Probing pairing correlations in nuclei with (*t*,*p*) reactions

Gregory Potel Aguilar

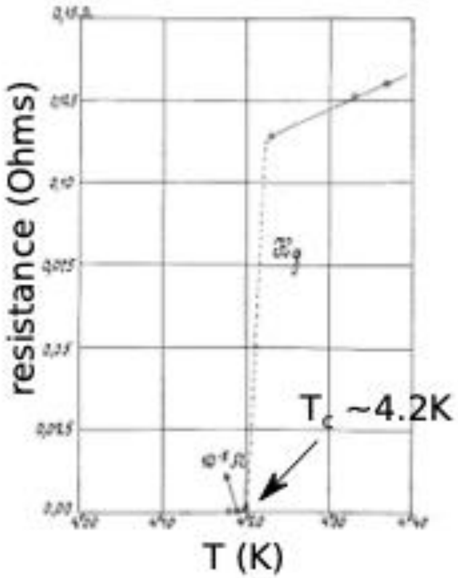
Whistler, August 21 2024

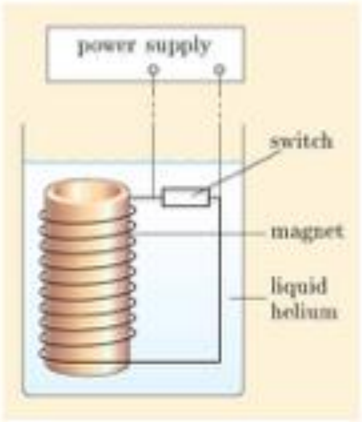
LLNL-PRES-XXXXXX

Lawrence Livermore National Laboratory

Introduction: superconductivity in metals

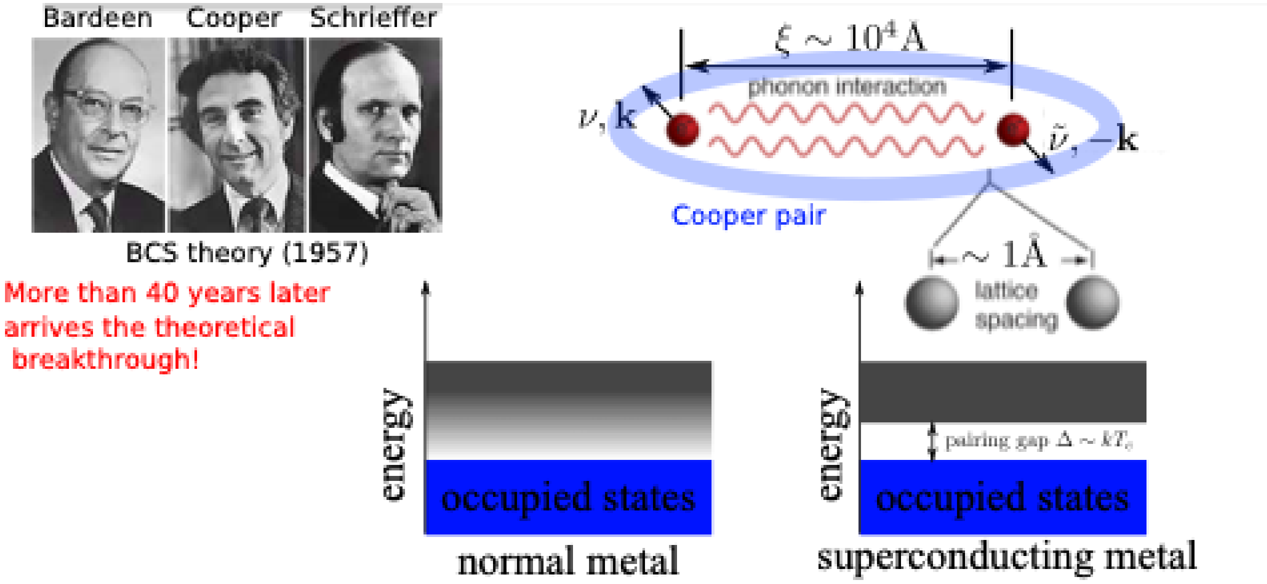
H. Kamerlingh Onnes





- In 1911, H. K. Onnes liquefies Helium and discovers superconductivity in mercury.
- When cooled below a critical temperature (e.g. $T_c = 7.26$ K for lead, $T_c = 3.69$ K for tin), many metals become superconductors.
- Persistent supercurrents can be induced in superconducting coils.

BCS theory and Cooper pairs



BCS theory (1957)

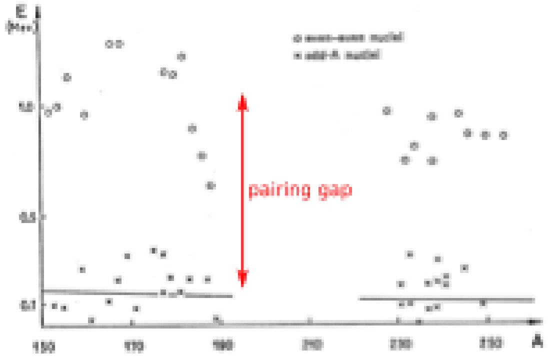
More than 40 years later arrives the theoretical breakthrough!

- Below T_c, electrons form enormous (correlation length $\xi \sim 10^4\text{Å}$) quasi-bosons (Cooper pairs).
- The binding interaction results from the screening of the Coulomb force and the exchange of lattice phonons.
- An energy gap develops in the low-lying spectrum.
- The Cooper pairs form a condensate
  $|BCS\rangle = \prod_\nu \left(U_\nu + V_\nu e^{i\phi} a^\dagger_\nu a^\dagger_{\tilde{\nu}} \right) |0\rangle$

Some experimental evidence of nuclear superfluidity

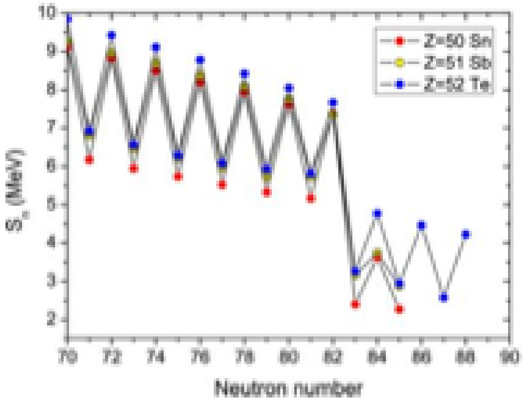
- Gap in the spectrum of even–even nuclei associated with the breaking of a Cooper pair.
- Odd–even mass staggering: enhanced binding for even number of nucleons.
- Enhanced two–nucleon transfer reactions due to the coherence of the Cooper pair wave function.

Bohr, Mottelson and Pines (1958)

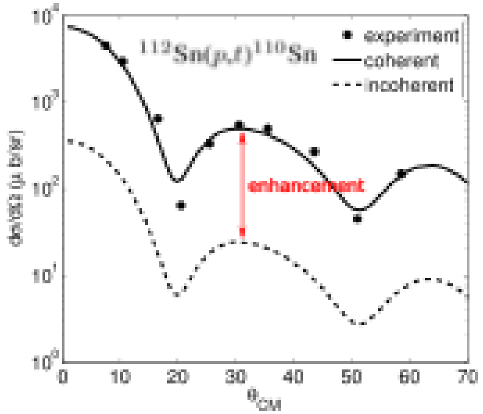


gap in low-lying spectrum

Figure 27 from A Kankainen et al 2012 J. Phys. G: Nucl. Part. Phys. 39 093101

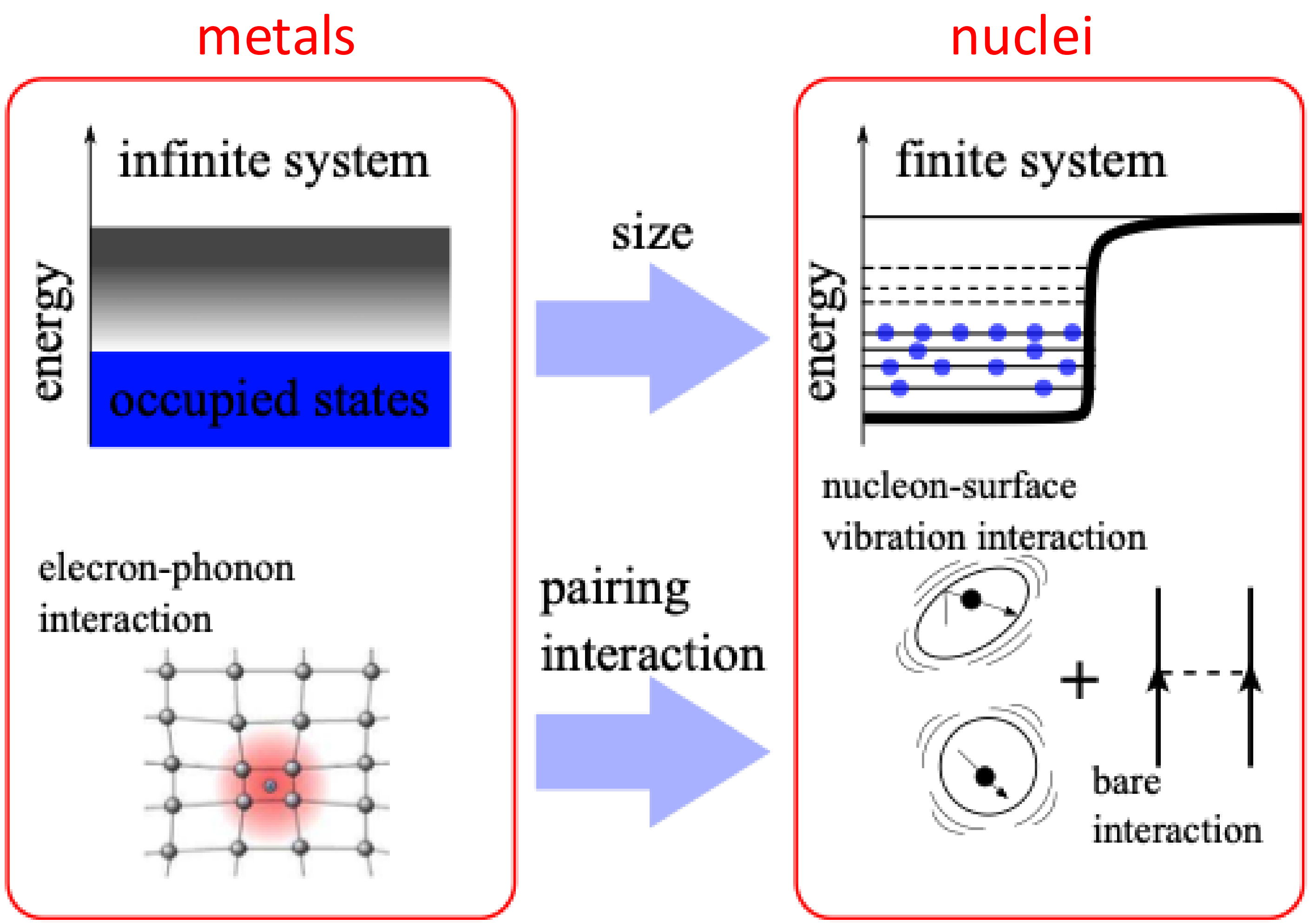


odd-even staggering



enhancement of 2-transfer

But, metals and nuclei are quite different, aren't they?

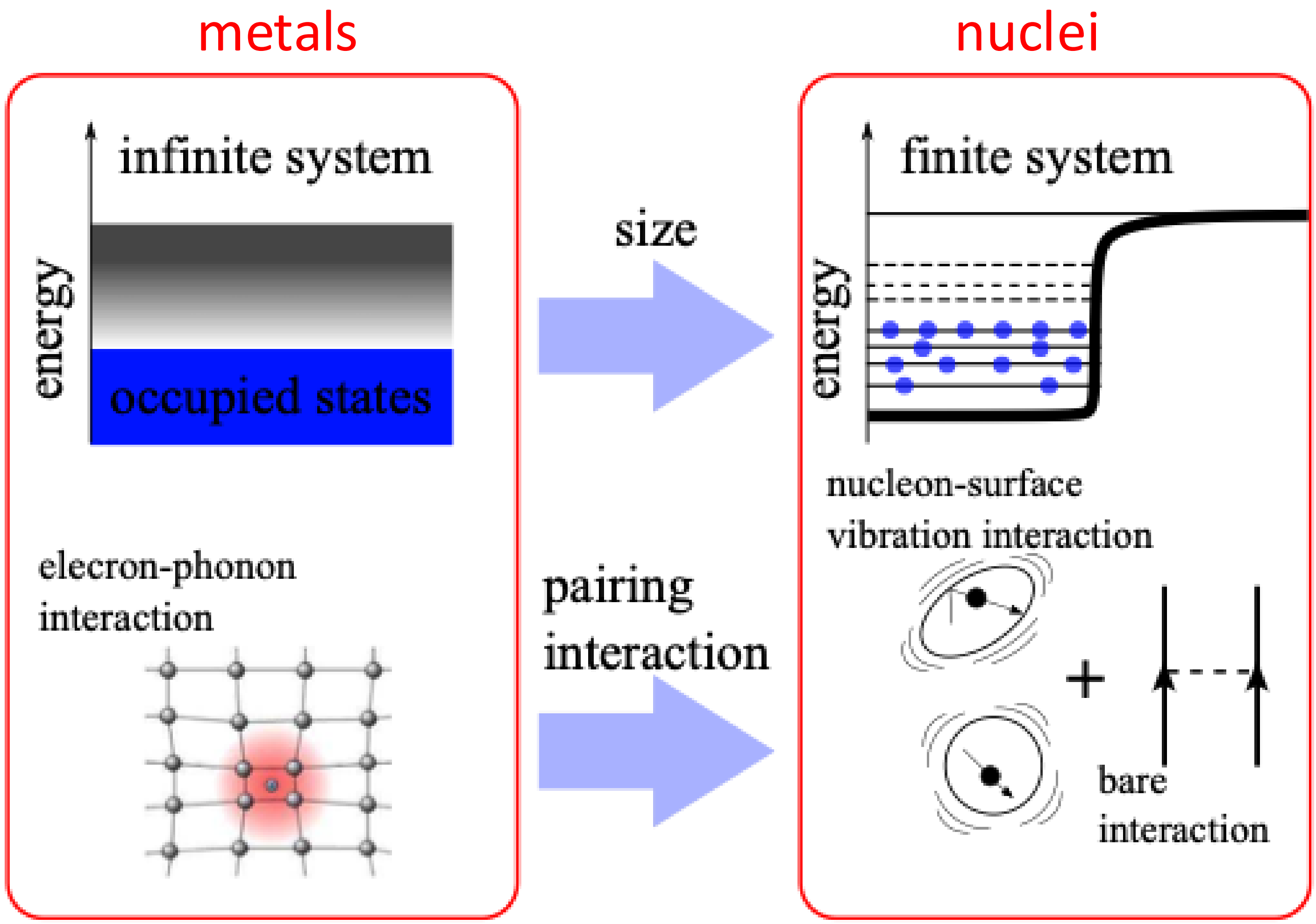

metals

nuclei

questions still arise

- Can we observe Cooper pairs in nuclei?
- How do we make a quantitative assessment of pair correlations in nuclei?
- How do we export our knowledge of nuclear superfluidity to nuclear matter?

But, metals and nuclei are quite different, aren't they?

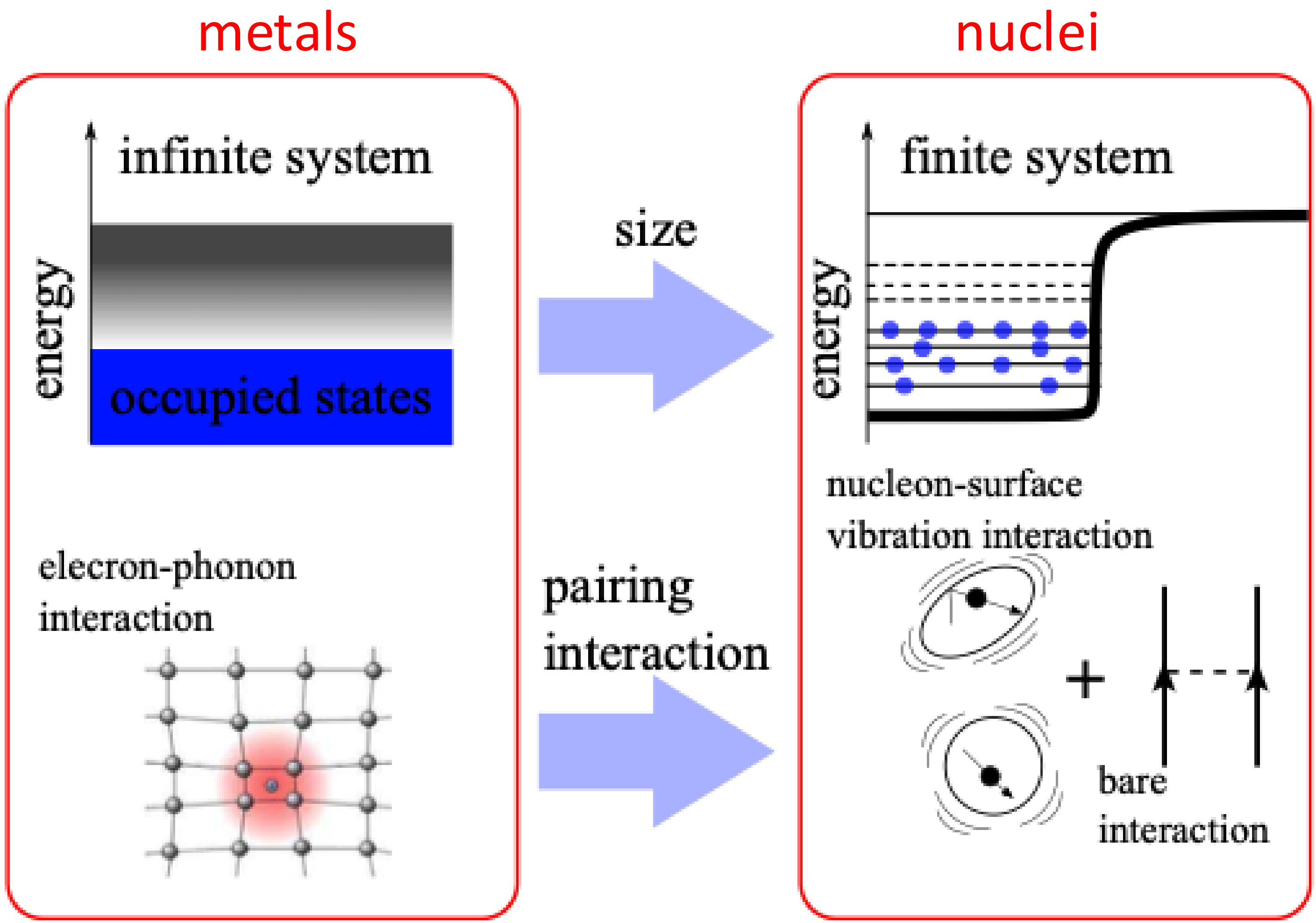


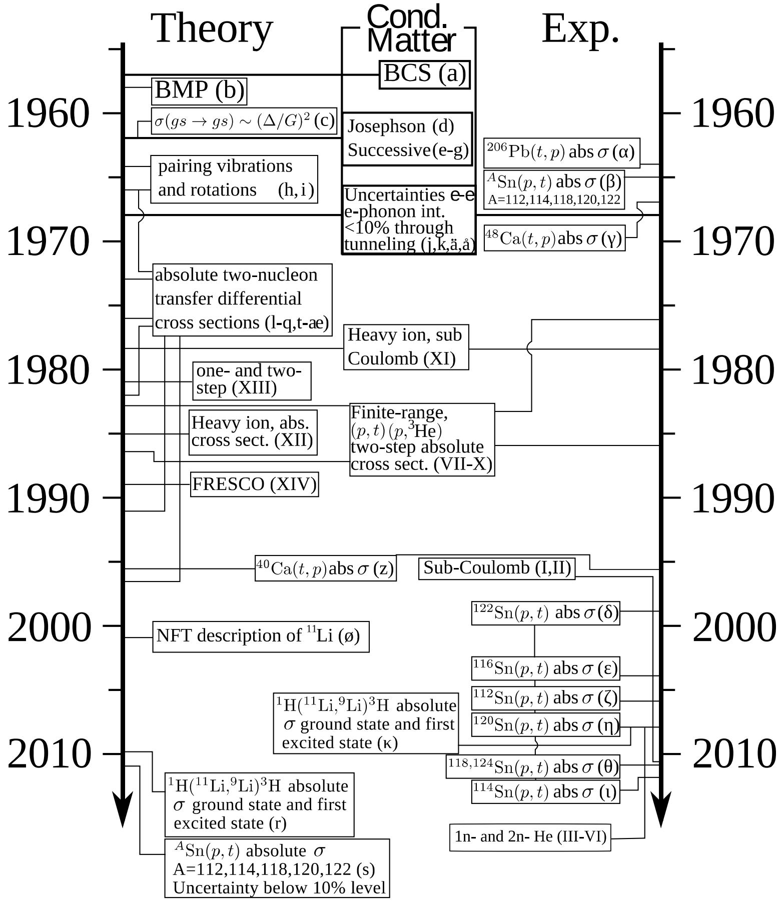
questions still arise

- Can we observe Cooper pairs in nuclei?
- How do we make a quantitative assessment of pair correlations in nuclei?
- How do we export our knowledge of nuclear superfluidity to nuclear matter?

(t,p) reactions are a specific probe of nuclear pairing correlations

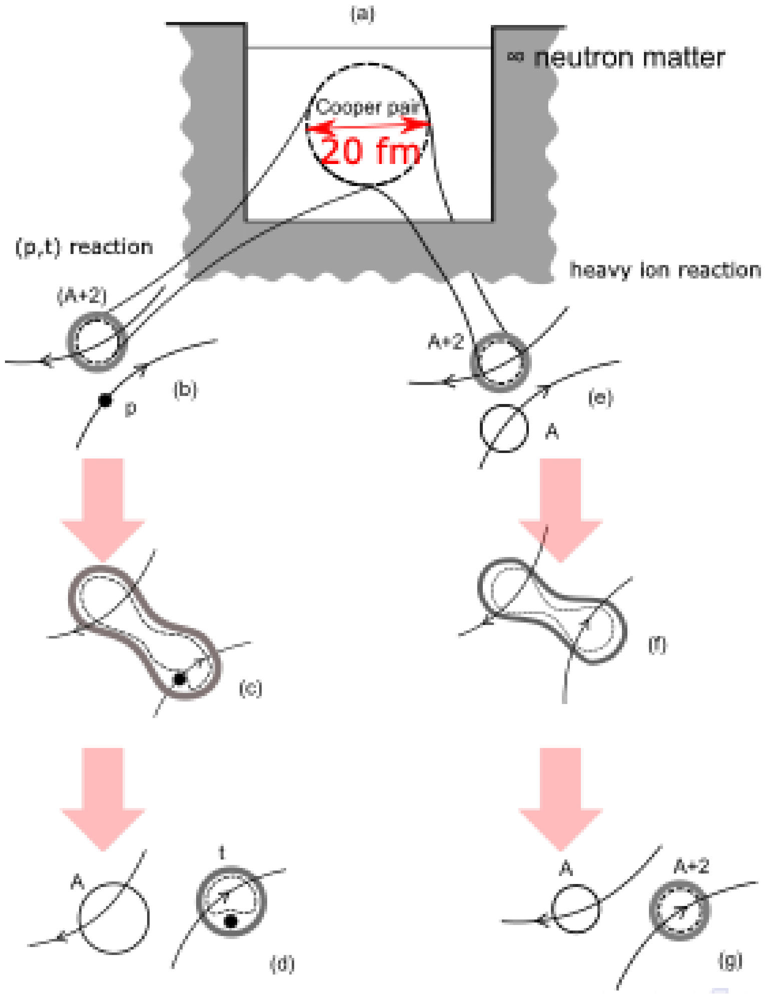
But, metals and nuclei are quite different, aren't they?



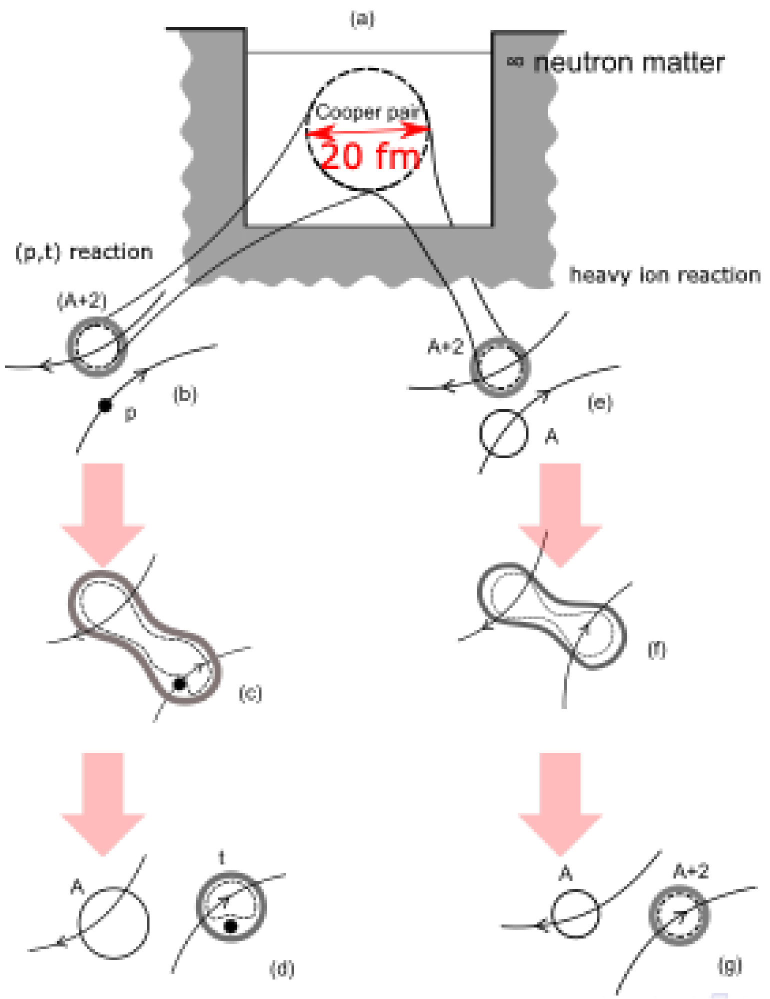


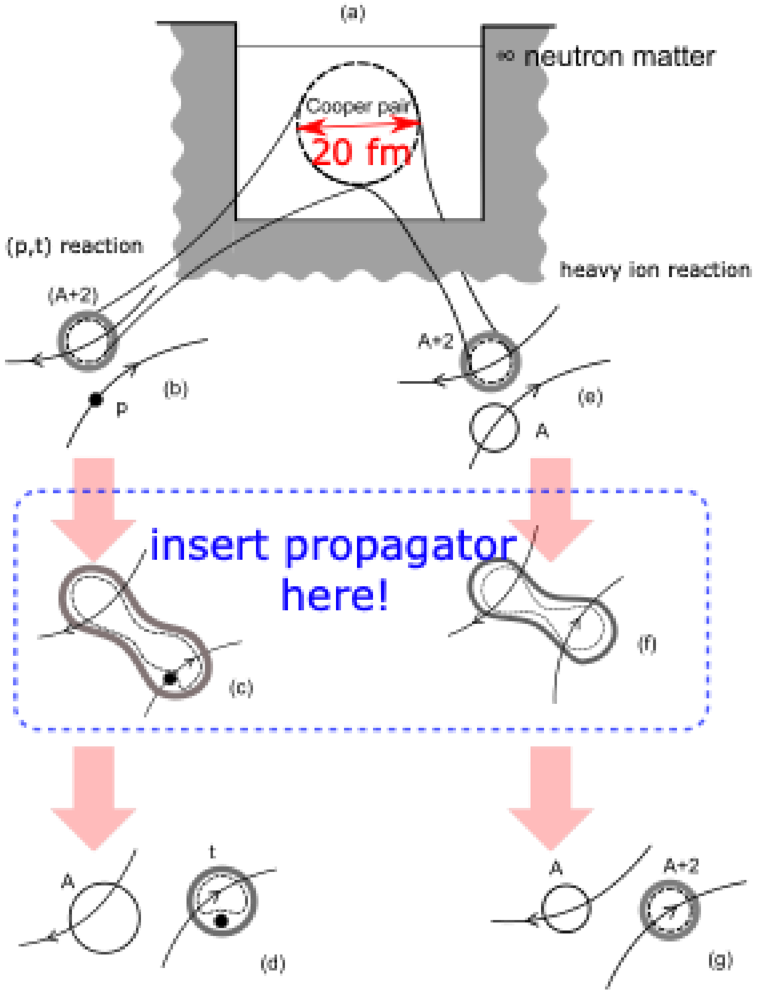
Rep. Prog. Phys. **76** (2013) 106301
GP, Idini, Barranco, Vigezzi, Broglia

The 2 neutron transfer process is very delocalized

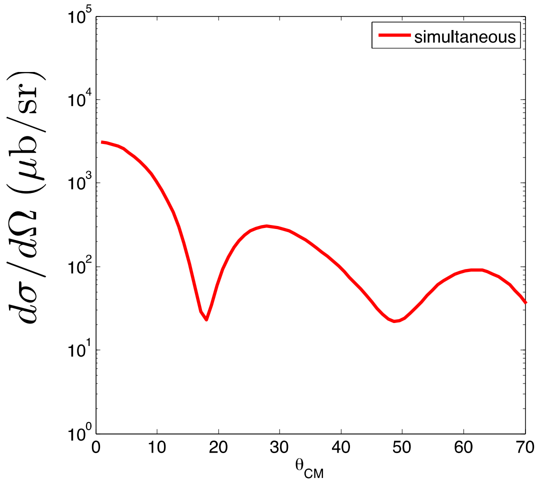


The 2 neutron transfer process is very delocalized

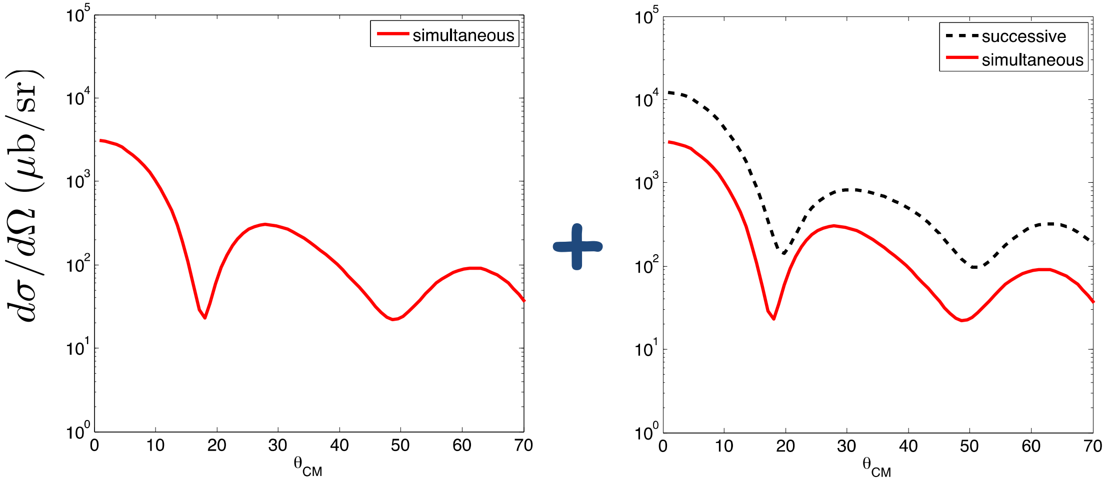




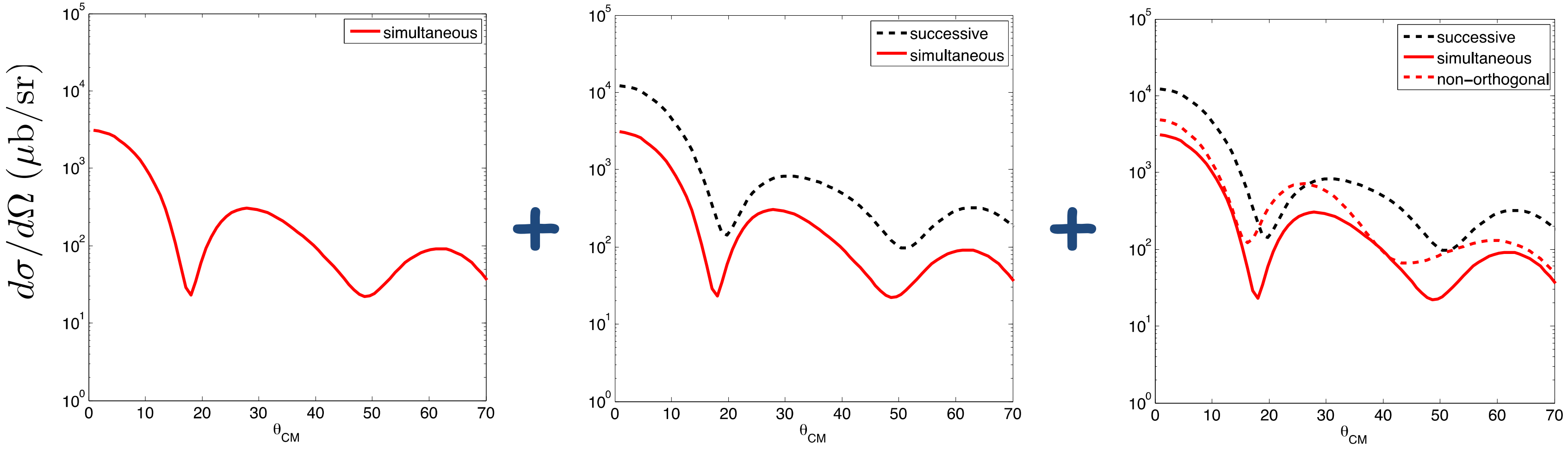
Computing ^{112}Sn(p,t)^{110}Sn in second order DWBA



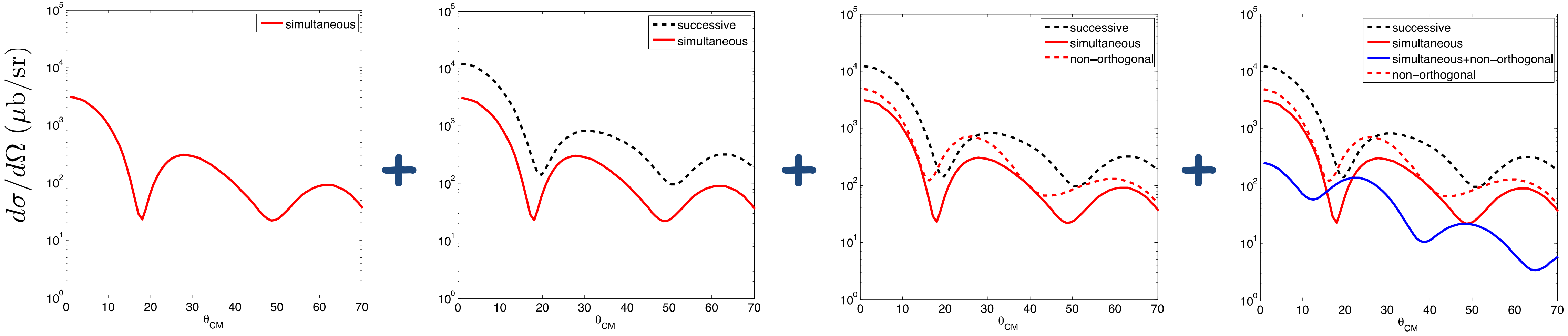
Computing ^{112}Sn(p,t)^{110}Sn in second order DWBA



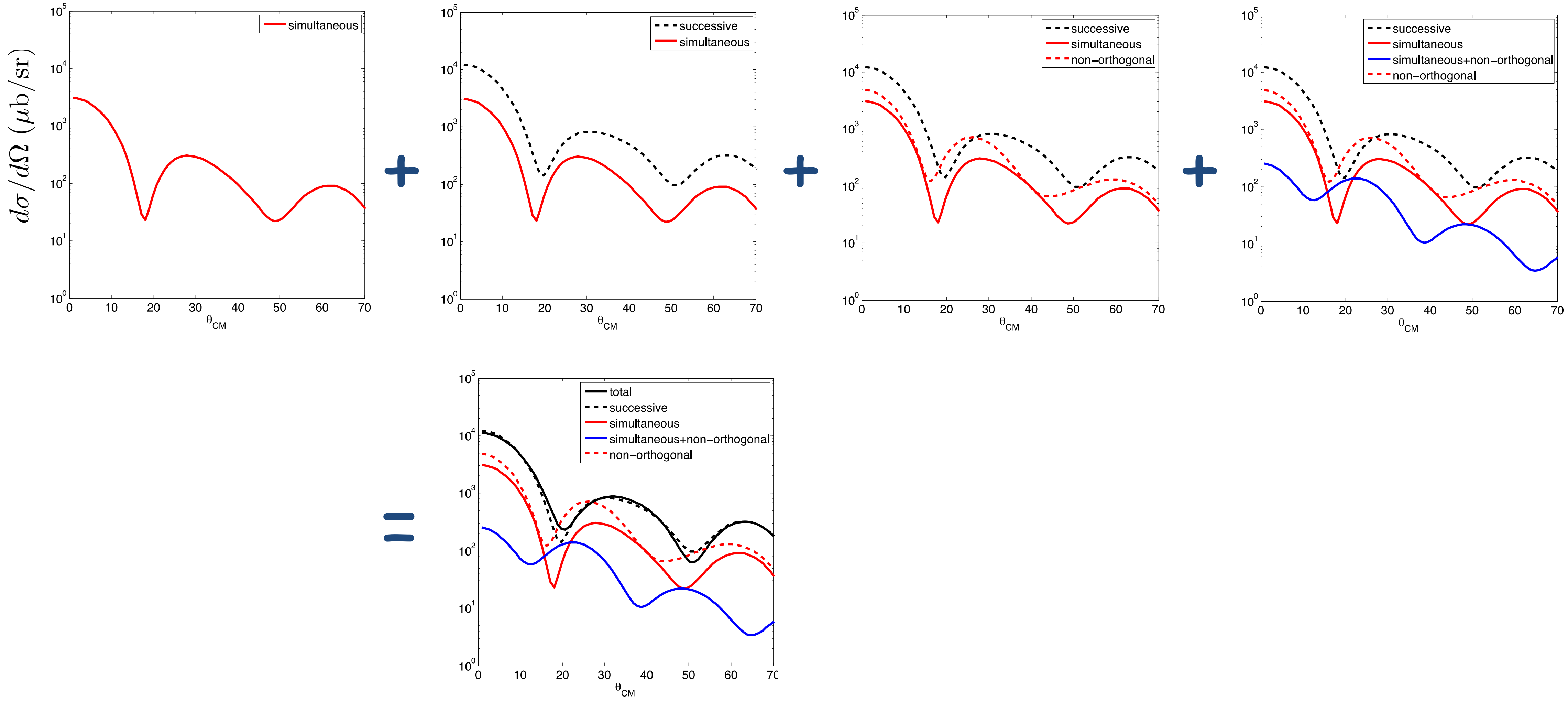
Computing ^{112}Sn(p,t)^{110}Sn in second order DWBA



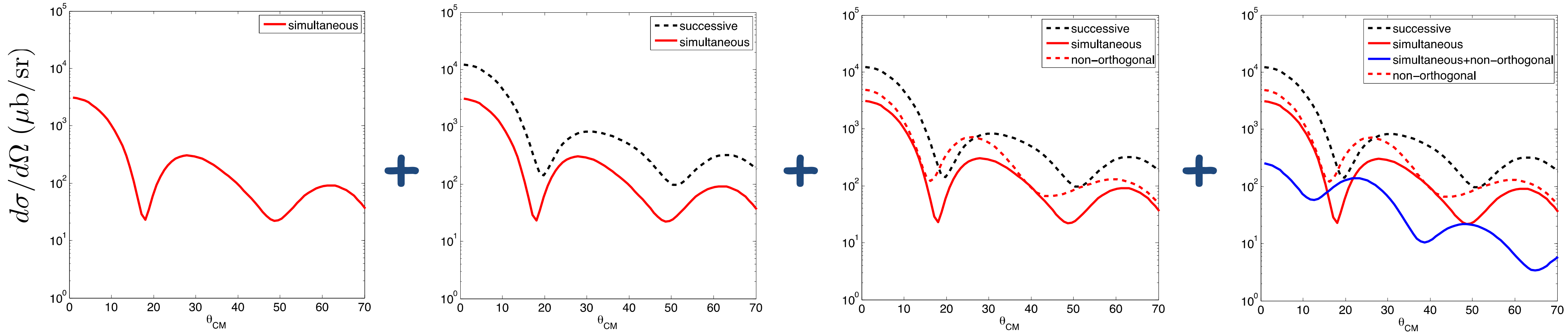
Computing ^{112}Sn(p,t)^{110}Sn in second order DWBA

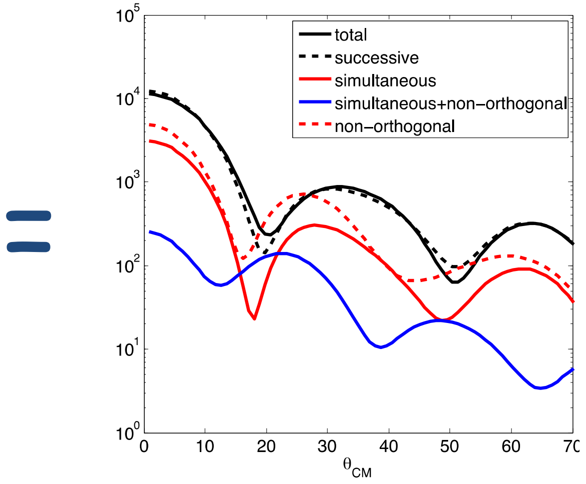


Computing ^{112}Sn(p,t)^{110}Sn in second order DWBA



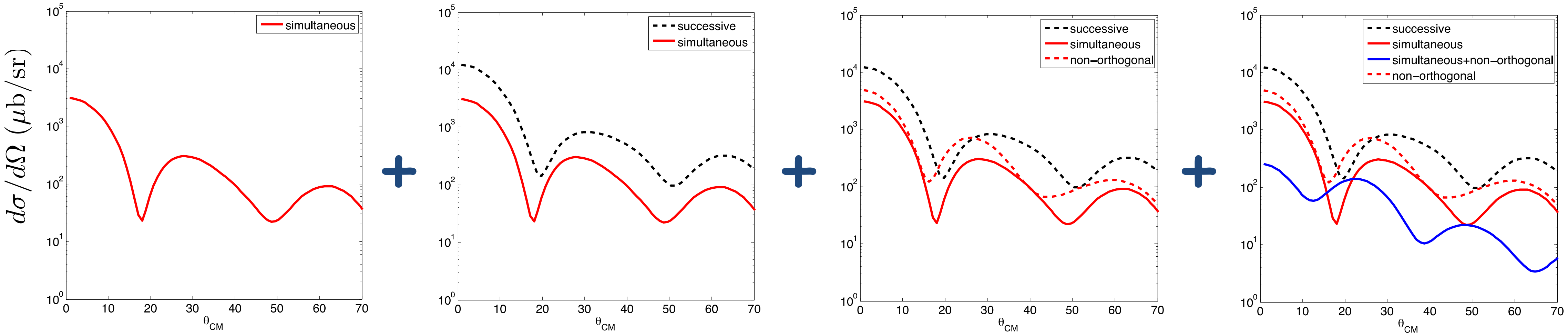
Computing ^{112}Sn(p,t)^{110}Sn in second order DWBA



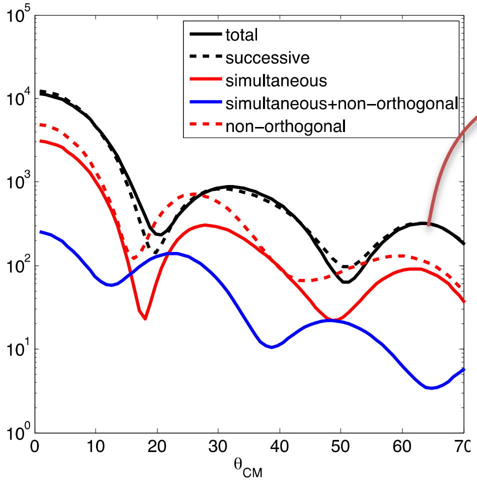


The (t,p) process is essentially a successive transfer of two correlated neutrons

Computing ^{112}Sn(p,t)^{110}Sn in second order DWBA

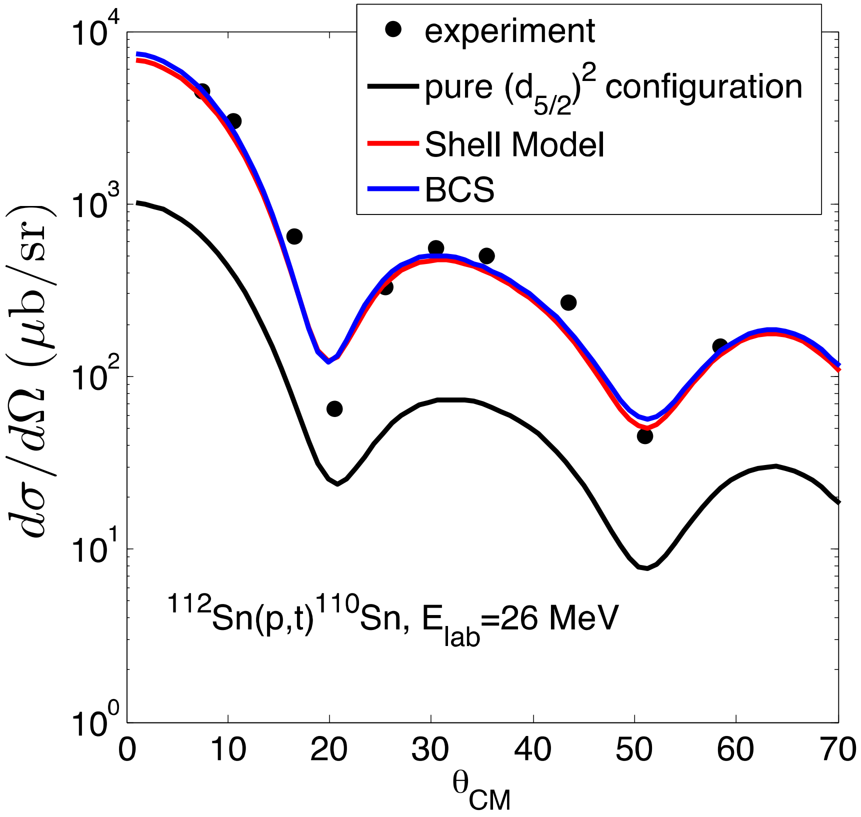


=



The (t,p) process is essentially a successive transfer of two correlated neutrons

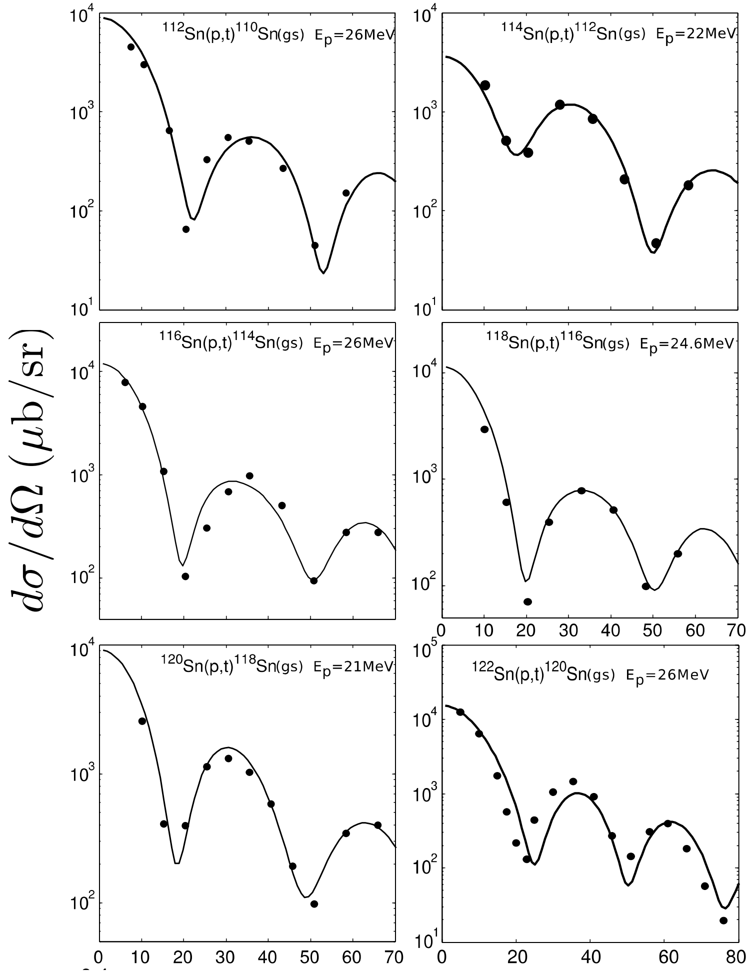
Theory should account for the *absolute value* of the cross section



enhancement factor with respect to the transfer of uncorrelated neutrons: $\varepsilon = 20.6$

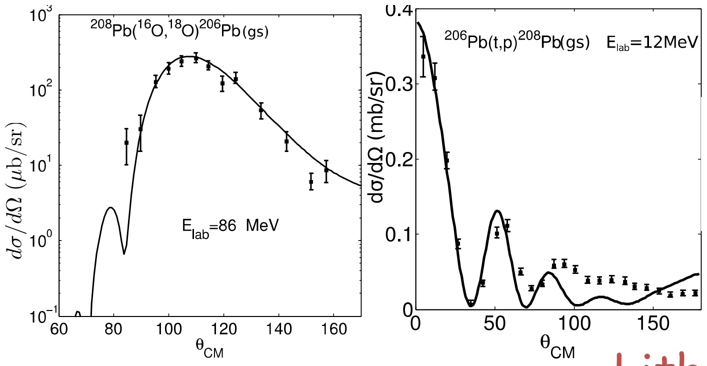
Experimental data and shell model wavefunction from Guazzoni *et al.* PRC **74** 054605 (2006)

Reaction+Structure theory works well across the nuclear chart



Sn isotopes (BCS)

Pb ground state and excited states (QRPA)

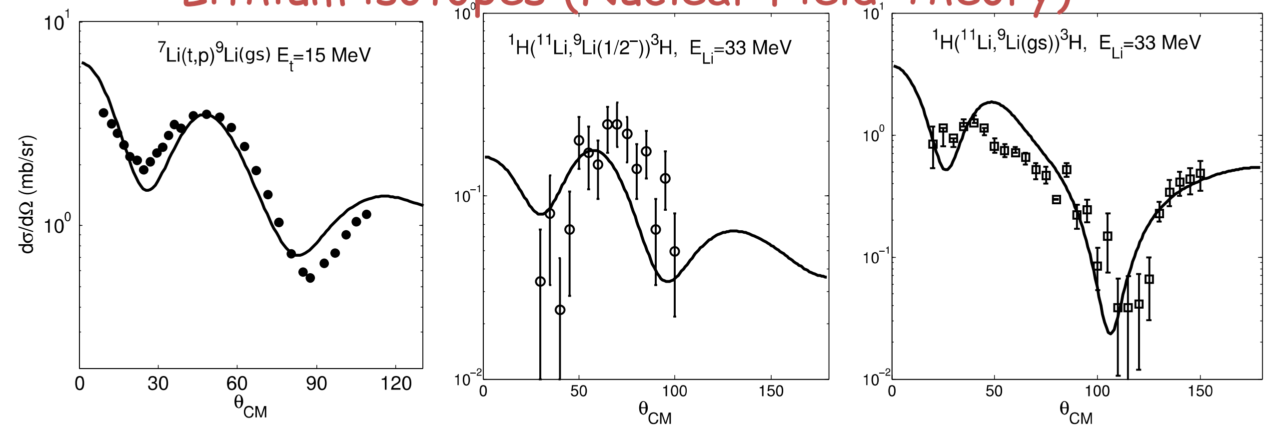


Rep. Prog. Phys. **76** (2013) 106301 (21pp)

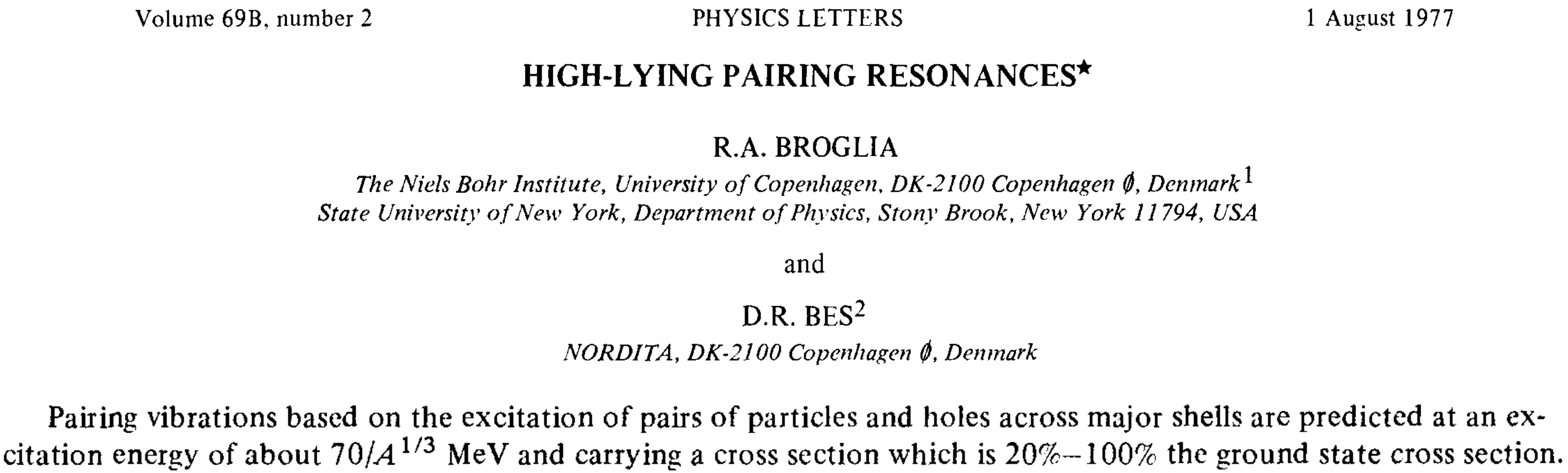
Cooper pair transfer in nuclei

G Potel[1], A Idini[2,3,4], F Barranco[5], E Vigezzi[4] and R A Broglia[3,4,6,7]

Lithium isotopes (Nuclear Field Theory)



Looking for something new in the nuclear spectrum: The Giant Pairing Vibration (GPV)



Volume 69B, number 2 PHYSICS LETTERS 1 August 1977

HIGH-LYING PAIRING RESONANCES*

R.A. BROGLIA
The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen Ø, Denmark[1]
State University of New York, Department of Physics, Stony Brook, New York 11794, USA

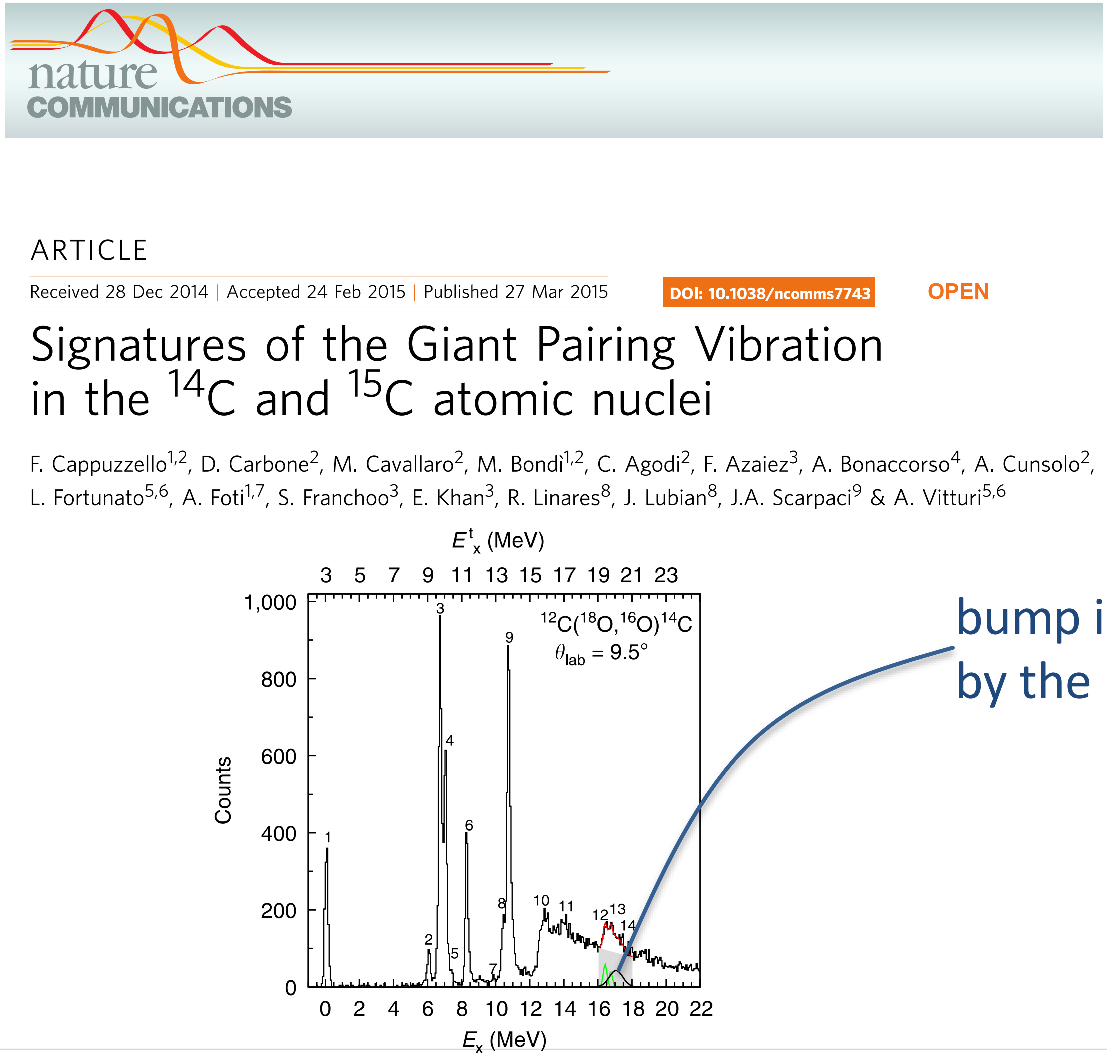
and

D.R. BES[2]
NORDITA, DK-2100 Copenhagen Ø, Denmark

Pairing vibrations based on the excitation of pairs of particles and holes across major shells are predicted at an excitation energy of about $70/A^{1/3}$ MeV and carrying a cross section which is 20%–100% the ground state cross section.

Collective pairing mode predicted almost 50 years ago, awaiting experimental confirmation?

(t,p) is an ideal process to populate the elusive Giant Pairing Vibration



nature COMMUNICATIONS

ARTICLE

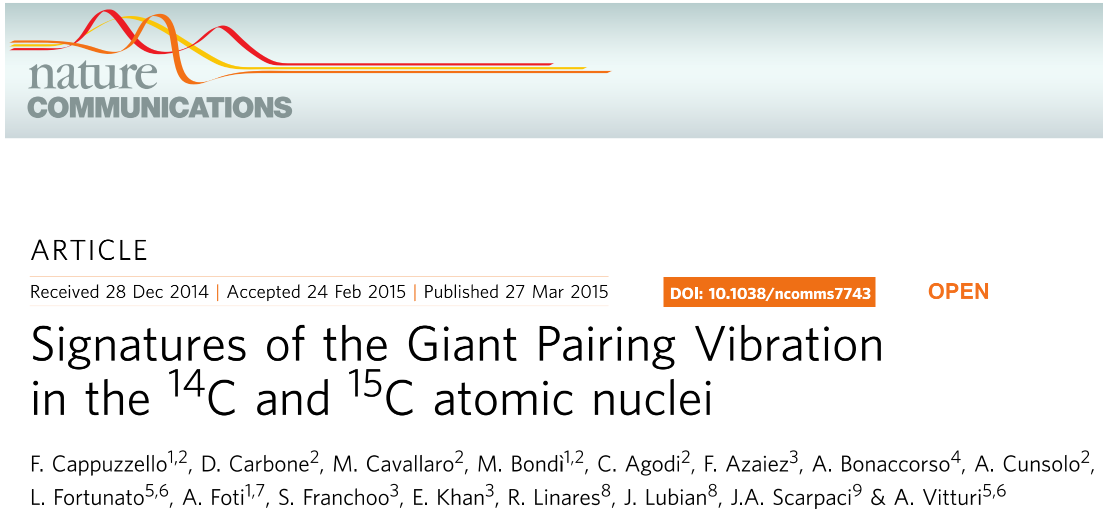
Received 28 Dec 2014 | Accepted 24 Feb 2015 | Published 27 Mar 2015 DOI: 10.1038/ncomms7743 OPEN

Signatures of the Giant Pairing Vibration in the ^{14}C and ^{15}C atomic nuclei

F. Cappuzzello[1,2], D. Carbone[2], M. Cavallaro[2], M. Bondi[1,2], C. Agodi[2], F. Azaiez[3], A. Bonaccorso[4], A. Cunsolo[2], L. Fortunato[5,6], A. Foti[1,7], S. Franchoo[3], E. Khan[3], R. Linares[8], J. Lubian[8], J.A. Scarpaci[9] & A. Vitturi[5,6]

bump in the continuum populated by the reaction $^{12}C(^{18}O,^{16}O)^{14}C$

(t,p) is an ideal process to populate the elusive Giant Pairing Vibration



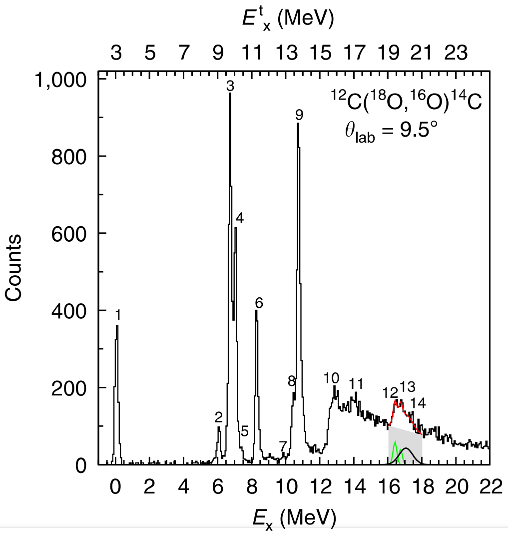
nature COMMUNICATIONS

ARTICLE

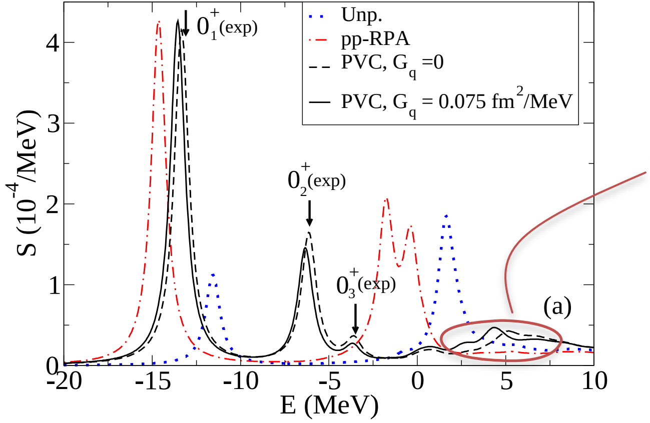
Received 28 Dec 2014 | Accepted 24 Feb 2015 | Published 27 Mar 2015 DOI: 10.1038/ncomms7743 OPEN

Signatures of the Giant Pairing Vibration in the ^{14}C and ^{15}C atomic nuclei

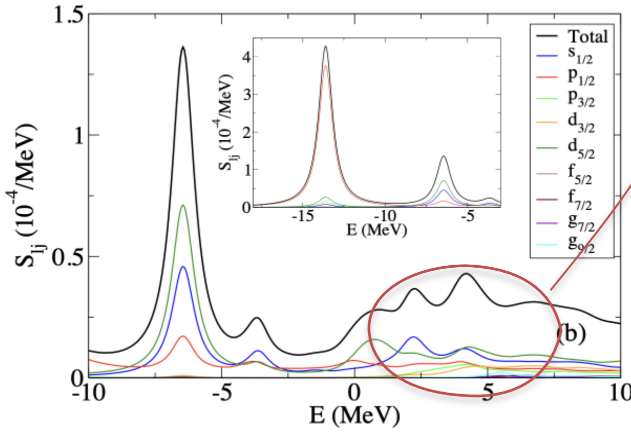
F. Cappuzzello[1,2], D. Carbone[2], M. Cavallaro[2], M. Bondi[1,2], C. Agodi[2], F. Azaiez[3], A. Bonaccorso[4], A. Cunsolo[2], L. Fortunato[5,6], A. Foti[1,7], S. Franchoo[3], E. Khan[3], R. Linares[8], J. Lubian[8], J.A. Scarpaci[9] & A. Vitturi[5,6]



monopole strength in ^{14}C



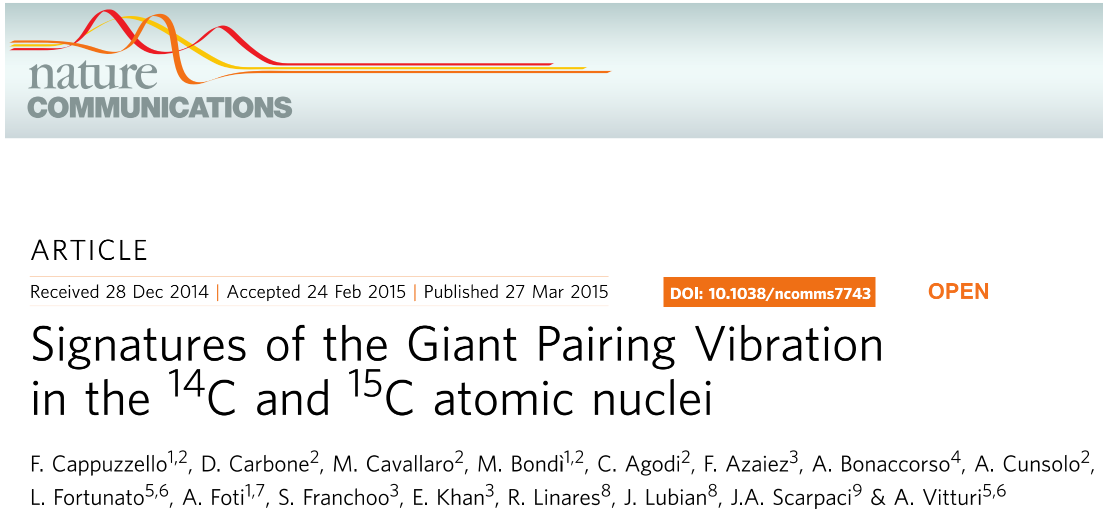
we predict a rather broad structure in the continuum



Fragmentation of the Giant Pairing Vibration in ^{14}C induced by many-body processes

F. Barranco,[1] G. Potel,[2] and E. Vigezzi[3]

(t,p) is an ideal process to populate the elusive Giant Pairing Vibration

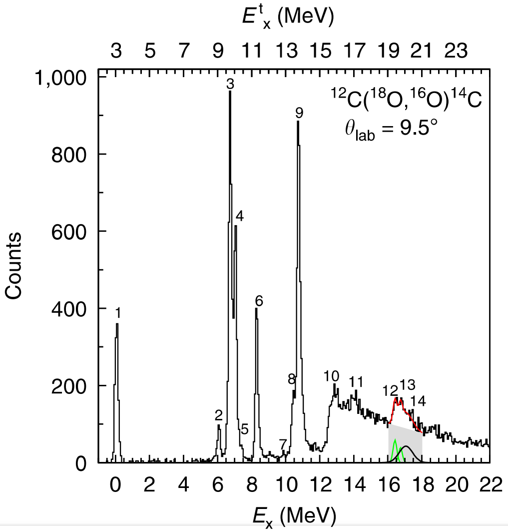


ARTICLE

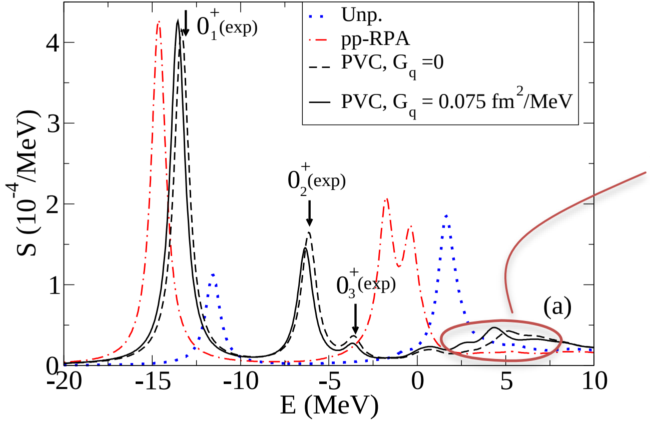
Received 28 Dec 2014 | Accepted 24 Feb 2015 | Published 27 Mar 2015 DOI: 10.1038/ncomms7743 OPEN

Signatures of the Giant Pairing Vibration in the ^{14}C and ^{15}C atomic nuclei

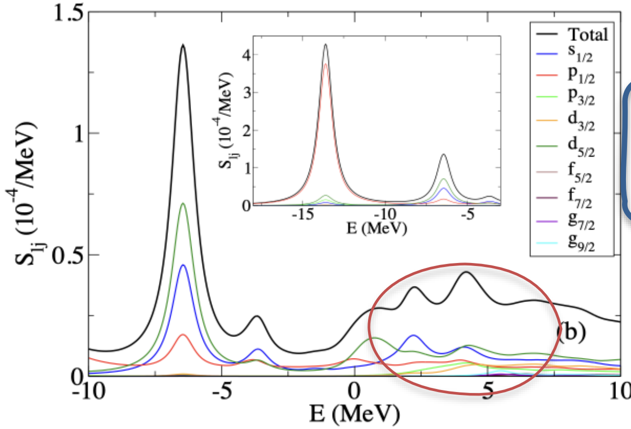
F. Cappuzzello[1,2], D. Carbone[2], M. Cavallaro[2], M. Bondì[1,2], C. Agodi[2], F. Azaiez[3], A. Bonaccorso[4], A. Cunsolo[2], L. Fortunato[5,6], A. Foti[1,7], S. Franchoo[3], E. Khan[3], R. Linares[8], J. Lubian[8], J.A. Scarpaci[9] & A. Vitturi[5,6]



monopole strength in ^{14}C



we predict a rather broad structure in the continuum



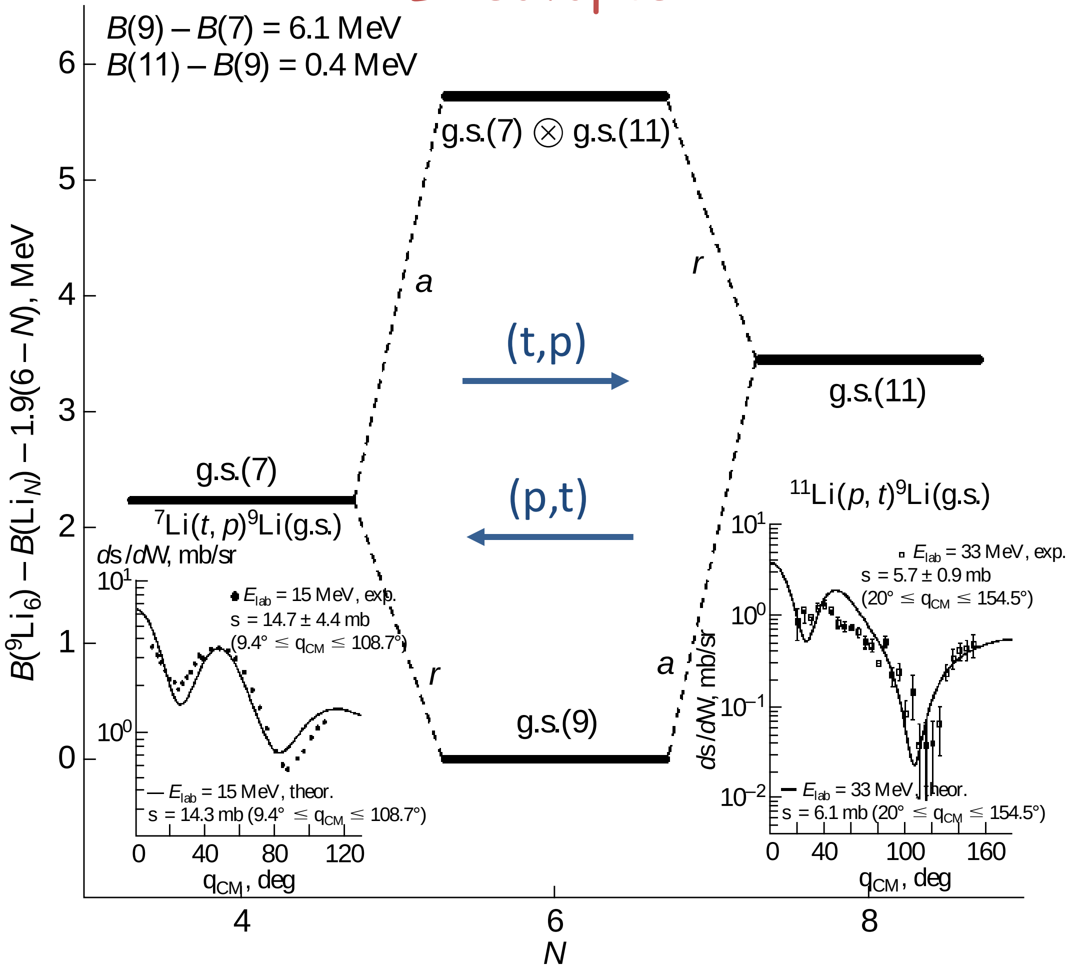
working on a theoretical estimate of ^{12}C(t,p)^{14}C(GPV)

Fragmentation of the Giant Pairing Vibration in ^{14}C induced by many-body processes

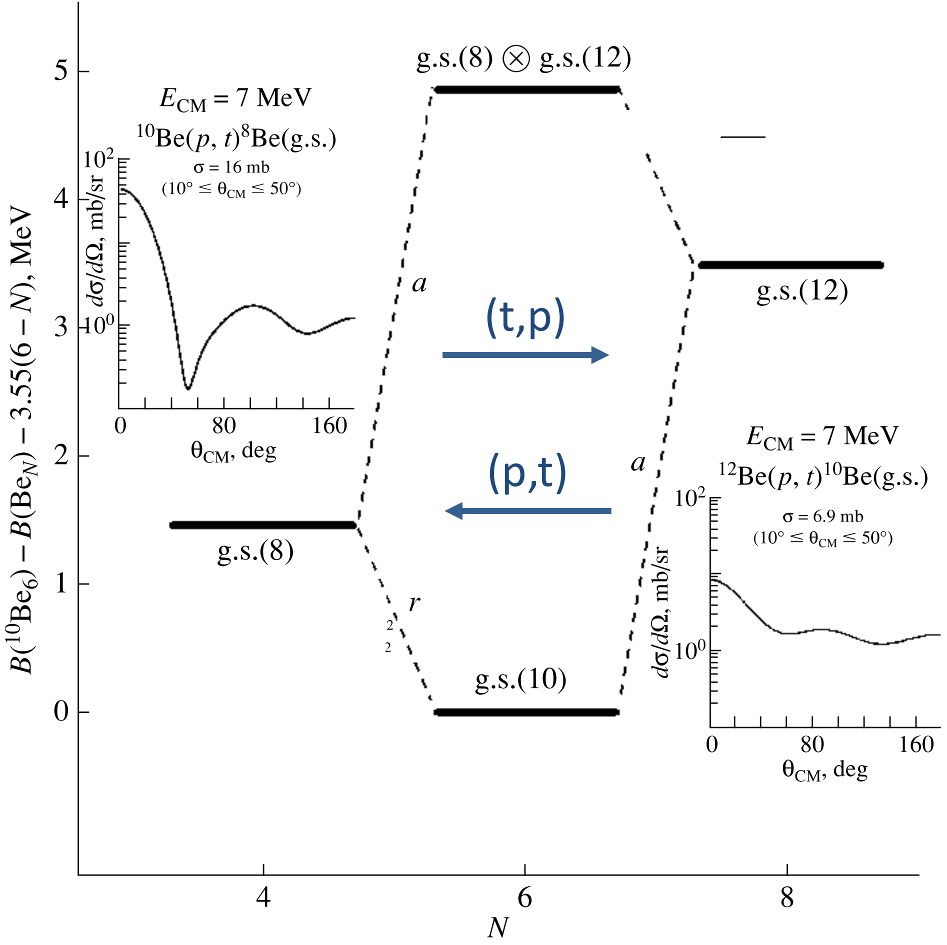
F. Barranco,[1] G. Potel,[2] and E. Vigezzi[3]

Excited halo state in ^{12}Be (0^+_2)

Li isotopes

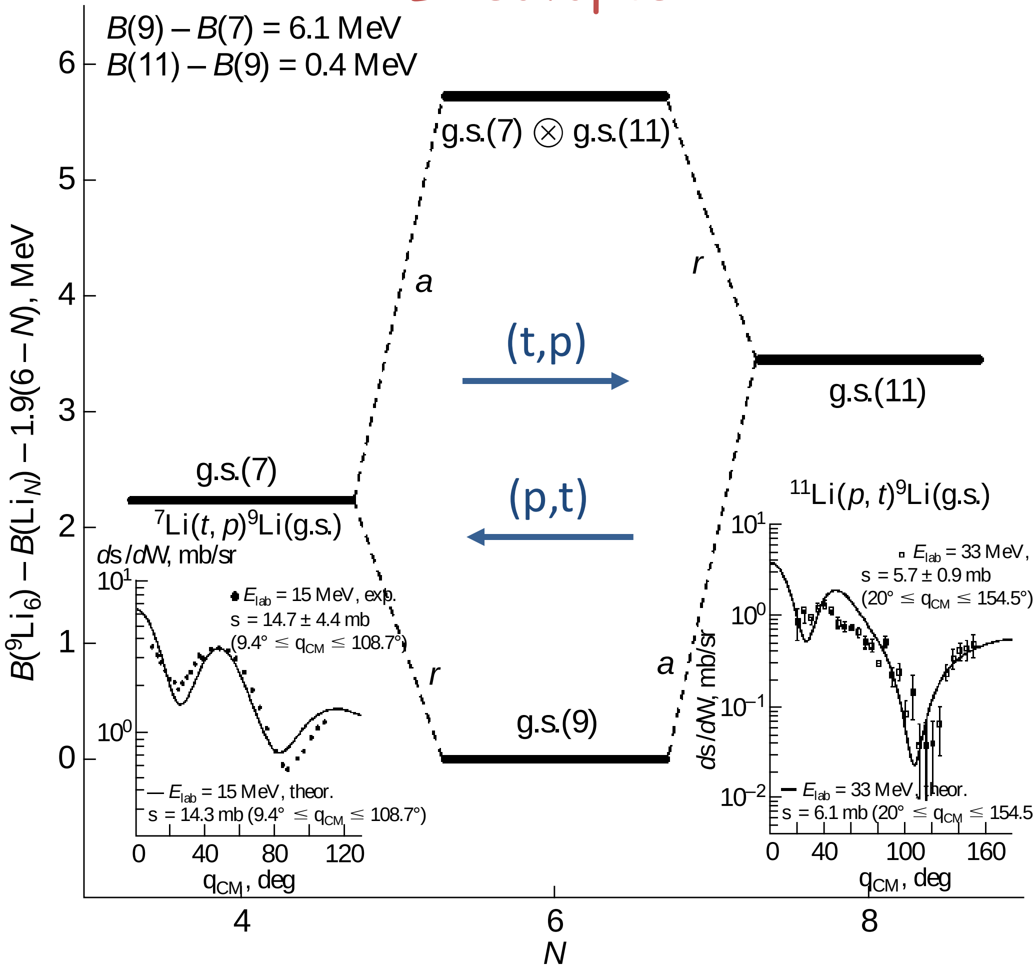


Be isotopes

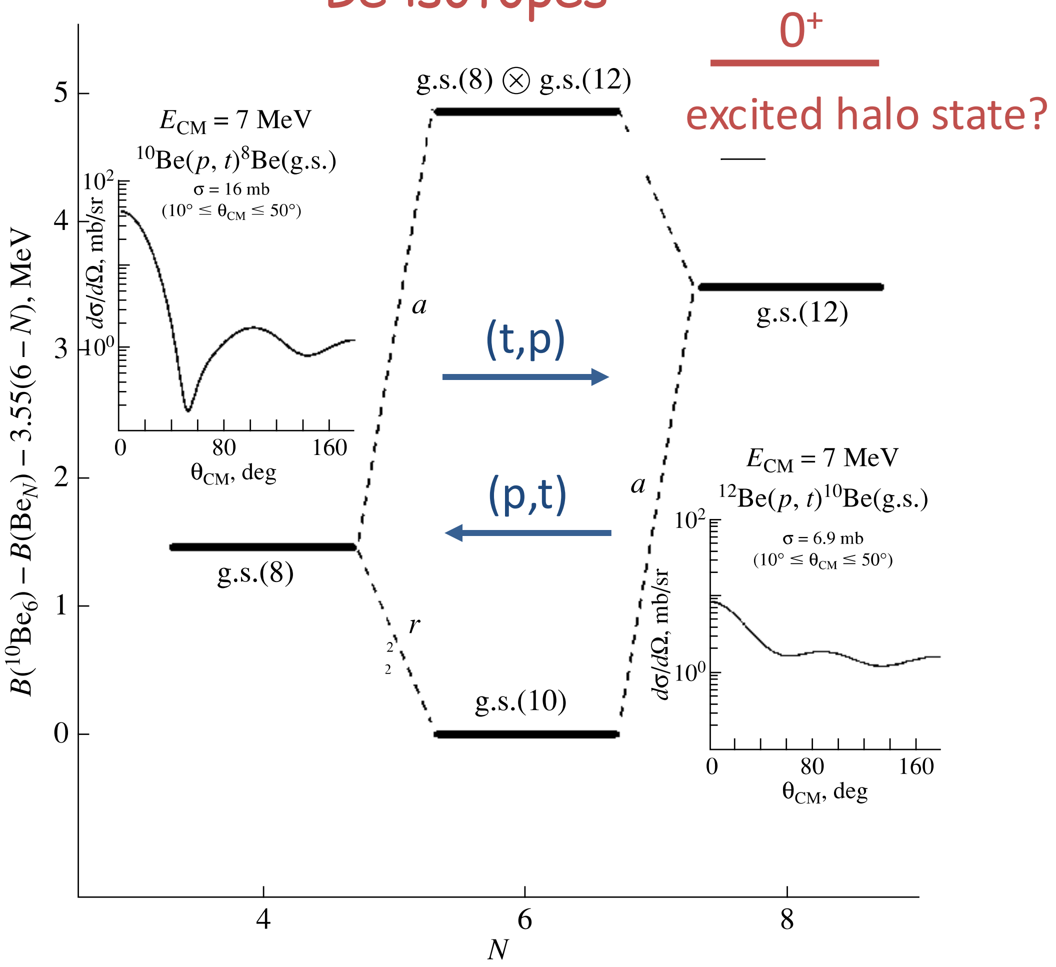


Excited halo state in ^{12}Be (0^+_2)

Li isotopes



Be isotopes



The Pygmy Dipole Resonance (PDR) as a two-quasiparticle mode

- The PDR is rather well described in the harmonic approximation (RPA, QRPA) as a two-quasiparticle mode.
- Therefore, PDR in a nucleus A_0 can be better probed with two-quasiparticle fields, i.e., particle-hole (*ph*), particle-particle (*pp*), and hole-hole (*hh*) fields.

ph

Coulomb, inelastic, and γ-induced excitation on A_0:

- A_0(d,d')A_0(PDR)
- A_0(p,p') A_0(PDR)
- $A_0(\alpha,\alpha')$ A_0(PDR)
- $A_0(\gamma,\gamma')$ A_0(PDR)
- A_0(n,n') A_0(PDR)
- A_0(X,X') A_0(PDR)

one-nucleon transfer on A_0-1:

- A_0-1(d,p) A_0(PDR)

Spieker et al., PRL (2020)

Weinert et al., PRL (2021)

pp

two-nucleon transfer on A_0-2:

- A_0-2(t,p) A_0(PDR)

proposed
in this talk

The Pygmy Dipole Resonance (PDR) as a two-quasiparticle mode

- The PDR is rather well described in the harmonic approximation (RPA, QRPA) as a two-quasiparticle mode.
- Therefore, PDR in a nucleus A_0 can be better probed with two-quasiparticle fields, i.e., particle-hole (*ph*), particle-particle (*pp*), and hole-hole (*hh*) fields.

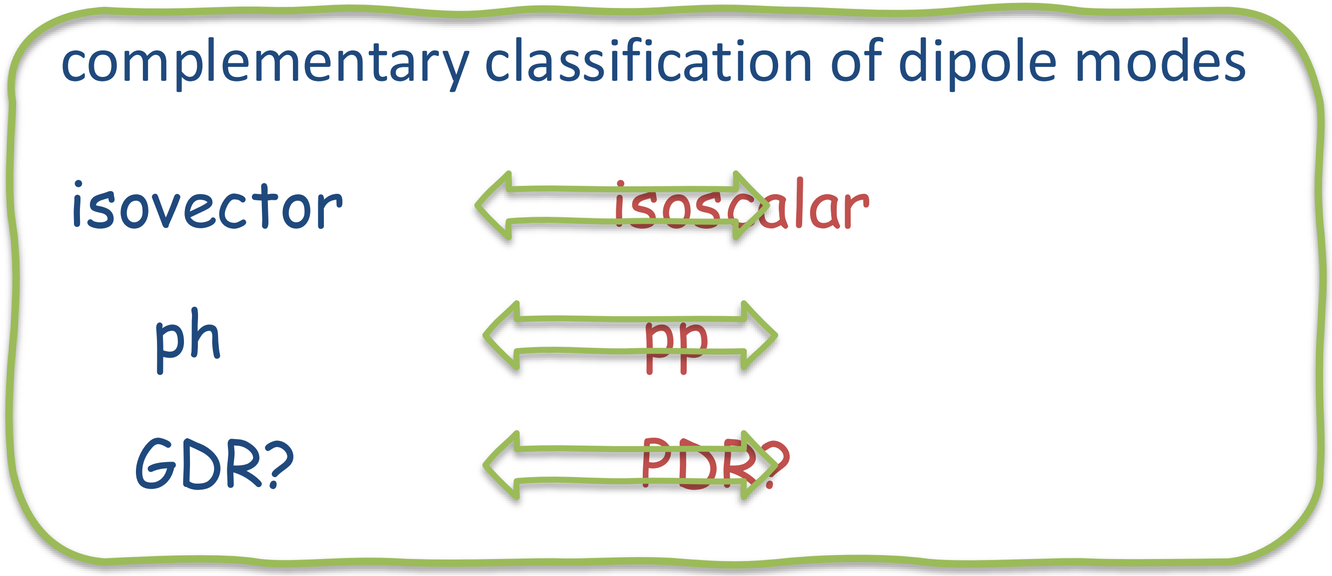
complementary classification of dipole modes

isovector ⟺ isoscalar

ph ⟺ pp

The Pygmy Dipole Resonance (PDR) as a two-quasiparticle mode

- The PDR is rather well described in the harmonic approximation (RPA, QRPA) as a two-quasiparticle mode.
- Therefore, PDR in a nucleus A_0 can be better probed with two-quasiparticle fields, i.e., particle-hole (*ph*), particle-particle (*pp*), and hole-hole (*hh*) fields.



complementary classification of dipole modes

isovector ↔ isoscalar

ph ↔ pp

GDR? ↔ PDR?

Probing the ^{11}Li PDR with 2-neutron transfer

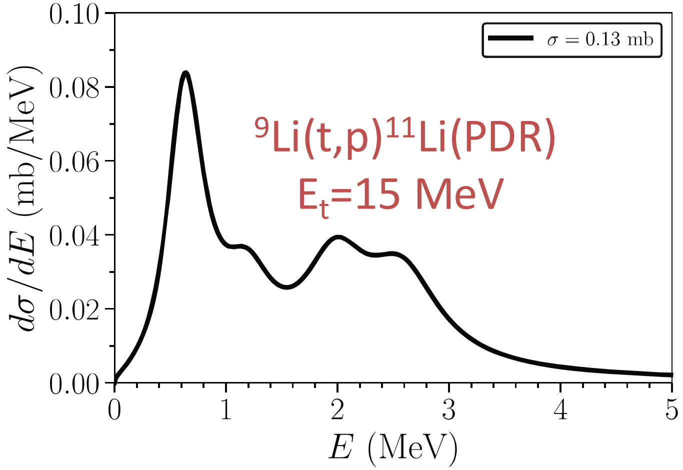
Eur. Phys. J. A (2019) **55**: 243
DOI 10.1140/epja/i2019-12789-y

THE EUROPEAN PHYSICAL JOURNAL A

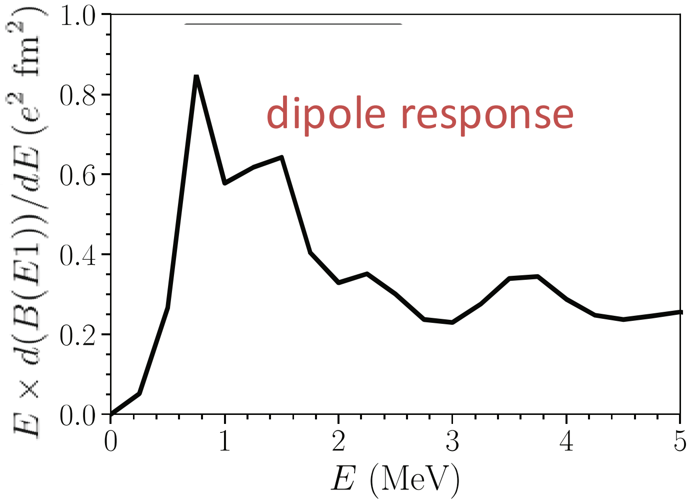
Regular Article – Theoretical Physics

Characterization of vorticity in pygmy resonances and soft-dipole modes with two-nucleon transfer reactions*

R.A. Broglia[1,2], F. Barranco[3], G. Potel[4,a], and E. Vigezzi[5]



^{9}Li(t,p)^{11}Li(PDR)
E_t=15 MeV



dipole response

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Probing the ^{11}Li low-lying dipole strength via ^{9}Li(t,p) with the ISS

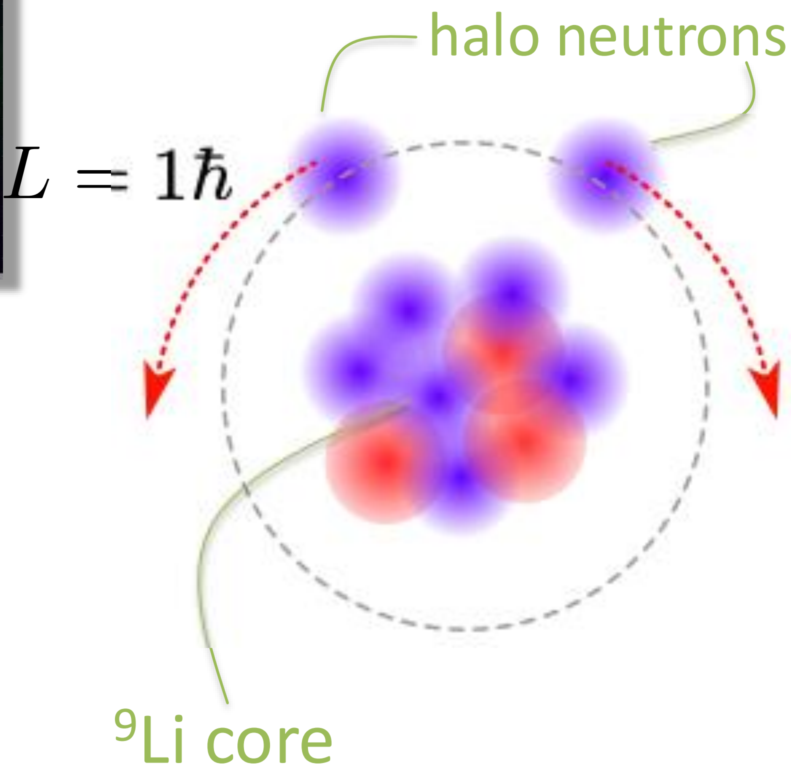
Y. Ayyad[1], E. Vigezzi[2], G. Potel[3], R. Broglia[4,5], B.P. Kay[6],
A.O. Macchiavelli[7],H. Alvarez-Pol[8], F. Barranco[9], D. Bazin[1,10], M. Caamaño[8],
A. Ceulemans[11], J. Chen[1], H.L. Crawford[7], B. Fernández-Domínguez[8], S.J. Freeman[12],
L.P. Gaffney[13], C.R. Hoffman[6], R. Kanungo[14], C. Morse[7], O .Poleshchuk[11], R. Raabe[11],
C.A. Santamaria[7], D.K. Sharp[12], T. L. Tang[6], K .Wimmer[15], A.H. Wuosmaa[16]

experiment approved at ISOLDE facility (CERN). Spokepersons: Ayyad, Vigezzi

the ^{11}Li PDR has the structure of an elementary quantum vortex

structure of a multipolar (1^{-}) Cooper pair:

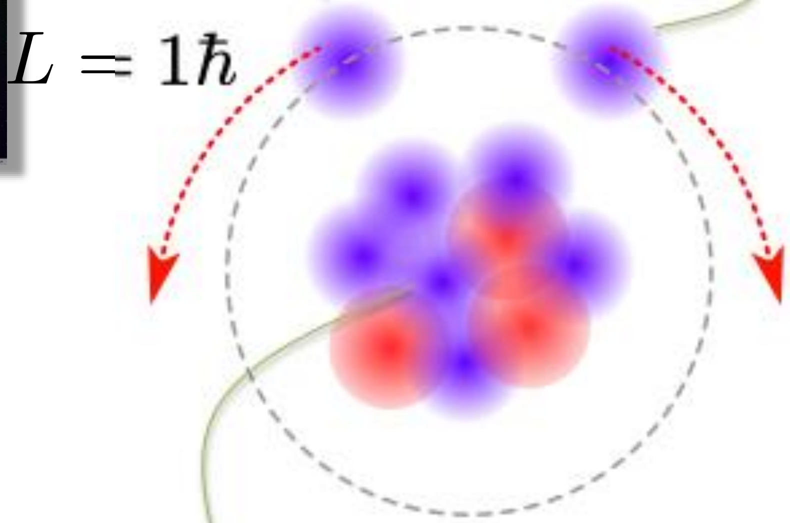
elementary quantum vortex



the ^{11}Li PDR has the structure of an elementary quantum vortex

structure of a multipolar (1$^-$) Cooper pair:

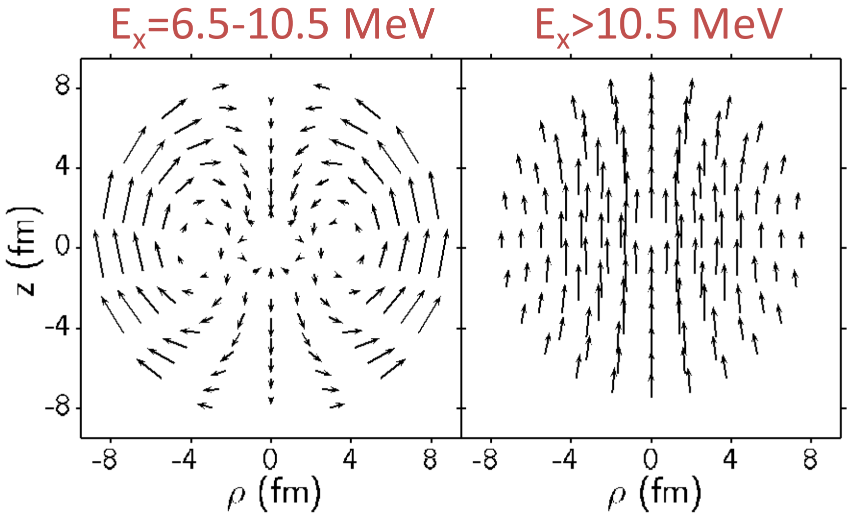
elementary quantum vortex



halo neutrons

^{9}Li core

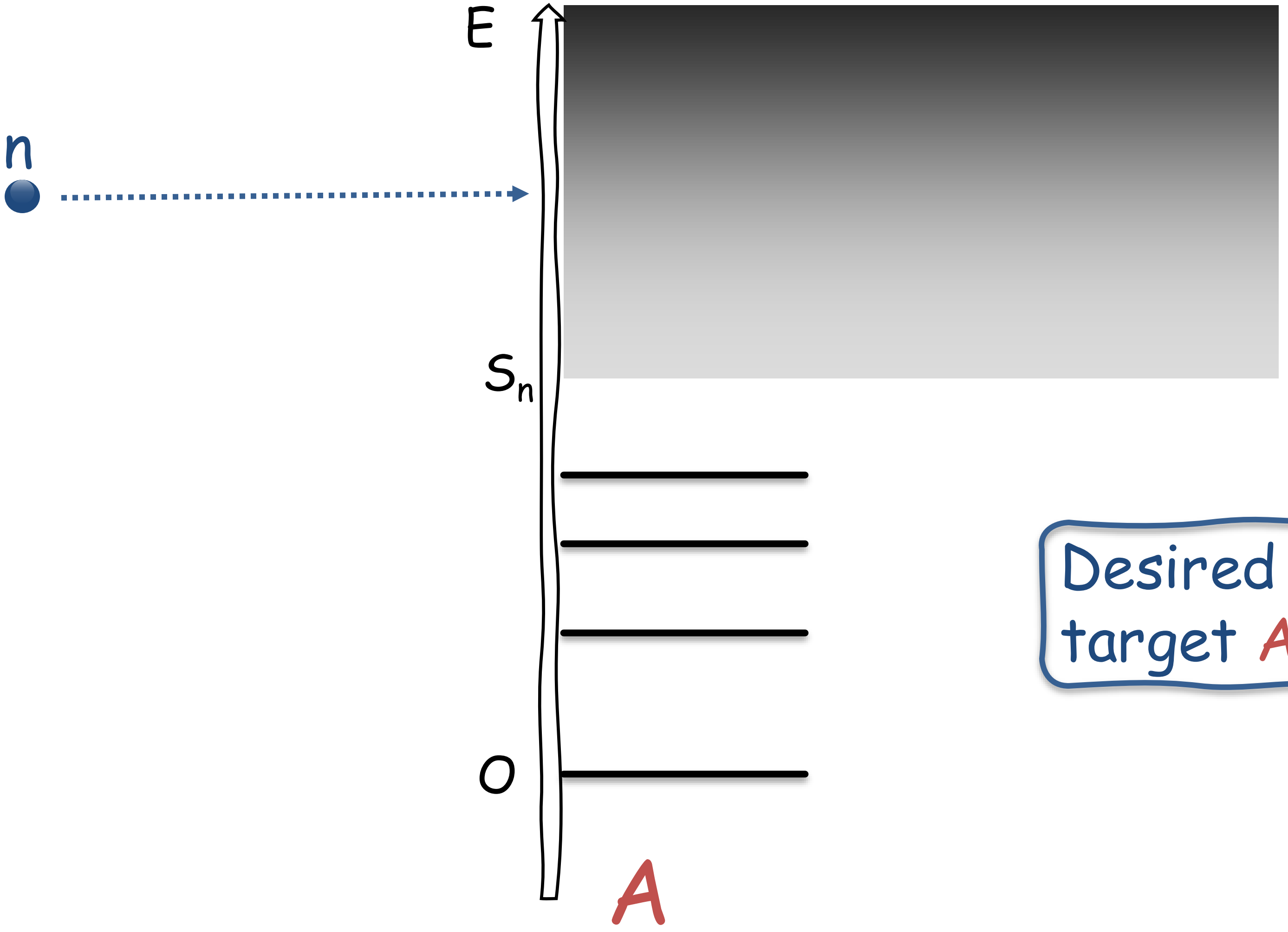
velocity field of ^{208}Pb dipole states



Ryezayeva *et al.* PRL **89** (2002) 272502

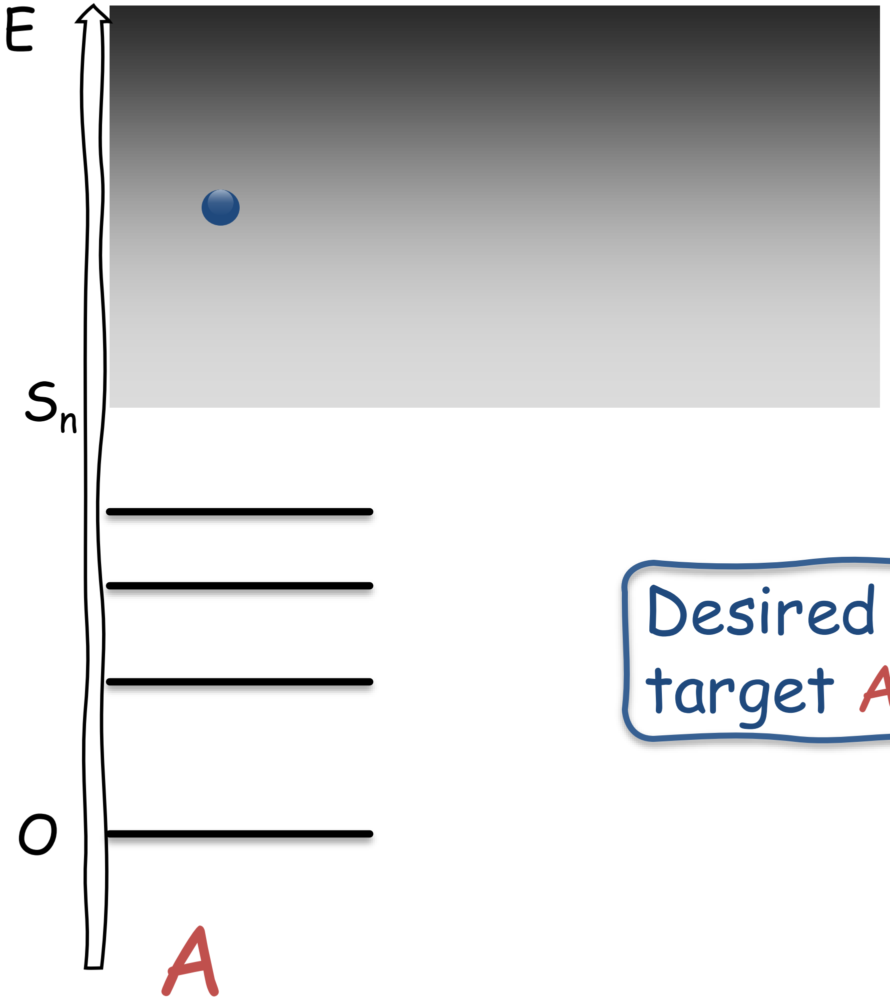
- Is vorticity a signature of PDR?
- Is there an experimental signature for it?

Using the Surrogate Reaction Method (SRM) to infer $^{A}X(n,\gamma)^{A+1}X$ from $^{A}X(d,p\gamma)^{A+1}X$



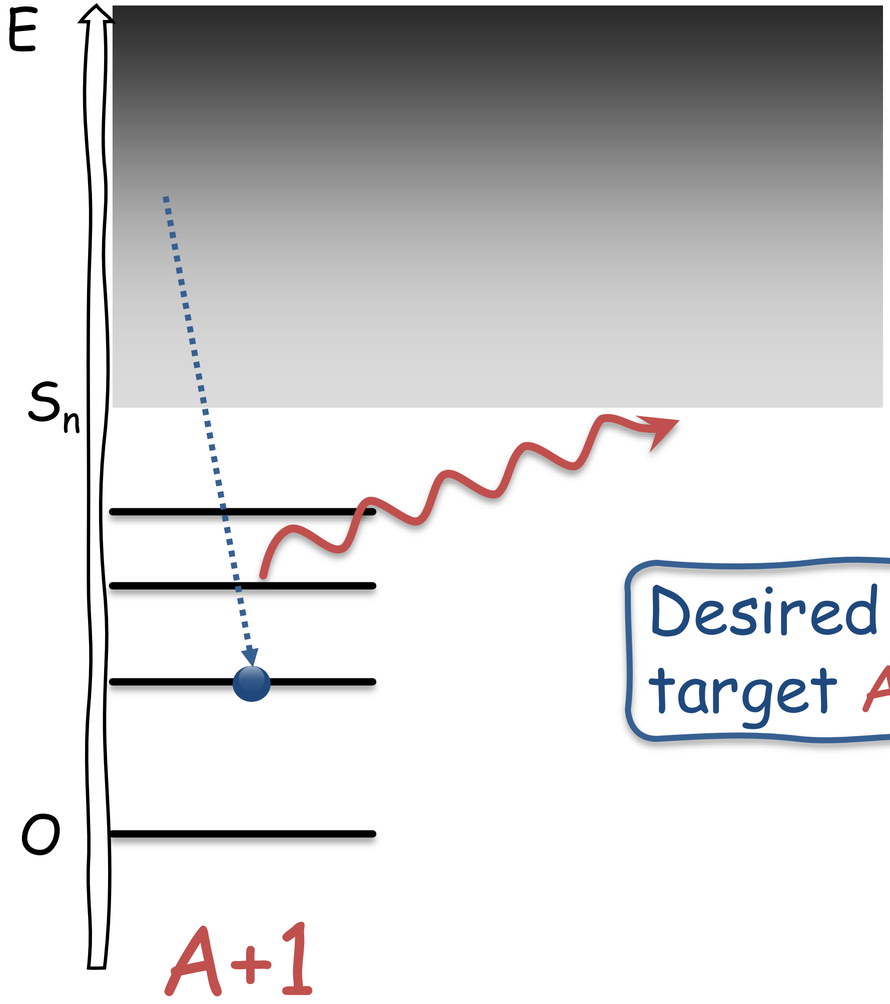
Desired reaction: neutron capture on target *A*

Using the Surrogate Reaction Method (SRM) to infer ${}^{A}X(n,\gamma){}^{A+1}X$ from ${}^{A}X(d,p\gamma){}^{A+1}X$



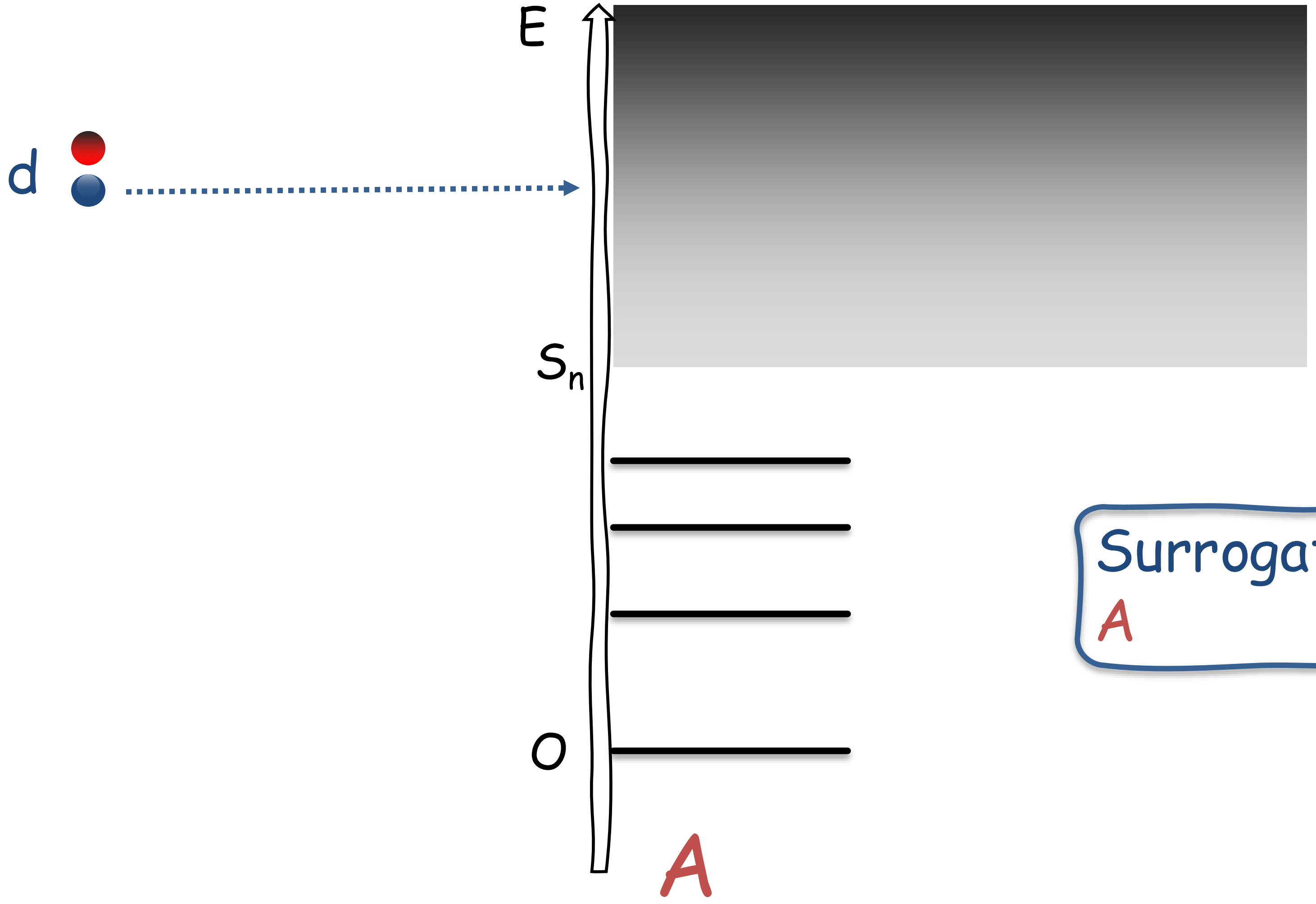
Desired reaction: neutron capture on target *A*

Using the Surrogate Reaction Method (SRM) to infer $^{A}X(n,\gamma)^{A+1}X$ from $^{A}X(d,p\gamma)^{A+1}X$



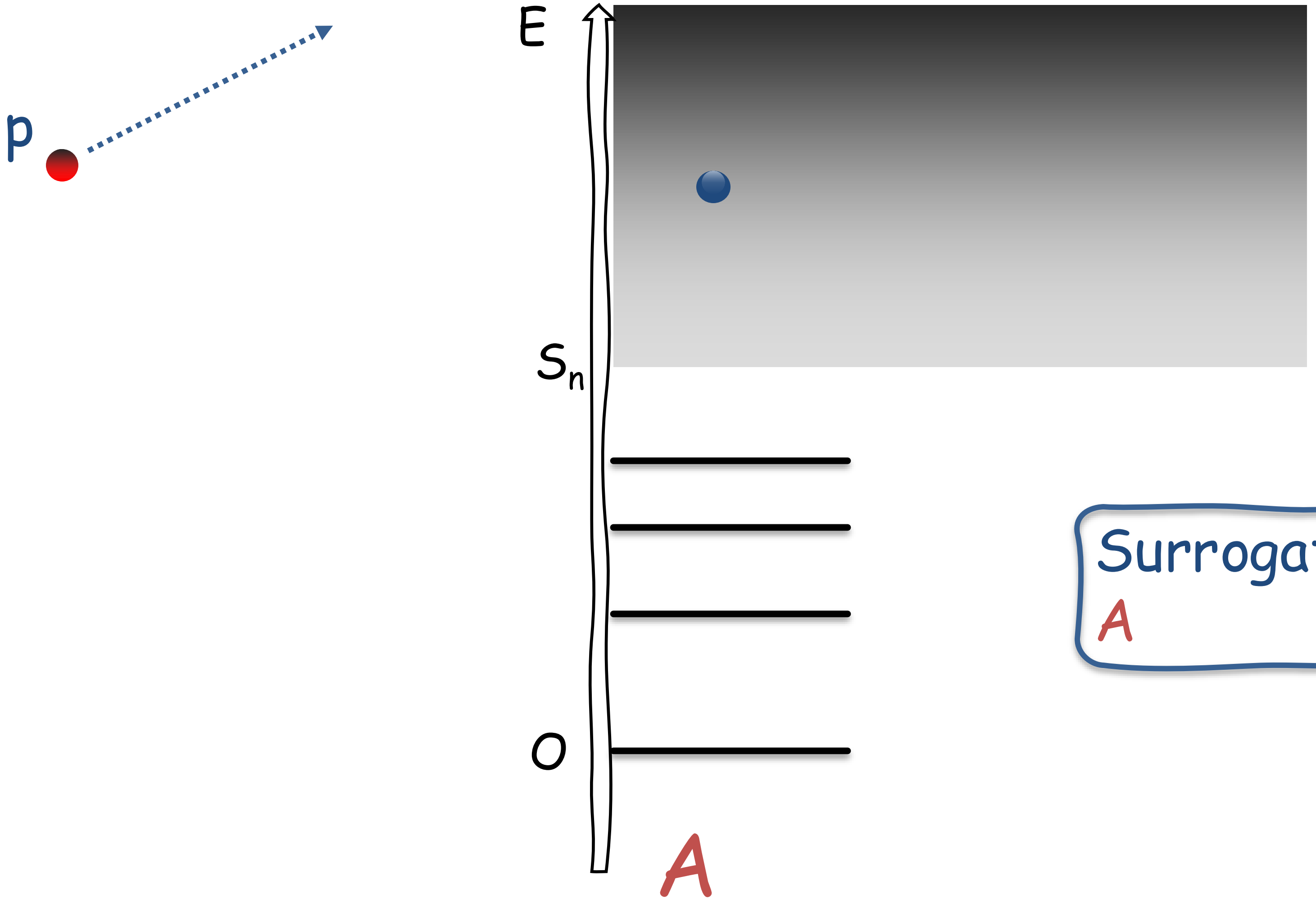
Desired reaction: neutron capture on target *A*

Using the Surrogate Reaction Method (SRM) to infer $^{A}X(n,\gamma)^{A+1}X$ from $^{A}X(d,p\gamma)^{A+1}X$



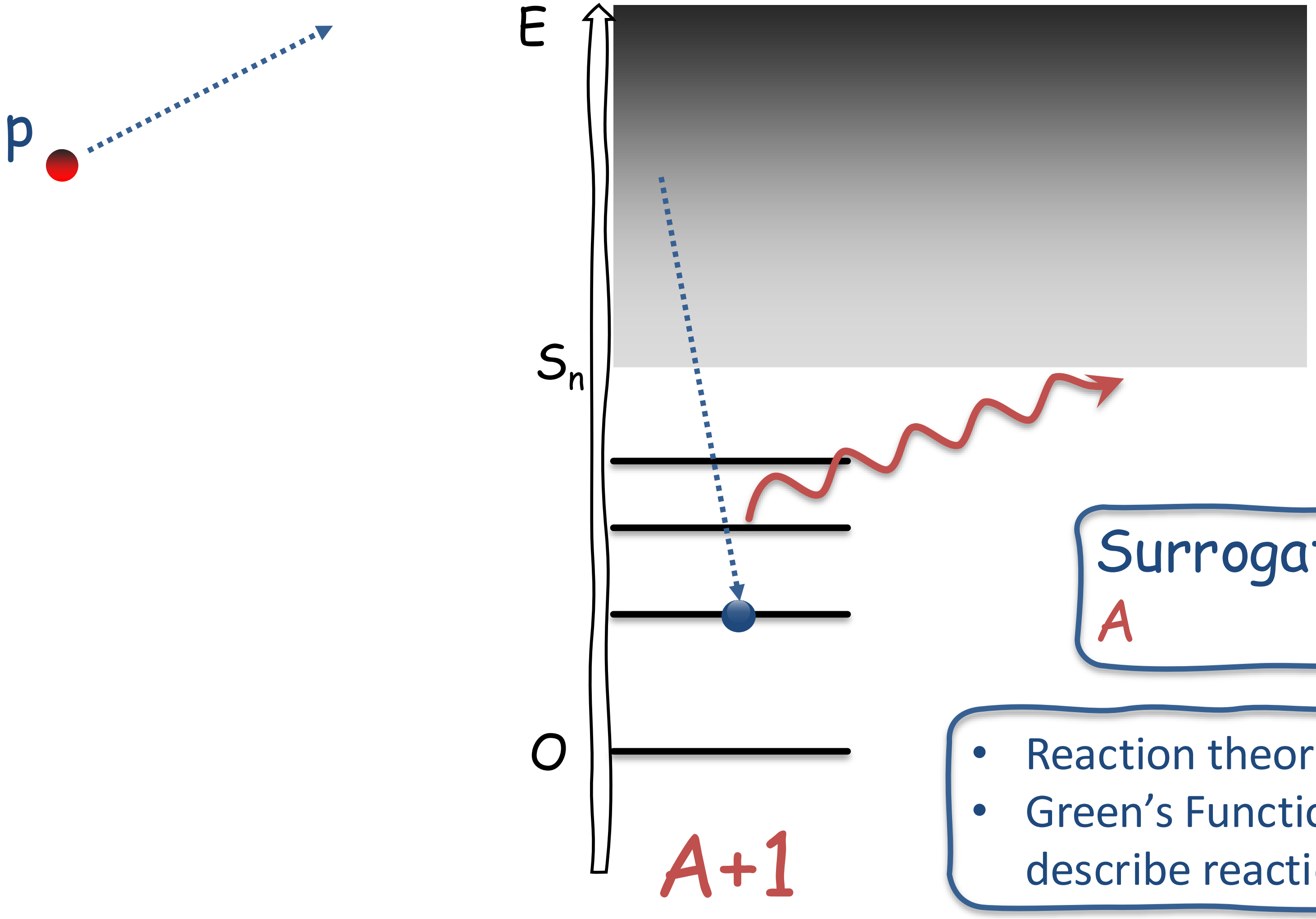
Surrogate: (d,p) reaction on target *A*

Using the Surrogate Reaction Method (SRM) to infer $^{A}X(n,\gamma)^{A+1}X$ from $^{A}X(d,p\gamma)^{A+1}X$



Surrogate: (d,p) reaction on target *A*

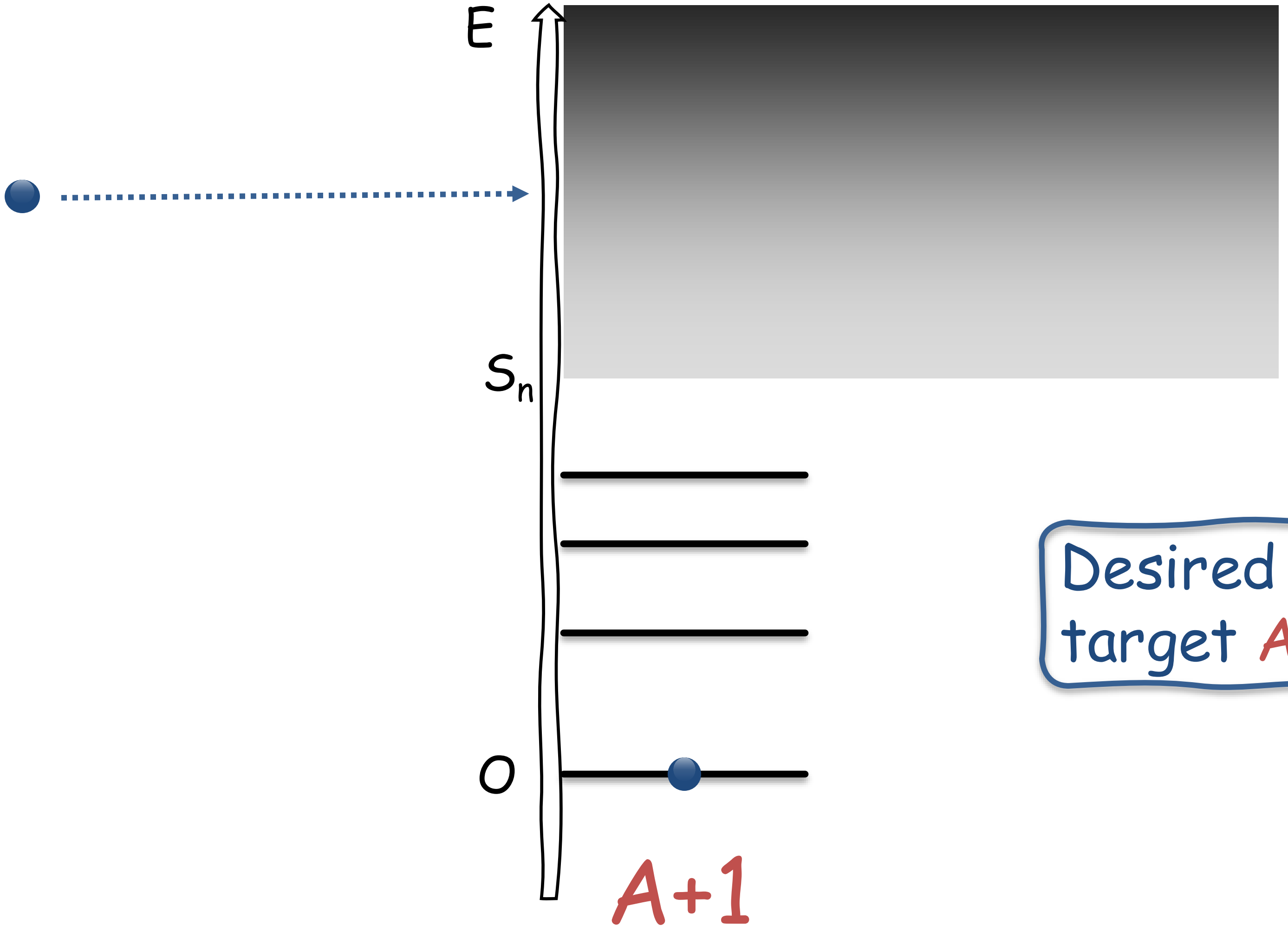
Using the Surrogate Reaction Method (SRM) to infer $^{A}X(n,\gamma)^{A+1}X$ from $^{A}X(d,p\gamma)^{A+1}X$



Surrogate: (d,p) reaction on target A

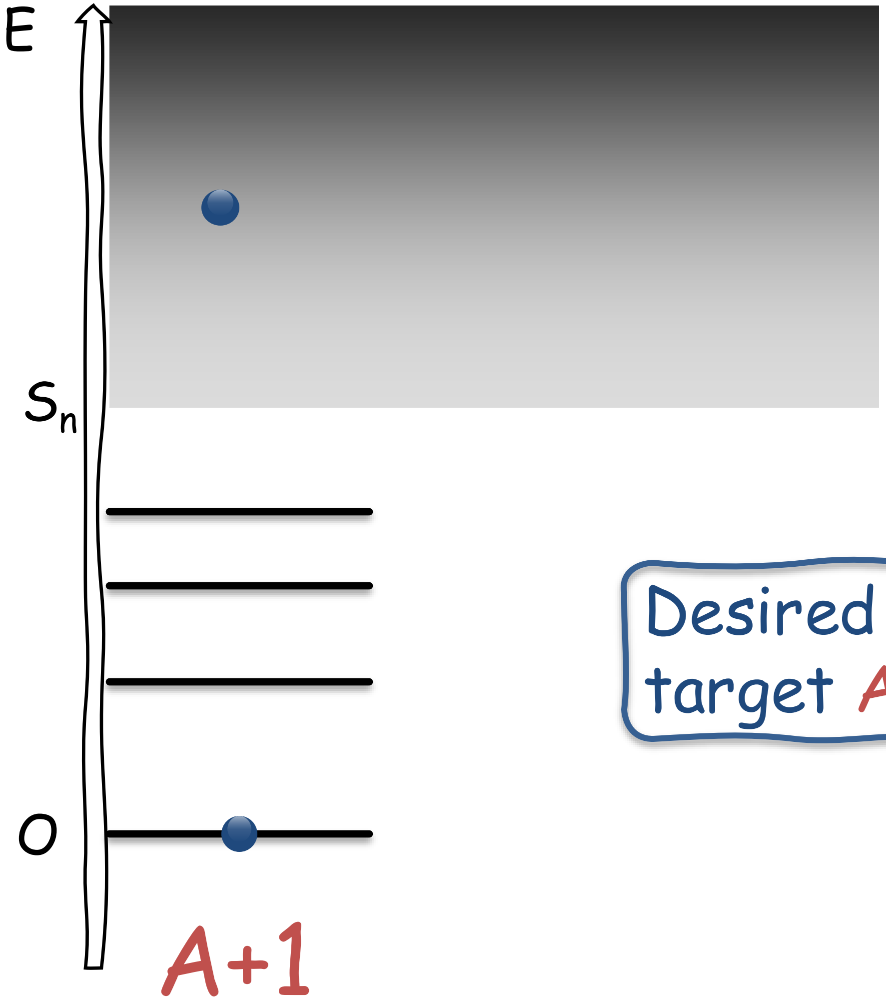
- Reaction theory needed to determine spin distribution
- Green's Function Transfer (GFT) formalism used to describe reaction process

Using the SRM to infer $^{A+1}X(n,\gamma)^{A+2}X$ from $^{A}X(t,p\gamma)^{A+2}X$



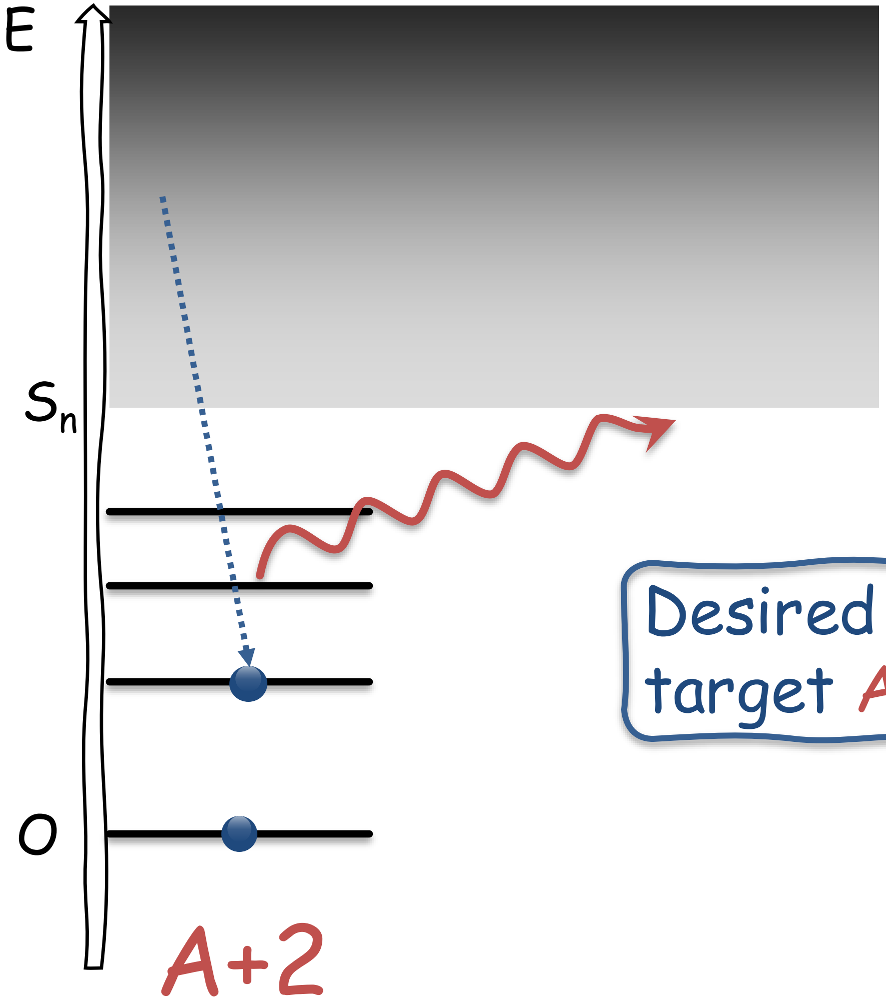
Desired reaction: neutron capture on target A+1

Using the SRM to infer $^{A+1}X(n,\gamma)^{A+2}X$ from $^{A}X(t,p\gamma)^{A+2}X$



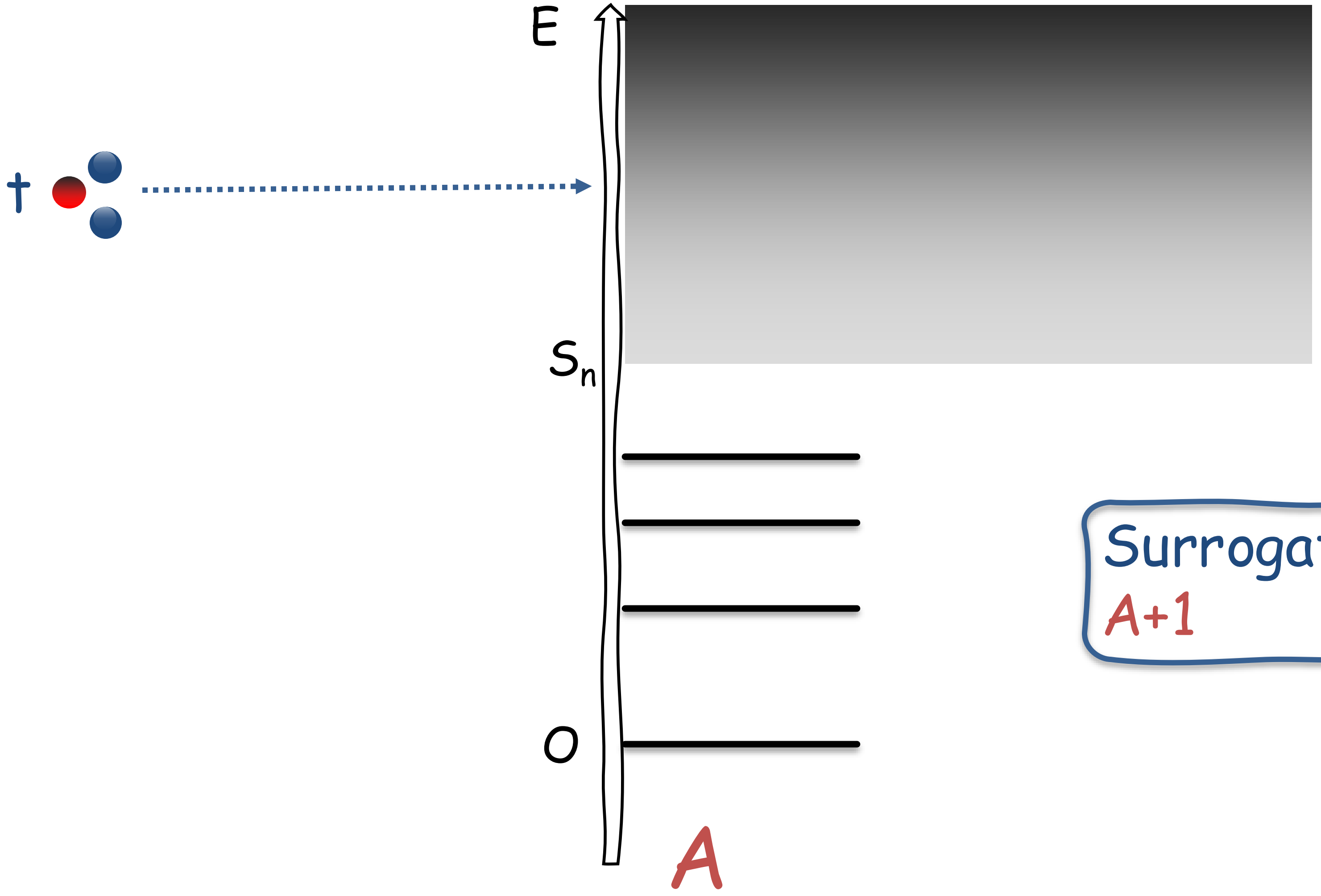
Desired reaction: neutron capture on target A+1

Using the SRM to infer $^{A+1}X(n,\gamma)^{A+2}X$ from $^{A}X(t,p\gamma)^{A+2}X$



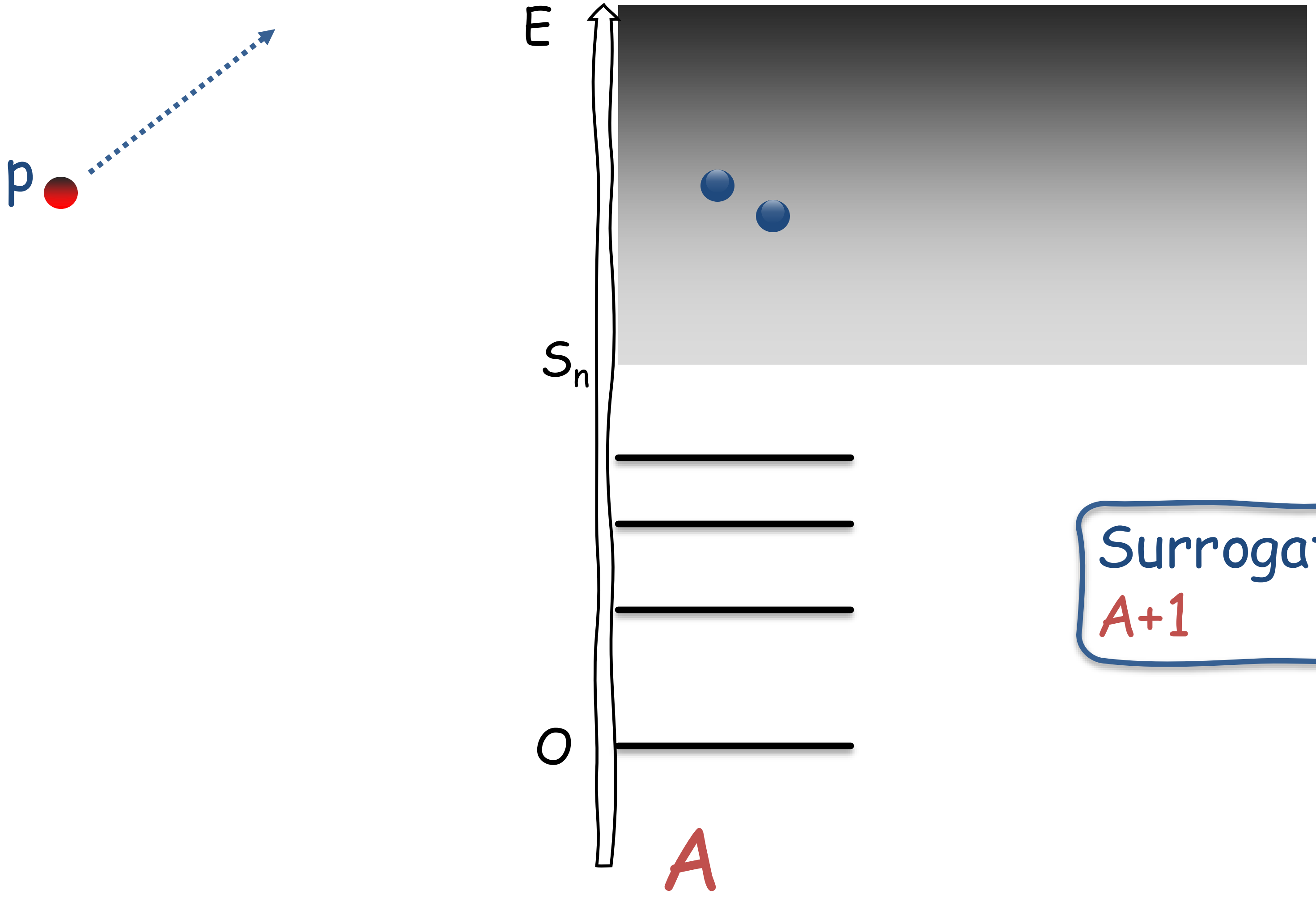
Desired reaction: neutron capture on target A+1

Using the SRM to infer $^{A+1}X(n,\gamma)^{A+2}X$ from $^{A}X(t,p\gamma)^{A+2}X$



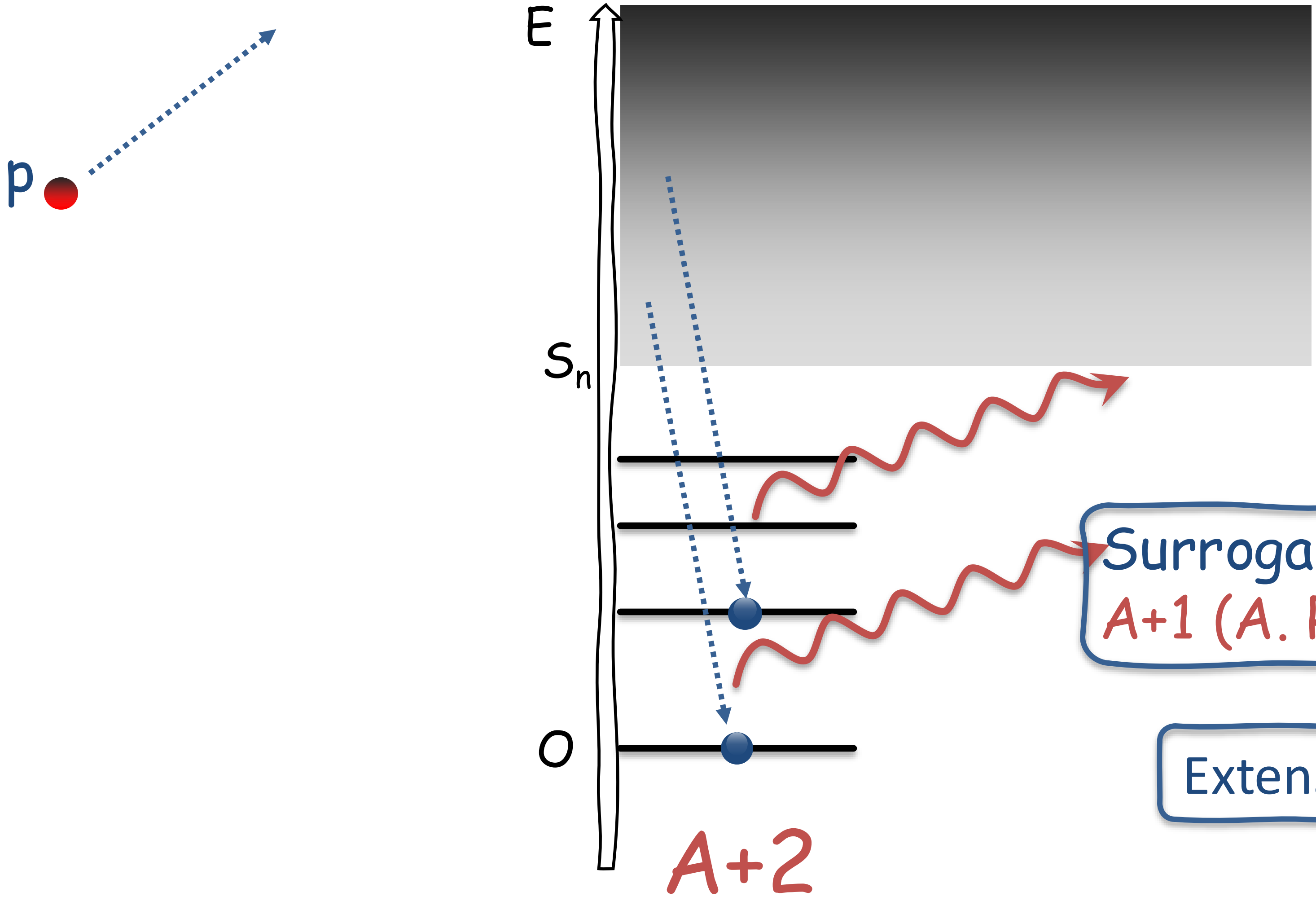
Surrogate: (t,p) reaction on target A+1

Using the SRM to infer $^{A+1}X(n,\gamma)^{A+2}X$ from $^{A}X(t,p\gamma)^{A+2}X$



Surrogate: (t,p) reaction on target A+1

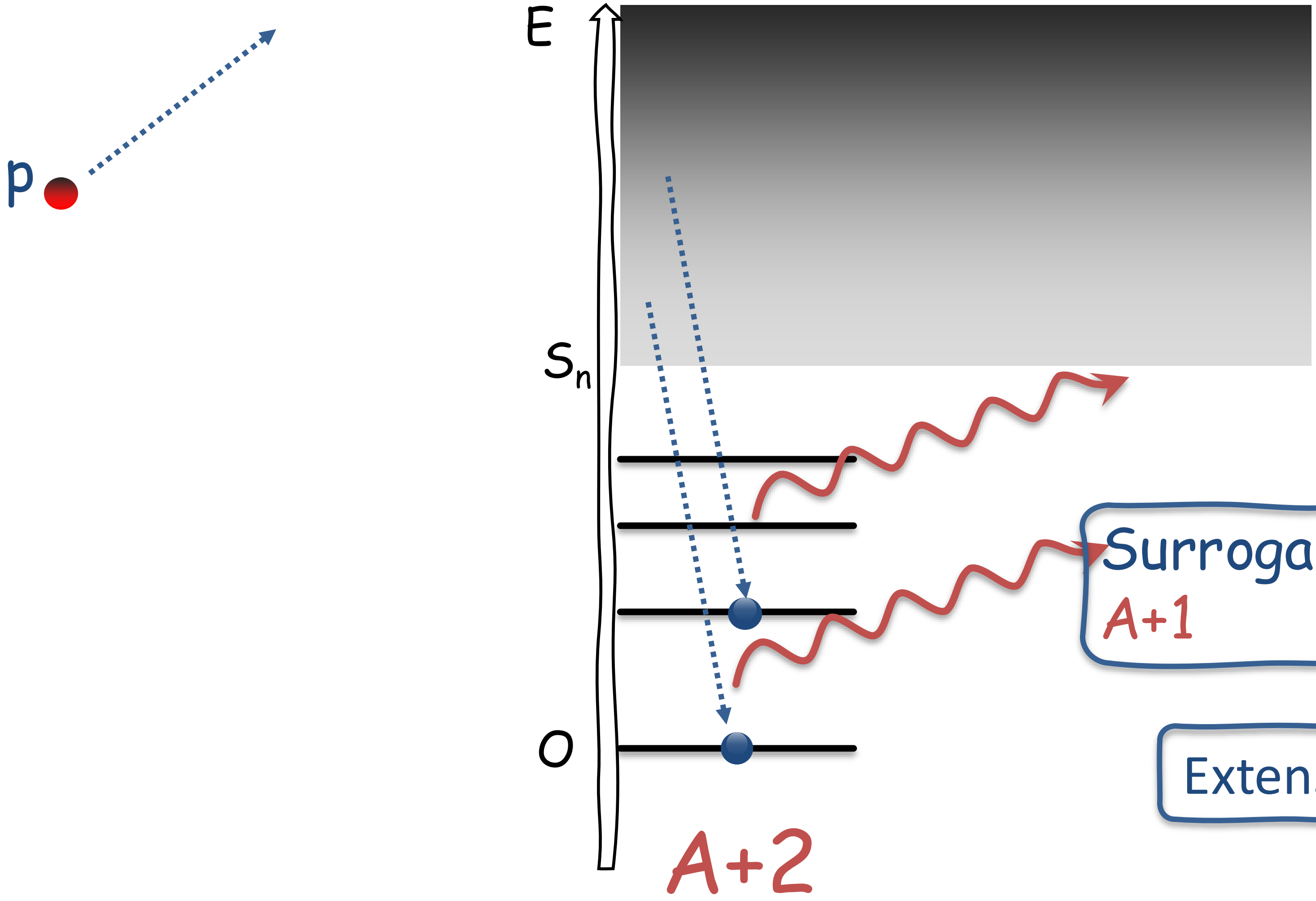
Using the SRM to infer $^{A+1}X(n,\gamma)^{A+2}X$ from $^{A}X(t,p\gamma)^{A+2}X$



Surrogate: (t,p) reaction on target A+1 (A. Richards talk)

Extension of GFT to (t,p) reactions

Using the SRM to infer $^{A+1}X(n,\gamma)^{A+2}X$ from $^{A}X(t,p\gamma)^{A+2}X$

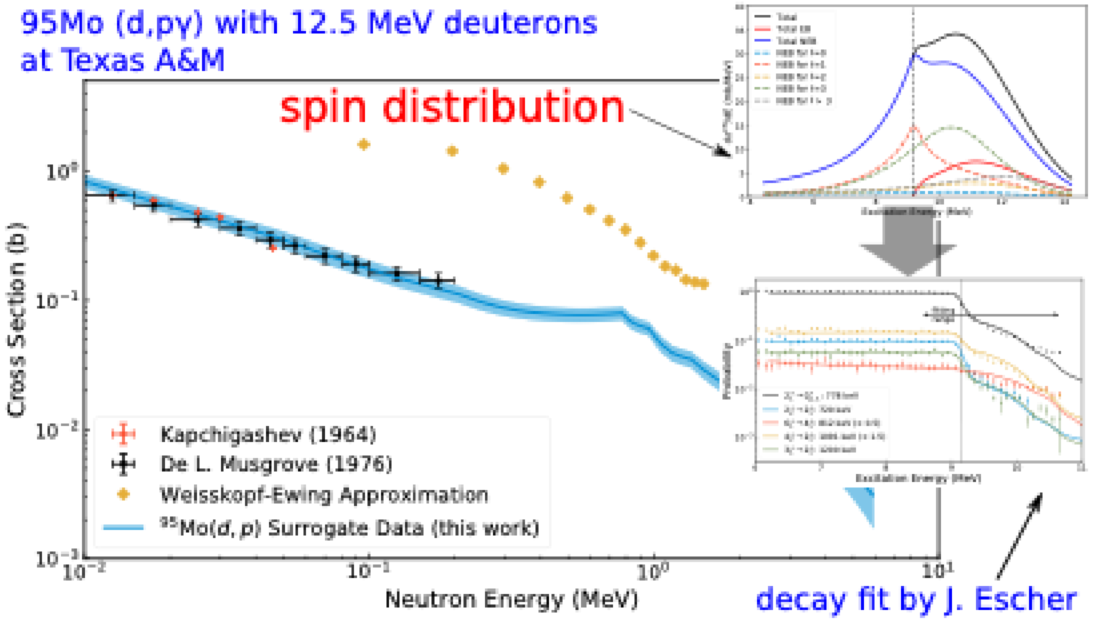


Possible extension to (t,pf)
(talks by Devlin and Bulgac)

Surrogate: (t,p) reaction on target A+1

Extension of GFT to (t,p) reactions

An opportunity to thoroughly benchmark the SRM with ^{95}Mo(n,γ)


95Mo (d,pγ) with 12.5 MeV deuterons at Texas A&M

spin distribution

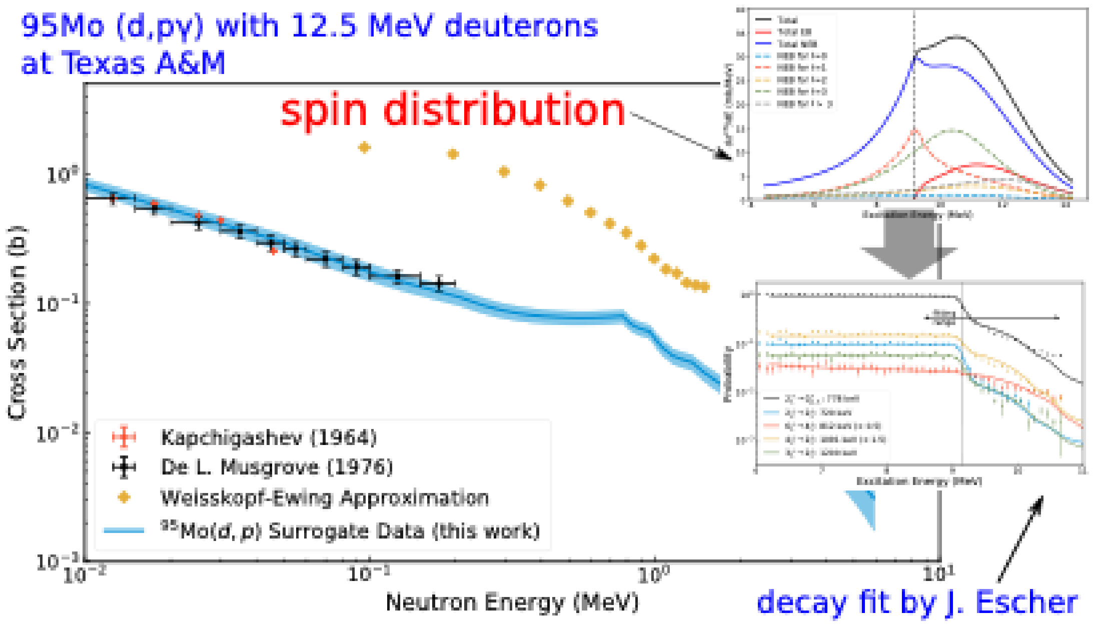
decay fit by J. Escher

Ratkiewicz, Cizewski, Escher, GP, et al. Phys. Rev. Lett. 122052502 (2019)

- Excellent agreement with (n, γ) data.
- The fitted Hauser-Feshbach decay is used to infer (n, γ) rates.

- No previous knowledge of D_0, and/or $\langle \Gamma_\gamma \rangle$ is needed.
- No need for separate determination of NLD and γSF.

An opportunity to thoroughly benchmark the SRM with ^{95}Mo(n,γ)

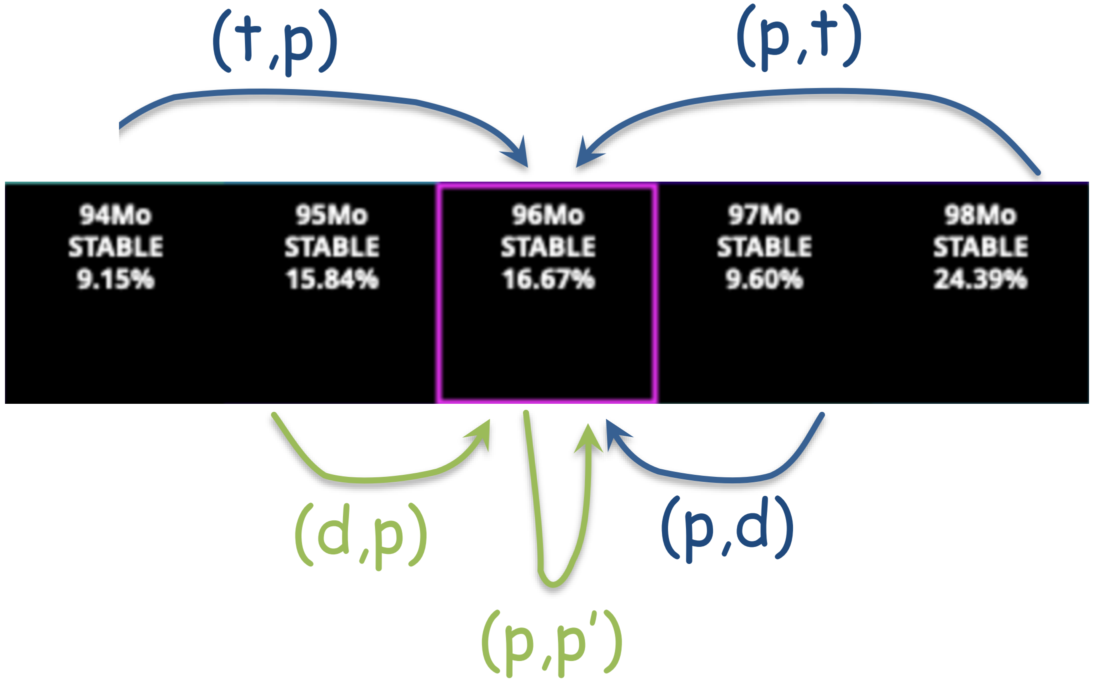


95Mo (d,pγ) with 12.5 MeV deuterons at Texas A&M

spin distribution

decay fit by J. Escher

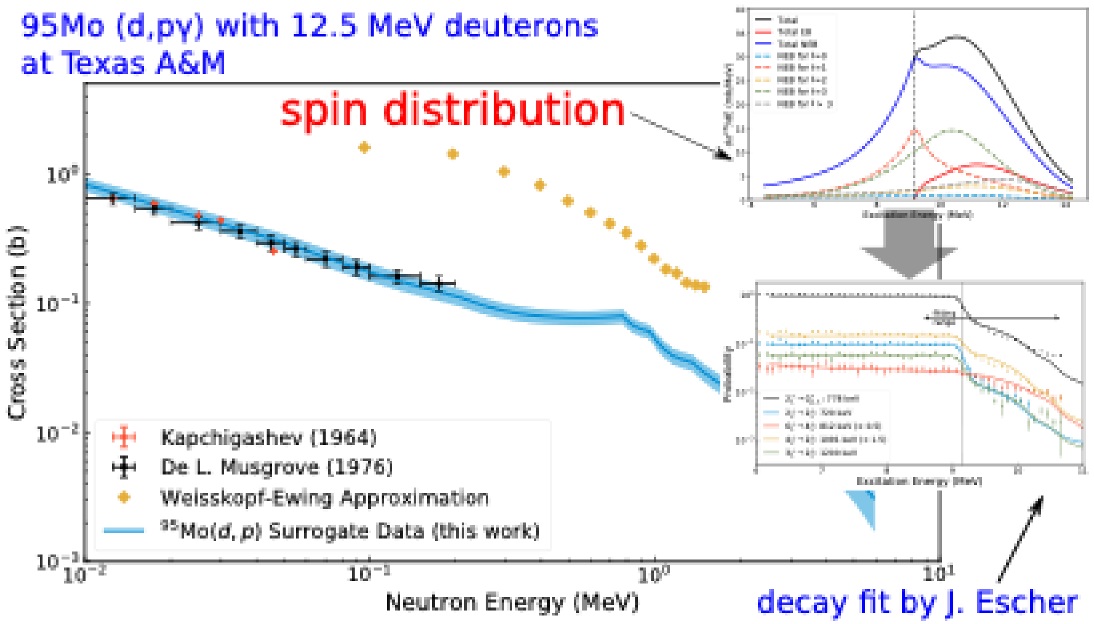
Ratkiewicz, Cizewski, Escher, GP, et al. Phys. Rev. Lett. 122052502 (2019)



- Excellent agreement with (n, γ) data.
- The fitted Hauser-Feshbach decay is used to infer (n, γ) rates.

- No previous knowledge of D_0, and/or $\langle \Gamma_\gamma \rangle$ is needed.
- No need for separate determination of NLD and γSF.

An opportunity to thoroughly benchmark the SRM with ^{95}Mo(n,γ)



95Mo (d,pγ) with 12.5 MeV deuterons at Texas A&M

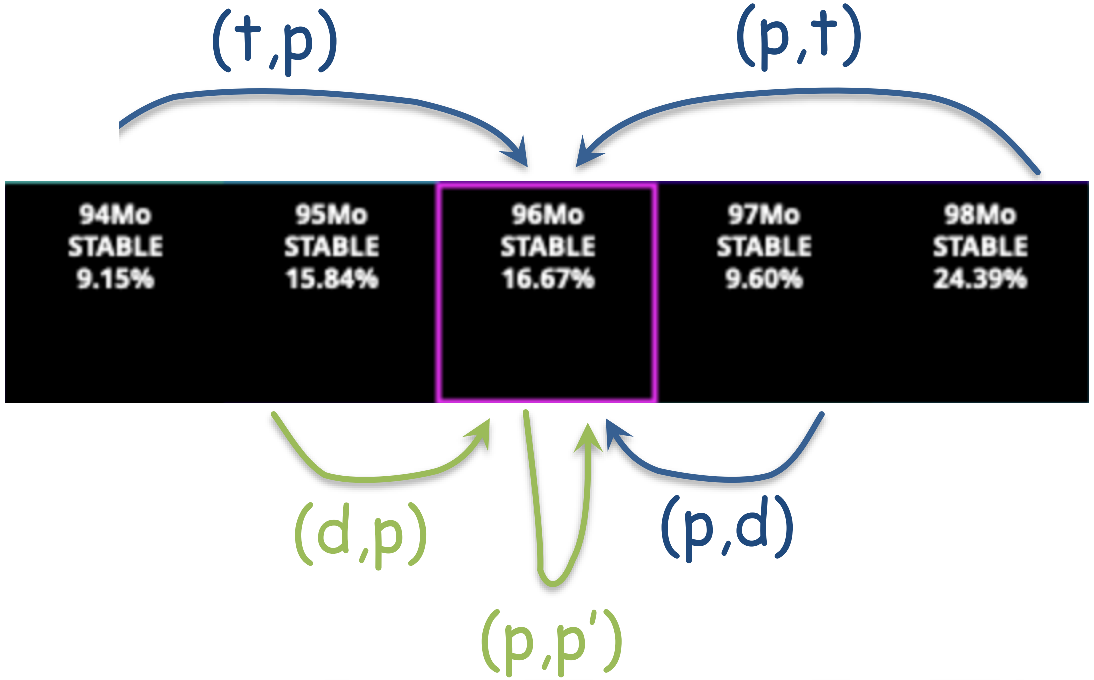
spin distribution

decay fit by J. Escher

Ratkiewicz, Cizewski, Escher, GP, et al. Phys. Rev. Lett. 122052502 (2019)

- Excellent agreement with (n,γ) data.
- The fitted Hauser-Feshbach decay is used to infer (n,γ) rates.

- No previous knowledge of D_0, and/or $\langle\Gamma_\gamma\rangle$ is needed.
- No need for separate determination of NLD and γSF.



(t,p)

(p,t)

94Mo STABLE 9.15%	95Mo STABLE 15.84%	96Mo STABLE 16.67%	97Mo STABLE 9.60%	98Mo STABLE 24.39%

(d,p)

(p,d)

(p,p')

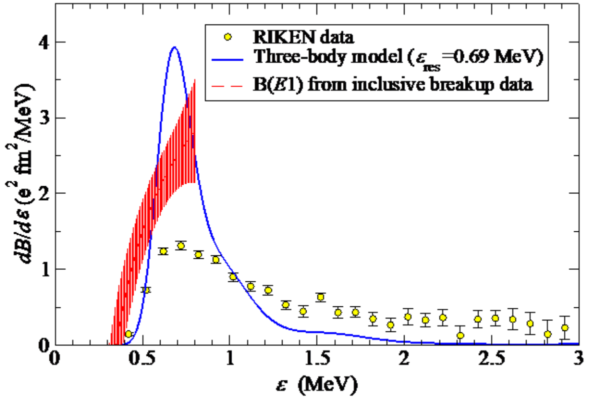
- $^{94\text{-}98}$Mo are all stable
- ^{95}Mo(n,γ) is known
- ^{95}Mo(d,pγ) and ^{95}Mo(p,p'γ) have been measured
- Opportunity to benchmark many SRM techniques

Thank you for your attention!

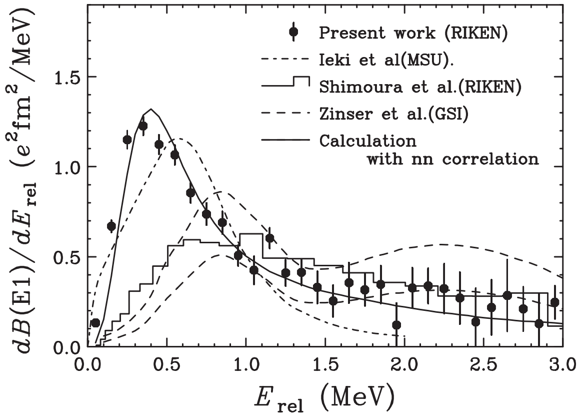
Lawrence Livermore
National Laboratory

Is there a pygmy resonance in ^{11}Li? What's its structure?

Coulomb breakup

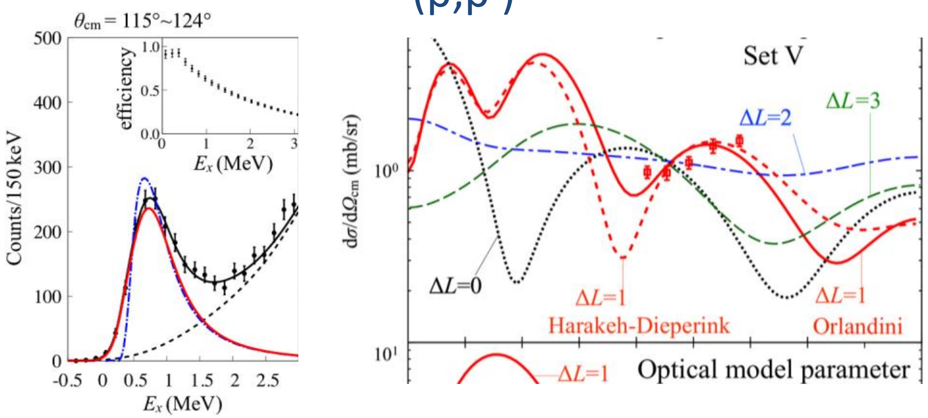


Fernández *et al*. PRL **110**, 142701 (2013)



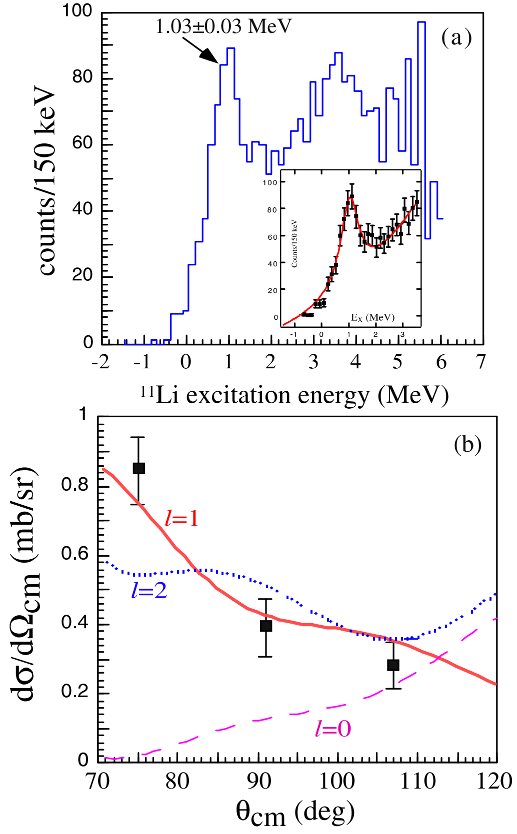
Nakamura *et al*. PRL **96**, 252502 (2006)

(p,p')



J. Tanaka et al. / Physics Letters B 774 (2017) 268–272

(d,d')

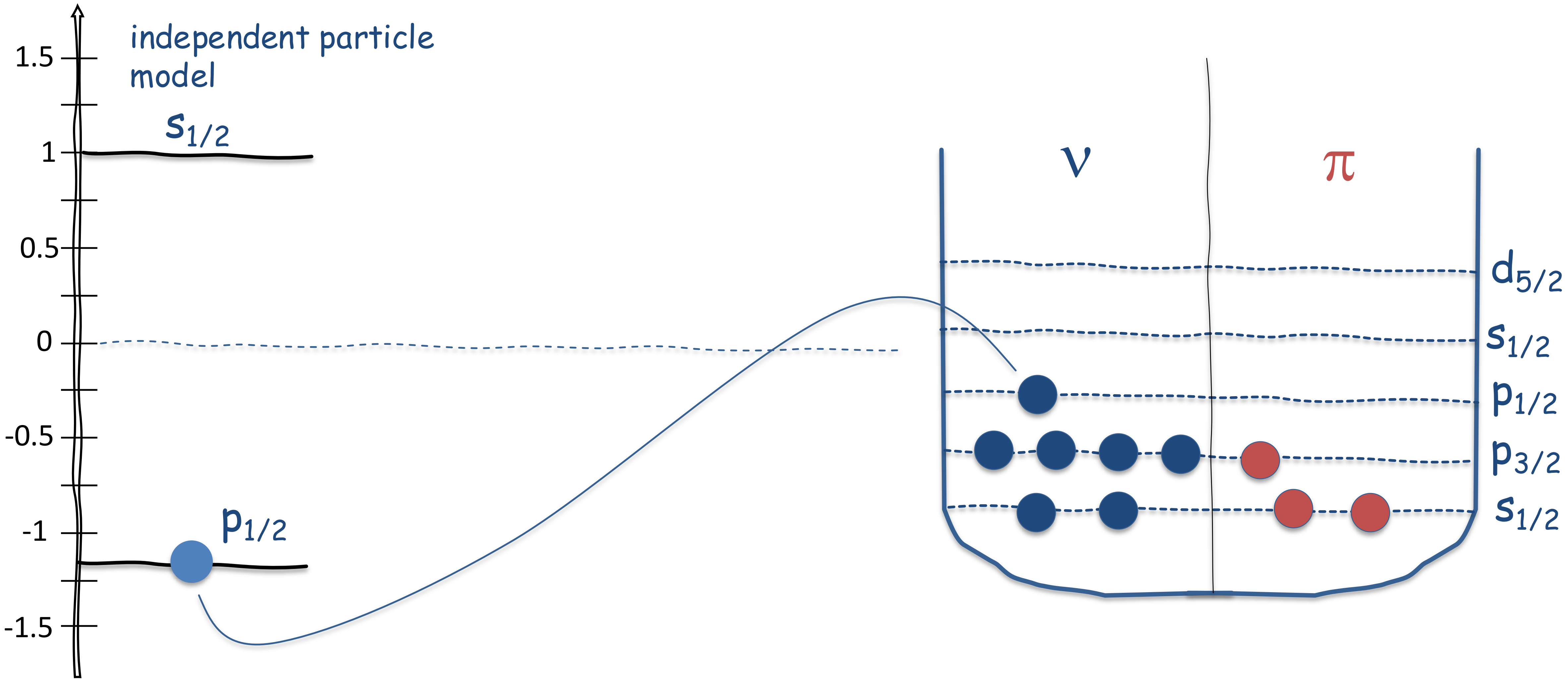


Kanungo *et al.* PRL **114**, 192502 (2015)

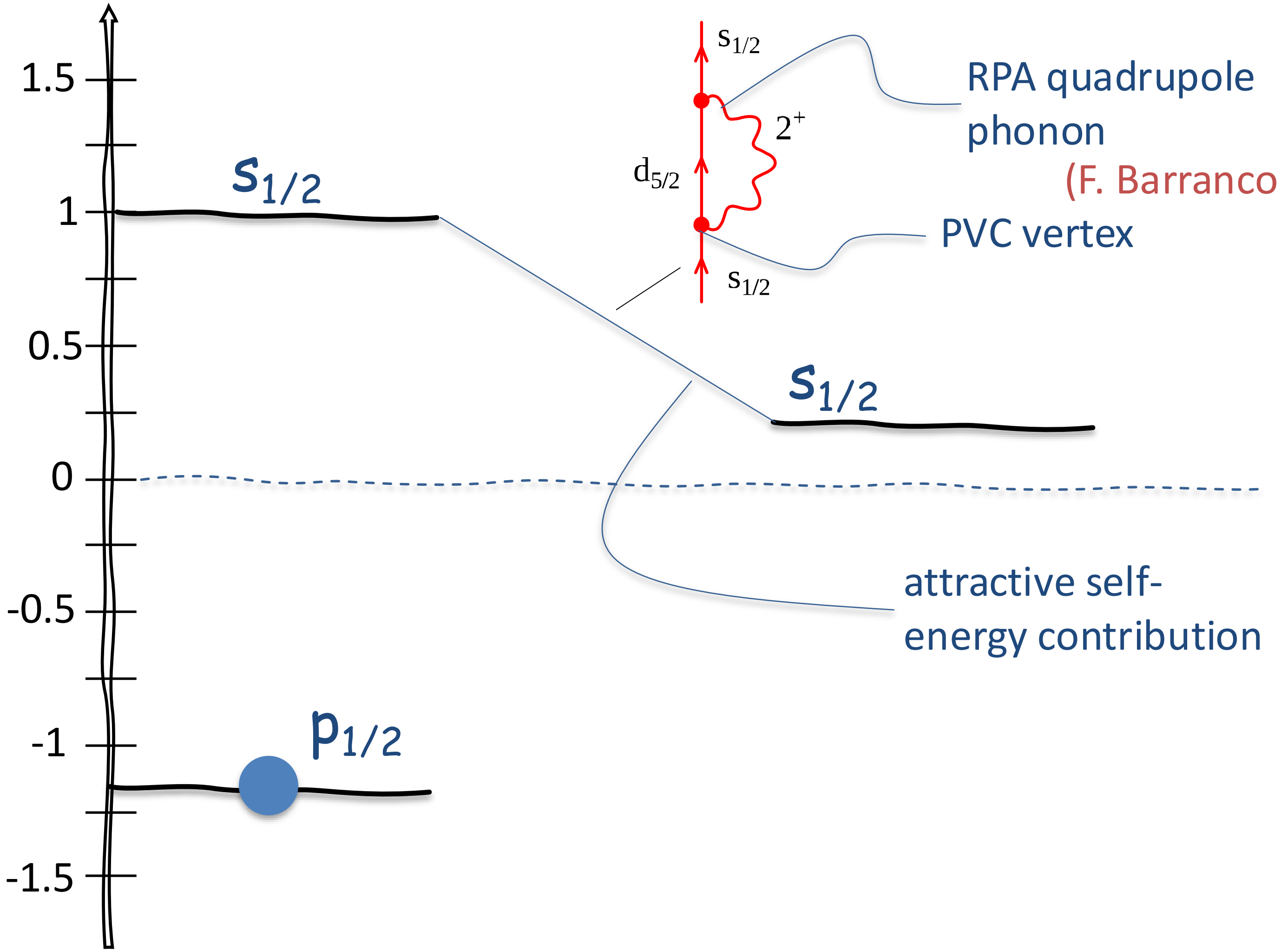
some questions to address:

- How do we characterize the PDR?
- Is it distinct from the GDR?
- How does it compare with theory?

Structure of ^{10}Li in nuclear field theory (NFT): the precursor of ^{11}Li



Structure of ^{10}Li in nuclear field theory (NFT): the precursor of ^{11}Li



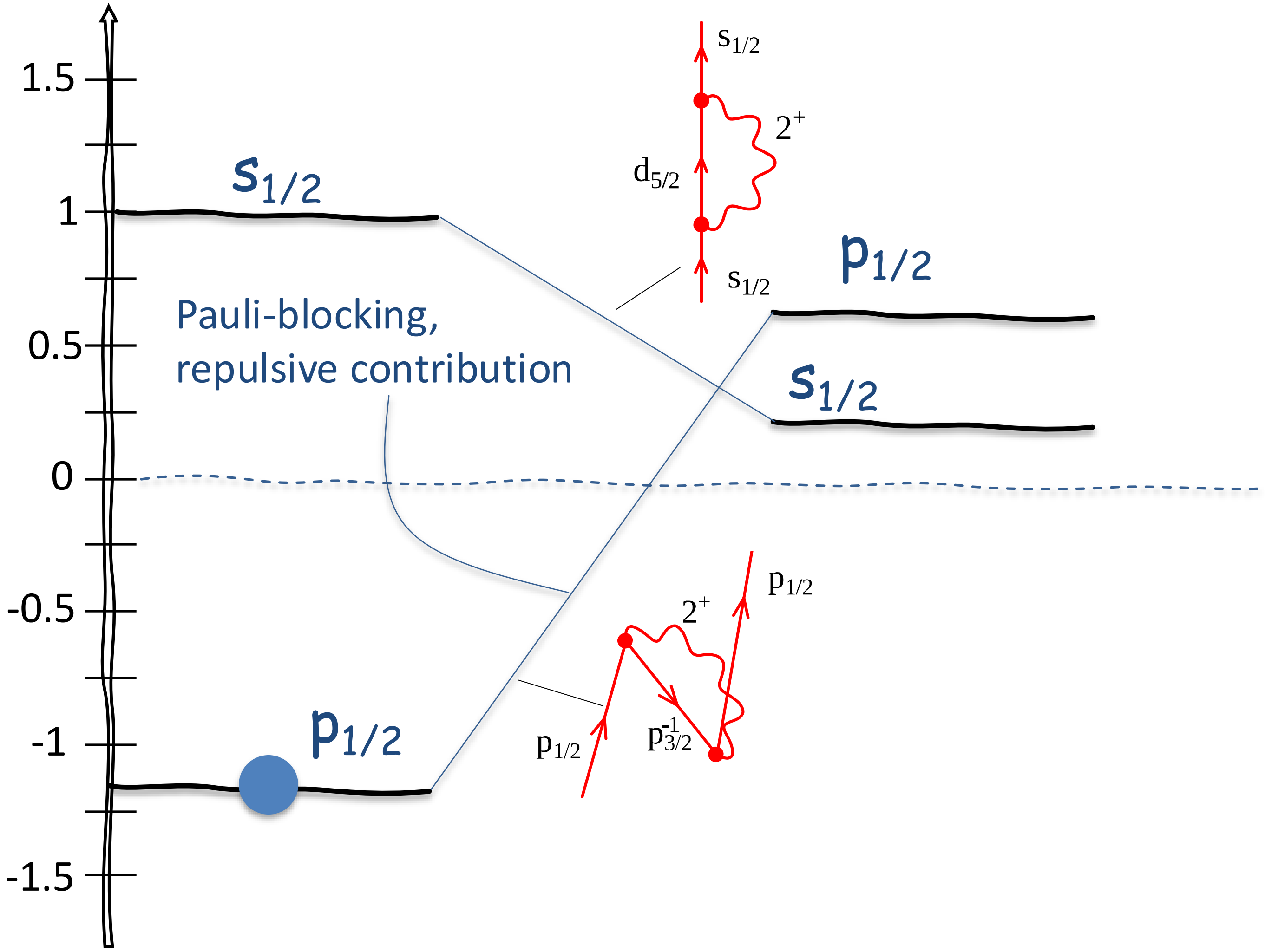
RPA quadrupole phonon

(F. Barranco talk yesterday)

PVC vertex

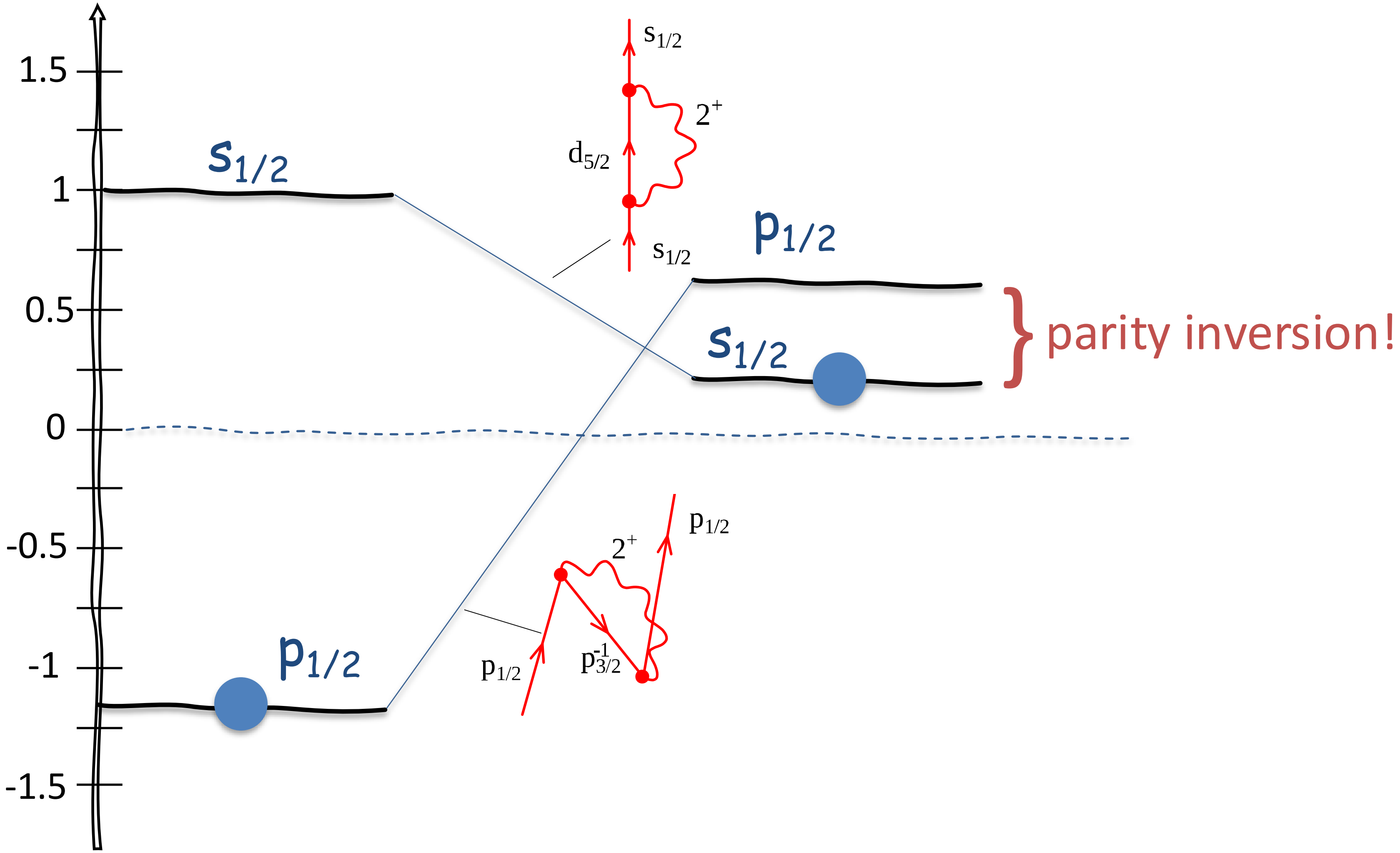
attractive self-energy contribution

Structure of ^{10}Li in nuclear field theory (NFT): the precursor of ^{11}Li



Pauli-blocking, repulsive contribution

Structure of ^{10}Li in nuclear field theory (NFT): the precursor of ^{11}Li

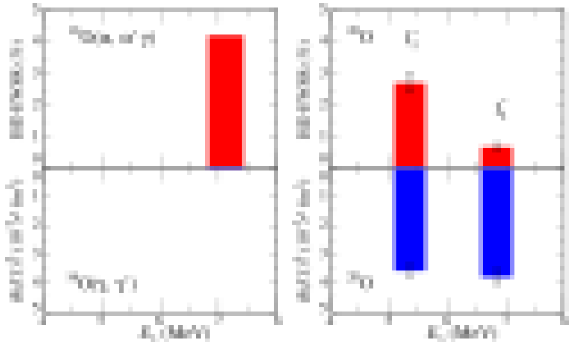


Is the PDR a *bona fide* collective mode, distinct from GDR?

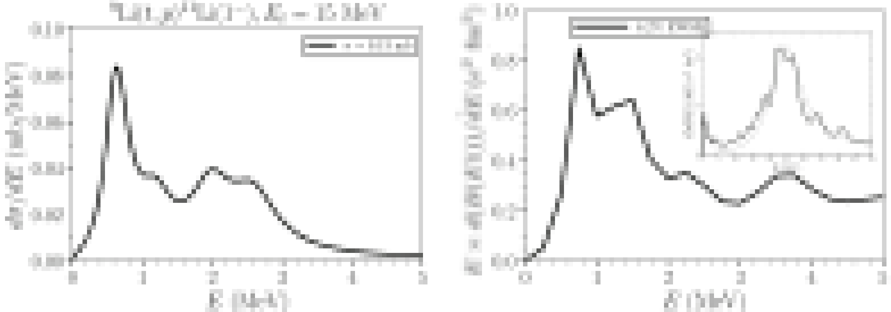
multi-messenger approach
in order to characterize PDR

↓

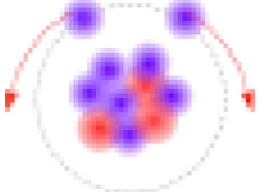
standard probes: (α,α'), (p,p')
(γ,γ')



N. Nakatsuka et al.
Physics Letters B
768 (2017) 387



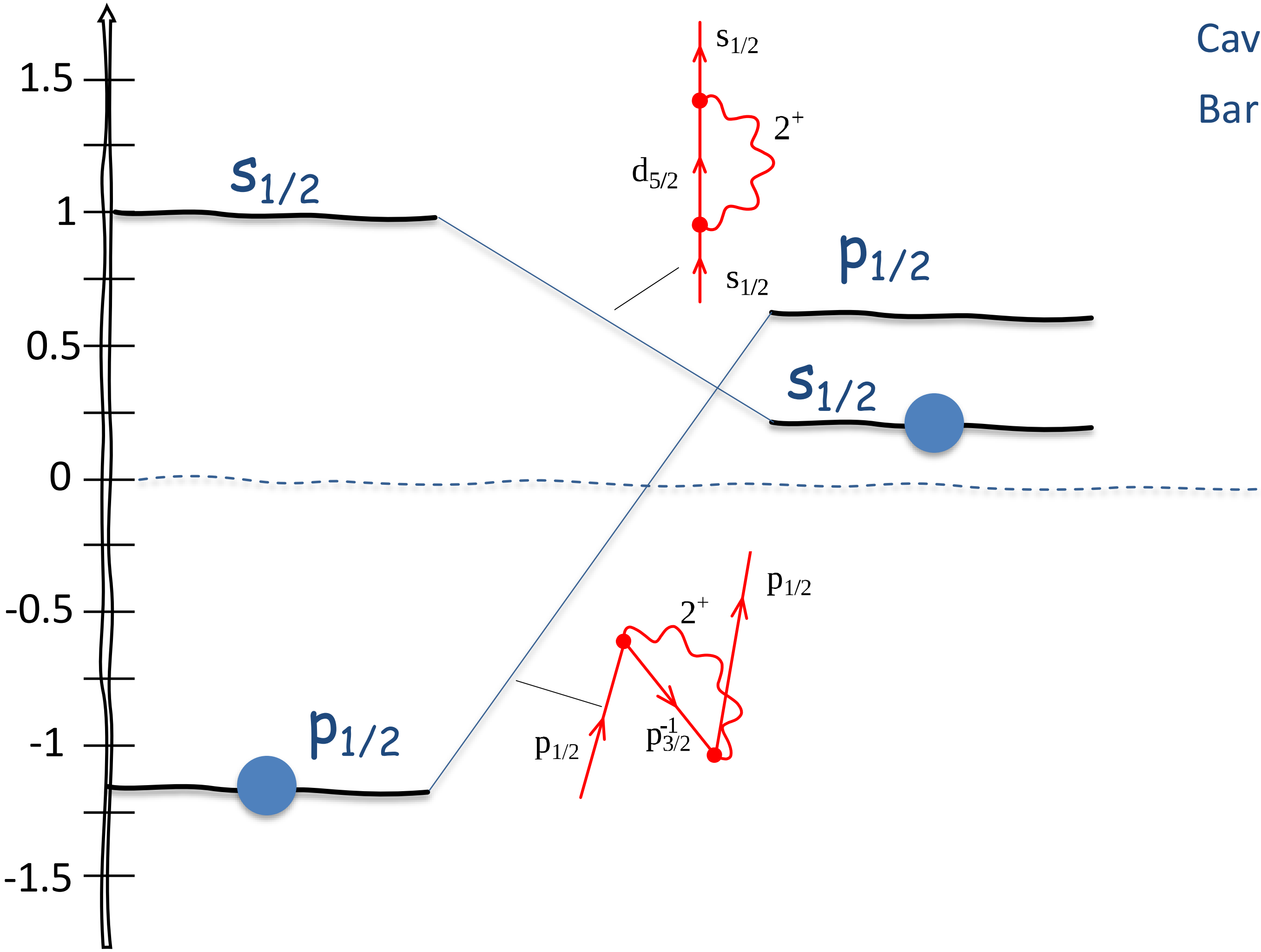
populating the ^{11}Li PDR
with (t,p)



Broglia et al. Eur. Phys. J. A
(2019) **55**: 243

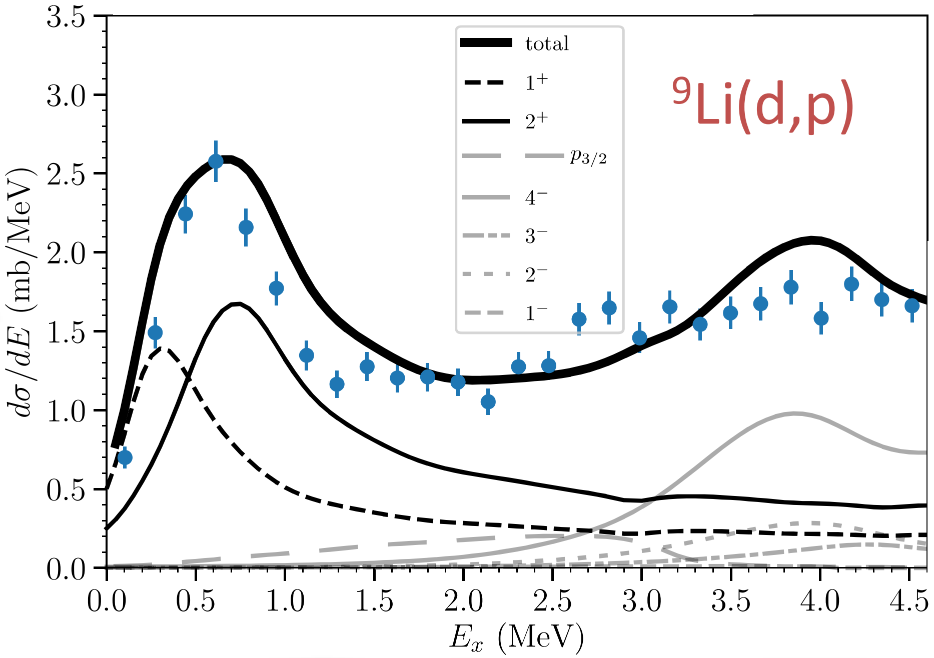
particle-particle correlations might be a distinctive feature of PDRs

Structure of ^{10}Li in nuclear field theory (NFT): the precursor of ^{11}Li



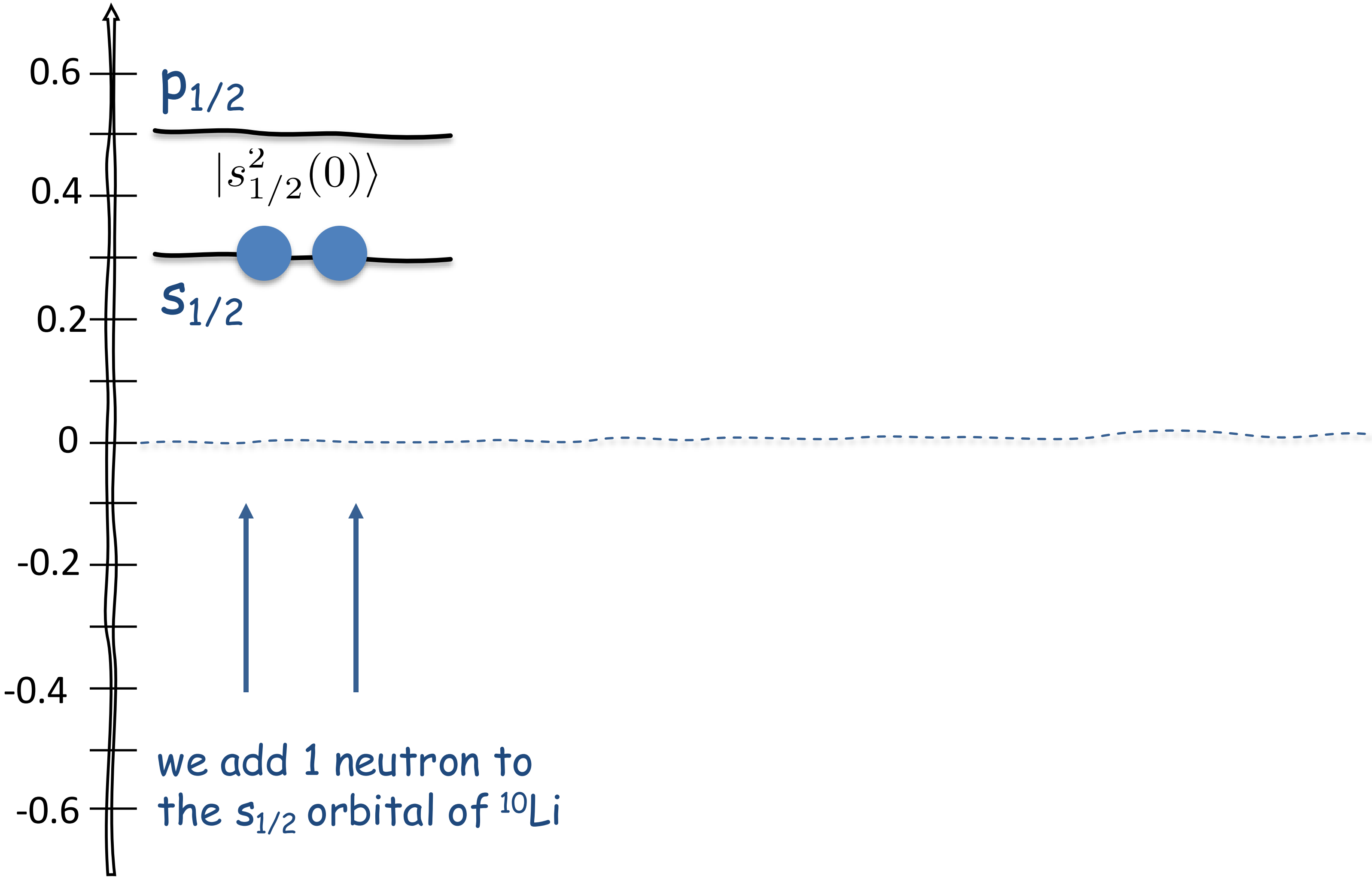
Cavallaro *et al.*, PRL **118**, 012701 (2017)

Barranco, GP, Vigezzi, Broglia PRC **101**, 031305(R) (2020)



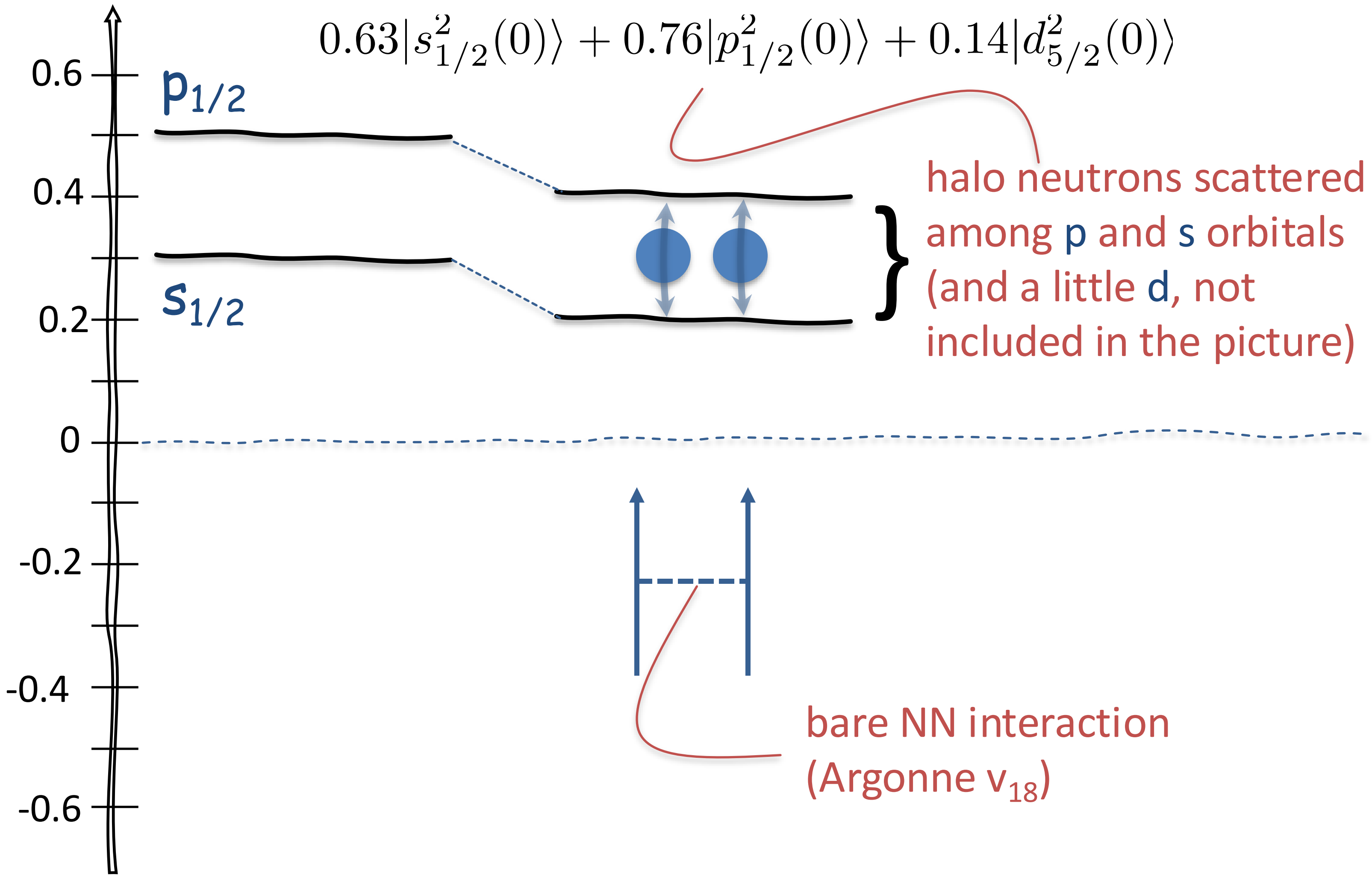
theoretical description validated by experiment

Nuclear field theory (NFT) highlights the role of the PDR in ^{11}Li structure



we add 1 neutron to the $s_{1/2}$ orbital of ^{10}Li

Nuclear field theory (NFT) highlights the role of the PDR in ^{11}Li structure



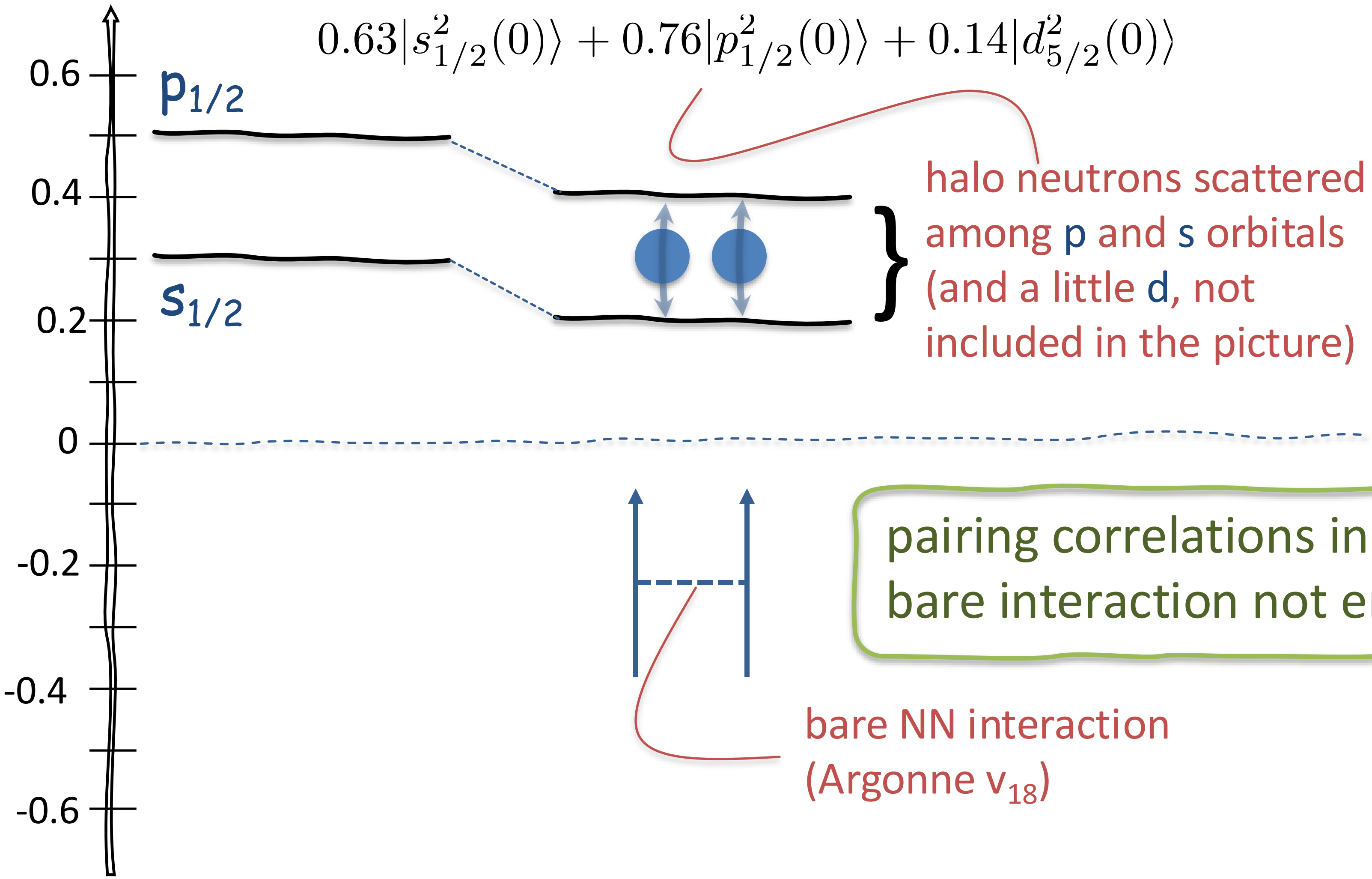
$$0.63|s^2_{1/2}(0)\rangle + 0.76|p^2_{1/2}(0)\rangle + 0.14|d^2_{5/2}(0)\rangle$$

halo neutrons scattered among p and s orbitals (and a little d, not included in the picture)

bare NN interaction (Argonne v_{18})

Nuclear field theory (NFT) highlights the role of the PDR in ^{11}Li structure

$$0.63|s^2_{1/2}(0)\rangle + 0.76|p^2_{1/2}(0)\rangle + 0.14|d^2_{5/2}(0)\rangle$$

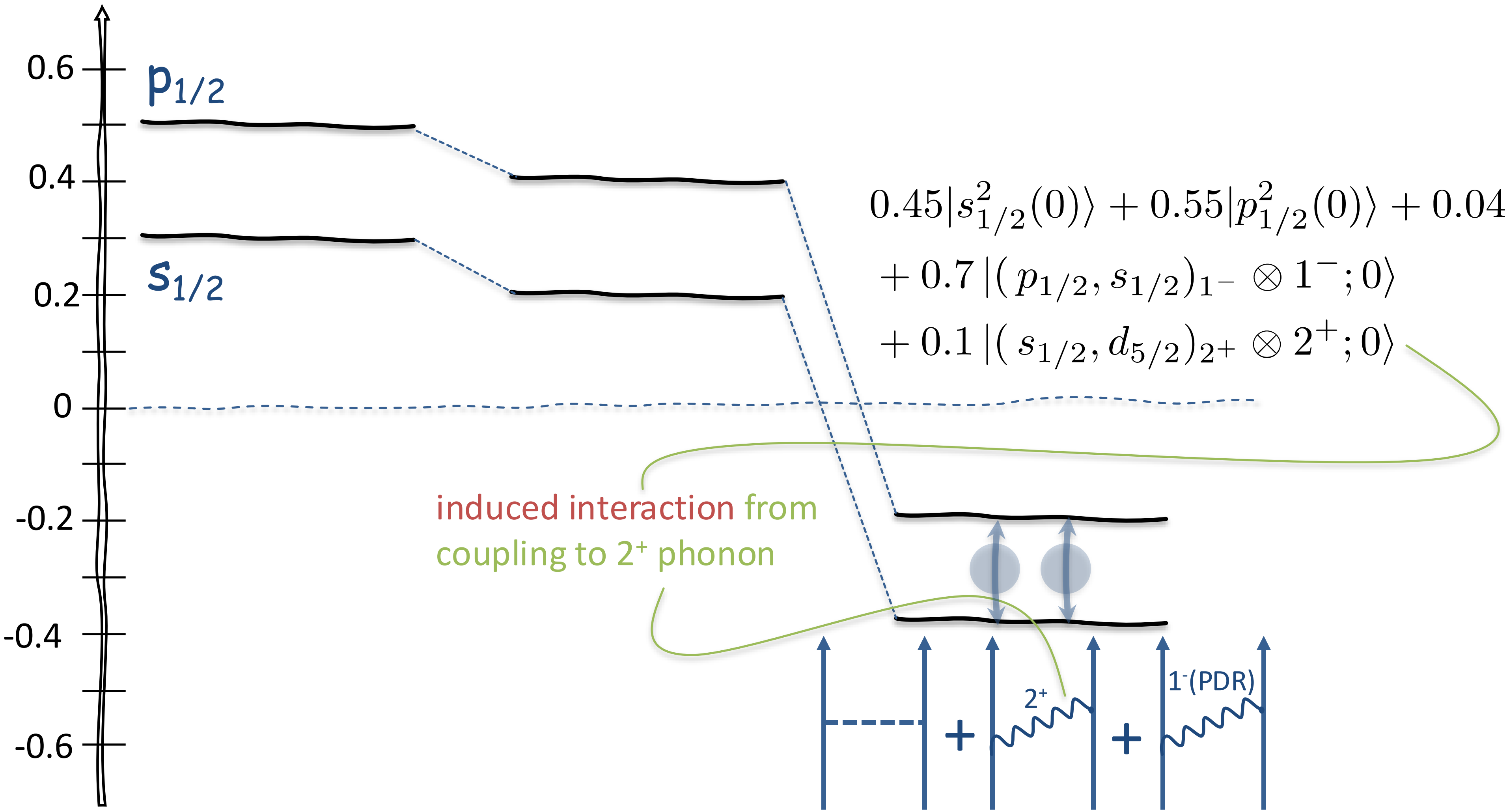


halo neutrons scattered among p and s orbitals (and a little d, not included in the picture)

pairing correlations induced by short-range, bare interaction not enough to bind ^{11}Li

bare NN interaction (Argonne v_{18})

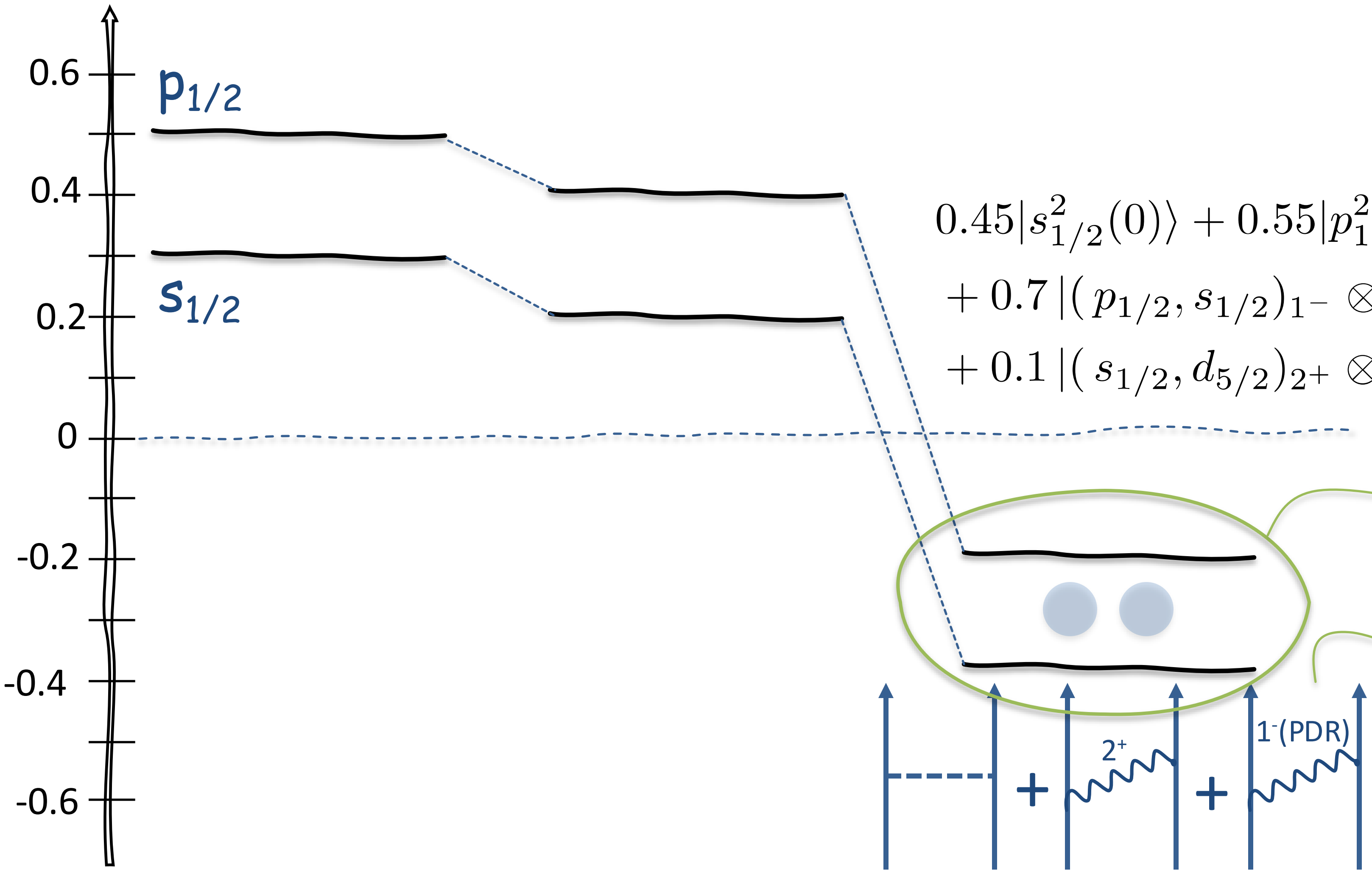
Nuclear field theory (NFT) highlights the role of the PDR in ^{11}Li structure



$$0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$
$$+\,0.7\,|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-; 0\rangle$$
$$+\,0.1\,|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+; 0\rangle$$

induced interaction from coupling to 2^+ phonon

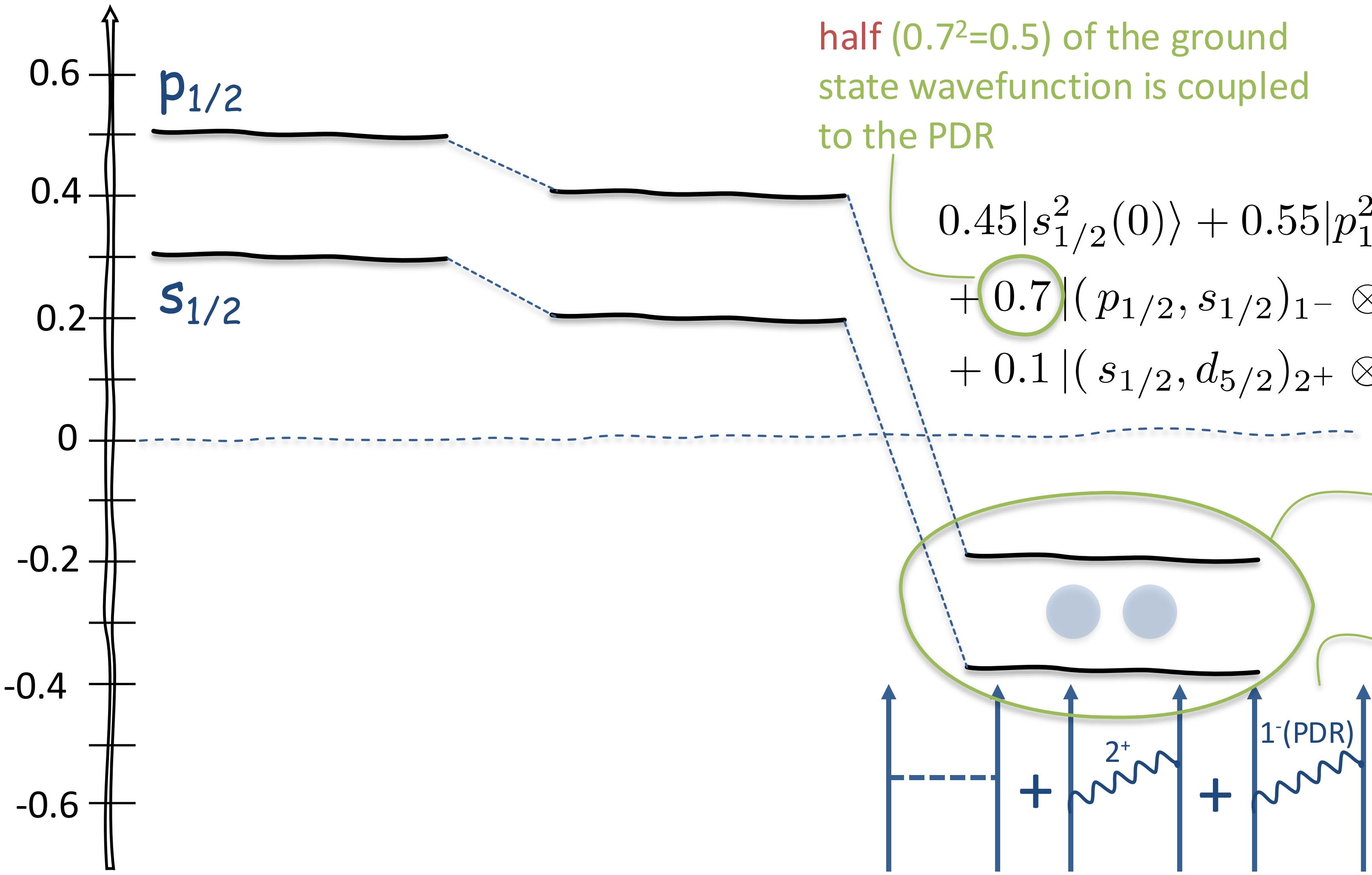
Nuclear field theory (NFT) highlights the role of the PDR in ^{11}Li structure



$$0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$
$$+\,0.7\,|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-;0\rangle$$
$$+\,0.1\,|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+;0\rangle$$

2 low-angular momentum sates of opposite parity at threshold: ideal scenario for PDR

Nuclear field theory (NFT) highlights the role of the PDR in ^{11}Li structure

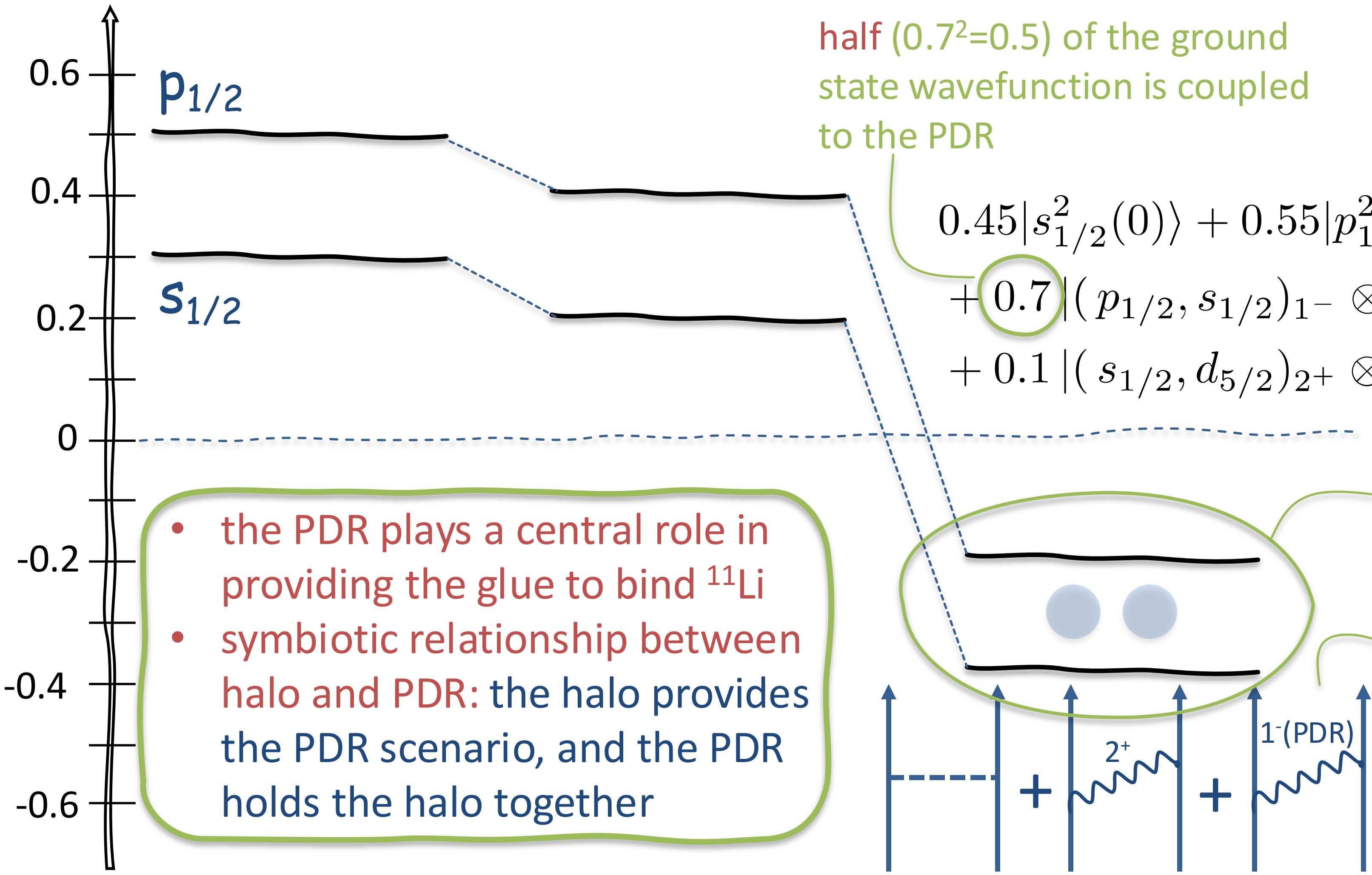


half (0.7^2=0.5) of the ground state wavefunction is coupled to the PDR

$$0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$
$$+\,\boxed{0.7}\,|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-;0\rangle$$
$$+\,0.1\,|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+;0\rangle$$

2 low-angular momentum sates of opposite parity at threshold: ideal scenario for PDR

Nuclear field theory (NFT) highlights the role of the PDR in ^{11}Li structure



half ($0.7^2=0.5$) of the ground state wavefunction is coupled to the PDR

$$0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$
$$+\boxed{0.7}\,|(p_{1/2},s_{1/2})_{1^-}\otimes 1^-;0\rangle$$
$$+\,0.1\,|(s_{1/2},d_{5/2})_{2^+}\otimes 2^+;0\rangle$$

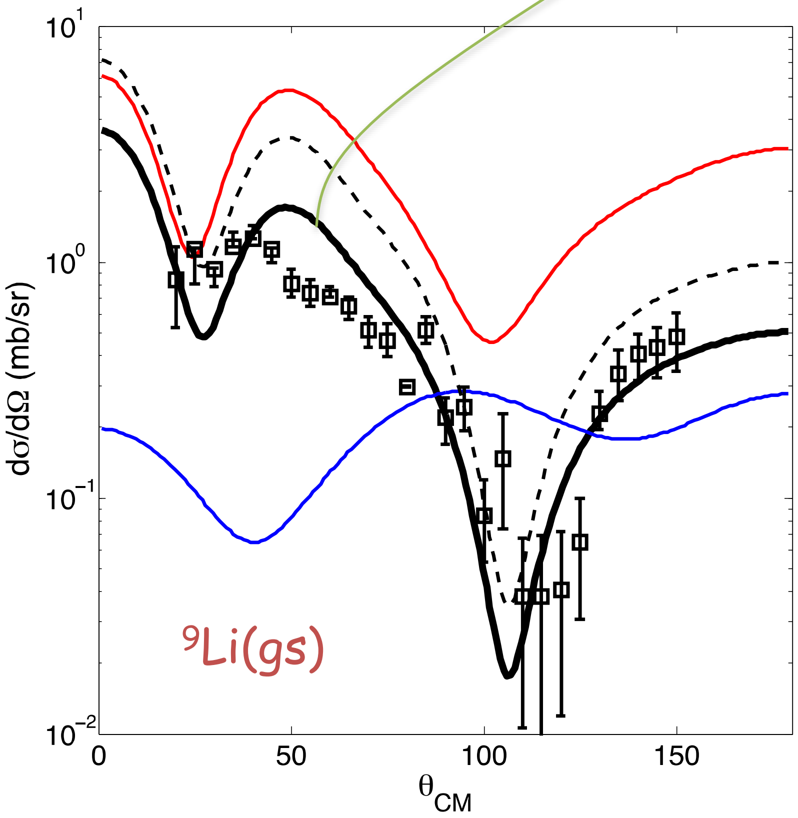
2 low-angular momentum sates of opposite parity at threshold: ideal scenario for PDR

- the PDR plays a central role in providing the glue to bind ^{11}Li
- symbiotic relationship between halo and PDR: the halo provides the PDR scenario, and the PDR holds the halo together

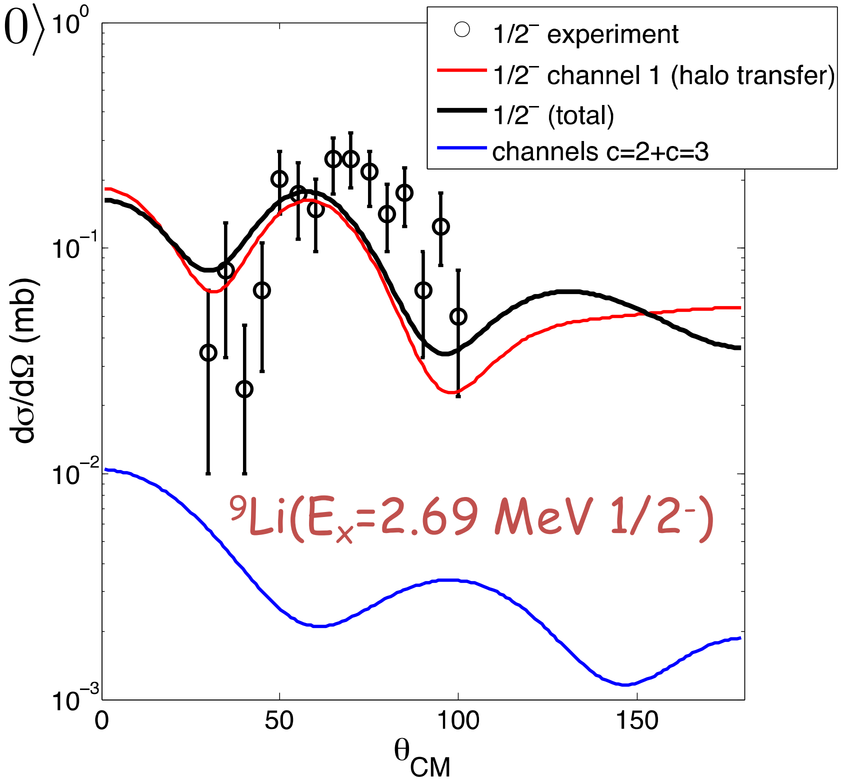
theory confirmed by ^{11}Li(p,t)^{9}Li(gs;E_x=2.69 MeV 1/2$^-$)

GP, Barranco, Vigezzi, Broglia
PRL **105** 172502 (2010)

$$0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$
$$+\,0.7\,|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-; 0\rangle$$
$$+\,0.1\,|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+; 0\rangle$$



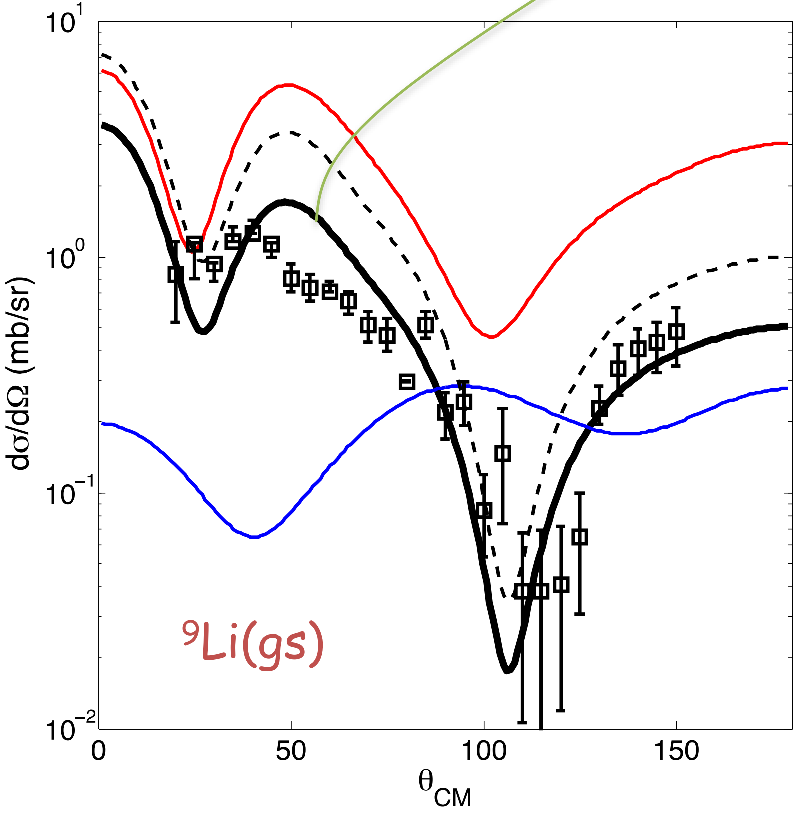
reaction calculation in 2-order DWBA, dominated by successive transfer of the 2 neutrons (E. Vigezzi talk yesterday)

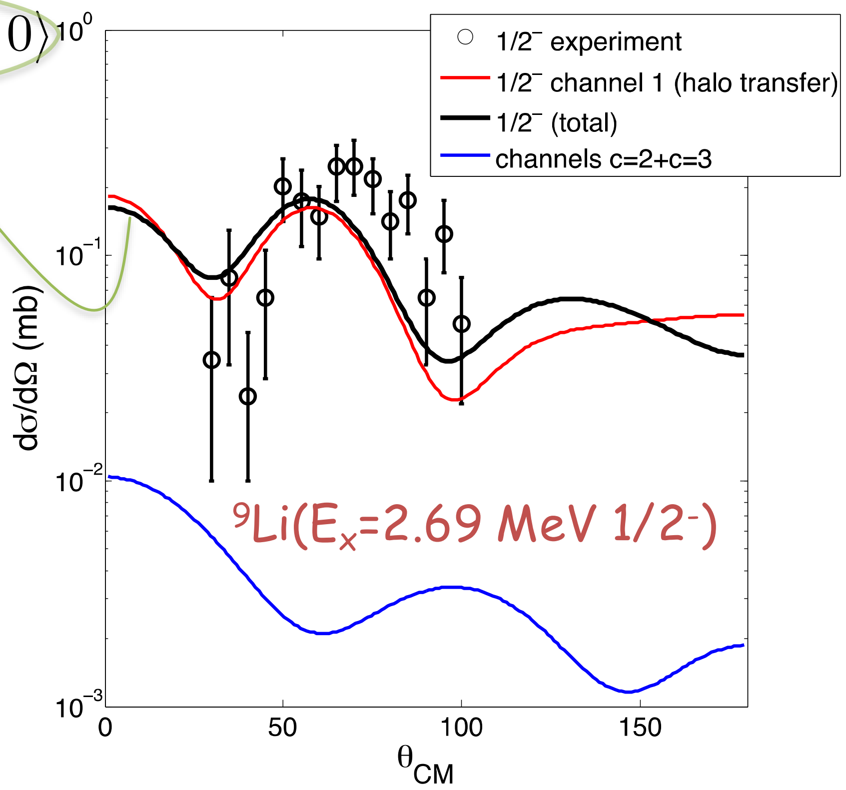


theory confirmed by ^{11}Li(p,t)^{9}Li(gs;E$_x$=2.69 MeV 1/2$^-$)

GP, Barranco, Vigezzi, Broglia
PRL **105** 172502 (2010)

$$0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$
$$+\,0.7\,|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-;0\rangle$$
$$+\,0.1\,|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+;0\rangle$$





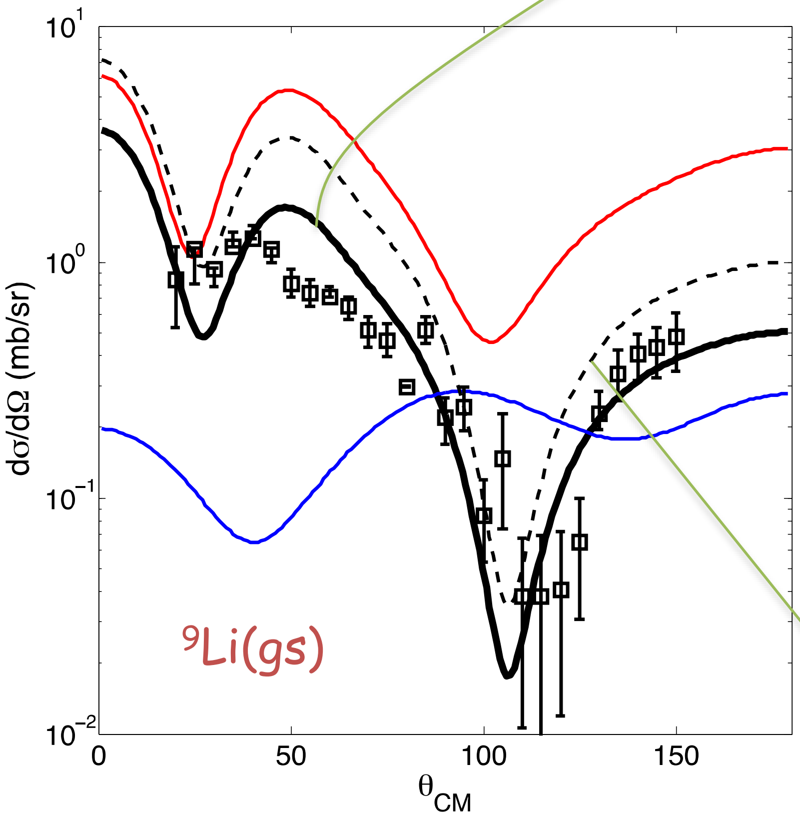
theory confirmed by ^{11}Li(p,t)^{9}Li(gs;E_x=2.69 MeV 1/2$^-$)

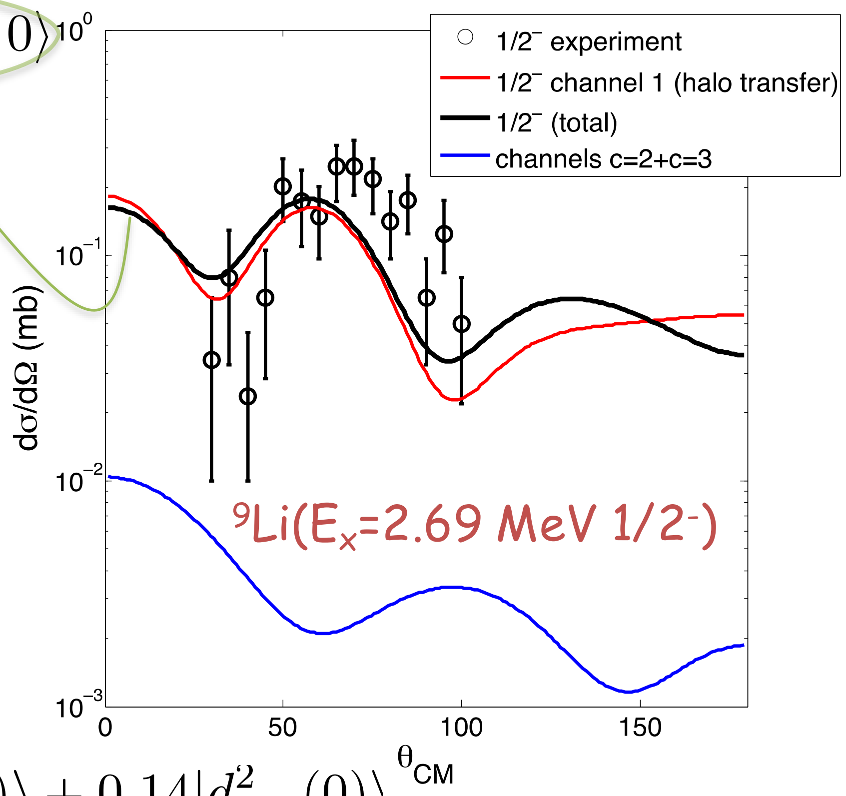
GP, Barranco, Vigezzi, Broglia
PRL **105** 172502 (2010)

$$0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$

$$+\,0.7\,|(p_{1/2},s_{1/2})_{1^-}\otimes 1^-;0\rangle$$

$$+\,0.1\,|(s_{1/2},d_{5/2})_{2^+}\otimes 2^+;0\rangle$$





$$0.63|s^2_{1/2}(0)\rangle + 0.76|p^2_{1/2}(0)\rangle + 0.14|d^2_{1/2}(0)\rangle$$

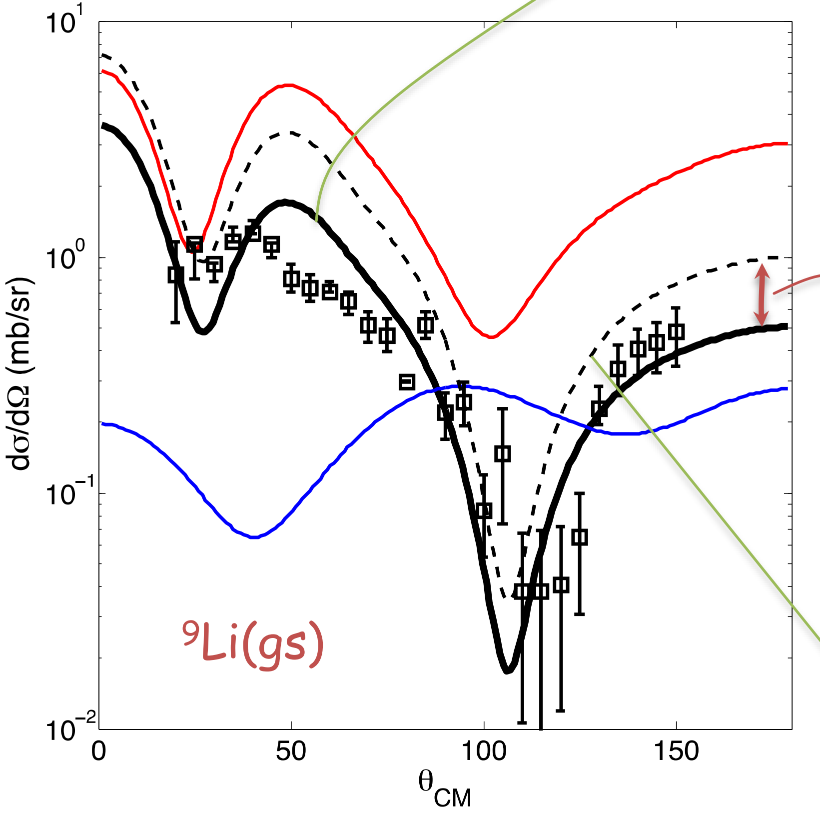
theory confirmed by ^{11}Li(p,t)^{9}Li(gs;E$_x$=2.69 MeV 1/2$^-$)

GP, Barranco, Vigezzi, Broglia
PRL **105** 172502 (2010)

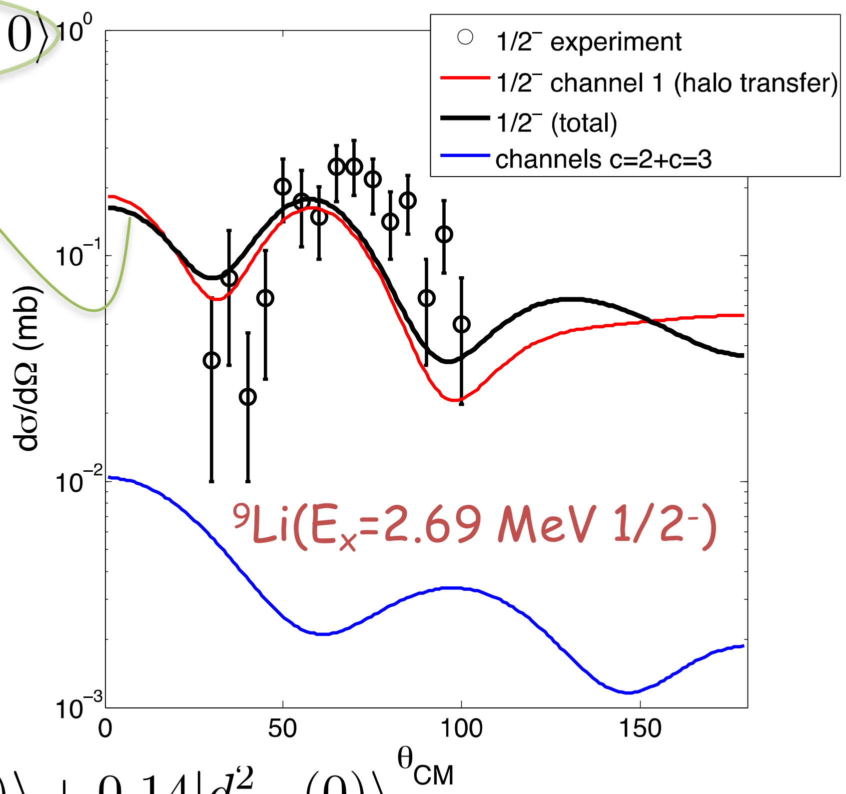
$$0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$

$$+\,0.7\,|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-; 0\rangle$$

$$+\,0.1\,|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+; 0\rangle$$



depletion of pp strength due to coupling with PDR



$$0.63|s^2_{1/2}(0)\rangle + 0.76|p^2_{1/2}(0)\rangle + 0.14|d^2_{1/2}(0)\rangle$$

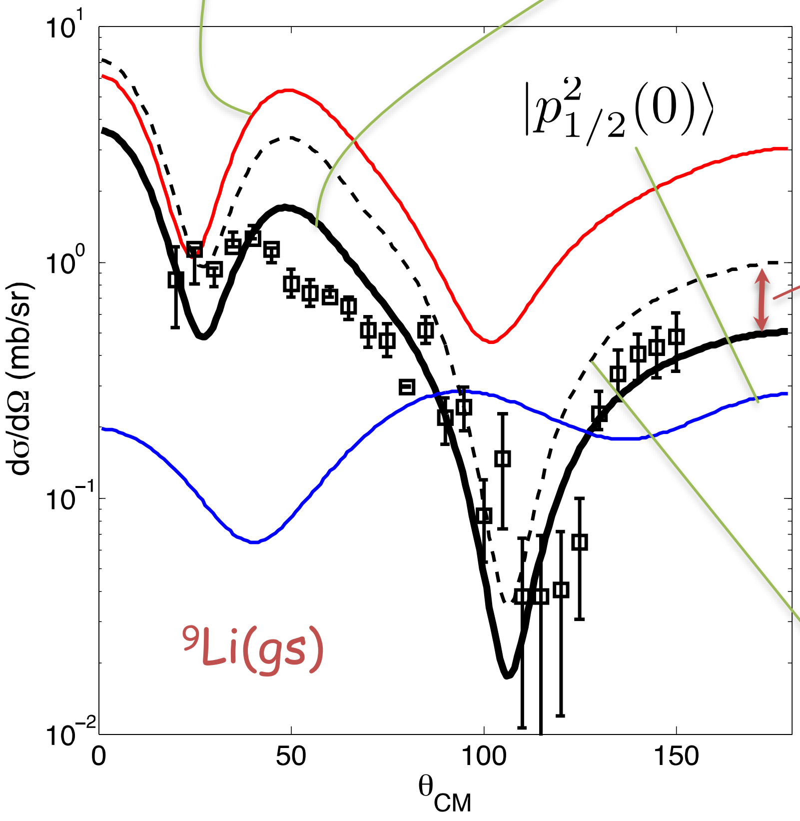
theory confirmed by ^{11}Li(p,t)^{9}Li(gs;E$_x$=2.69 MeV 1/2$^-$)

$$0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$

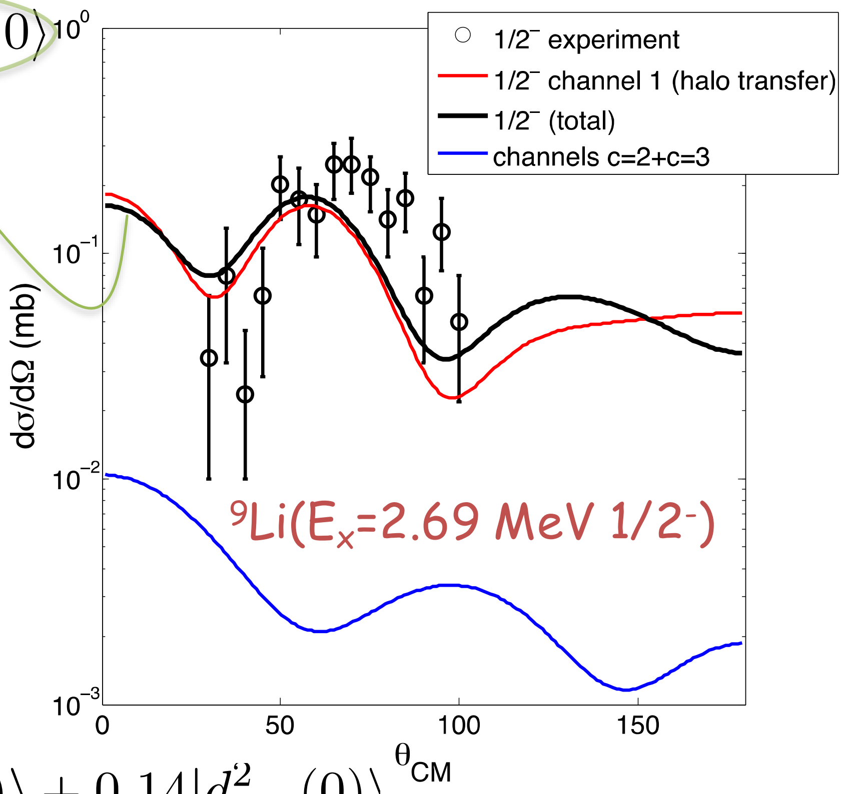
$$+\,0.7\,|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-; 0\rangle$$

$$+\,0.1\,|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+; 0\rangle$$

$$|s^2_{1/2}(0)\rangle$$



depletion of pp strength due to coupling with PDR



$$0.63|s^2_{1/2}(0)\rangle + 0.76|p^2_{1/2}(0)\rangle + 0.14|d^2_{1/2}(0)\rangle$$

The PDR as a two-quasiparticle mode

- The PDR is rather well described in the harmonic approximation (RPA, QRPA) as a two-quasiparticle mode.
- Therefore, PDR in a nucleus A_0 can be better probed with two-quasiparticle fields, i.e., particle-hole (*ph*), particle-particle (*pp*), and hole-hole (*hh*) fields.

ph

Coulomb, inelastic, and γ-induced excitation on A_0:

- A_0(d,d')A_0(PDR)
- A_0(p,p') A_0(PDR)
- A_0(α,α') A_0(PDR)
- A_0(γ,γ') A_0(PDR)
- A_0(n,n') A_0(PDR)
- A_0(X,X') A_0(PDR)

(Vandebrouck talk)

one-nucleon transfer on A_0-1:

- A_0-1(d,p) A_0(PDR)

(Spieker, Weinert, and Khumalo talks)

pp

two-nucleon transfer on A_0-2:

- A_0-2(t,p) A_0(PDR)

proposed in this talk

The PDR as a two-quasiparticle mode

- The PDR is rather well described in the harmonic approximation (RPA, QRPA) as a two-quasiparticle mode.
- Therefore, PDR in a nucleus A_0 can be better probed with two-quasiparticle fields, i.e., particle-hole (*ph*), particle-particle (*pp*), and hole-hole (*hh*) fields.

complementary classification of dipole modes

isovector ⟺ isoscalar

ph ⟺ pp

The PDR as a two-quasiparticle mode

- The PDR is rather well described in the harmonic approximation (RPA, QRPA) as a two-quasiparticle mode.
- Therefore, PDR in a nucleus A_0 can be better probed with two-quasiparticle fields, i.e., particle-hole (*ph*), particle-particle (*pp*), and hole-hole (*hh*) fields.

complementary classification of dipole modes

isovector ↔ isoscalar

ph ↔ pp

GDR? ↔ PDR?

we compute the ^{11}Li PDR structure in RPA

3 representative low-lying dipole RPA peaks

	E=0.65 MeV					E=1.21 MeV					E=2 MeV			
	i	j	X_{ij}	Y_{ij}		i	j	X_{ij}	Y_{ij}		i	j	X_{ij}	Y_{ij}
ν	$2s_{1/2}$	$1p_{1/2}$	−0.780	0.078	ν	$2s_{1/2}$	$1p_{1/2}$	−0.119	0.048	ν	$3s_{1/2}$	$1p_{1/2}$	−0.118	0.040
ν	$3s_{1/2}$	$1p_{1/2}$	0.479	0.108	ν	$3s_{1/2}$	$1p_{1/2}$	−0.748	0.074	ν	$4s_{1/2}$	$1p_{1/2}$	−0.821	0.046
ν	$4s_{1/2}$	$1p_{1/2}$	0.220	0.106	ν	$4s_{1/2}$	$1p_{1/2}$	0.410	0.080	ν	$5s_{1/2}$	$1p_{1/2}$	0.250	0.046
ν	$5s_{1/2}$	$1p_{1/2}$	0.144	0.093	ν	$5s_{1/2}$	$1p_{1/2}$	0.181	0.075	ν	$6s_{1/2}$	$1p_{1/2}$	0.116	0.043
ν	$6s_{1/2}$	$1p_{1/2}$	0.106	0.080	ν	$6s_{1/2}$	$1p_{1/2}$	0.117	0.067	ν	$1p_{3/2}$	$4d_{5/2}$	0.144	0.081
ν	$1p_{3/2}$	$4d_{5/2}$	0.166	0.139	ν	$1p_{3/2}$	$4d_{5/2}$	0.170	0.121	ν	$1p_{3/2}$	$5d_{5/2}$	0.201	0.125
ν	$1p_{3/2}$	$5d_{5/2}$	0.241	0.208	ν	$1p_{3/2}$	$5d_{5/2}$	0.243	0.183	ν	$1p_{3/2}$	$6d_{5/2}$	0.201	0.135
ν	$1p_{3/2}$	$6d_{5/2}$	0.250	0.221	ν	$1p_{3/2}$	$6d_{5/2}$	0.249	0.196	ν	$1p_{3/2}$	$7d_{5/2}$	0.156	0.112
ν	$1p_{3/2}$	$7d_{5/2}$	0.199	0.180	ν	$1p_{3/2}$	$7d_{5/2}$	0.196	0.161	ν	$1p_{3/2}$	$8d_{5/2}$	0.113	0.085
ν	$1p_{3/2}$	$8d_{5/2}$	0.148	0.135	ν	$1p_{3/2}$	$8d_{5/2}$	0.144	0.122	ν	$1p_{1/2}$	$9d_{3/2}$	−0.126	0.014
ν	$1p_{3/2}$	$9d_{5/2}$	0.110	0.102	ν	$1p_{3/2}$	$9d_{5/2}$	0.107	0.093	ν	$1p_{1/2}$	$10d_{3/2}$	0.187	0.026
ν	$1p_{1/2}$	$4d_{3/2}$	0.103	0.075	ν	$1p_{1/2}$	$2d_{3/2}$	0.168	0.024	ν	$1p_{1/2}$	$11d_{3/2}$	0.121	0.040
ν	$1p_{1/2}$	$5d_{3/2}$	0.119	0.095	ν	$1p_{1/2}$	$3d_{3/2}$	0.114	0.043	ν	$1p_{1/2}$	$12d_{3/2}$	0.113	0.053
ν	$1p_{1/2}$	$6d_{3/2}$	0.128	0.108	ν	$1p_{1/2}$	$4d_{3/2}$	0.117	0.063	ν	$1p_{1/2}$	$13d_{3/2}$	0.111	0.064
ν	$1p_{1/2}$	$7d_{3/2}$	0.128	0.112	ν	$1p_{1/2}$	$5d_{3/2}$	0.126	0.081	ν	$1p_{1/2}$	$14d_{3/2}$	0.104	0.068
ν	$1p_{1/2}$	$8d_{3/2}$	0.117	0.106	ν	$1p_{1/2}$	$6d_{3/2}$	0.131	0.094	π	$1p_{3/2}$	$1d_{5/2}$	0.245	0.210
π	$2s_{1/2}$	$1p_{3/2}$	−0.136	−0.131	ν	$1p_{1/2}$	$7d_{3/2}$	0.128	0.099					
π	$1p_{3/2}$	$1d_{5/2}$	0.337	0.322	ν	$1p_{1/2}$	$8d_{3/2}$	0.116	0.094					
					π	$2s_{1/2}$	$1p_{3/2}$	−0.130	−0.12					
					π	$1p_{3/2}$	$1d_{5/2}$	0.322	0.294					

IOP Publishing

Physica Scripta

Phys. Scr. **94** (2019) 114002 (18pp)

https://doi.org/10.1088/1402-4896/ab2431

Pygmy resonances: what's in a name?

R A Broglia[1,2,7], **F Barranco**[3], **A Idini**[4], **G Potel**[5] **and E Vigezzi**[6]

we compute the ^{11}Li PDR structure in RPA

3 representative low-lying dipole RPA peaks

E=0.65 MeV					E=1.21 MeV					E=2 MeV				
	i	j	X_{ij}	Y_{ij}		i	j	X_{ij}	Y_{ij}		i	j	X_{ij}	Y_{ij}
ν	$2s_{1/2}$	$1p_{1/2}$	−0.780	0.078	ν	$2s_{1/2}$	$1p_{1/2}$	−0.119	0.048	ν	$3s_{1/2}$	$1p_{1/2}$	−0.118	0.040
ν	$3s_{1/2}$	$1p_{1/2}$	0.479	0.108	ν	$3s_{1/2}$	$1p_{1/2}$	−0.748	0.074	ν	$4s_{1/2}$	$1p_{1/2}$	−0.821	0.046
ν	$4s_{1/2}$	$1p_{1/2}$	0.220	0.106	ν	$4s_{1/2}$	$1p_{1/2}$	0.410	0.080	ν	$5s_{1/2}$	$1p_{1/2}$	0.250	0.046
ν	$5s_{1/2}$	$1p_{1/2}$	0.144	0.093	ν	$5s_{1/2}$	$1p_{1/2}$	0.181	0.075	ν	$6s_{1/2}$	$1p_{1/2}$	0.116	0.043
ν	$6s_{1/2}$	$1p_{1/2}$	0.106	0.080	ν	$6s_{1/2}$	$1p_{1/2}$	0.117	0.067	ν	$1p_{3/2}$	$4d_{5/2}$	0.144	0.081
ν	$1p_{3/2}$	$4d_{5/2}$	0.166	0.139	ν	$1p_{3/2}$	$4d_{5/2}$	0.170	0.121	ν	$1p_{3/2}$	$5d_{5/2}$	0.201	0.125
ν	$1p_{3/2}$	$5d_{5/2}$	0.241	0.208	ν	$1p_{3/2}$	$5d_{5/2}$	0.243	0.183	ν	$1p_{3/2}$	$6d_{5/2}$	0.201	0.135
ν	$1p_{3/2}$	$6d_{5/2}$	0.250	0.221	ν	$1p_{3/2}$	$6d_{5/2}$	0.249	0.196	ν	$1p_{3/2}$	$7d_{5/2}$	0.156	0.112
ν	$1p_{3/2}$	$7d_{5/2}$	0.199	0.180	ν	$1p_{3/2}$	$7d_{5/2}$	0.196	0.161	ν	$1p_{3/2}$	$8d_{5/2}$	0.113	0.085
ν	$1p_{3/2}$	$8d_{5/2}$	0.148	0.135	ν	$1p_{3/2}$	$8d_{5/2}$	0.144	0.122	ν	$1p_{1/2}$	$9d_{3/2}$	−0.126	0.014
ν	$1p_{3/2}$	$9d_{5/2}$	0.110	0.102	ν	$1p_{3/2}$	$9d_{5/2}$	0.107	0.093	ν	$1p_{1/2}$	$10d_{3/2}$	0.187	0.026
ν	$1p_{1/2}$	$4d_{3/2}$	0.103	0.075	ν	$1p_{1/2}$	$2d_{3/2}$	0.168	0.024	ν	$1p_{1/2}$	$11d_{3/2}$	0.121	0.040
ν	$1p_{1/2}$	$5d_{3/2}$	0.119	0.095	ν	$1p_{1/2}$	$3d_{3/2}$	0.114	0.043	ν	$1p_{1/2}$	$12d_{3/2}$	0.113	0.053
ν	$1p_{1/2}$	$6d_{3/2}$	0.128	0.108	ν	$1p_{1/2}$	$4d_{3/2}$	0.117	0.063	ν	$1p_{1/2}$	$13d_{3/2}$	0.111	0.064
ν	$1p_{1/2}$	$7d_{3/2}$	0.128	0.112	ν	$1p_{1/2}$	$5d_{3/2}$	0.126	0.081	ν	$1p_{1/2}$	$14d_{3/2}$	0.104	0.068
ν	$1p_{1/2}$	$8d_{3/2}$	0.117	0.106	ν	$1p_{1/2}$	$6d_{3/2}$	0.131	0.094	π	$1p_{3/2}$	$1d_{5/2}$	0.245	0.210
π	$2s_{1/2}$	$1p_{3/2}$	−0.136	−0.131	ν	$1p_{1/2}$	$7d_{3/2}$	0.128	0.099					
π	$1p_{3/2}$	$1d_{5/2}$	0.337	0.322	ν	$1p_{1/2}$	$8d_{3/2}$	0.116	0.094					
					π	$2s_{1/2}$	$1p_{3/2}$	−0.130	−0.12					
					π	$1p_{3/2}$	$1d_{5/2}$	0.322	0.294					


IOP Publishing Physica Scripta

Phys. Scr. **94** (2019) 114002 (18pp) https://doi.org/10.1088/1402-4896/ab2431

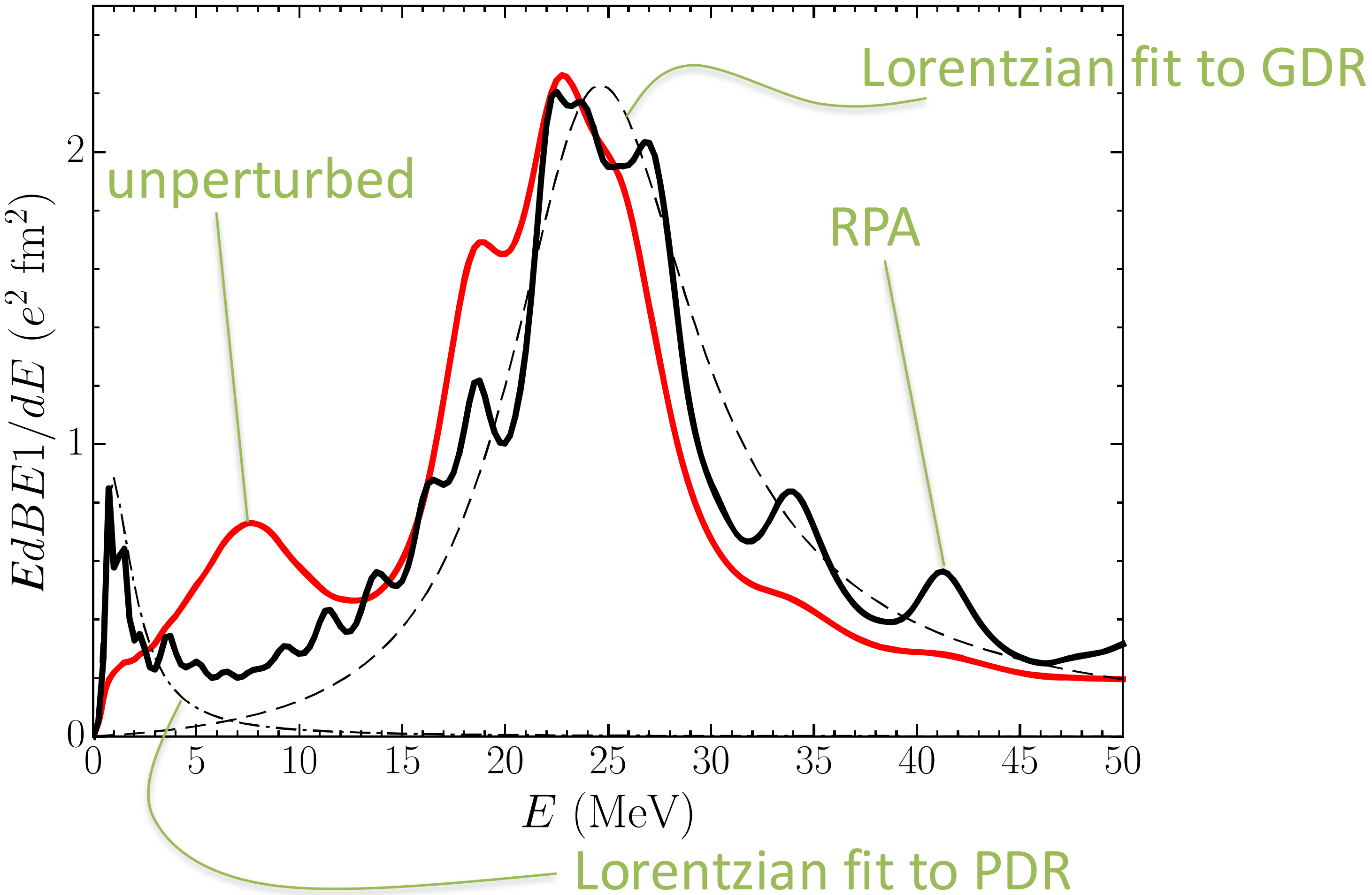
Pygmy resonances: what's in a name?

R A Broglia[1,2,7], **F Barranco**[3], **A Idini**[4], **G Potel**[5] **and E Vigezzi**[6]

largest components are 2-quasiparticle neutron halo $(s_{1/2}\ p_{1/2})_{1^-}$ states

the PDR exhausts about 8% of the EWSR

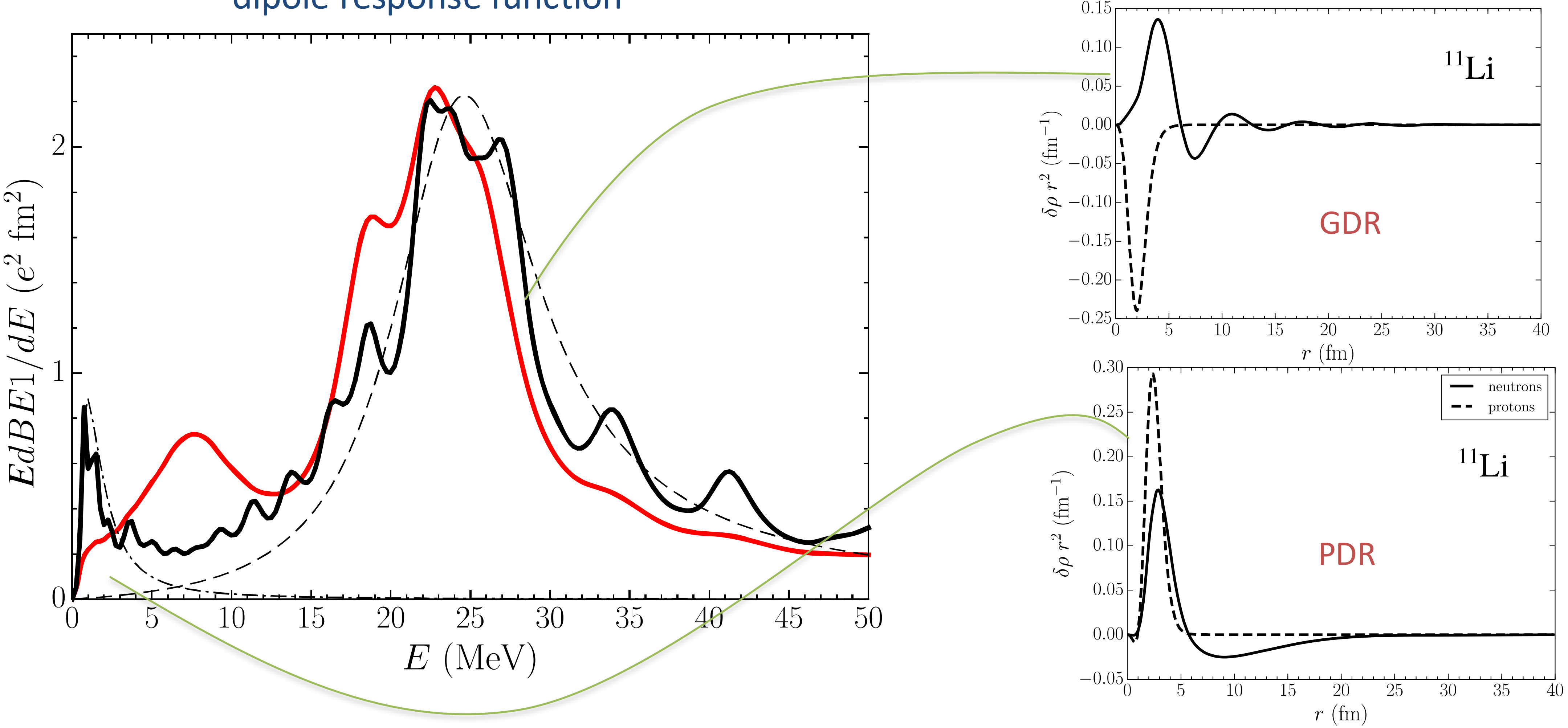
dipole response function



the PDR exhausts about 8% of the EWSR

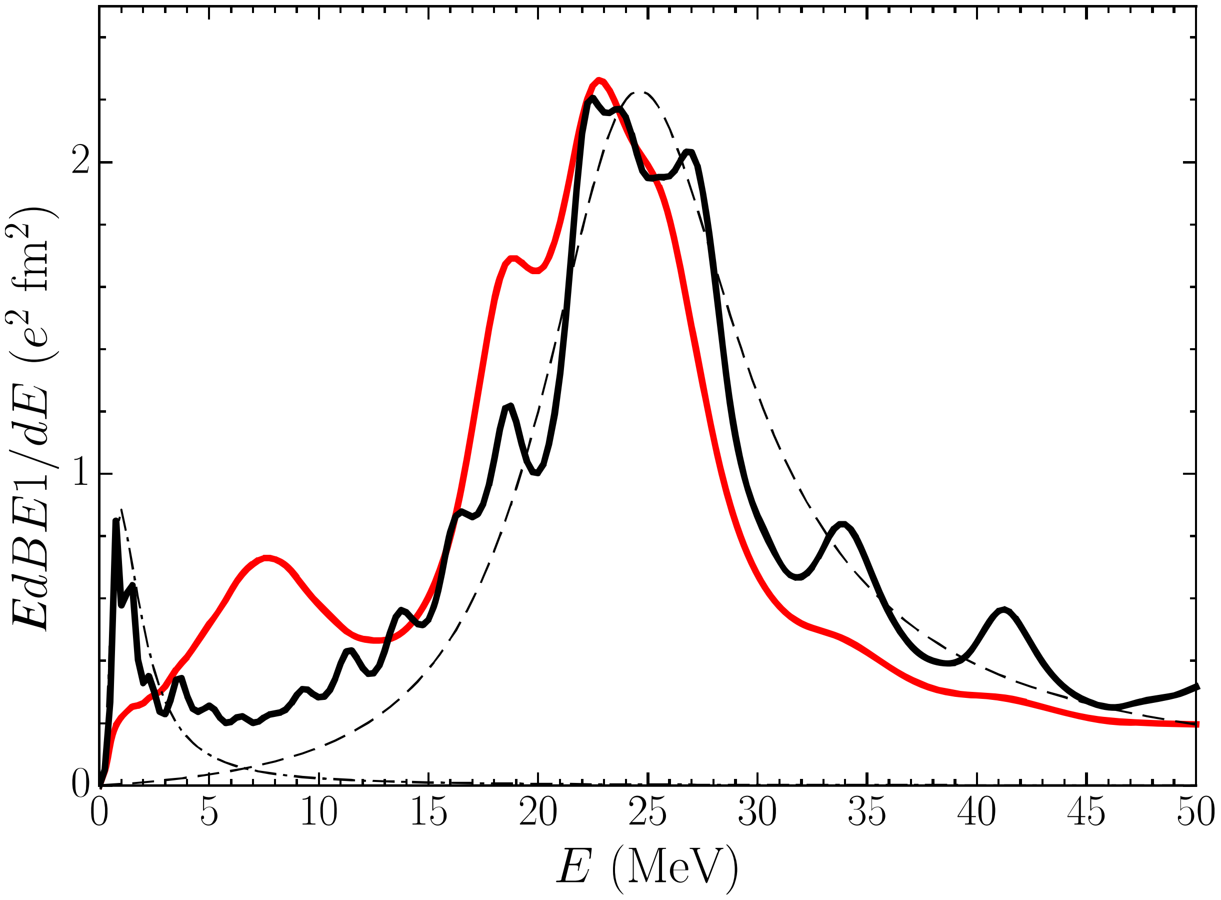
dipole response function

transition densities



the PDR exhausts about 8% of the EWSR

dipole response function

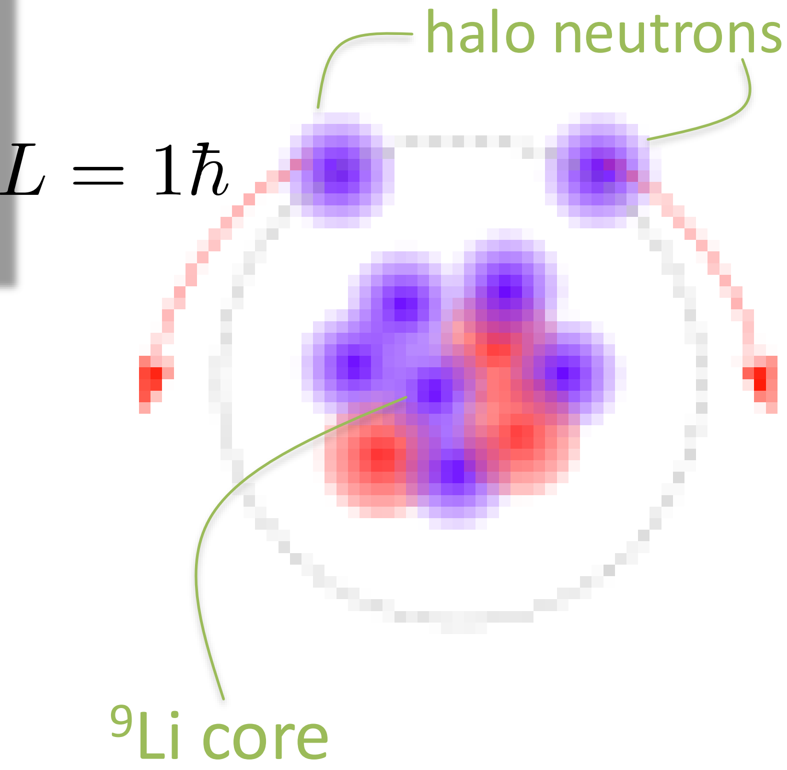


experiment approved at FRIB to probe the whole dipole response with (*p*,*p*’). Spokepersons: Ayyad, Zamora

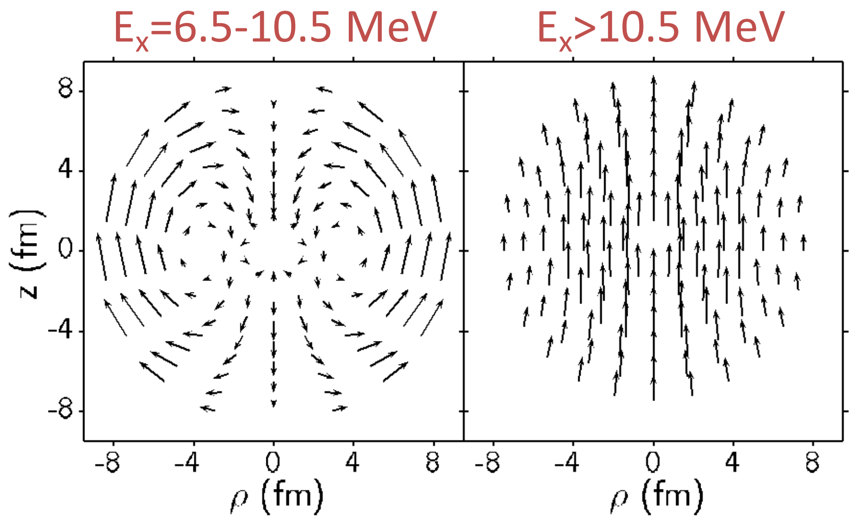
the PDR has the structure of an elementary quantum vortex

structure of a multipolar (1$^-$) Cooper pair:

elementary quantum vortex



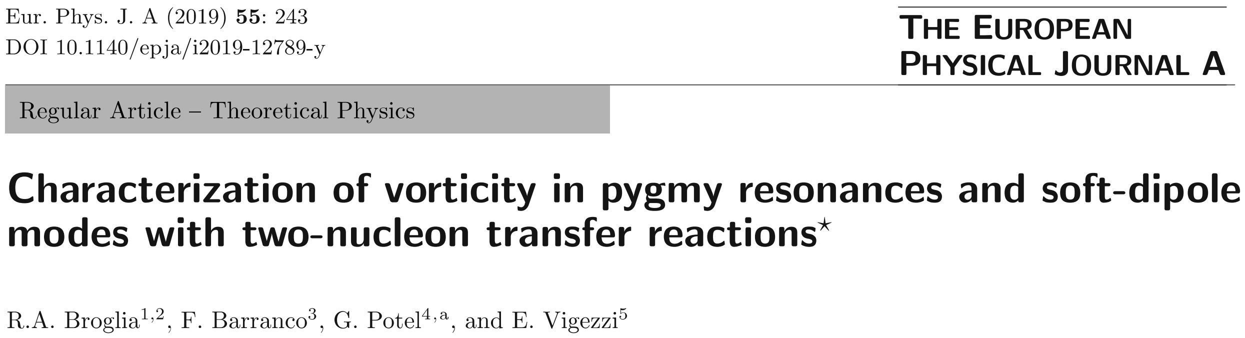
velocity field of ^{208}Pb dipole states



Ryezayeva *et al.* PRL **89** (2002) 272502

- Is vorticity a signature of PDR?
- Is there an experimental signature for it?

Probing the ^{11}Li PDR with 2-neutron transfer



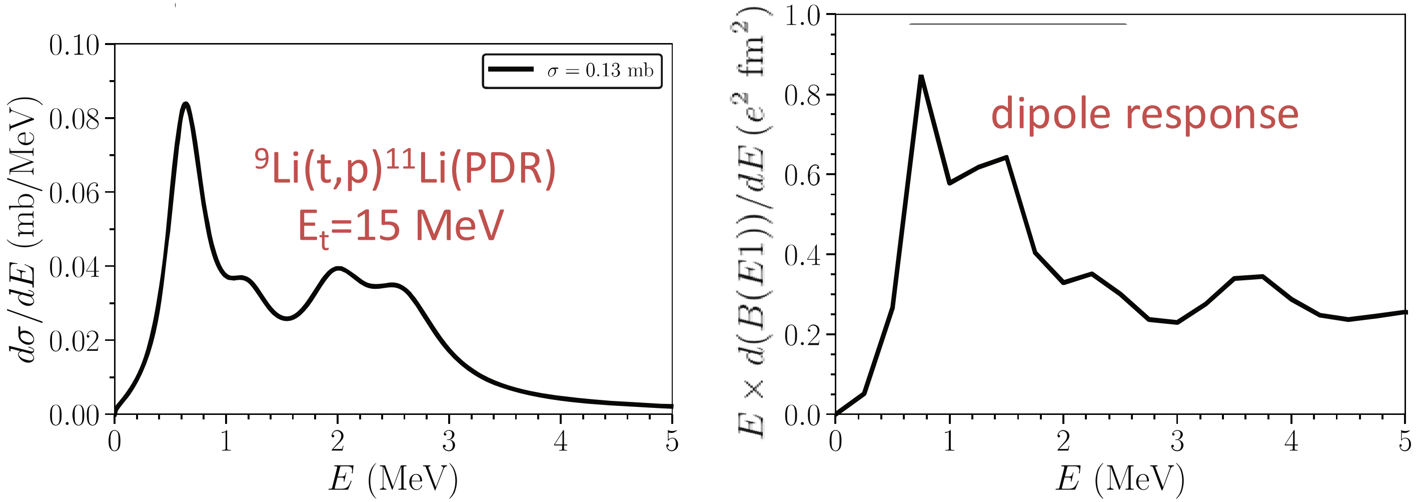
Eur. Phys. J. A (2019) **55**: 243
DOI 10.1140/epja/i2019-12789-y

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Theoretical Physics

Characterization of vorticity in pygmy resonances and soft-dipole modes with two-nucleon transfer reactions*

R.A. Broglia[1,2], F. Barranco[3], G. Potel[4,a], and E. Vigezzi[5]

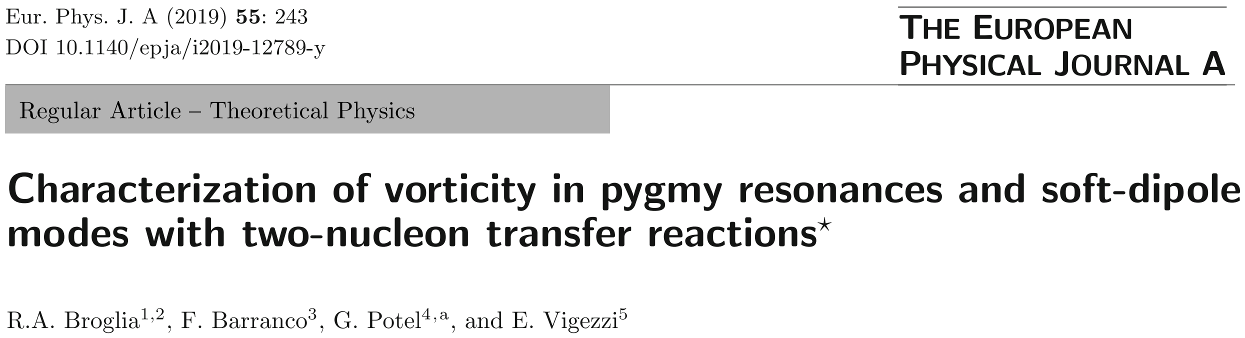


^{9}Li(t,p)^{11}Li(PDR)
E_t=15 MeV

dipole response

- we predict the population of the PDR with the 2-neutron transfer reaction ^{9}Li(t,p)^{11}Li(PDR), with cross section σ=0.3mb
- shape of differential cross section very similar to that of the dipole response
- absolute value of cross section is a measure of the pp nature of the PDR

Probing the ^{11}Li PDR with 2-neutron transfer



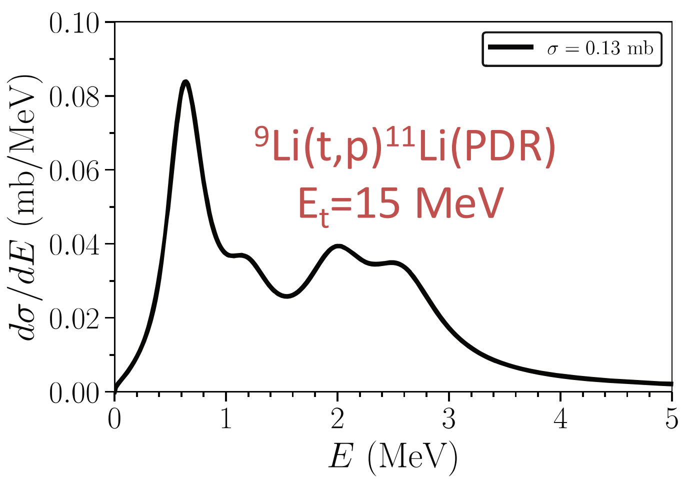
Eur. Phys. J. A (2019) **55**: 243
DOI 10.1140/epja/i2019-12789-y

THE EUROPEAN PHYSICAL JOURNAL A

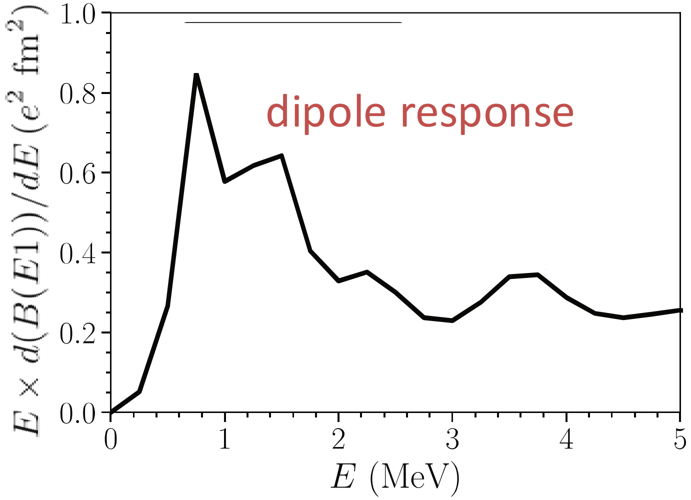
Regular Article – Theoretical Physics

Characterization of vorticity in pygmy resonances and soft-dipole modes with two-nucleon transfer reactions*

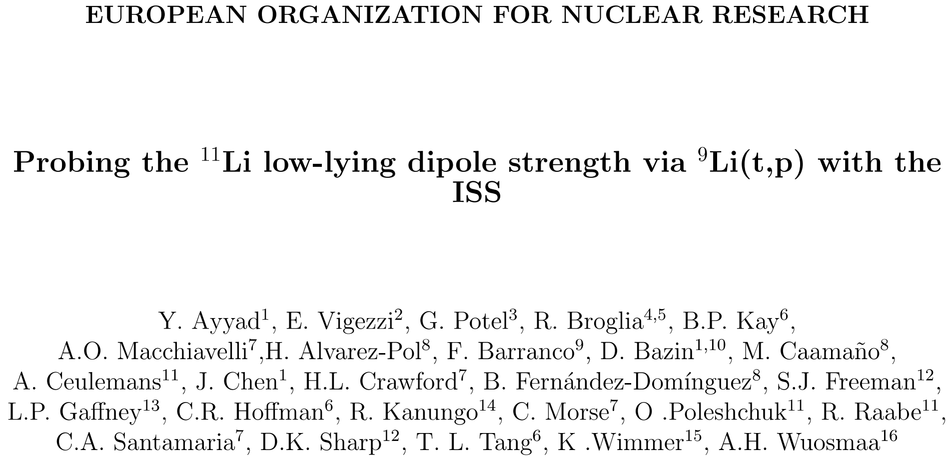
R.A. Broglia[1,2], F. Barranco[3], G. Potel[4,a], and E. Vigezzi[5]



^{9}Li(t,p)^{11}Li(PDR)
E_t=15 MeV



dipole response



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Probing the ^{11}Li low-lying dipole strength via ^{9}Li(t,p) with the ISS

Y. Ayyad[1], E. Vigezzi[2], G. Potel[3], R. Broglia[4,5], B.P. Kay[6],
A.O. Macchiavelli[7],H. Alvarez-Pol[8], F. Barranco[9], D. Bazin[1,10], M. Caamaño[8],
A. Ceulemans[11], J. Chen[1], H.L. Crawford[7], B. Fernández-Domínguez[8], S.J. Freeman[12],
L.P. Gaffney[13], C.R. Hoffman[6], R. Kanungo[14], C. Morse[7], O .Poleshchuk[11], R. Raabe[11],
C.A. Santamaria[7], D.K. Sharp[12], T. L. Tang[6], K .Wimmer[15], A.H. Wuosmaa[16]

experiment approved at ISOLDE facility (CERN). Spokepersons: Ayyad, Vigezzi

Conclusions

- the PDR plays an important role in the structure of the exotic two-neutron halo nucleus ^{11}Li: halo-PDR symbiotic nature
- our calculations point to a strong ***pp*** component of the PDR, as opposed to the more ***ph*** nature of the GDR

complementary classification of dipole modes

isovector ⟺ isoscalar
ph ⟺ pp
GDR? ⟺ PDR?

talks by Vandebrouck, Spieker, Weinert, Khumalo

- PDR of ^{11}Li as a vortical excitation of the halo. Extrapolable to neutron skins?
- Approved experiments: ^{11}Li(p,p')^{11}Li* @ FRIB, and ^{9}Li(t,p)^{11}Li(PDR) @ ISOLDE

- along with (d,p) and (n,n'), (t,p) to join the ranks of novel probes to the PDR
- personal wish: (t,p) measurements on nuclei with neutron skin. Maybe with new FSU triton beam?

we compute the ^{11}Li PDR structure and the ^{9}Li $(t,p)^{11}$Li(PDR) cross section

3 representative low-lying dipole RPA peaks

E=0.65 MeV

	i	j	X_{ij}	Y_{ij}
ν	$2s_{1/2}$	$1p_{1/2}$	-0.780	0.078
ν	$3s_{1/2}$	$1p_{1/2}$	0.479	0.108
ν	$4s_{1/2}$	$1p_{1/2}$	0.220	0.106
ν	$5s_{1/2}$	$1p_{1/2}$	0.144	0.093
ν	$6s_{1/2}$	$1p_{1/2}$	0.106	0.080
ν	$1p_{3/2}$	$4d_{5/2}$	0.166	0.139
ν	$1p_{3/2}$	$5d_{5/2}$	0.241	0.208
ν	$1p_{3/2}$	$6d_{5/2}$	0.250	0.221
ν	$1p_{3/2}$	$7d_{5/2}$	0.199	0.180
ν	$1p_{3/2}$	$8d_{5/2}$	0.148	0.135
ν	$1p_{3/2}$	$9d_{5/2}$	0.110	0.102
ν	$1p_{1/2}$	$4d_{3/2}$	0.103	0.075
ν	$1p_{1/2}$	$5d_{3/2}$	0.119	0.095
ν	$1p_{1/2}$	$6d_{3/2}$	0.128	0.108
ν	$1p_{1/2}$	$7d_{3/2}$	0.128	0.112
ν	$1p_{1/2}$	$8d_{3/2}$	0.117	0.106
π	$2s_{1/2}$	$1p_{3/2}$	-0.136	-0.131
π	$1p_{3/2}$	$1d_{5/2}$	0.337	0.322

E=1.21 MeV

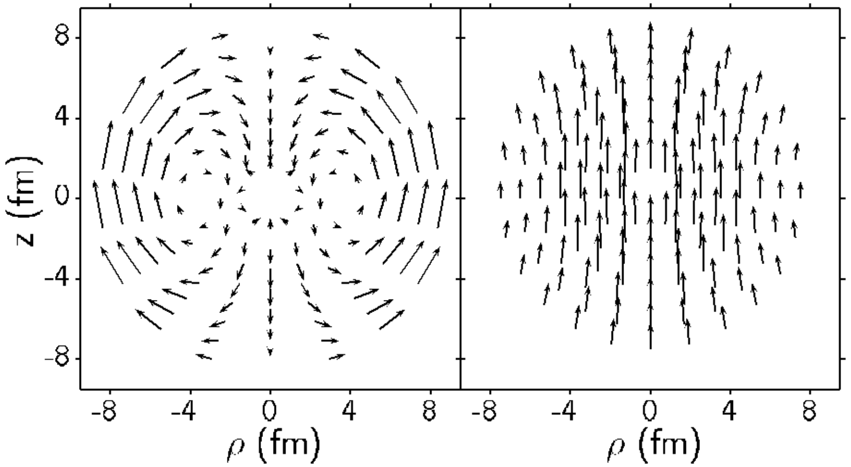
	i	j	X_{ij}	Y_{ij}
ν	$2s_{1/2}$	$1p_{1/2}$	-0.119	0.048
ν	$3s_{1/2}$	$1p_{1/2}$	-0.748	0.074
ν	$4s_{1/2}$	$1p_{1/2}$	0.410	0.080
ν	$5s_{1/2}$	$1p_{1/2}$	0.181	0.075
ν	$6s_{1/2}$	$1p_{1/2}$	0.117	0.067
ν	$1p_{3/2}$	$4d_{5/2}$	0.170	0.121
ν	$1p_{3/2}$	$5d_{5/2}$	0.243	0.183
ν	$1p_{3/2}$	$6d_{5/2}$	0.249	0.196
ν	$1p_{3/2}$	$7d_{5/2}$	0.196	0.161
ν	$1p_{3/2}$	$8d_{5/2}$	0.144	0.122
ν	$1p_{3/2}$	$9d_{5/2}$	0.107	0.093
ν	$1p_{1/2}$	$2d_{3/2}$	0.168	0.024
ν	$1p_{1/2}$	$3d_{3/2}$	0.114	0.043
ν	$1p_{1/2}$	$4d_{3/2}$	0.117	0.063
ν	$1p_{1/2}$	$5d_{3/2}$	0.126	0.081
ν	$1p_{1/2}$	$6d_{3/2}$	0.131	0.094
ν	$1p_{1/2}$	$7d_{3/2}$	0.128	0.099
ν	$1p_{1/2}$	$8d_{3/2}$	0.116	0.094
π	$2s_{1/2}$	$1p_{3/2}$	-0.130	-0.12
π	$1p_{3/2}$	$1d_{5/2}$	0.322	0.294

E=2 MeV

	i	j	X_{ij}	Y_{ij}
ν	$3s_{1/2}$	$1p_{1/2}$	-0.118	0.040
ν	$4s_{1/2}$	$1p_{1/2}$	-0.821	0.046
ν	$5s_{1/2}$	$1p_{1/2}$	0.250	0.046
ν	$6s_{1/2}$	$1p_{1/2}$	0.116	0.043
ν	$1p_{3/2}$	$4d_{5/2}$	0.144	0.081
ν	$1p_{3/2}$	$5d_{5/2}$	0.201	0.125
ν	$1p_{3/2}$	$6d_{5/2}$	0.201	0.135
ν	$1p_{3/2}$	$7d_{5/2}$	0.156	0.112
ν	$1p_{3/2}$	$8d_{5/2}$	0.113	0.085
ν	$1p_{1/2}$	$9d_{3/2}$	-0.126	0.014
ν	$1p_{1/2}$	$10d_{3/2}$	0.187	0.026
ν	$1p_{1/2}$	$11d_{3/2}$	0.121	0.040
ν	$1p_{1/2}$	$12d_{3/2}$	0.113	0.053
ν	$1p_{1/2}$	$13d_{3/2}$	0.111	0.064
ν	$1p_{1/2}$	$14d_{3/2}$	0.104	0.068
π	$1p_{3/2}$	$1d_{5/2}$	0.245	0.210

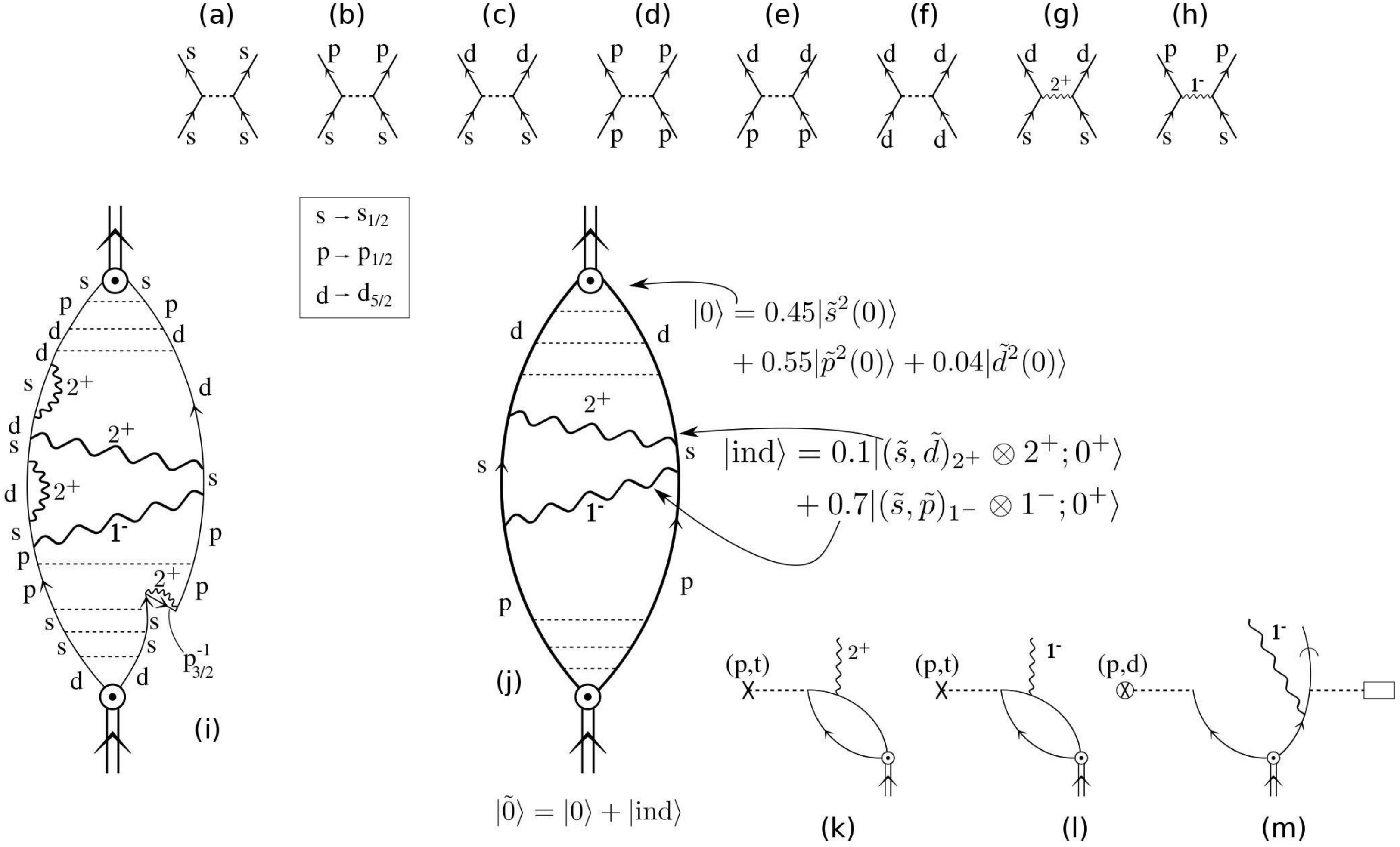
velocity field of ^{208}Pb dipole states

E_x=6.5-10.5 MeV E_x>10.5 MeV



Ryezayeva *et al.* PRL **89** (2002) 272502

Ground state of ^{11}Li



s → $s_{1/2}$
p → $p_{1/2}$
d → $d_{5/2}$

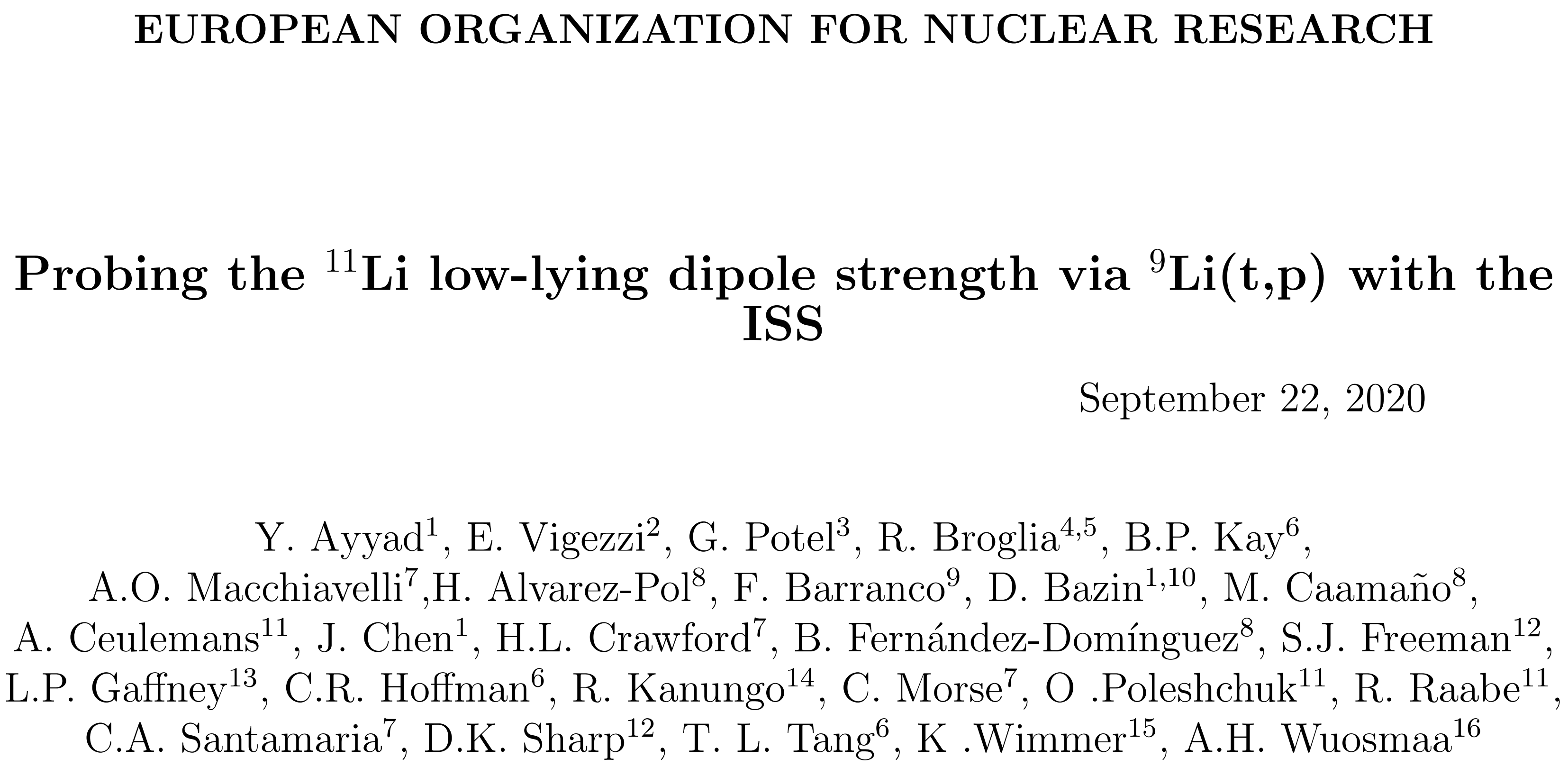
$$|0\rangle = 0.45|\tilde{s}^2(0)\rangle + 0.55|\tilde{p}^2(0)\rangle + 0.04|\tilde{d}^2(0)\rangle$$

$$|\mathrm{ind}\rangle = 0.1|(\tilde{s},\tilde{d})_{2^+} \otimes 2^+; 0^+\rangle + 0.7|(\tilde{s},\tilde{p})_{1^-} \otimes 1^-; 0^+\rangle$$

$$|\tilde{0}\rangle = |0\rangle + |\mathrm{ind}\rangle$$

we compute the ^{11}Li PDR structure and the ^{9}Li (t,p)^{11}Li(PDR) cross section

proposal to measure ^{9}Li(*t*,*p*)^{11}Li(PDR) approved at ISOLDE



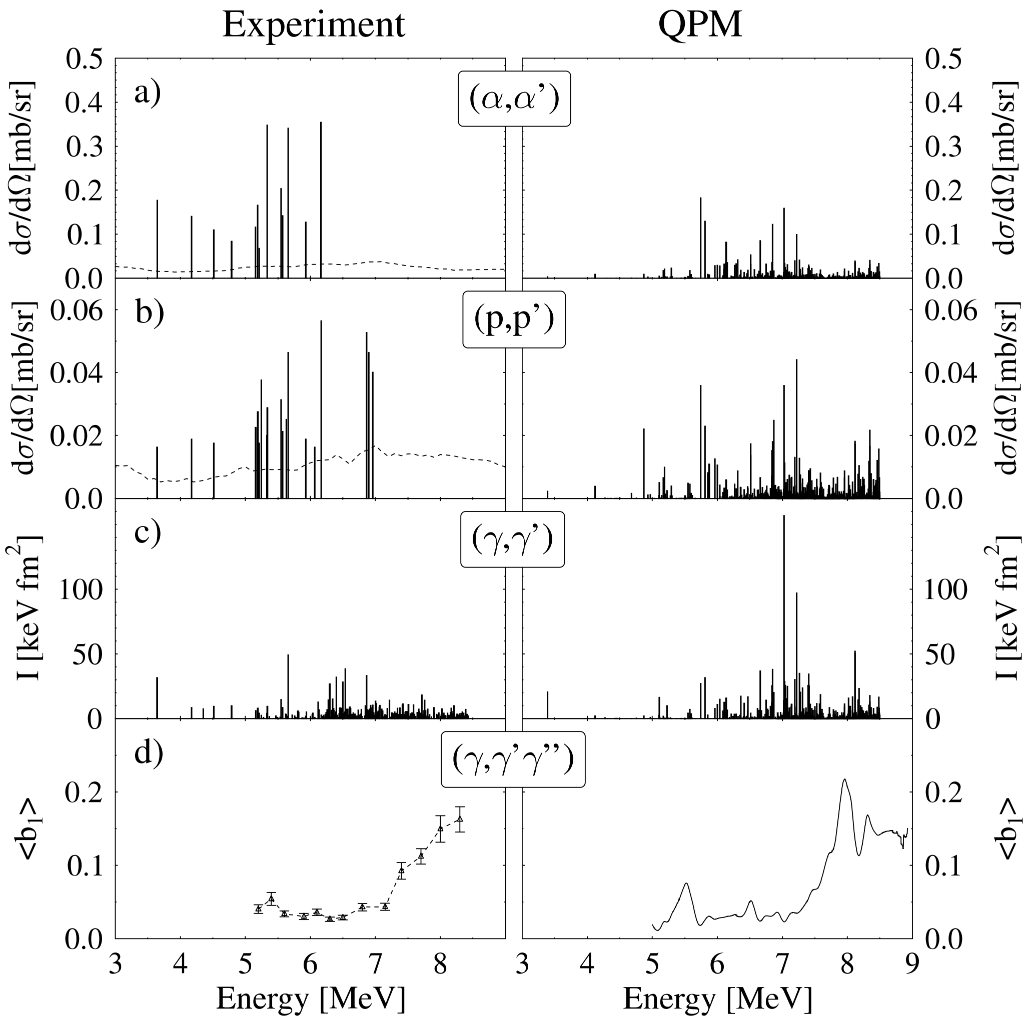
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Probing the ^{11}Li low-lying dipole strength via ^{9}Li(t,p) with the ISS

September 22, 2020

Y. Ayyad[1], E. Vigezzi[2], G. Potel[3], R. Broglia[4,5], B.P. Kay[6],
A.O. Macchiavelli[7],H. Alvarez-Pol[8], F. Barranco[9], D. Bazin[1,10], M. Caamaño[8],
A. Ceulemans[11], J. Chen[1], H.L. Crawford[7], B. Fernández-Domínguez[8], S.J. Freeman[12],
L.P. Gaffney[13], C.R. Hoffman[6], R. Kanungo[14], C. Morse[7], O .Poleshchuk[11], R. Raabe[11],
C.A. Santamaria[7], D.K. Sharp[12], T. L. Tang[6], K .Wimmer[15], A.H. Wuosmaa[16]

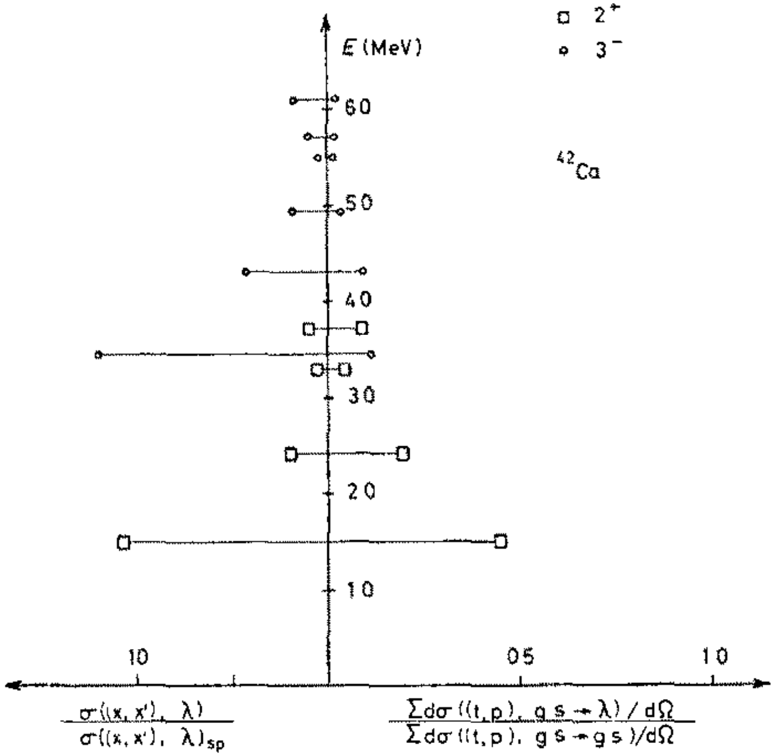
the structure of the PDR can be addressed with different probes

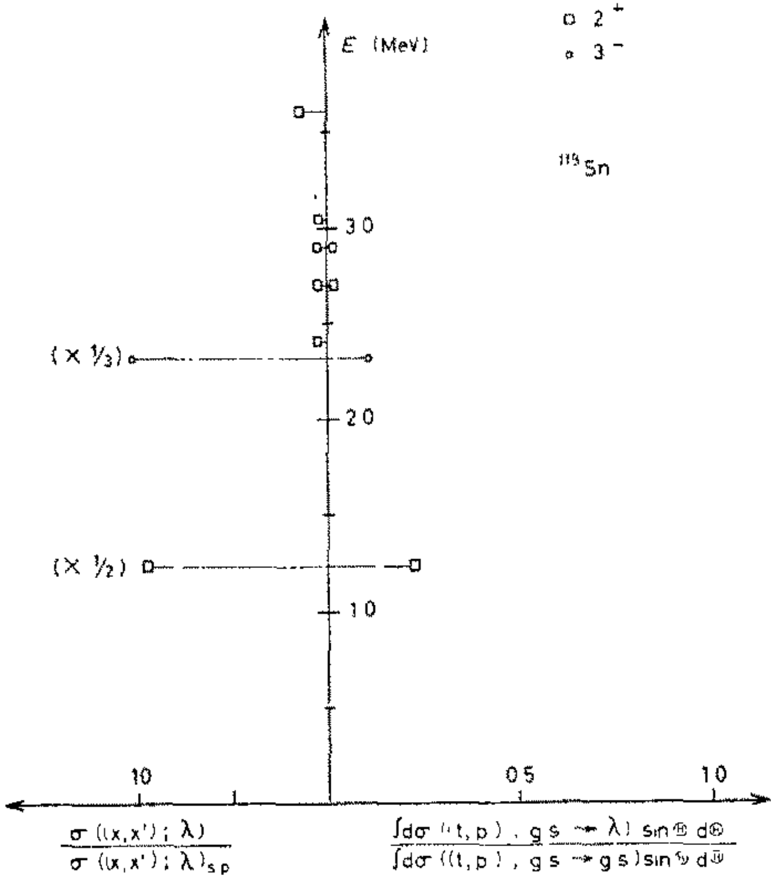


Vandebrouck talk

Savran 2018

Inelastic excitation and two-nucleon transfer populate the same states



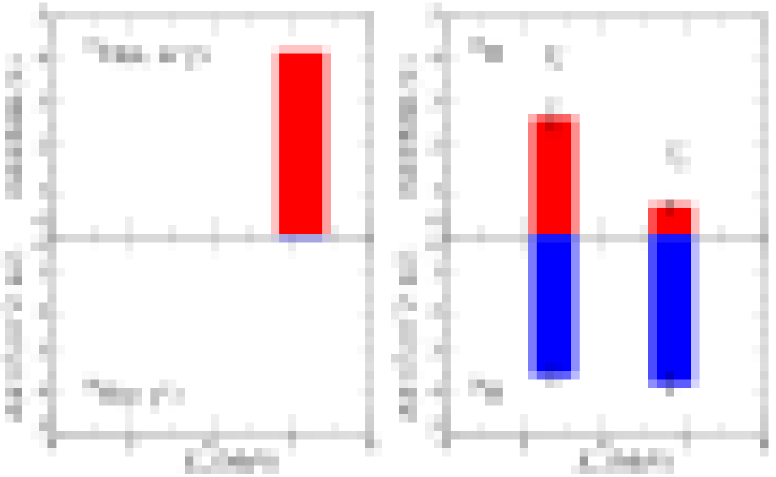


Two neutron transfer, a novel probe for the PDR?

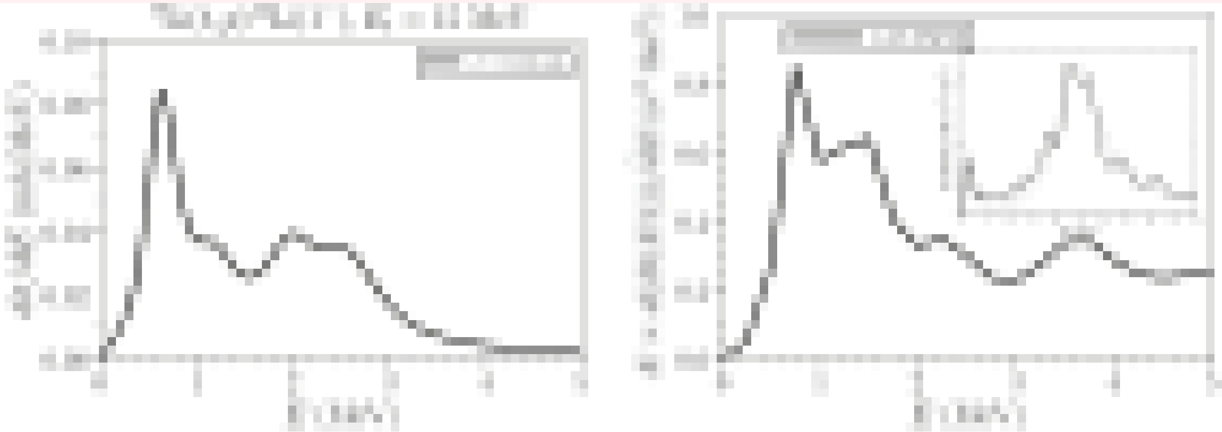
multi-messenger approach in order to characterize PDR

↓

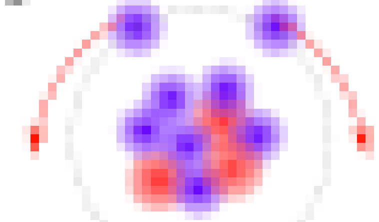
standard probes: (α,α'), (p,p') (γ,γ')



N. Nakatsuka et al. Physics Letters B 768 (2017) 387



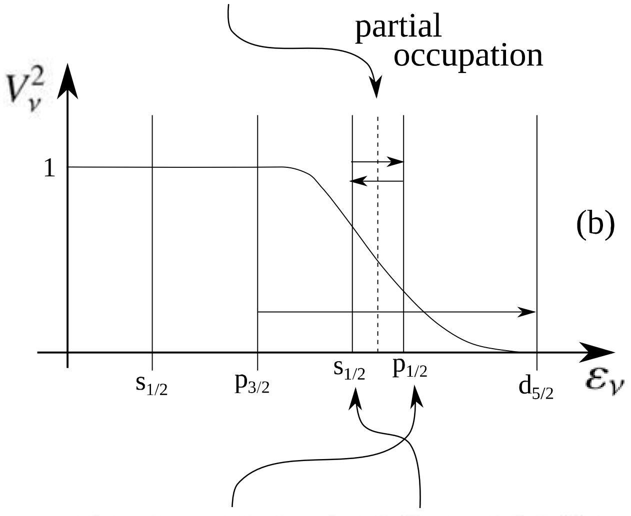
populating the ^{11}Li PDR with (t,p)



Broglia et al. Eur. Phys. J. A (2019) 55: 243

Low-lying dipole strength

$$|0\rangle_\nu = |0\rangle + 0.7|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-; 0\rangle + 0.1|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+; 0\rangle$$



$$|0\rangle = 0.55|p^2_{1/2}\rangle + 0.45|s^2_{1/2}\rangle + 0.04|d^2_{5/2}\rangle$$

$$|1^-, \text{pygmy}\rangle = \alpha\, \Gamma^\dagger_{\text{pygmy}}|\text{halo}\rangle + \beta\, \Gamma^\dagger_{\text{GDR}}|\text{core}\rangle$$

$\alpha^2 \gg \beta^2$

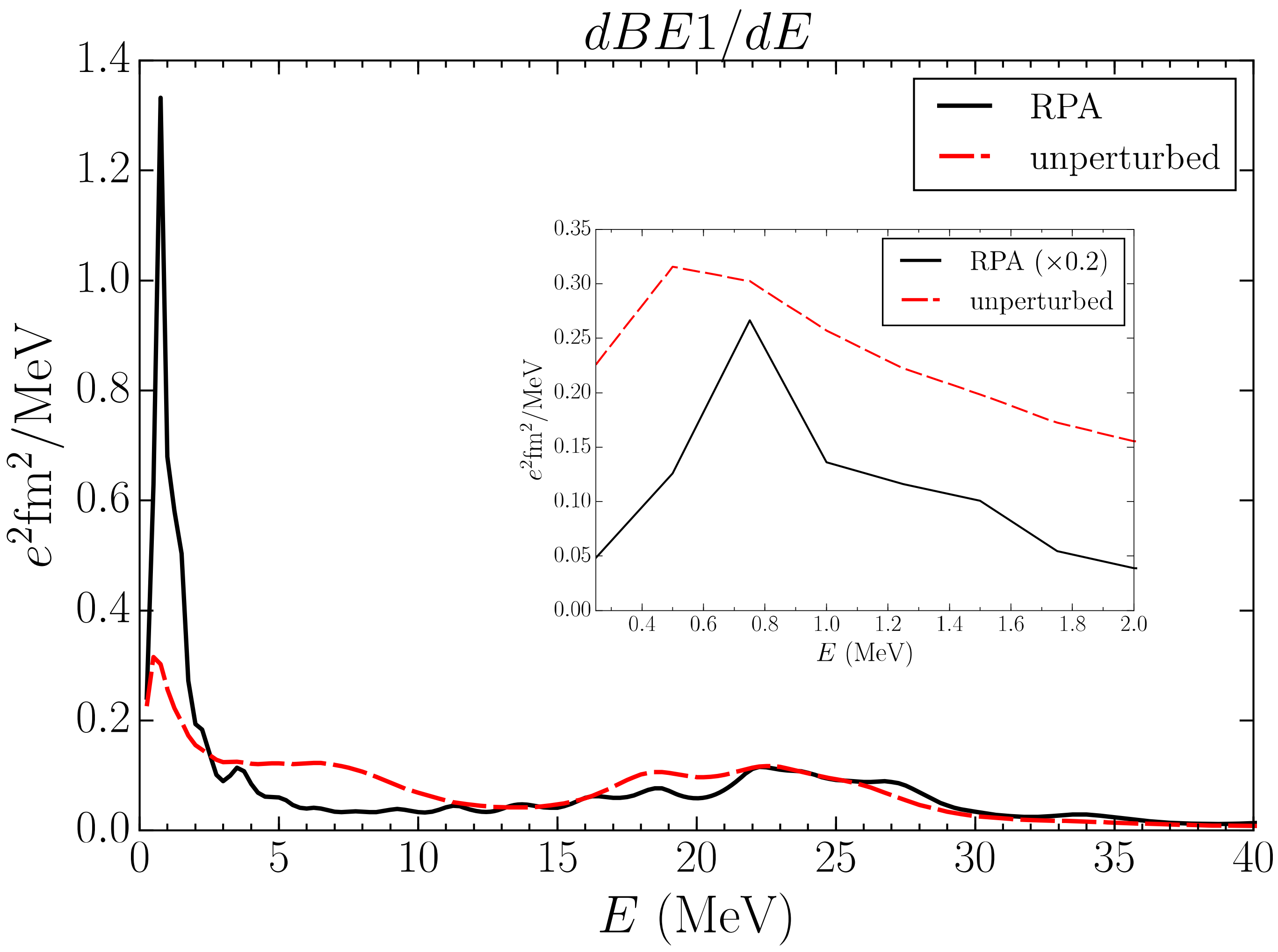
(a)

	$1p^{-1}_{1/2}2s_{1/2}$	$1p^{-1}_{1/2}3s_{1/2}$	$1p^{-1}_{1/2}4s_{1/2}$	$1p^{-1}_{1/2}1d_{3/2}$	$1p^{-1}_{3/2}4d_{5/2}$	$1p^{-1}_{3/2}5d_{5/2}$	$1p^{-1}_{3/2}6d_{5/2}$
X	-0.780	0.479	0.220	0.103	0.166	0.241	0.250
Y	0.078	0.108	0.106	0.075	0.139	0.208	0.221

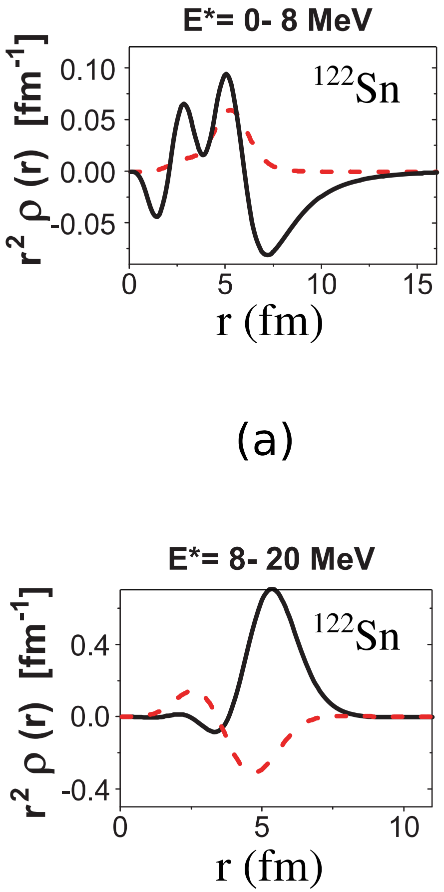
8% EWSR

$E_{1^-} \approx 0.7$ MeV

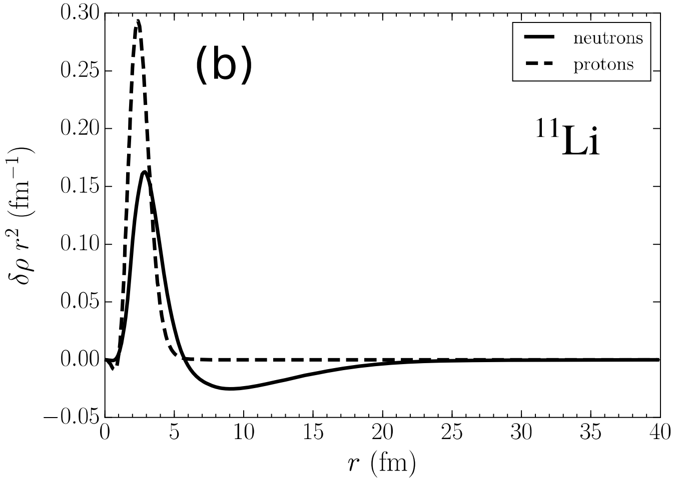
Full dipole strength

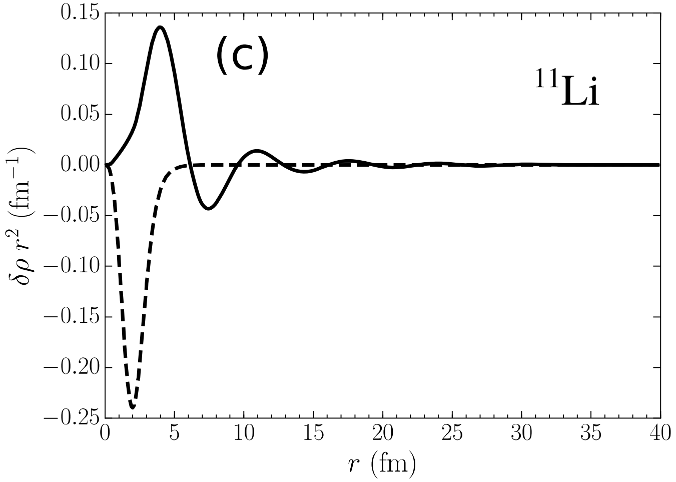


Transition densities

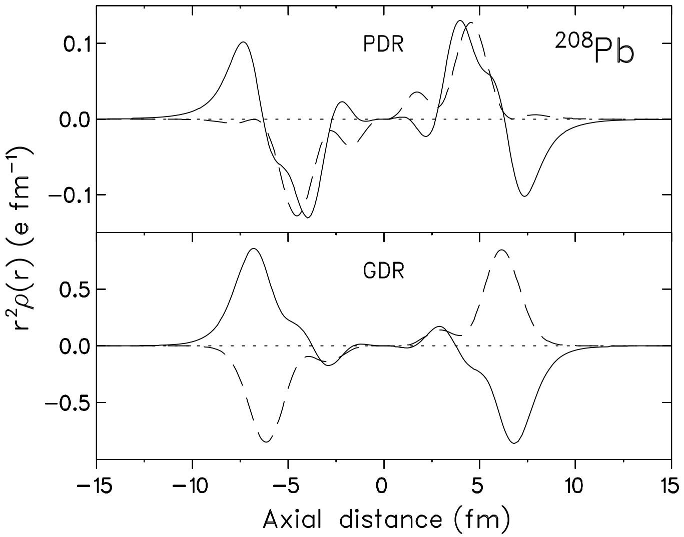


(a)



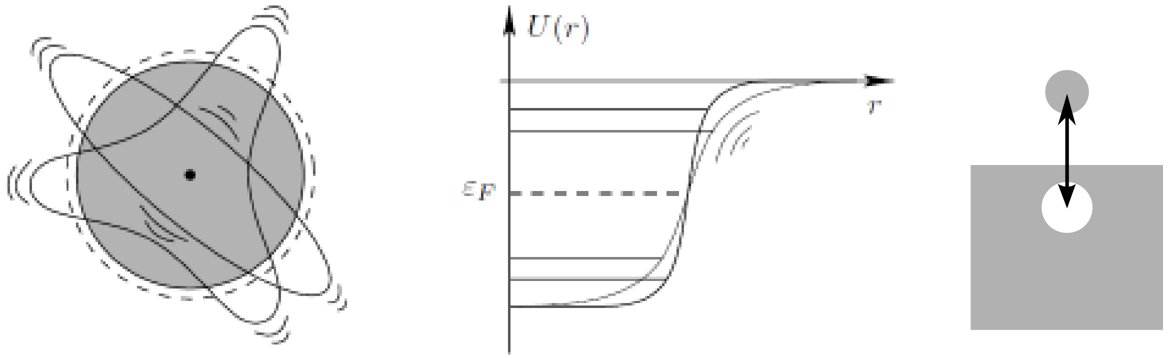


(d)

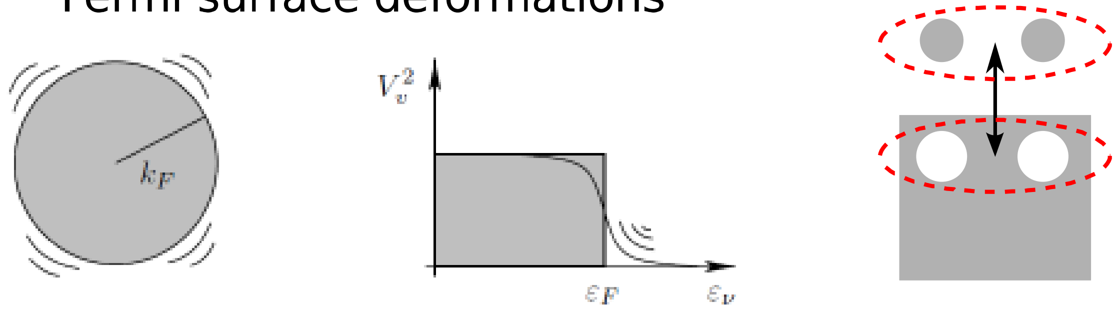


Deformations in 3D space and in gauge space

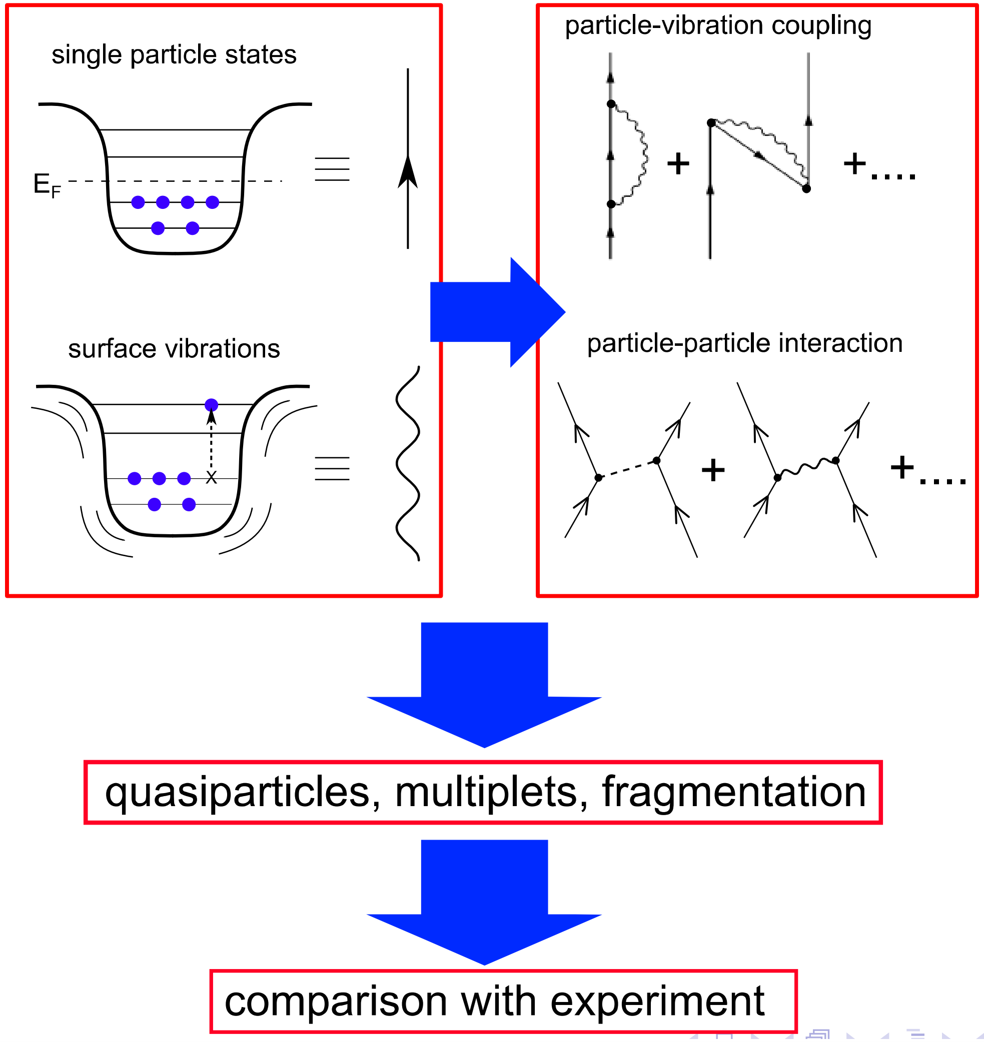
3D-surface deformations



Fermi surface deformations



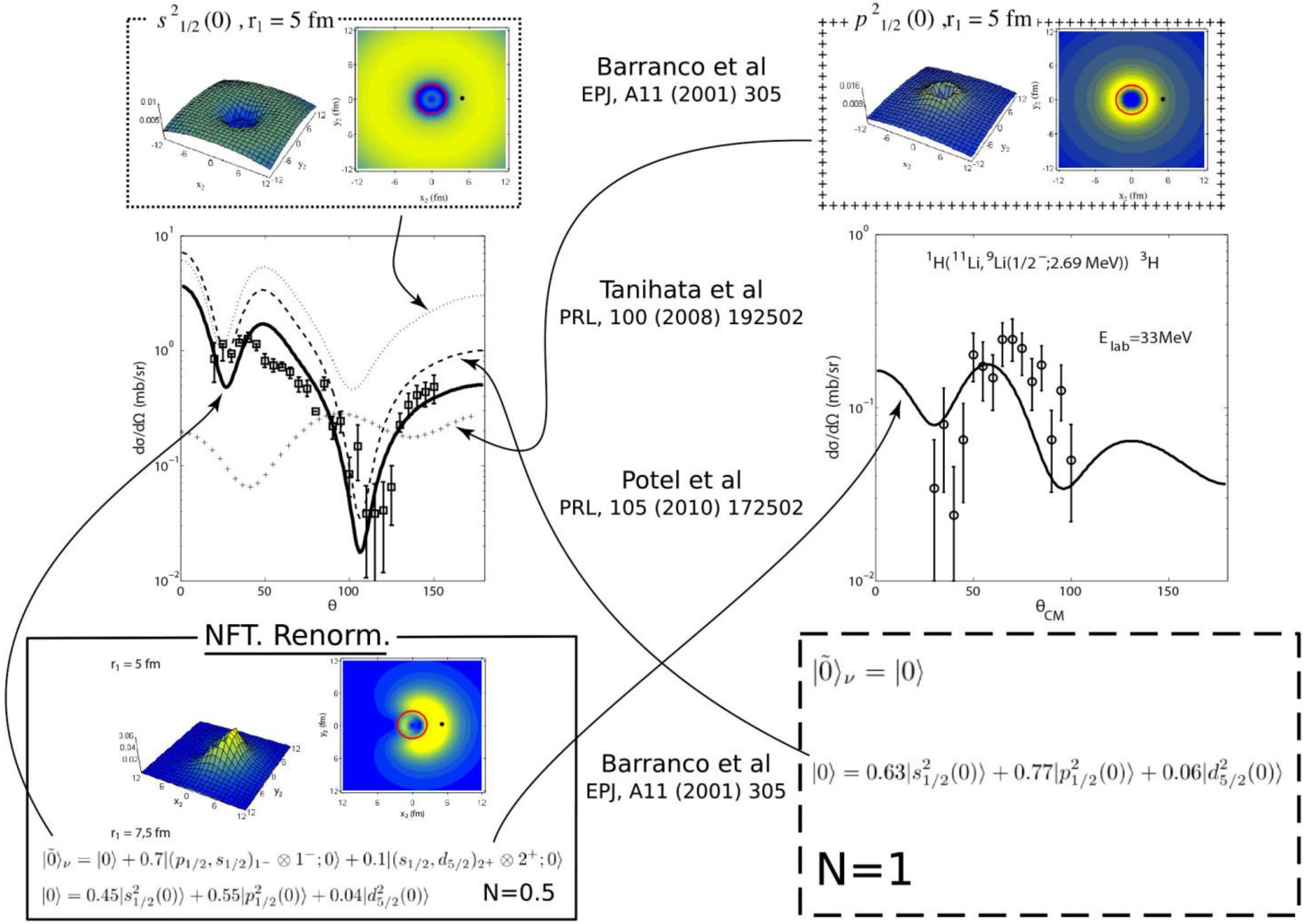
NFT



quasiparticles, multiplets, fragmentation

comparison with experiment

^{11}Li summary



Barranco et al
EPJ, A11 (2001) 305

Tanihata et al
PRL, 100 (2008) 192502

Potel et al
PRL, 105 (2010) 172502

Barranco et al
EPJ, A11 (2001) 305

$|\tilde{0}\rangle_\nu = |0\rangle + 0.7|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-; 0\rangle + 0.1|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+; 0\rangle$

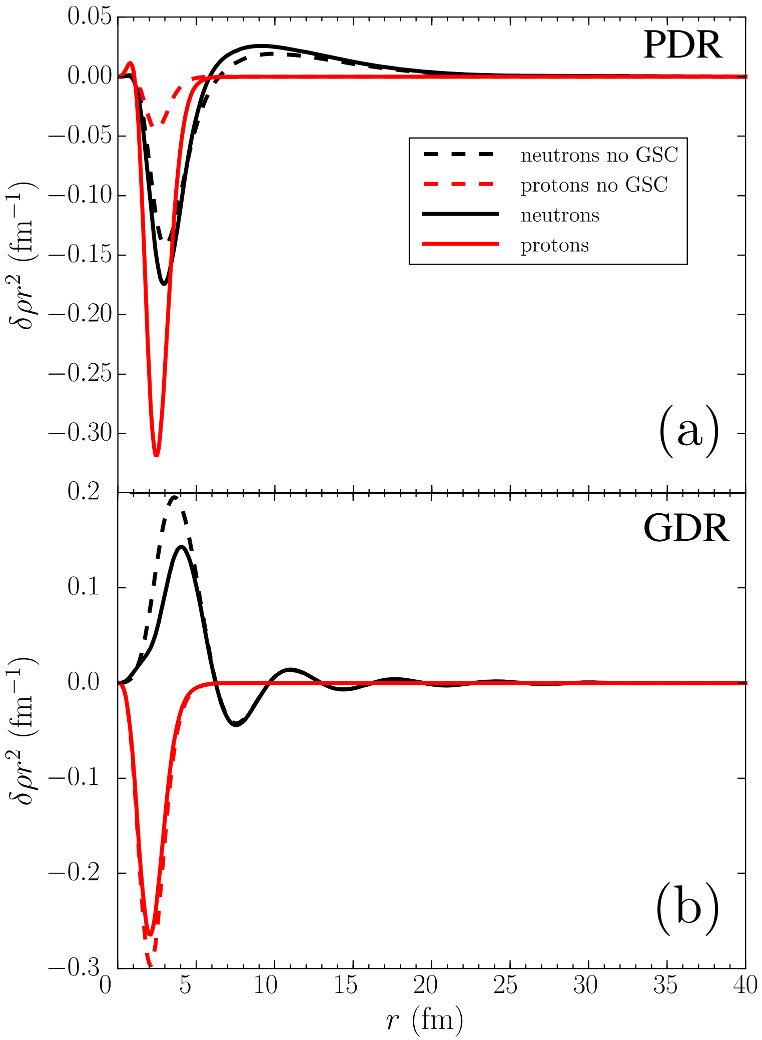
$|0\rangle = 0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$ N=0.5

$|\tilde{0}\rangle_\nu = |0\rangle$

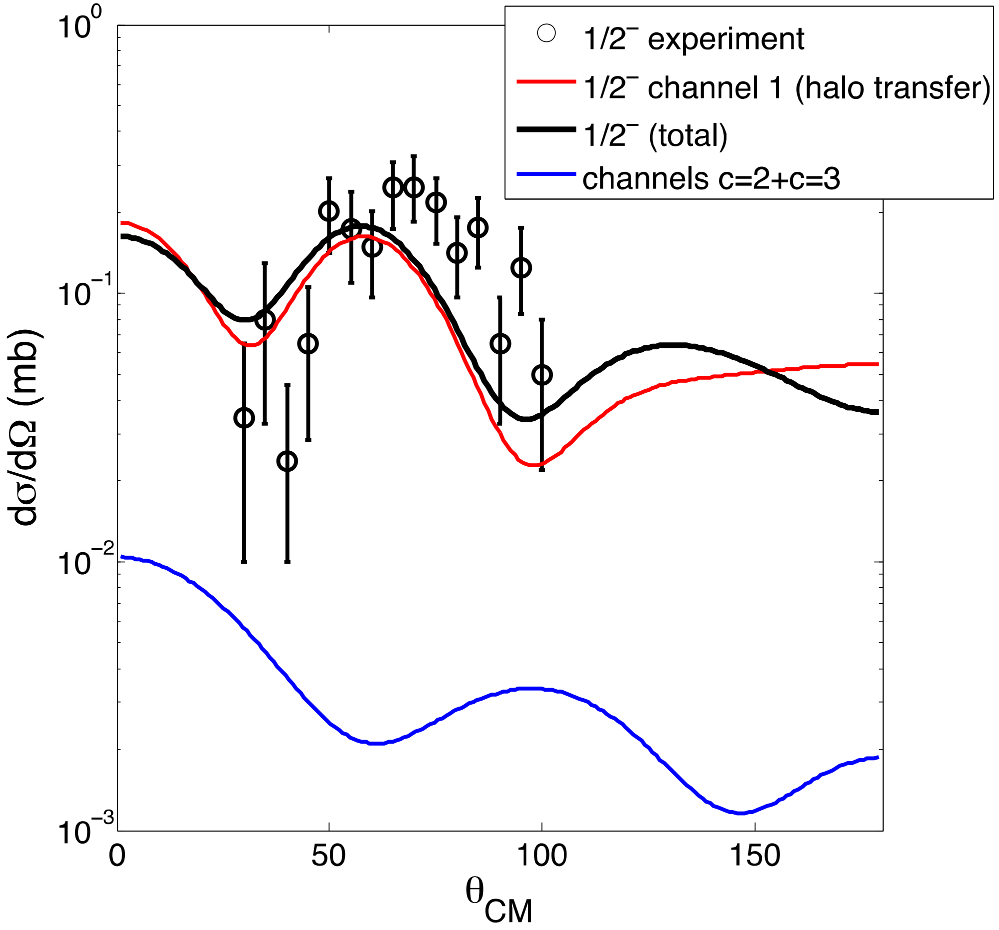
$|0\rangle = 0.63|s^2_{1/2}(0)\rangle + 0.77|p^2_{1/2}(0)\rangle + 0.06|d^2_{5/2}(0)\rangle$

N=1

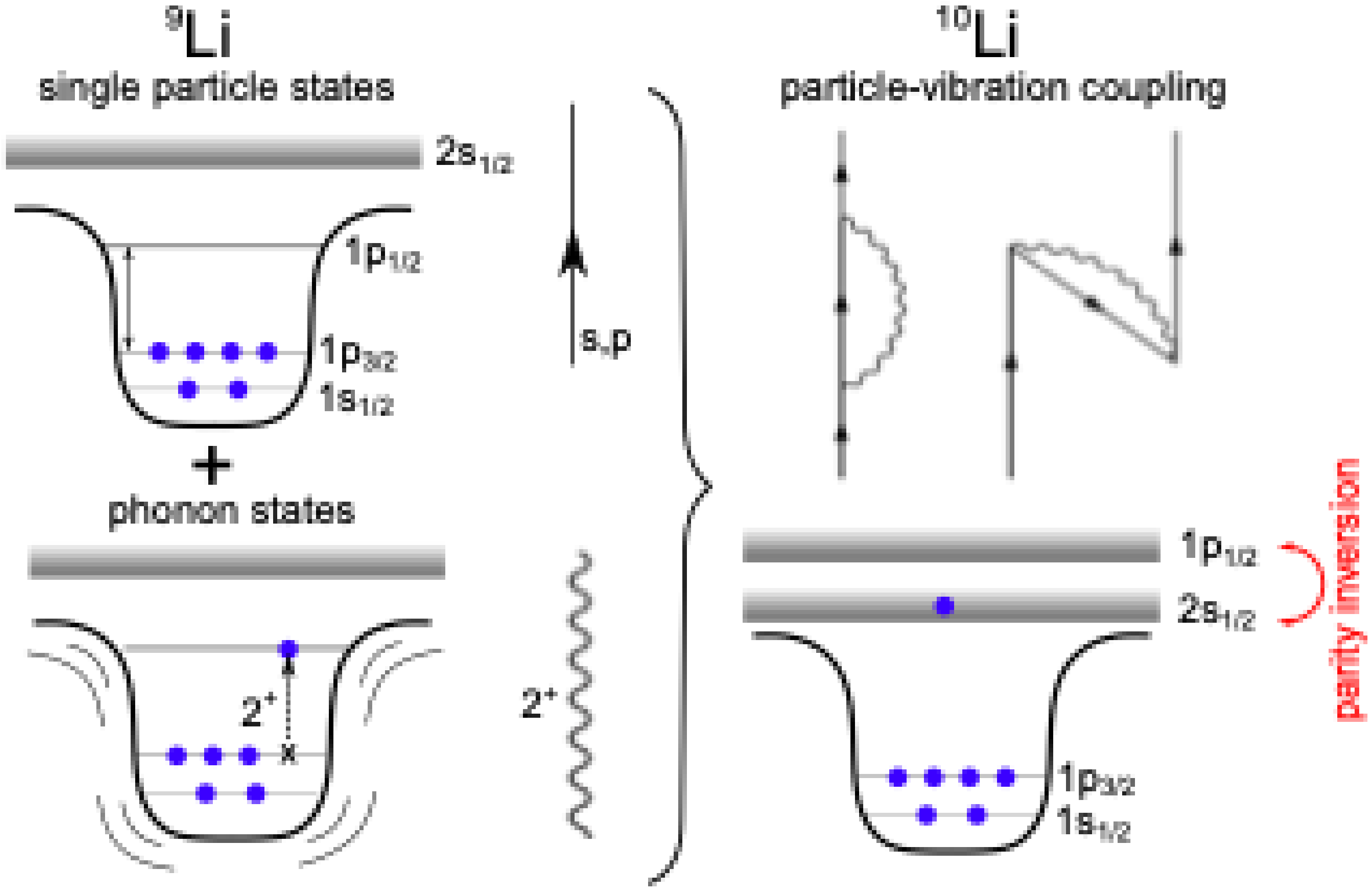
Role of ground state correlations



Transition to the first 1/2$^-$ (2.69 MeV) excited state of ^{9}Li

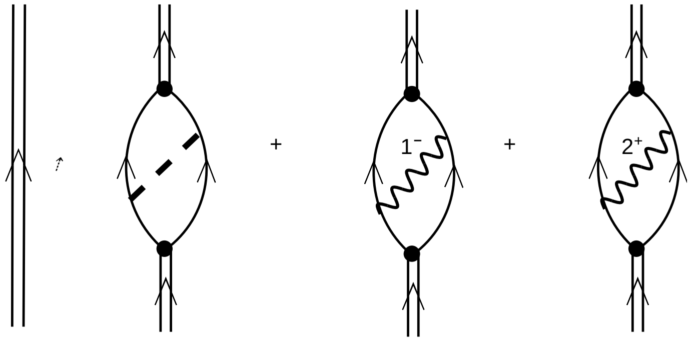


From 9Li to ^{10}Li…



… and from ^{10}Li to ^{11}Li

^{11}Li= ^{9}Li core+ 2–neutron halo (single Cooper pair). According to Barranco *et al.* (2001), the two neutrons correlate by means of the bare interaction (accounting for ↗ 20% of the ^{11}Li binding energy) and by exchanging 1^{-} and 2^{+} phonons (↗ 80% of the binding energy)



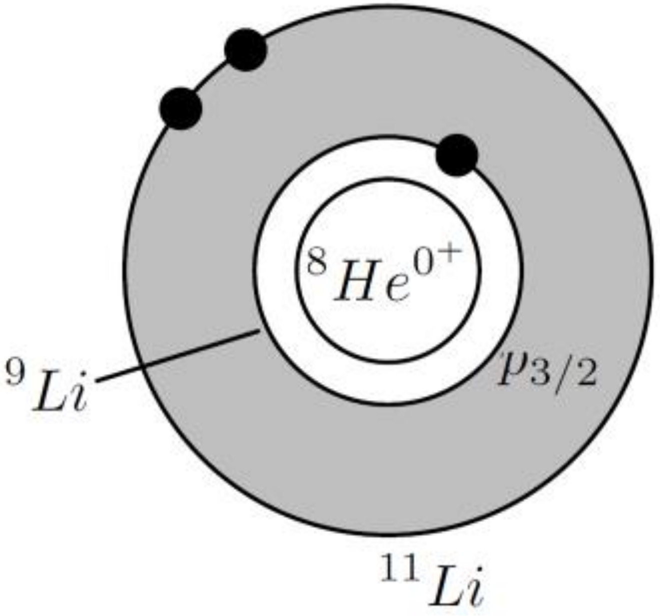
Within this model, the ^{11}Li wavefunction can be written as

$$|\tilde{0}i = 0.45|s^2_{1/2}(0)i + 0.55|p^2_{1/2}(0)i + 0.04|d^2_{5/2}(0)i$$

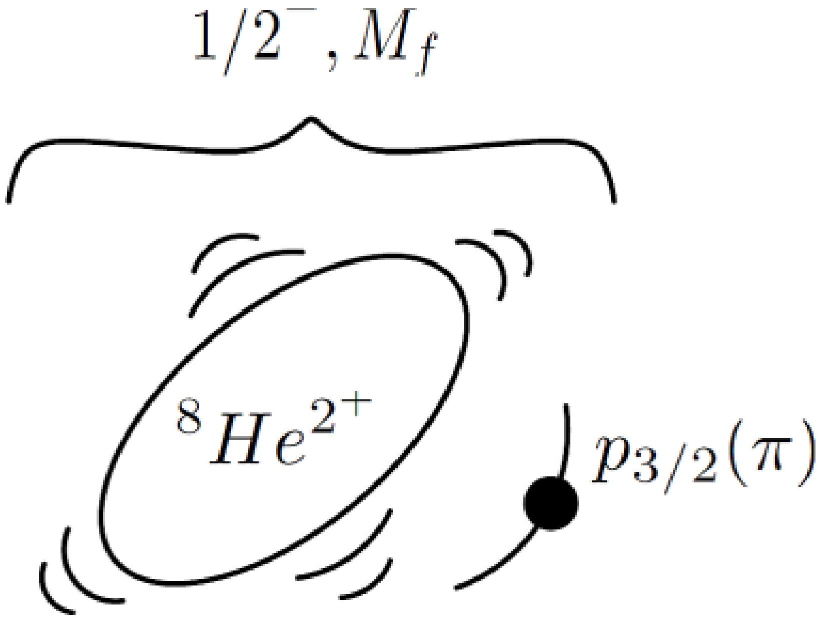
$$+\ 0.70|(ps)_{1^-} \boxtimes 1^-;0i + 0.10|(sd)_{2^+} \boxtimes 2^+;0i.$$

Note that the $p_{3/2}$ proton doesn't play any role and is not taken into account.

^{11}Li(*p*,*t*)^{9}Li(1/2^{-})



Schematic depiction of ^{11}Li

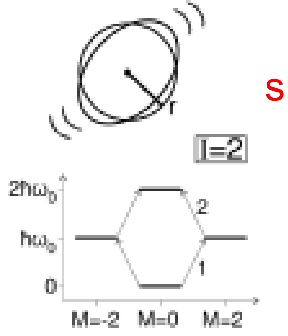


First excited state of ^{9}Li

Spontaneous symmetry breaking in nuclei

3D-space

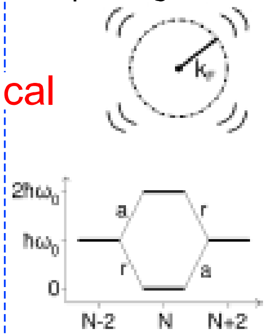
quadrupole vibration



spherical

gauge space

pairing vibration



rotation

Euler angle $(\Omega = (\phi, \theta, \psi))$

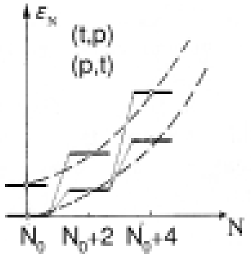
$$E_I = \frac{\hbar^2}{2\mathcal{I}_{rot}} I(I+1) + \omega I$$

deformed

pairing rotation

Gauge angle $(\Omega = \phi)$

$$E_N = \frac{\hbar^2}{2\mathcal{I}_{gauge}} (N - N_0)^2$$



theoretical description

vibrations in harmonic approximation

RPA
pp-RPA/QRPA

deformed mean field

Nilsson model
BCS