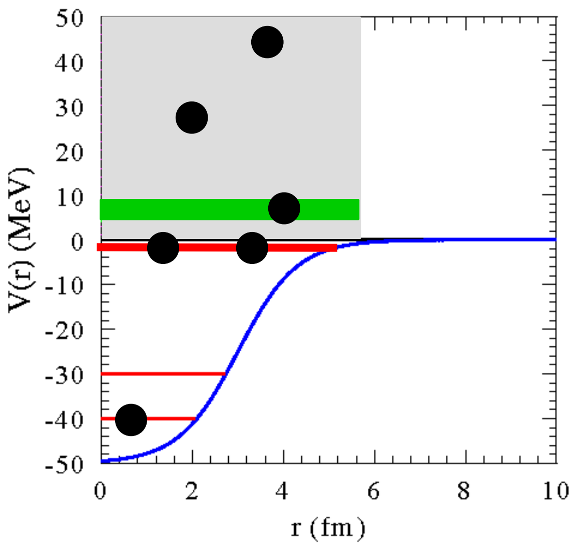
Closed quantum system description



Localized states only

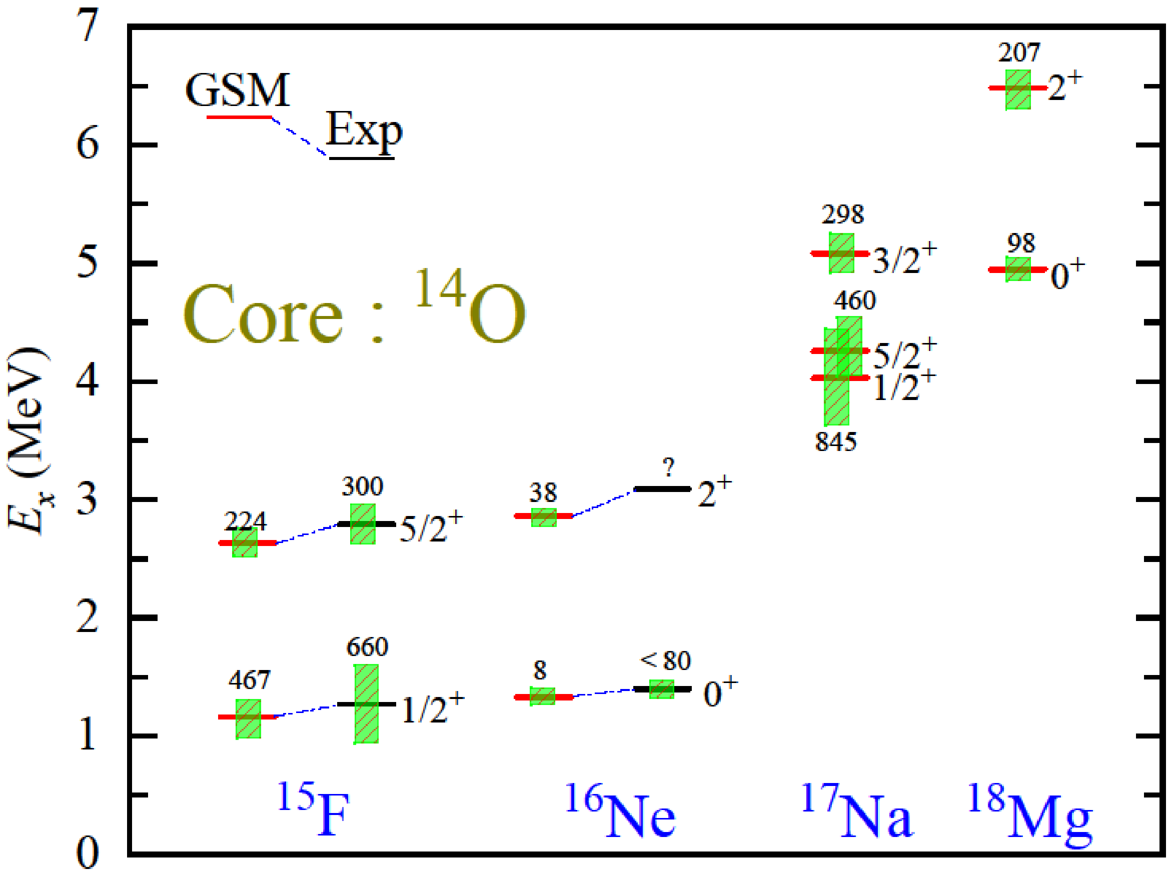
Gamow Shell Model

Open quantum system description



Localized states
Halo states of complex structure
Many-body resonances

Proton-rich carbon isotones with GSM



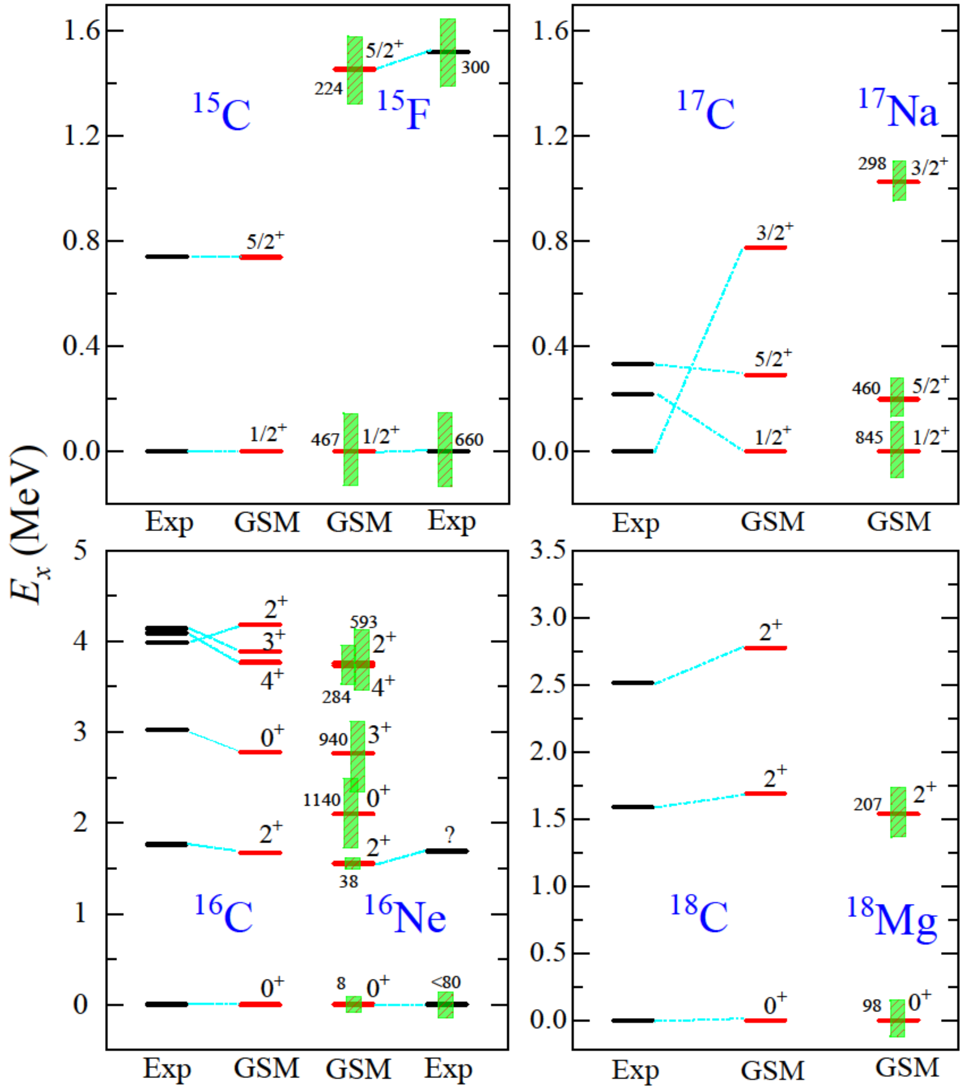
Interest
p, 2p emission in light nuclei

Model
GSM with a ^{14}O core
EFT interaction
psd Berggren basis

Spectra
Energies and widths
well reproduced

N. Michel, J. G. Li, F. R. Xu, W. Zuo, Phys. Rev. C **103**, 044319 (2021)

Isospin symmetry breaking in carbon isotopes and isotones with GSM



<u>Isospin symmetry breaking</u>

Carbon isotopes : well bound
Carbon isotones : unbound

Thomas-Ehrmann shift
induced by continuum coupling

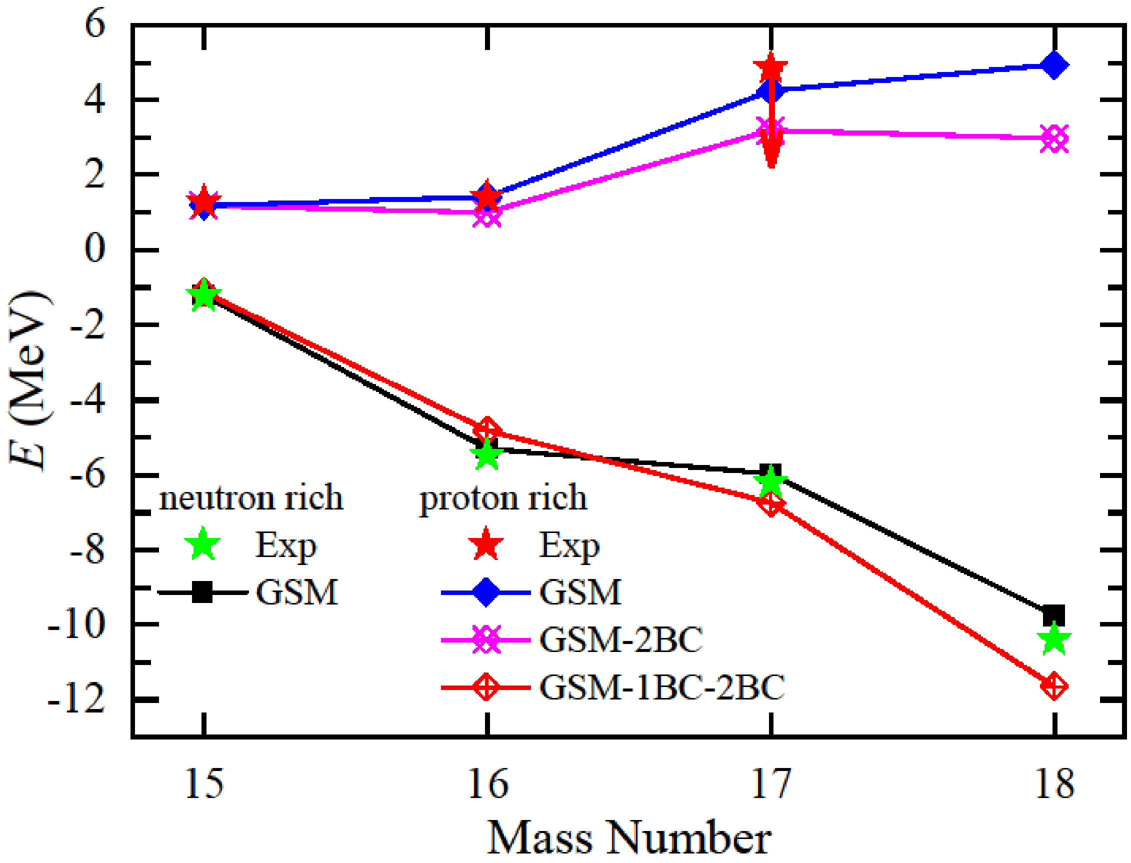
Increasing Coulomb interaction
Continuum coupling
Nuclear structure

Large width not necessarily induces
large Thomas-Ehrmann shift

Width prediction of ^{16}Ne and ^{18}Mg
1p ~100 keV, 2p ~10 keV

N. Michel, J. G. Li, F. R. Xu, W. Zuo,
Phys. Rev. C **103**, 044319 (2021)

Coulomb contribution in proton-rich nuclei

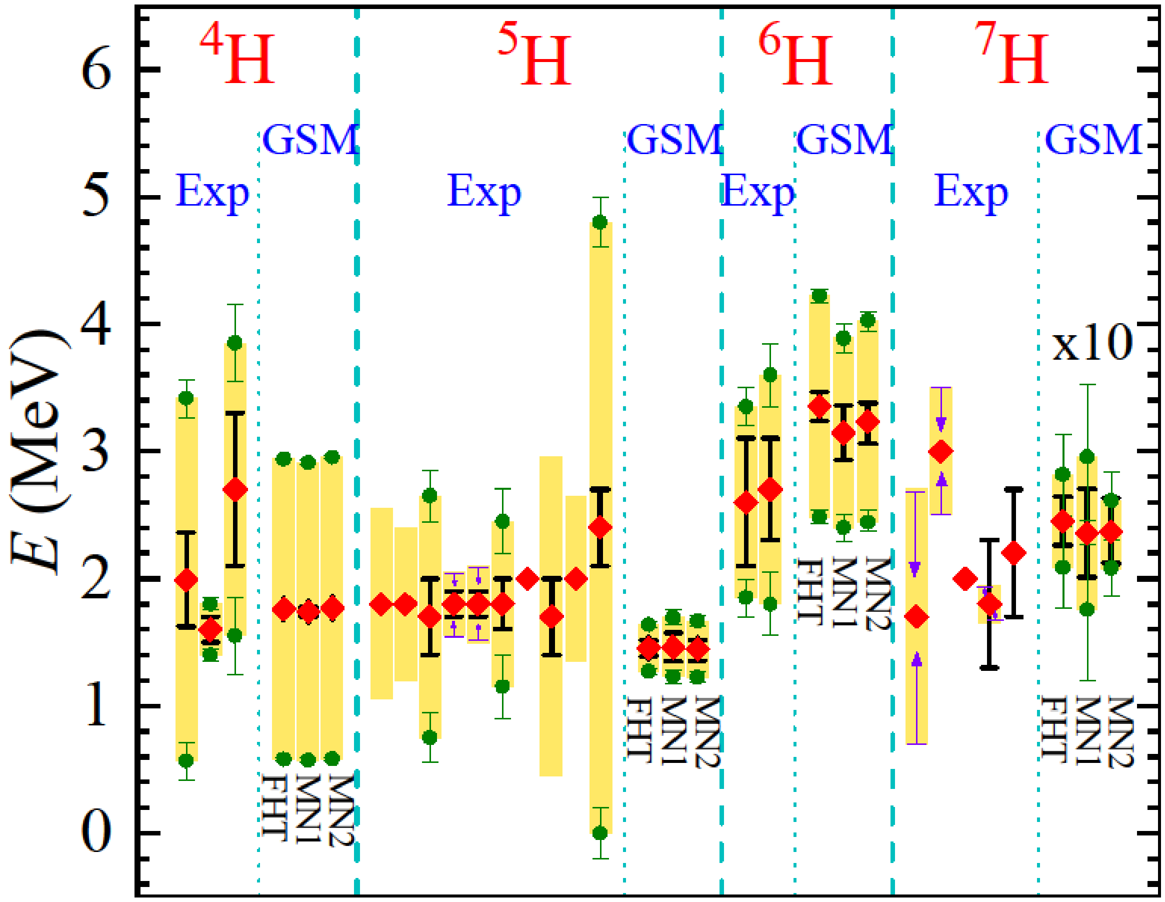


N. Michel, J. G. Li, F. R. Xu, W. Zuo, Phys. Rev. C **103**, 044319 (2021)

Coulomb contribution
^{14}O core potential : one-body part
Valence protons : two-body part
Coulomb interaction at proton drip-line

Comparison with carbon isotopes
Nuclear energy : similar to carbon isotopes
Energy difference : isospin symmetry breaking
Unintuitive behavior of energy : non monotonous

Unbound hydrogen isotopes with GSM



Odd unbound hydrogen isotopes

Experimental data with large errors
Similar results with FHT, Minnesota

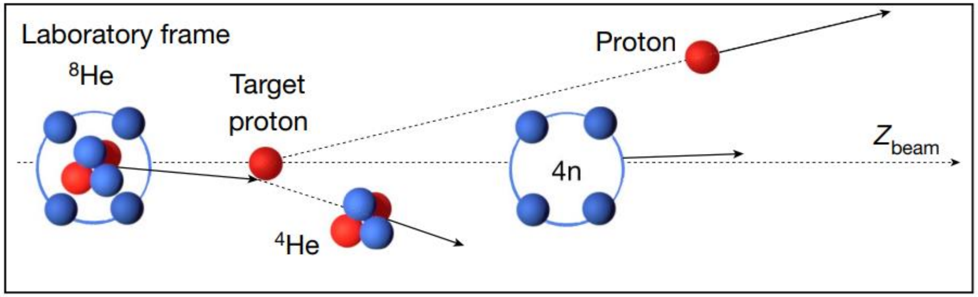
^{5}H : ~ 500 keV width, moderate
^{7}H : 10-250 keV width, narrow

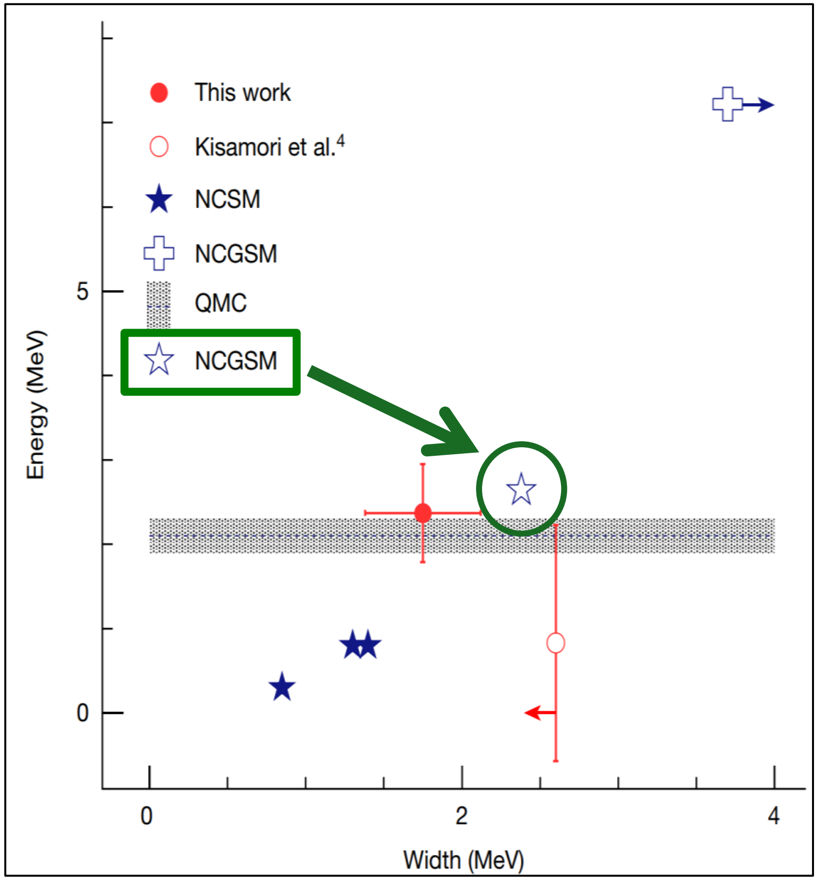
To be checked in future experiments

H. H. Li, J. G. Li, N. Michel, W. Zuo, Phys. Rev. C **104**, L061306 (2021)

Hydrogen isotopes
GSM with a core of ^{3}H (ab-initio GSM not applicable : model spaces too large)
FHT and Minnesota (MN1, MN2) interactions in spdf/spd space with the Berggren basis
Two-body interactions obtained from a fit of the He chain
Large widths for ^{4,6}H, smaller widths for ^{5,7}H

Application of ab-initio GSM to the tetraneutron





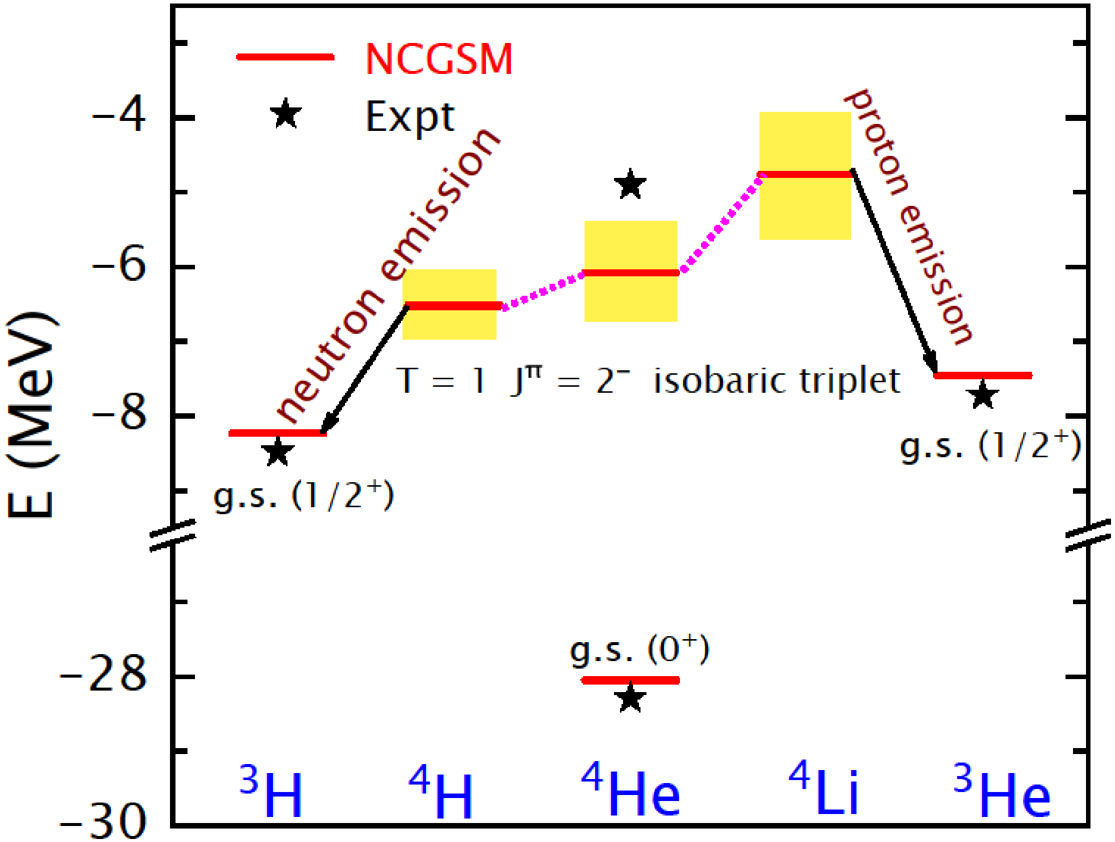
Full space results from 3p-3h + 4p-4h calculations

3n: E ~ 1.29 MeV , Γ ~ 0.91 MeV
4n: E ~ 2.65 MeV , Γ ~ 2.38 MeV

4n NCGSM results close to recent experimental data (M.Duer et al., Nature **606**, 678–682 (2022))

J.G. Li, N. Michel, B.S. Hu, W. Zuo, F.R. Xu, Phys. Rev. C **100**, 054313 (2019)

Isospin symmetry breaking in A=4 T=1 resonances with ab-initio GSM



N. Michel, J. G. Li, F. R. Xu, W. Zuo, Phys. Rev. C **104**, 024319 (2021)

Coulomb interaction

No Coulomb force in ^{4}H
Coulomb force moderate in ^{4}He
Coulomb force largest in ^{4}Li

Width increases from ^{4}H to ^{4}Li due to Coulomb force

Isospin symmetry breaking

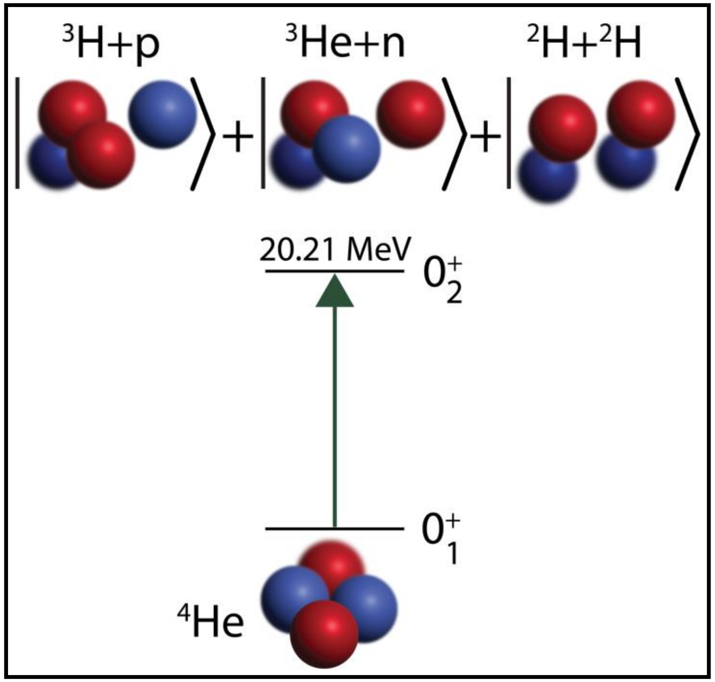
T=1 2- many body states
Isospin multiplet in A=4 states

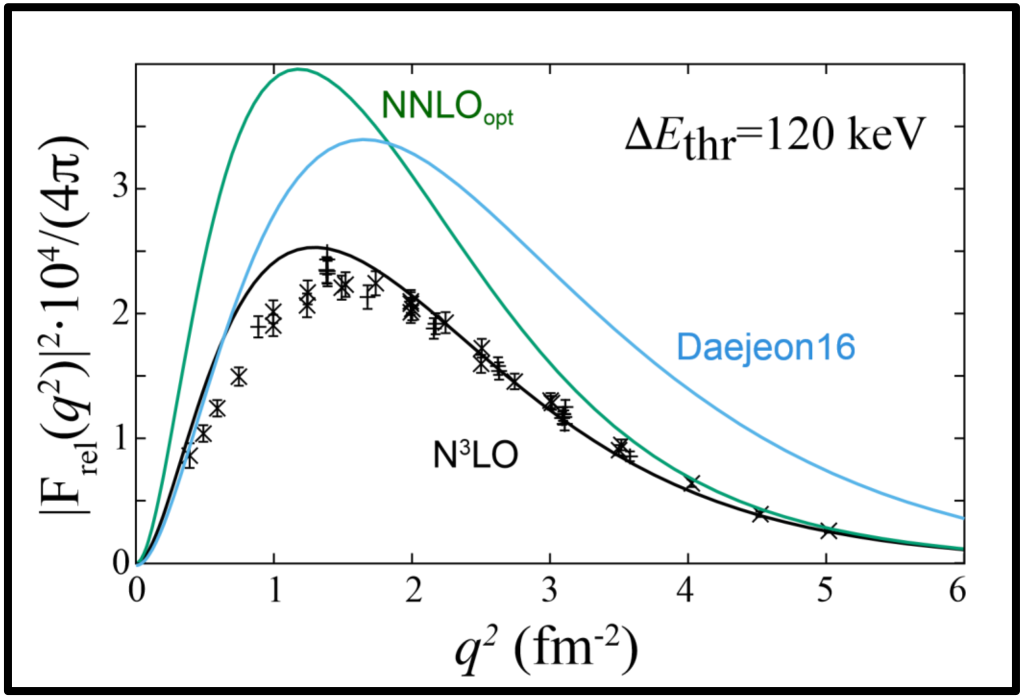
Unique situation
Broad resonances in T=1 multiplet

T = 1 in ^{4}H and ^{4}Li
T ~ 0.71 in ^{4}He

Isospin symmetry strongly broken

Proton resonance state of ^{4}He





No core GSM-CC with realistic interactions

Threshold-aligned resonance of the ^{3}H + p channel

Reproduction of monopole form factor (corrected figure)

Very strong energy + interaction dependence :

Not a good observable to constrain nuclear interactions

Lowest excited state of ^{4}He

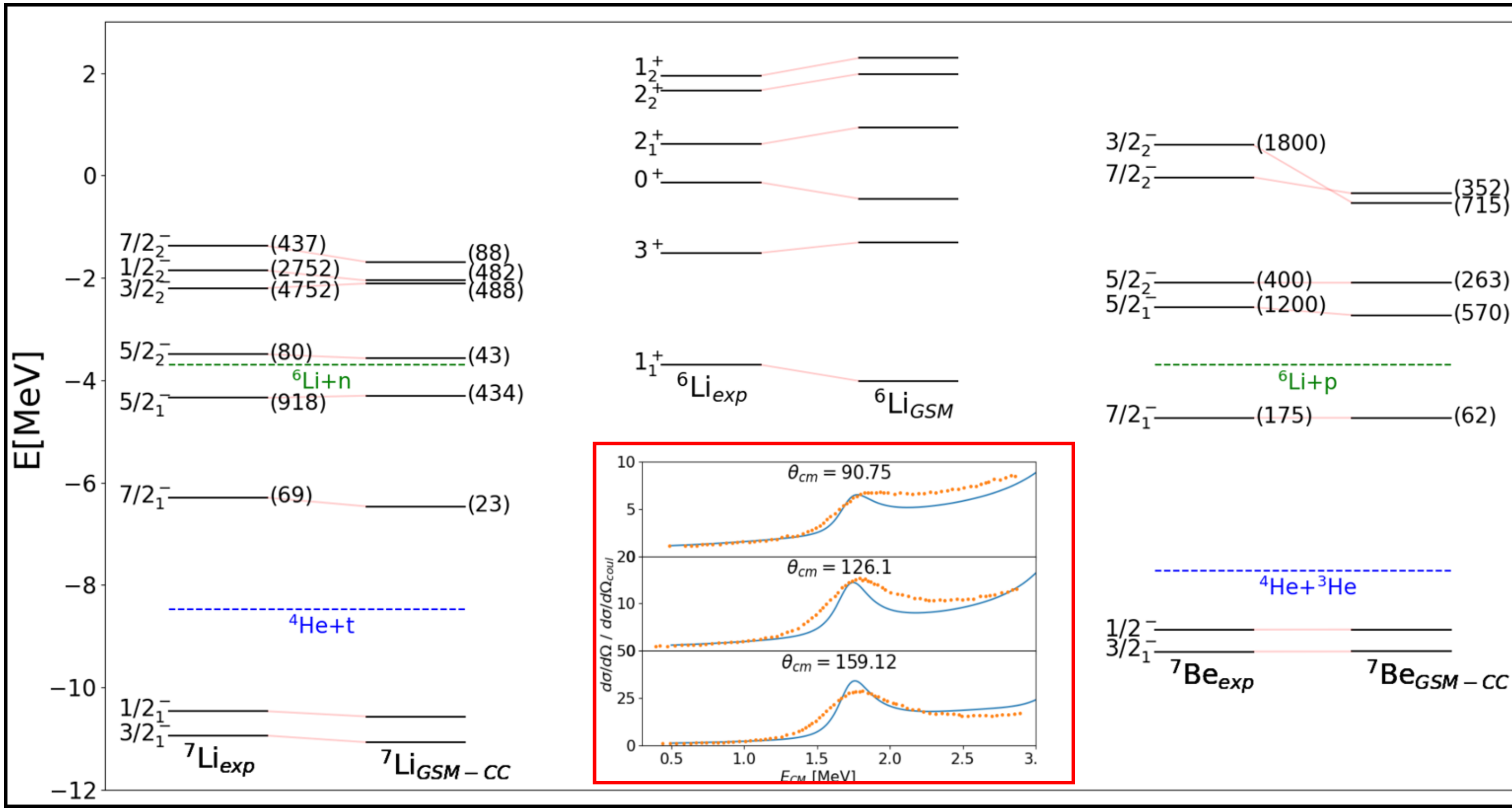
Proton resonance with Γ = 500 keV

Breathing mode ?

Particle-hole excitation ? Other ?

N. Michel, M. Płoszajczak, W. Nazarewicz,
Phys. Rev. Lett. **131**, 242502 (2023)

GSM-CC with ^3H and ^3He projectiles (1/2)



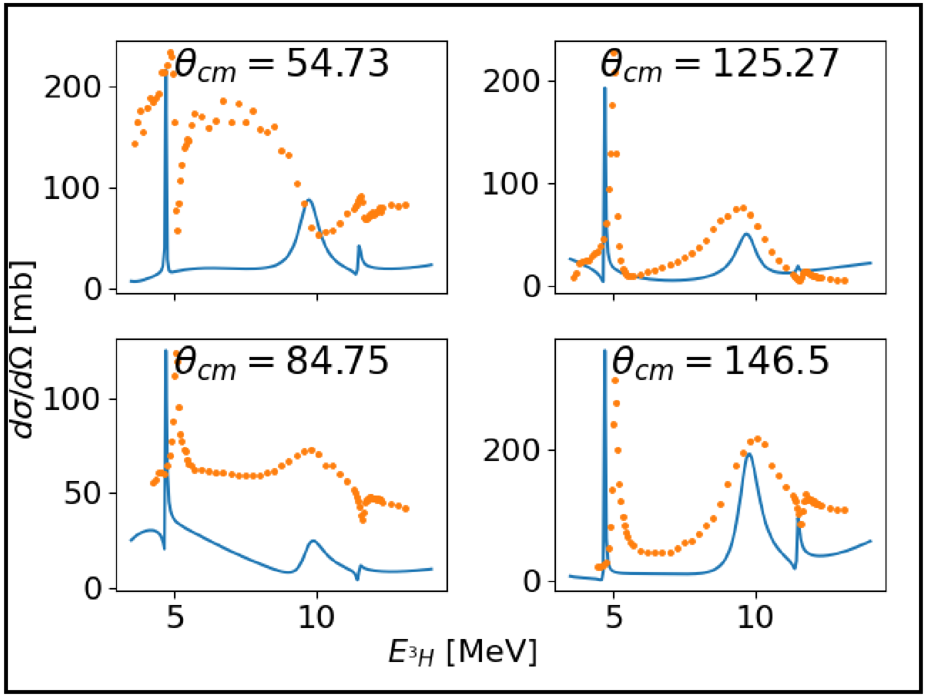
Hamiltonian : WS + FHT with alpha core

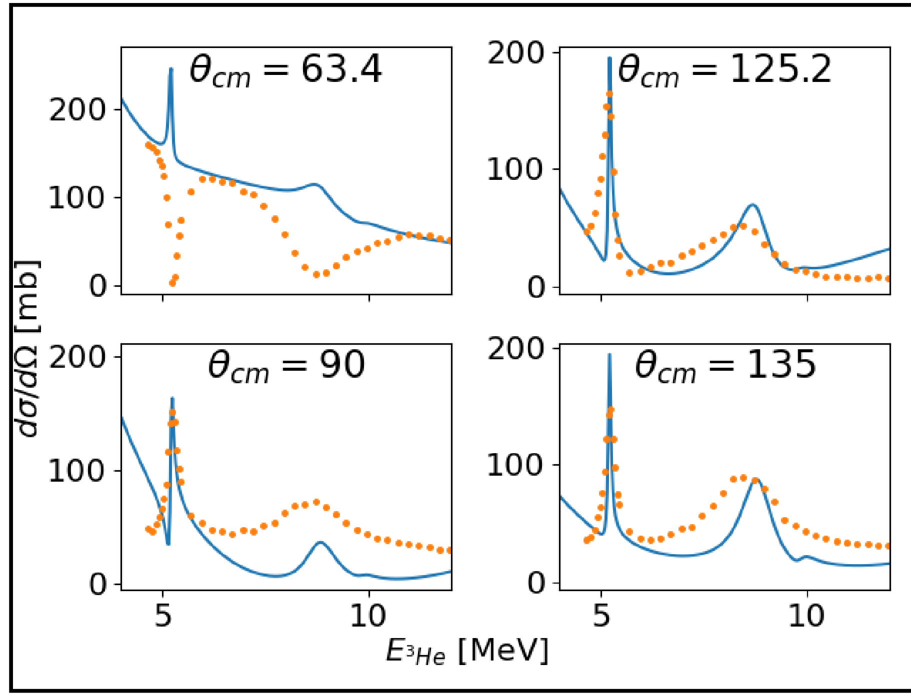
Spectrum well reproduced with GSM-CC

Cross sections of p + ^6Li reactions excellent

J. P. Linares Fernandez, N. Michel, M. Płoszajczak, A. Mercenne, Phys. Rev. C **108**, 044616 (2023)

GSM-CC with ^{3}H and ^{3}He projectiles (2/2)





FHT interaction between valence nucleons

N^{3}LO interaction for ^{3}H and ^{3}He projectile structure

Direct cross sections well reproduced in average

Results not satisfactory for small angles

Transfer reactions (not shown) too small

Imaginary part of potentials to determine

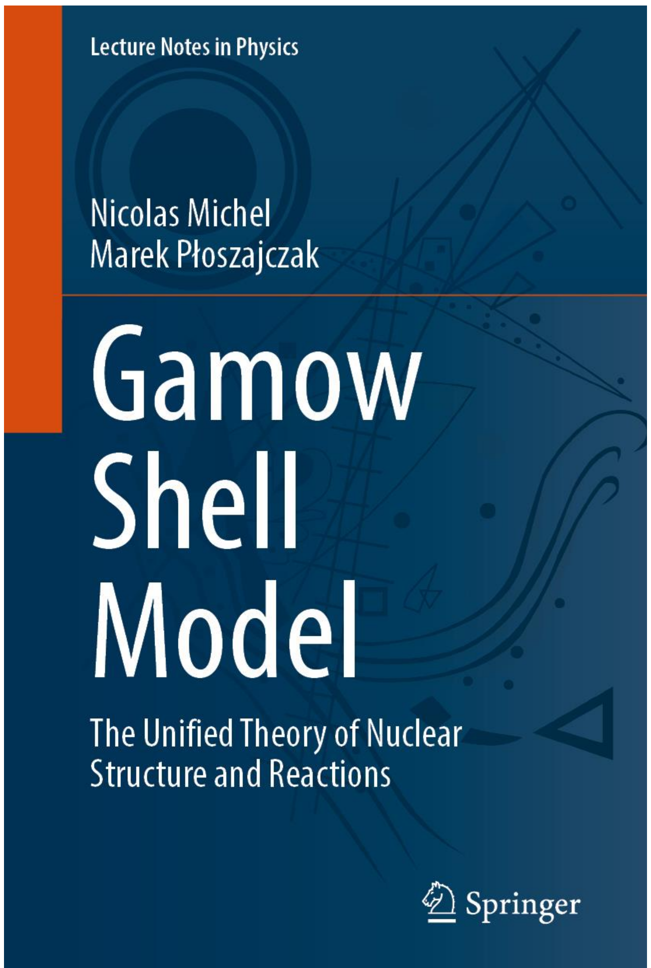
J. P. Linares Fernandez, N. Michel, M. Płoszajczak, A. Mercenne, Phys. Rev. C **108**, 044616 (2023)

Book on Gamow shell model

The Gamow Shell Model: the unified theory of nuclear structure and reactions

Authors : N. Michel and M. Płoszajczak

Publisher : Lectures Notes in Physics (Springer)



Background

Functional analysis, linear algebra, differential equations, standard quantum mechanics

Main topics

Introduction with one-body and two-body systems

Many-body theory of complex-energy physics

Halos and resonances in molecules and nuclei

Nuclear structure and reactions

Exercises and codes

Theoretical details + codes available from internet

Conclusion

Current status

GSM: structure model including the continuum

Realistic interactions in no-core GSM : A=3-5 unbound nuclear states

Effective interactions with core + valence nucleons : A=10-20 drip-line nuclei

Reaction observables calculated with GSM-CC : fine tuning of Hamiltonian necessary

Structure of the ^{4}He proton-resonance investigated : threshold-aligned resonance

Many-nucleon projectiles : agreement with experimental data satisfactory

Different Hamiltonians for many-nucleon projectiles and target

Book on GSM and GSM-CC published : theory, exercises, GSM codes publicly available

Perspectives

Eigenvector continuation for broad resonances and no-core GSM

Transfer reactions calculated with imaginary potentials to devise theoretically