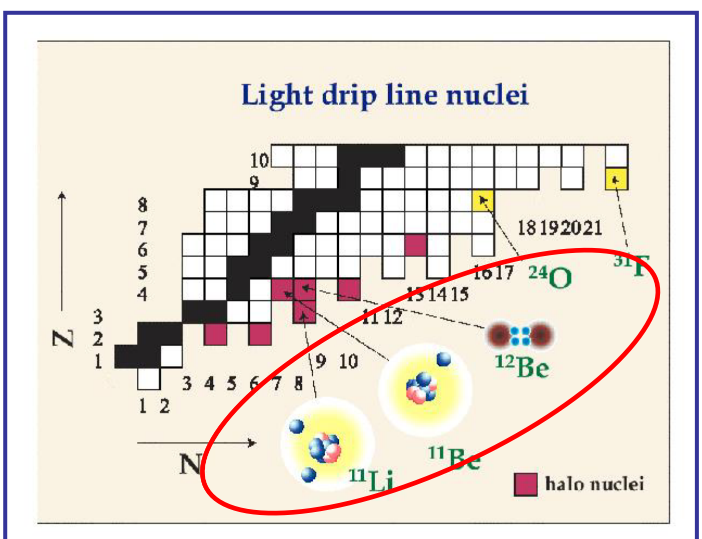
Particle-vibration coupling in halo nuclei

R.A. Broglia, P.F. Bortignon, G. Colo', G.Gori, E. Vigezzi (Milano)

F. Barranco (Sevilla)

F. Barranco et al., Eur.Phys.Jour. A 11(2001)385

G.Gori et al., nucl-th/0301097



Aim of the talk

To discuss the role of core polarization in halo nuclei.

To show that, based on limited phenomenological input, it is possible to provide a quantitative calculation of the basic features of ^{11}Be, ^{12}Be, ^{10}Li, ^{11}Li and of the spectroscopic factors, in reasonable agreement with experiment.

The parity inversion problem in ^{11}Be

	^{11}Be	^{10}Be
Separation energy	0.5 MeV	6.8 MeV
Lowest excited state	0.32 MeV,	3.4 MeV
Radius	3 fm	2.3 fm

Good situation for the mean field approximation:

But! The quantum numbers of the ground state are not those predicted by the mean field (1p1/2)

. *but* 2s1/2, in the next shell!!

Stronger spin-orbit force for halo states?

(N. Vinh Mau, *Nucl. Phys. A592(95)33*)

(F. Nunes et al., *Nucl. Phys. A596(96)171*)

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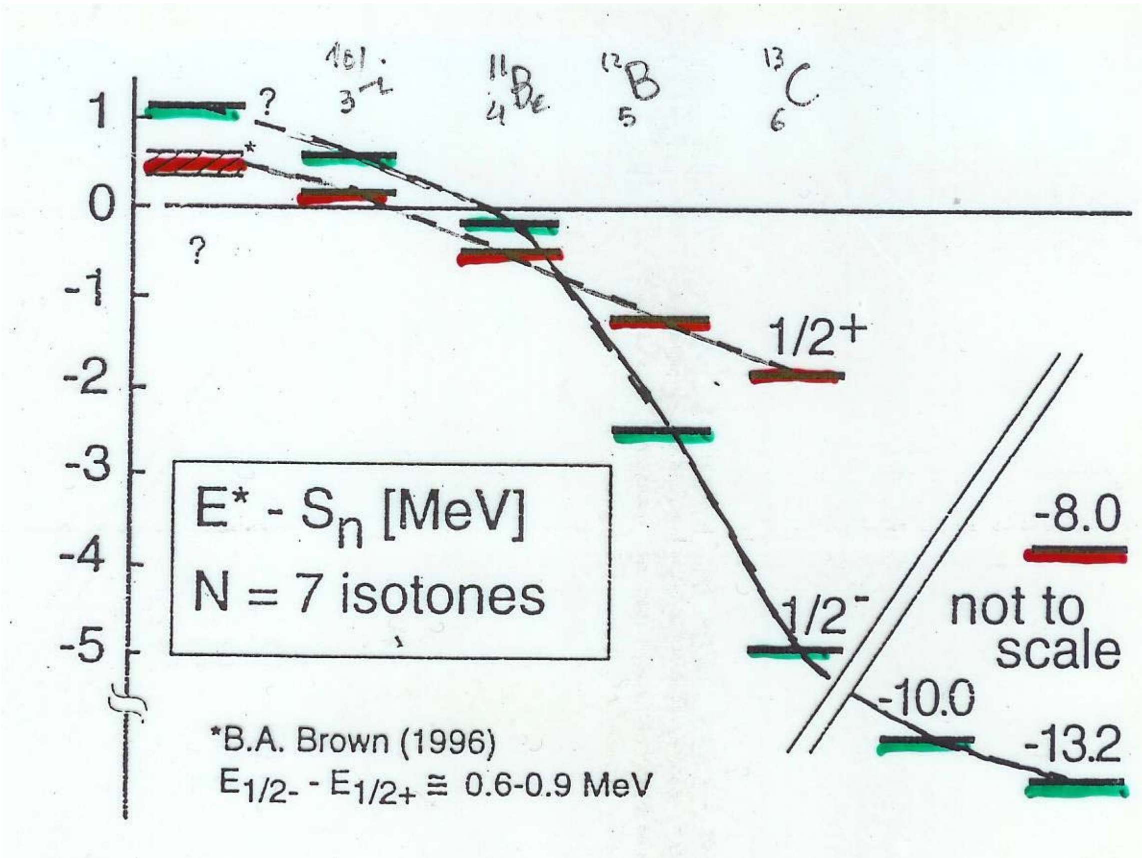
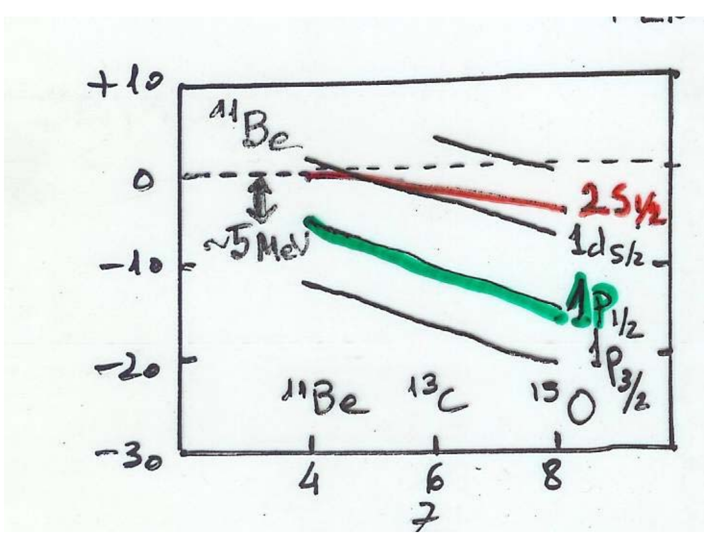
Experimental systematics



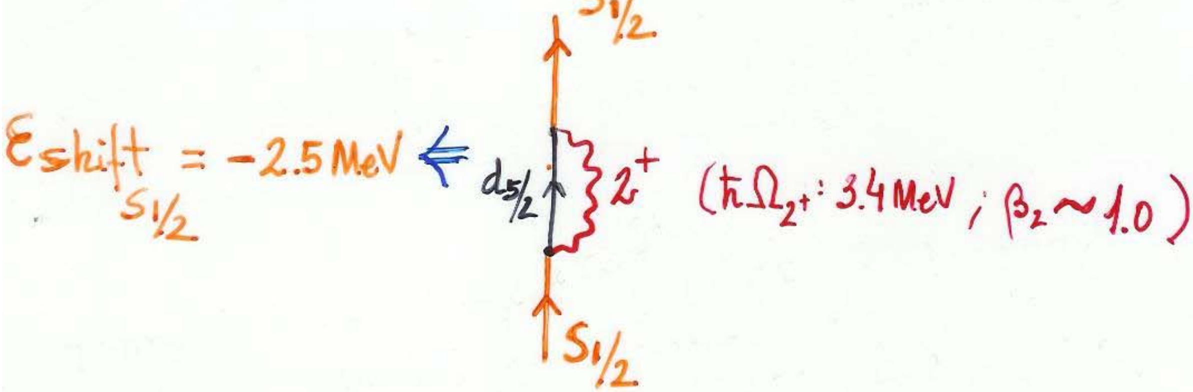
Mean-field results with Skyrme force

(Sagawa, Brown,Esbensen PLB 309(93)1)

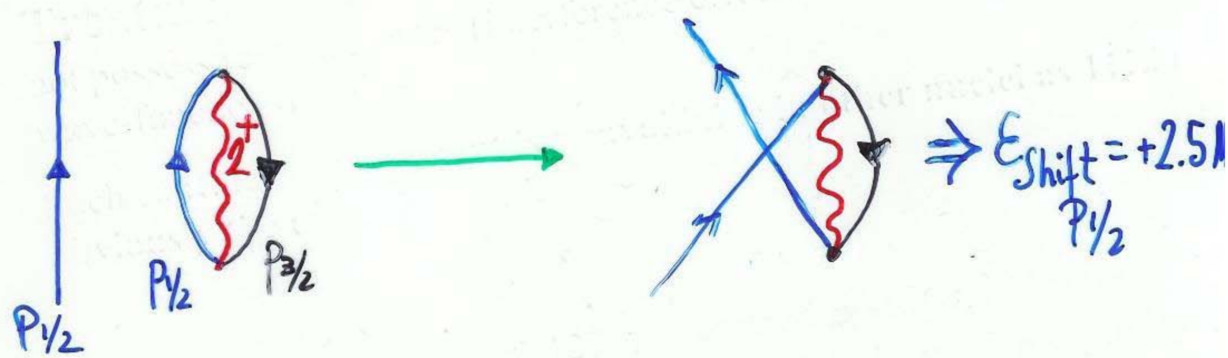


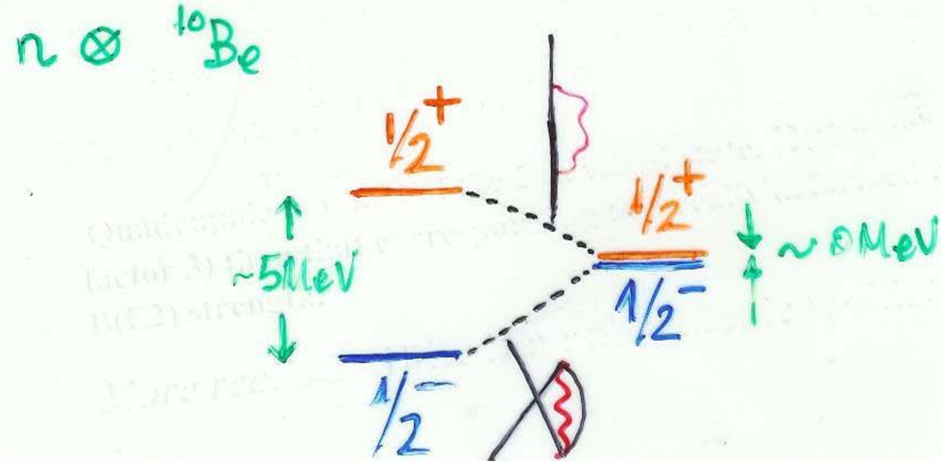
A. SELF ENERGY

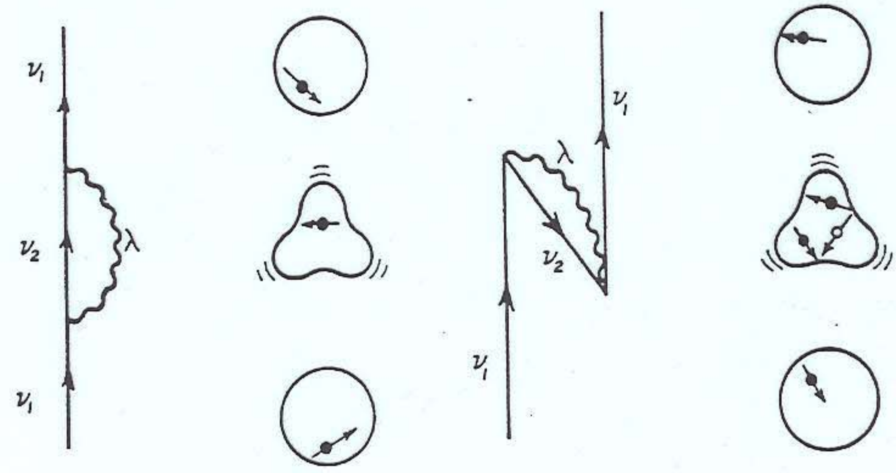
(^{11}Be case: Sagawa, Brown & Esbensen, PLB 309 (93))



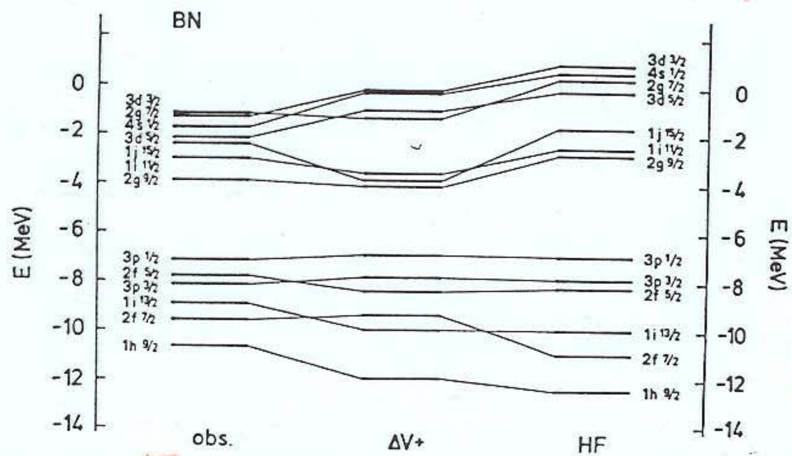
B. PAULI BLOCKING OF CORE GROUND STATE CORRELATIONS







 → Phys. Rep. 120 (85) 1



Bernard & Van Giai
Nucl. Phys. A348 (1980)

Fig. 4.29. Representation of the results of Bernard and Nguyen Van Giai [96] for the neutron quasiparticle energies in the valence shells of ^{208}Pb. The observed values are plotted on the left-hand side and the results of the Skyrme III–Hartree–Fock approximation on the right-hand side. The middle column gives the quasiparticle energies, see section 4.6.5.

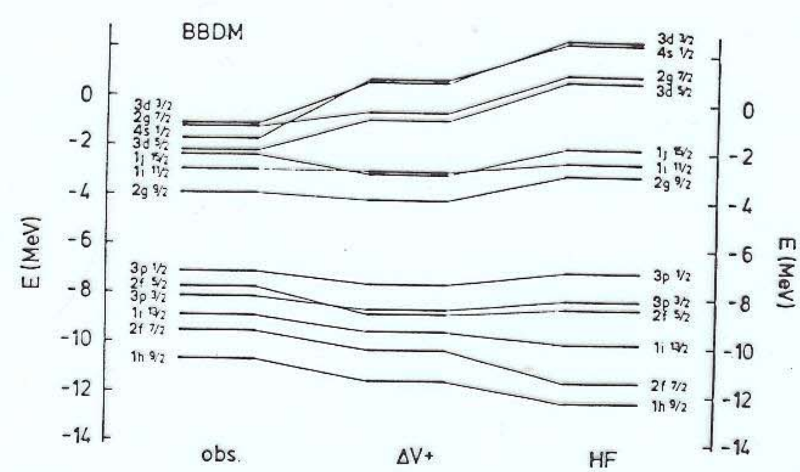


Fig. 4.30. Representation of the results of Bortignon et al. [315] for the neutron quasiparticle energies in the valence shells of ^{208}Pb. The notation is the same as in fig. 4.29.

COLLECTIVE SURFACE VIBRATIONS

$$R(\hat{\vartheta}) = R_0\left\{1+\sum_{\lambda\mu}\alpha^*_{\lambda\mu}Y_{\lambda\mu}(\hat{\vartheta})\right\} \quad ; \quad \lambda^\pi = 2^+, 3^-, 4^+, 5^-$$

WELL KNOWN FROM EXP.

$$H_{coll} = \frac{1}{2}\sum_{\lambda\mu}\left(B_\lambda|\dot{\alpha}_{\lambda\mu}|^2 + C_\lambda|\alpha_{\lambda\mu}|^2\right) ; \quad \hbar\omega_\lambda = \hbar\sqrt{\frac{C_\lambda}{B_\lambda}}$$

$$\beta_\lambda = \sqrt{2\lambda+1}\sqrt{\frac{\hbar\omega_\lambda}{2C_\lambda}}$$

The values of $\hbar\omega_\lambda$ and β_λ are taken from experiment or alternativelly from an RPA calculation

THE MODEL HAMILTONIAN

$$H = \frac{p^2}{2m} + U(\vec{r};\alpha) + H_{coll}$$

where

$$U(\vec{r};\alpha) = U_0\left(\frac{r}{1+\sum\alpha^*_{\lambda\mu}Y_{\lambda\mu}}\right) \simeq U_0(r) - r\frac{\partial U_0}{\partial r}\sum_{\lambda\mu}\alpha^*_{\lambda\mu}Y_{\lambda\mu}(\hat{\vartheta})$$

$$\Rightarrow H = \frac{p^2}{2m} + U_0(r) + H_{coll} + H_{pv}$$

With

$$H_{pv} = -r\frac{\partial U_0}{\partial r}\sum_{\lambda\mu}\sqrt{\frac{\hbar\omega_\lambda}{2C_\lambda}}\left[O^\dagger_{\lambda\mu} + (-1)^\mu O_{\lambda-\mu}\right]Y_{\lambda\mu}(\hat{\vartheta})$$

Pauli-blocking correlations

The ^{10}Be core itself is not a simple Slater determinant assupposed in mean field:

There are ground state correlations, that is, mixing of configurations ➔ partial occupation of orbits that in a pure mean field description are completely empty.

When the halo neutron is added to form ^{11}Be, the extra neutron will partially block the single-particle orbits available for ^{10}Be to correlate: the binding energy decreases.

The effect is strongest when associated to the lowest "empty" orbit, that is to the $1p_{1/2}$ orbit.

In this way Sagawa, Brown ed Esbensen explained the parity inversion in ^{11}Be.

Elaborating on the ^{11}Be calculation

New elements of our calculation:

Standard Woods-Saxon potential including spin-orbit according to Bohr and Mottelson

We include the (discretized) continuum for s-, p- and d-orbits:

Schrödinger equation solved with reflecting boundary conditions at a variable radius R => infinity

.

The calculations have been carried out using the Nuclear Field Theory: .. .

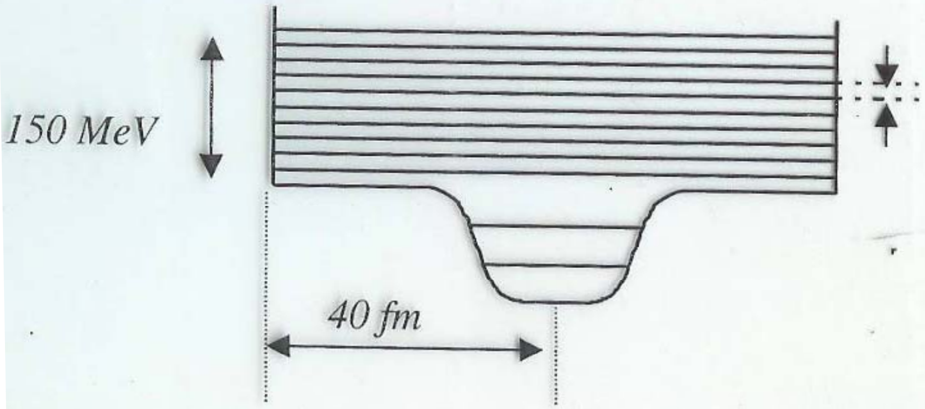
a systematic and fully consistent scheme for the particle-vibration coupling. It allows a coherent treatment of

configuration mixing, .

Pauli-blocking correlations

(Saxon - Woods + spin - orbit B + M Vol.1)

$$U_0 = -50\,MeV + \frac{N-Z}{A}\,33\,MeV$$



(hundred's of s.p. states)

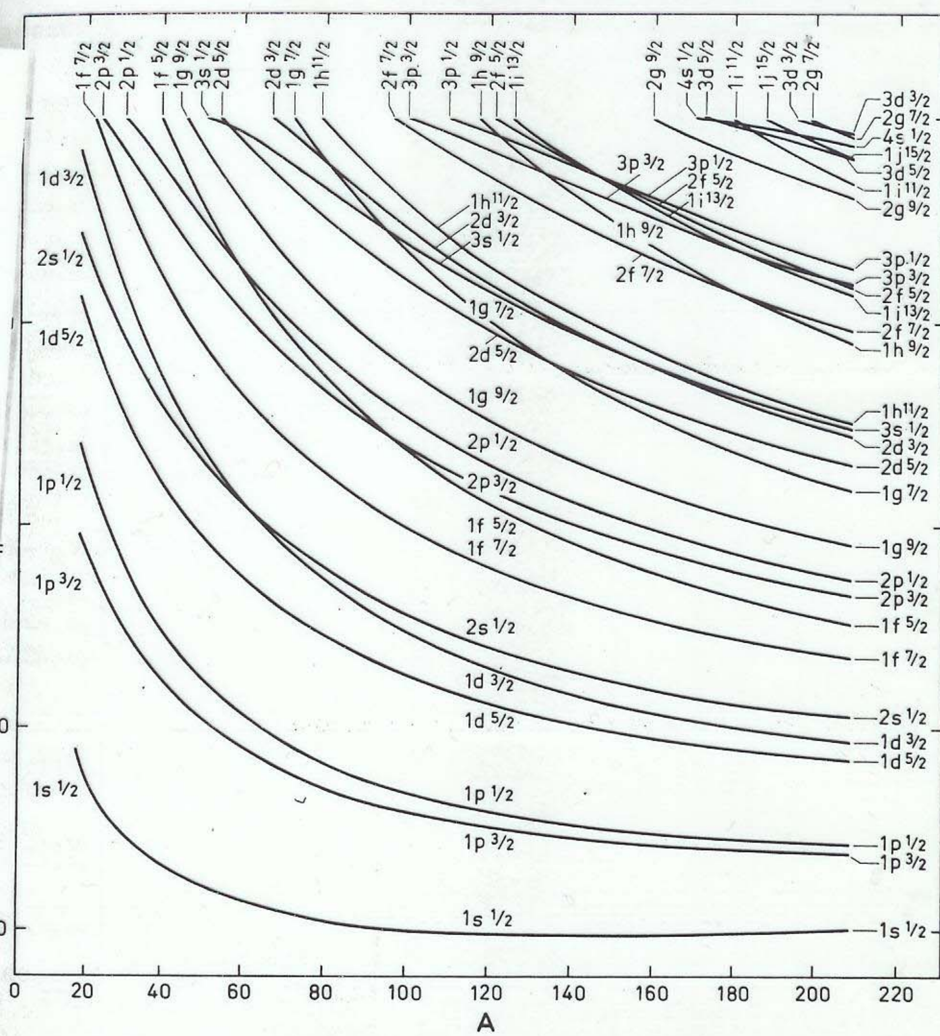
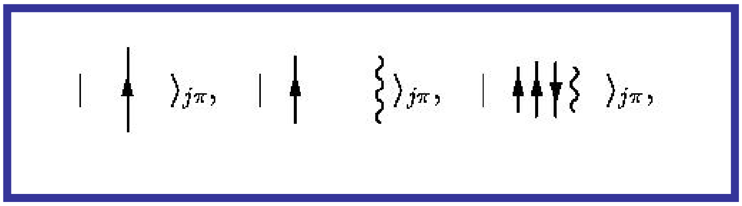


Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

^{11}Be



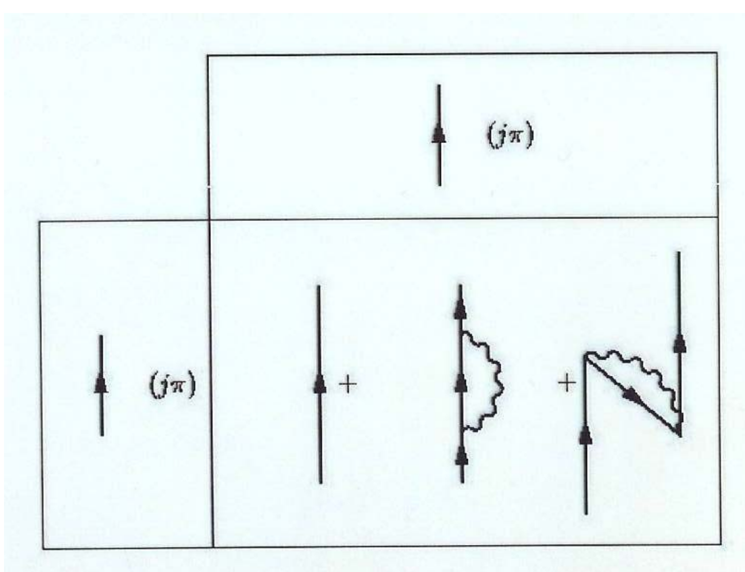
Fermionic degrees of freedom:

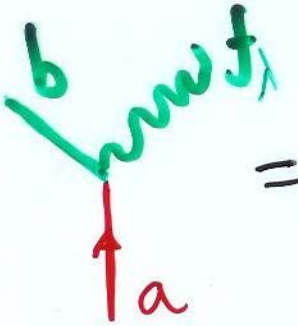
• s1/2, p1/2, d5/2 Wood-Saxon levels up to 150 MeV

Bosonic degrees of freedom:

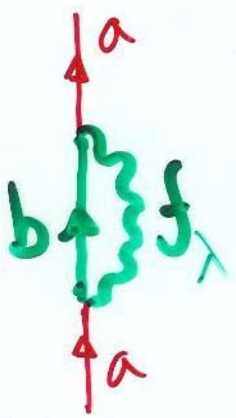
• 2+ and 3- QRPA solutions with energy up to 50 MeV; residual interaction: multipole-multipole separable with the coupling constant tuned to reproduce E(2+)=3.36 MeV e $0.6<\beta_2<0.7$

Effective, energy-dependent matrix (Bloch-Horowitz)

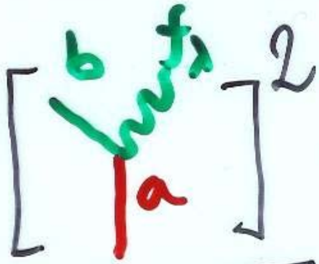




$$= \langle b | -r \frac{\partial U_0}{\partial r} Y_{\lambda\mu} | a \rangle \sqrt{\frac{\hbar\omega_\lambda}{C_\lambda}}$$

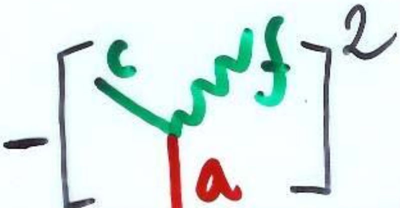


$=$



$$= \frac{\left[\ \cdot\ \right]^2}{\tilde{\varepsilon}_a - (\varepsilon_b + \hbar\omega_{f_\lambda})}$$

$=$

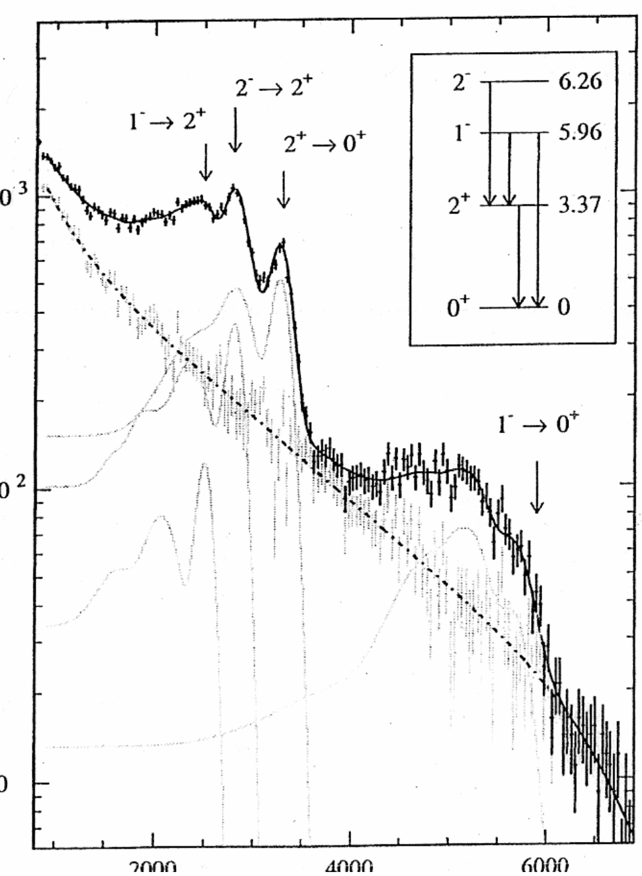


$$= \frac{-\left[\ \cdot\ \right]^2}{\tilde{\varepsilon}_a - (2\tilde{\varepsilon}_a - \varepsilon_c + \hbar\omega_{f_\lambda})}$$

Admixture of $d_{5/2}$ x 2^+ configuration in the $1/2^+$ g.s. of ^{11}Be is about 20%

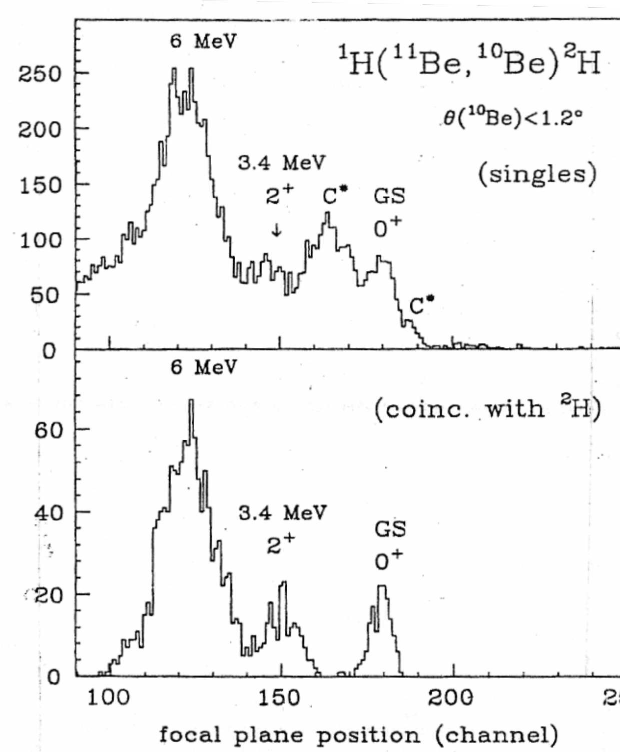
9Be(11Be,10Be+ γ) X

T. Aumann et al.
PRL 84(2000)35

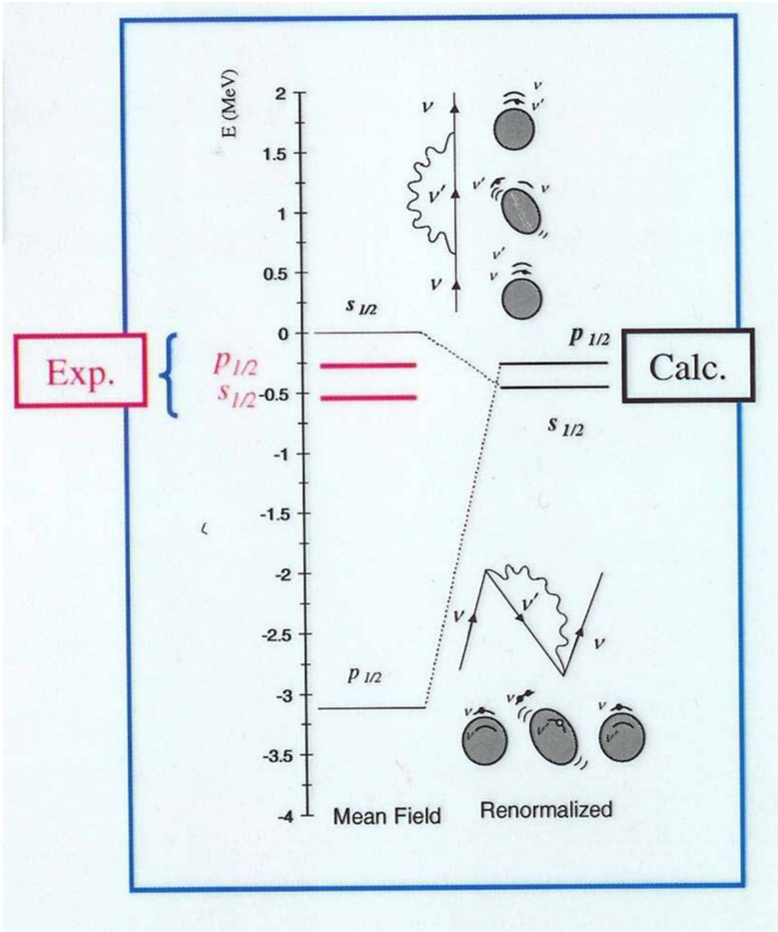


p(11Be,10Be)d

S. Fortier et al.
Phys. Lett.B461(1999)22



Particle-vibration coupling in ^{11}Be



NFT ground state

$$|1/2+\rangle = \sqrt{0.87}\,|s_{1/2}\rangle + \sqrt{0.13}\,|d_{5/2}\otimes 2+\rangle$$

Exp.:

J.S. Winfield et al., Nucl.Phys. **A683** (2001) 48

$$|1/2+\rangle = \sqrt{0.84}\,|s_{1/2}\rangle + \sqrt{0.16}\,|d_{5/2}\otimes 2+\rangle$$

11Be(p,d)10Be in inverse kinematic detecting both the ground state as well as the 2+ excited state of 10Be.

^{11}Be

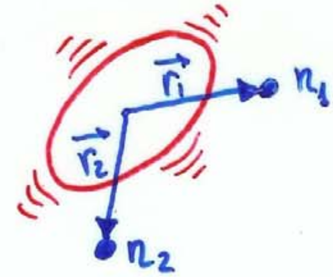
Good agreement between theory and experment concerning energy and spectroscopic factors

	Exper.	Theory	
		particle-vibration +Argonne	mean field
$E_{s_{1/2}}$	-0.504 MeV	-0.48 MeV	~ 0.14 MeV
$E_{p_{1/2}}$	-0.18 MeV	-0.27 MeV	-3.12 MeV
$S[1/2^+]$	0.77	0.87	1
$S[1/2^-]$	0.96	0.96	1

Experimental Spectroscopic Factors from

B. Zwieglinski et al., Nucl.Phys.A315(1979) 124

CORE + 2neutrons



COLLECTIVE SURFACE VIBRATIONS

$$R(\hat{\vartheta}) = R_0\left\{1 + \sum_{\lambda\mu} \alpha^*_{\lambda\mu} Y_{\lambda\mu}(\hat{\vartheta})\right\} \quad ; \quad \lambda^\pi = 2^+, 3^-, 4^+, 5^-$$

$$H_{coll} = \frac{1}{2}\sum_{\lambda\mu}\left(B_\lambda |\dot{\alpha}_{\lambda\mu}|^2 + C_\lambda |\alpha_{\lambda\mu}|^2\right) \quad ; \quad \hbar\omega_\lambda = \hbar\sqrt{\frac{C_\lambda}{B_\lambda}}$$

$$\beta_\lambda = \sqrt{2\lambda+1}\sqrt{\frac{\hbar\omega_\lambda}{2C_\lambda}}$$

MODEL HAMILTONIAN

$$H = \frac{p_1^2}{2m} + \frac{p_2^2}{2m} + \frac{p_{core}^2}{2M_{core}} + v_{nn}(|\vec{r}_1 - \vec{r}_2|) + U(\vec{r}_1;\alpha) + U(\vec{r}_2;\alpha) + H_{coll}$$

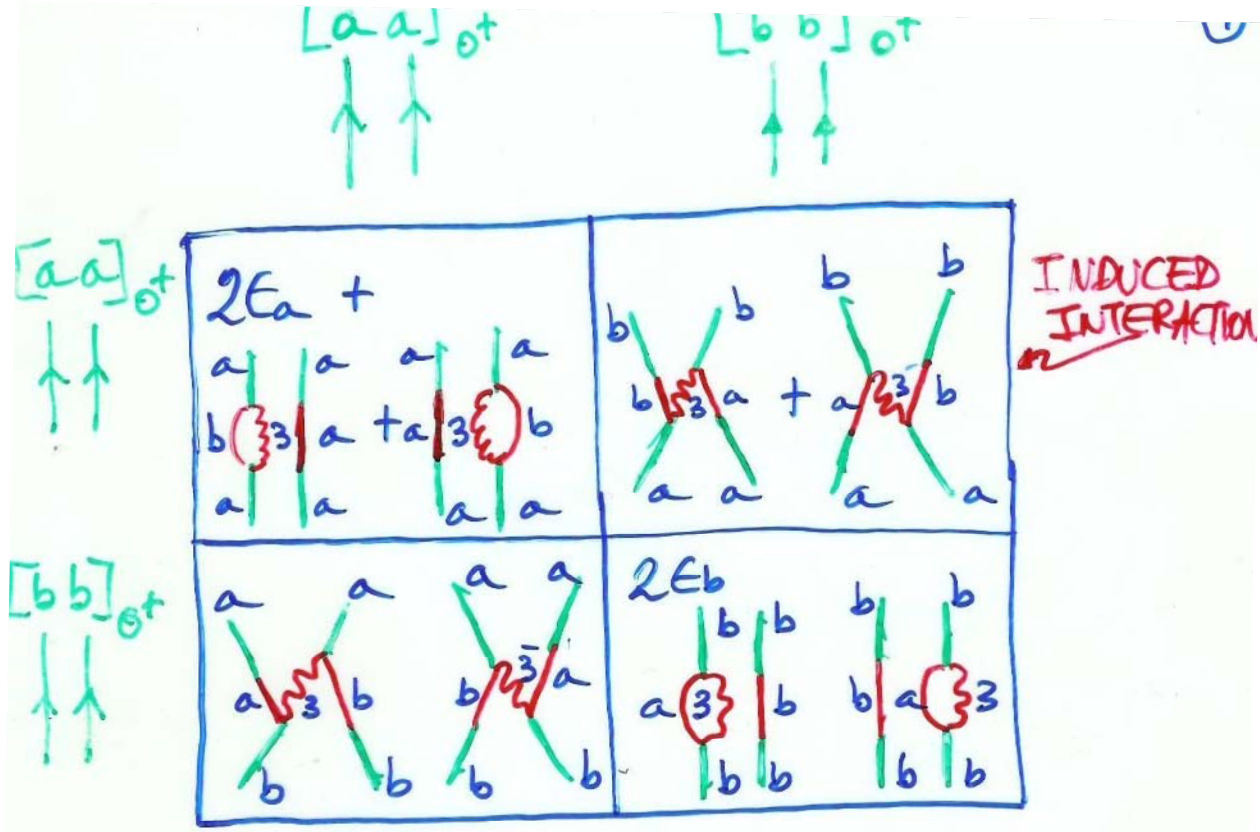
with $\vec{p}_{core} = -\vec{p}_1 - \vec{p}_2$

$$H = \frac{p_1^2}{2\mu} + \frac{p_2^2}{2\mu} + v_{nn}(|\vec{r}_1 - \vec{r}_2|) + U(\vec{r}_1;\alpha) + U(\vec{r}_2;\alpha) + H_{coll} + \frac{\vec{p}_1 \cdot \vec{p}_2}{M_{core}}$$

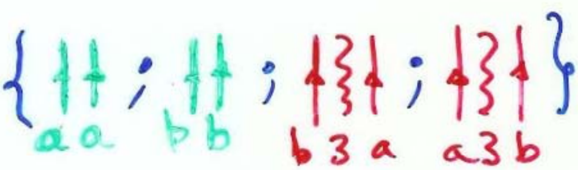
where

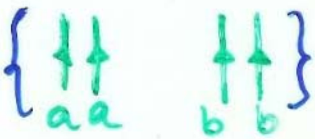
$$U(\vec{r};\alpha) = U_0\left(\frac{r}{1 + \sum \alpha^*_{\lambda\mu} Y_{\lambda\mu}}\right)$$

$$\cong U_0(r) - \chi\, r \frac{\partial U_0}{\partial r} \sum_{\lambda\mu} \alpha^*_{\lambda\mu} Y_{\lambda\mu}(\hat{\vartheta}) \quad ; \quad \chi \simeq 1.$$



Bloch-Horowitz perturbation method

> Total Space: 

> Model Space: 

Model Space States must not appear as intermediate states

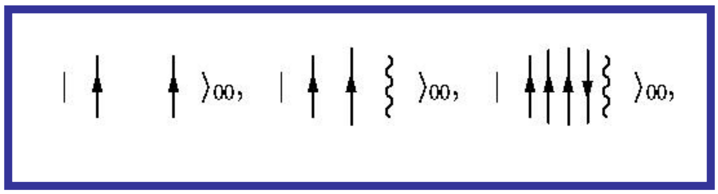
^{12}Be

Fermionic degrees of freedom:

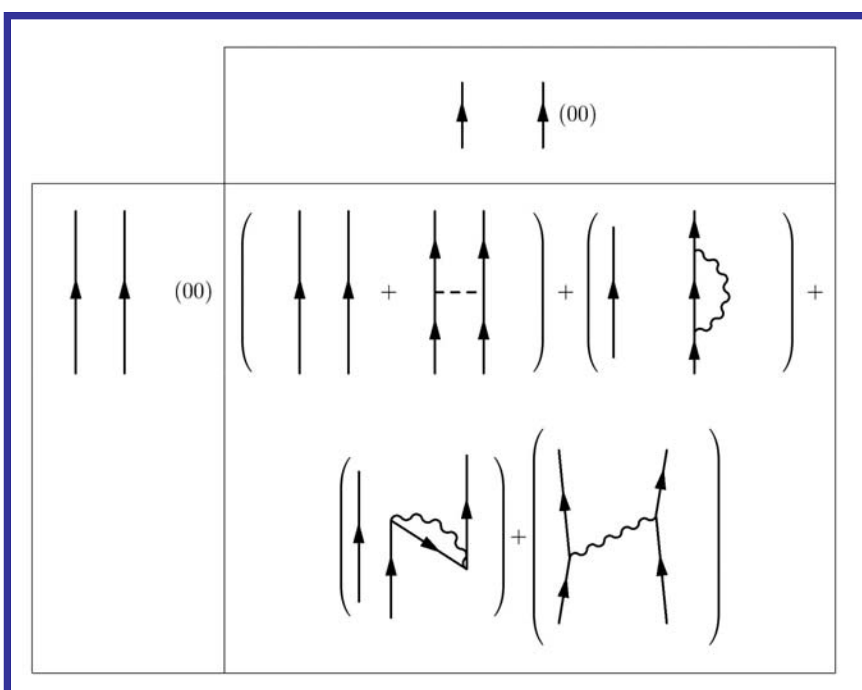
• two particle states coupled to zero angular momentum on s1/2, p1/2, d5/2 Woods-Saxon levels up to 150 MeV

Bosonic degrees of freedom:

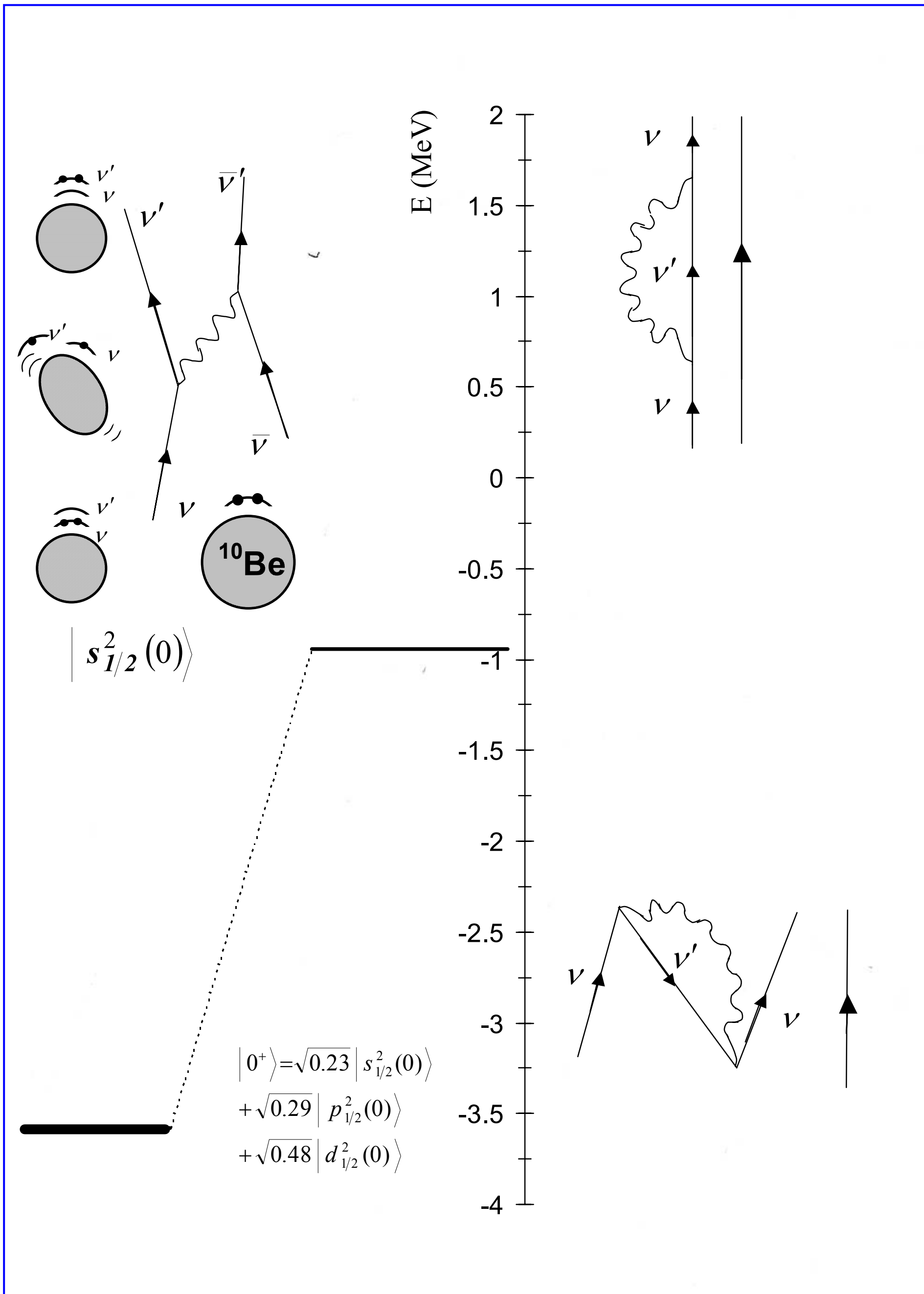
•1-, 2+ and 3- QRPA solutions up to 50 MeV, associated to a multipole-multipole separable interaction with coupling constant tuned to reproduce E(1-)=2.7 MeV and B(E1)=0.052 e^2fm^2 E(2+)=2.1 MeV and $0.6<\beta_2<0.7$



Effective, energy-dependent matrix



The pairing energy between the valence neutrons originates mostly from polarization effects, and not by the nucleon-nucleon bare interaction (Argonne potential)

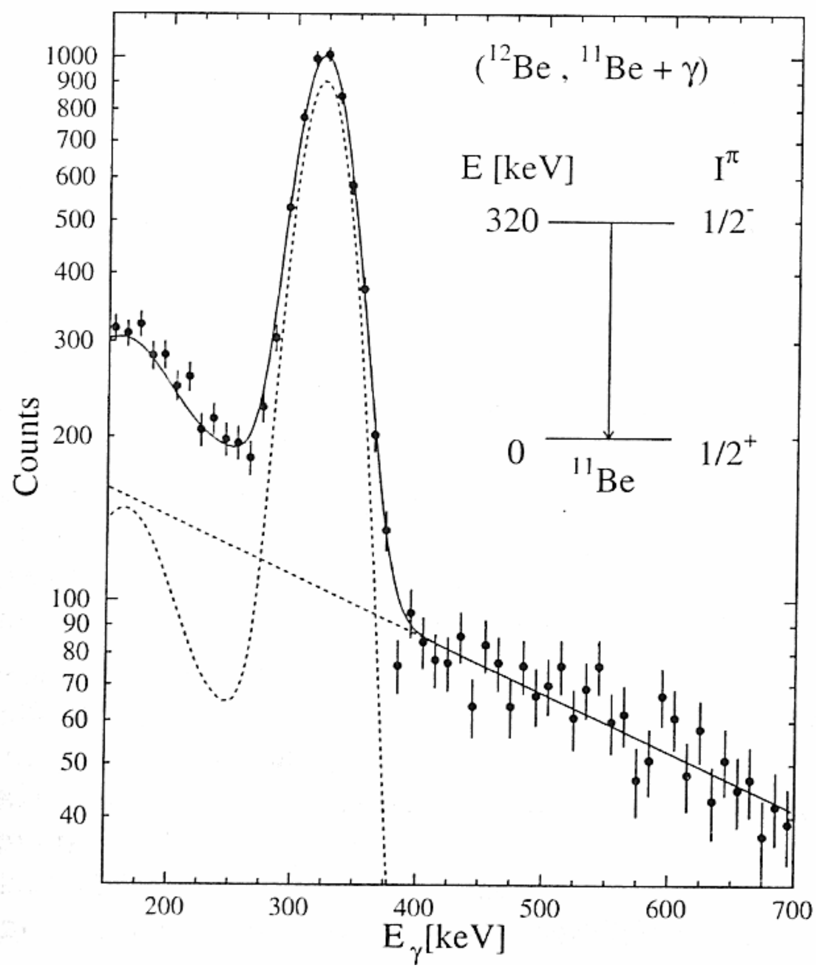


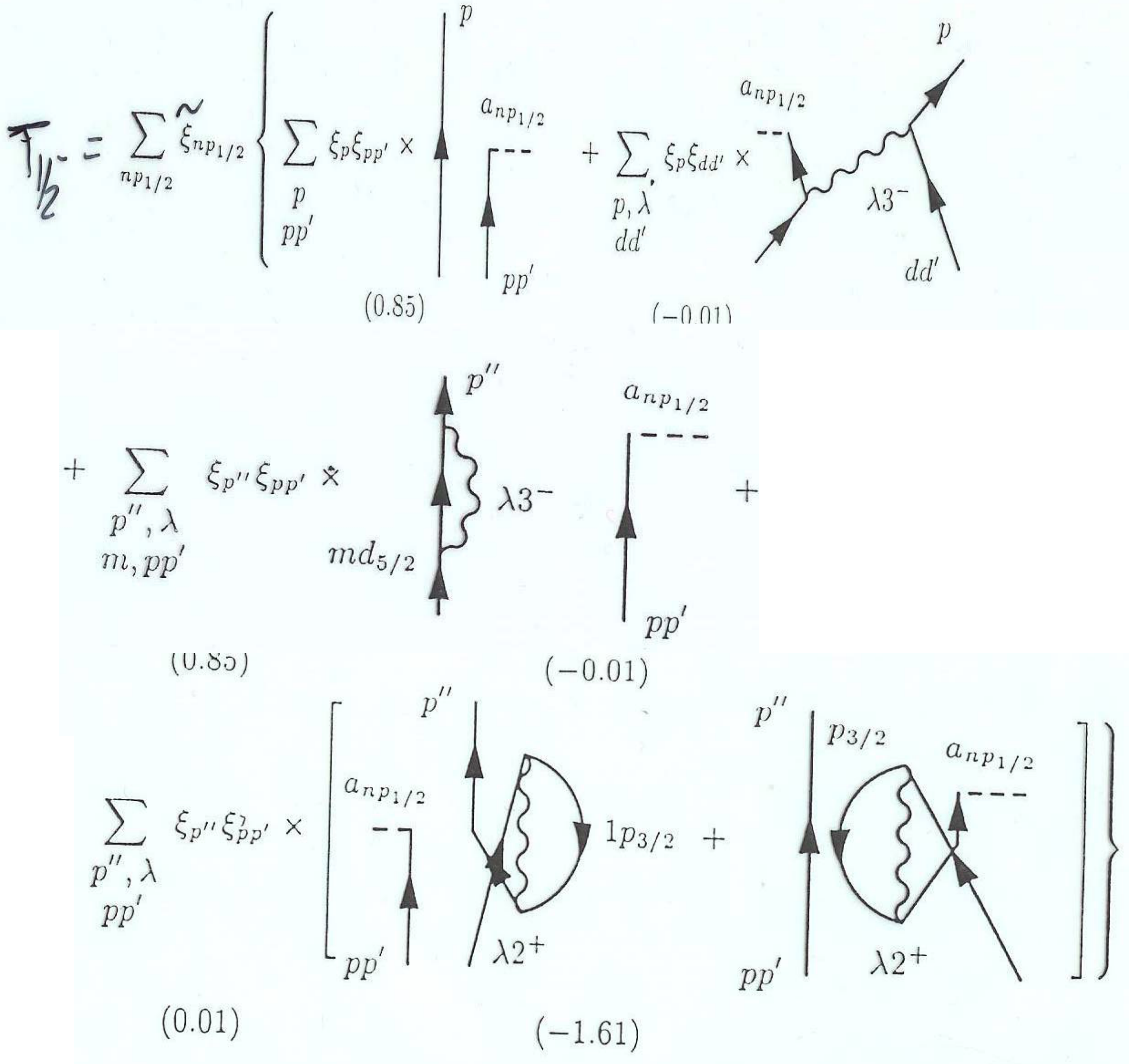
Calc.

Spectroscopic factors from (^{12}Be,^{11}Be+ γ) reaction to ½ $^{+}$ and ½ $^{-}$ final states:

S[1/2^{-}] =0.42 ± 0.10 S[1/2^{+}] = 0.37± 0.10

A. Navin et al., PRL 85(2000)266

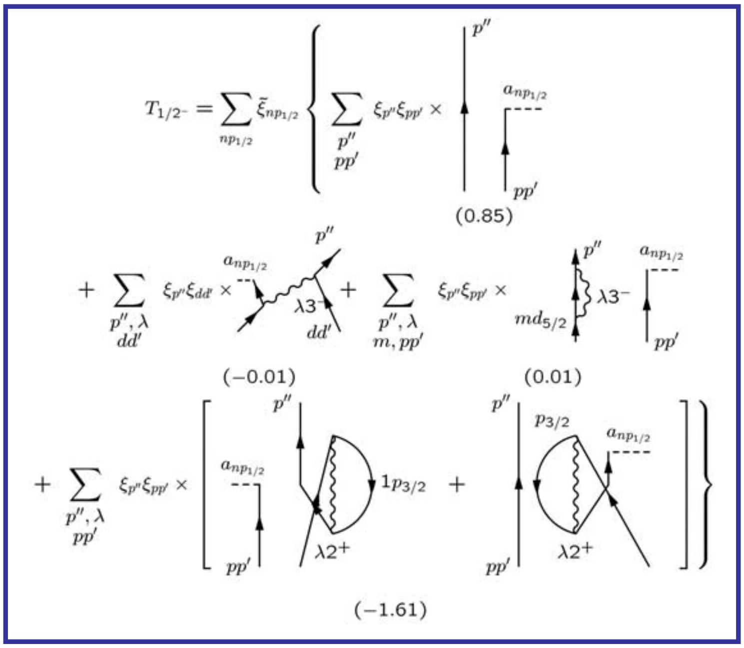




$$\xi_p = \tilde{\xi}_p / \sqrt{N(^{11}\mathrm{Be})}, \qquad \xi_{ii'} = \tilde{\xi}_{ii'} / \sqrt{N(^{12}\mathrm{Be})},$$

ξ_i are obtained diagonalizing the energy-dependent matrix

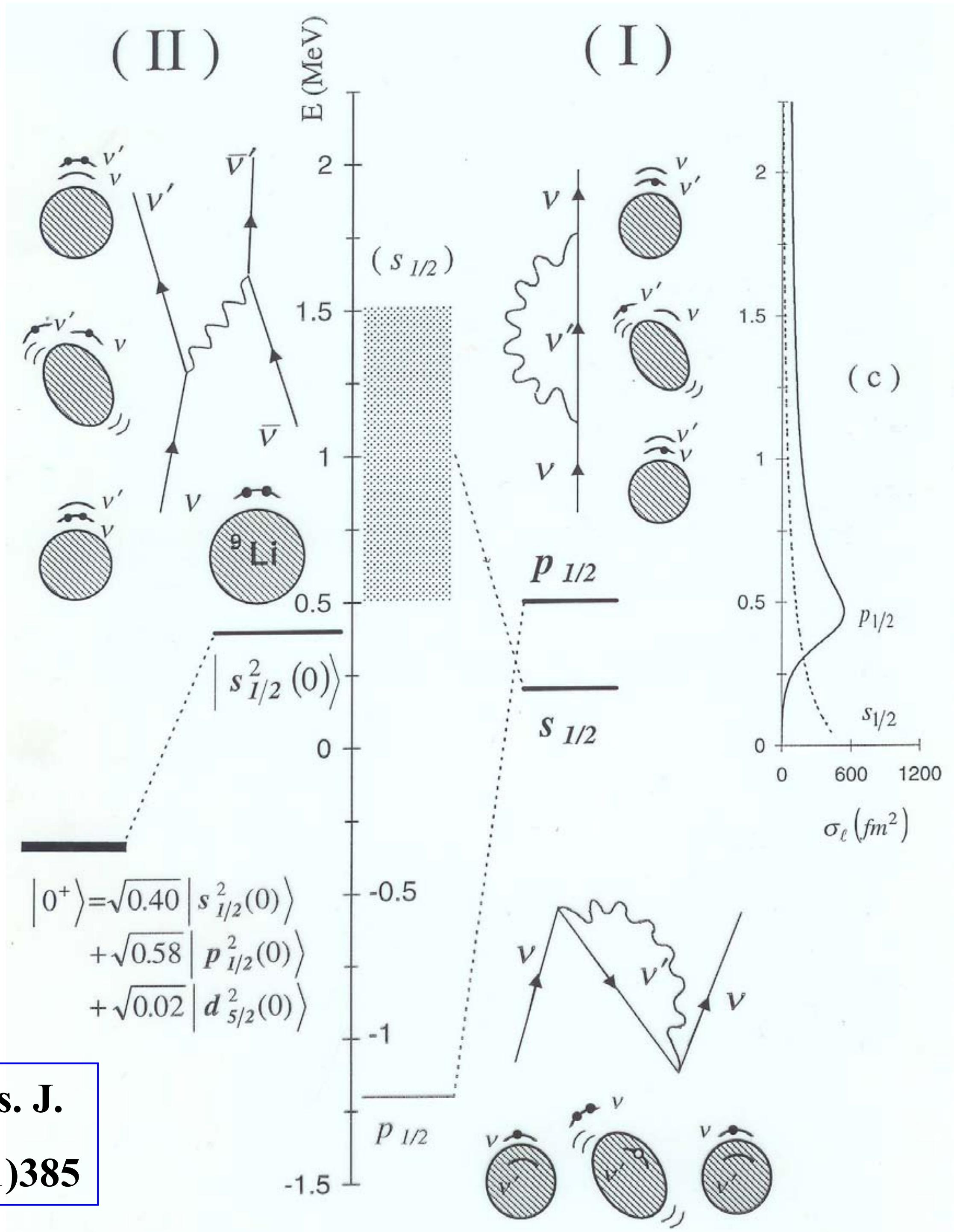
Spectroscopic factors measure the overlap between ^{11}Be and ^{12}Be



Good agreement between theory and experiment concerning energy and spectroscopic factors

	Exper.	Theory	
		particle-vibration +Argonne	mean field
S_{2n}	-3.673 MeV	-3.58 MeV	-6.24 MeV
s^2,p^2,d^2		23%, 29%, 48%	0%,100%,0%
S[1/2$^+$]	0.42±0.10	0.31	0
S[1/2$^-$]	0.37±0.10	0.57	1

Particle-vibration coupling in ^{10}Li and ^{11}Li

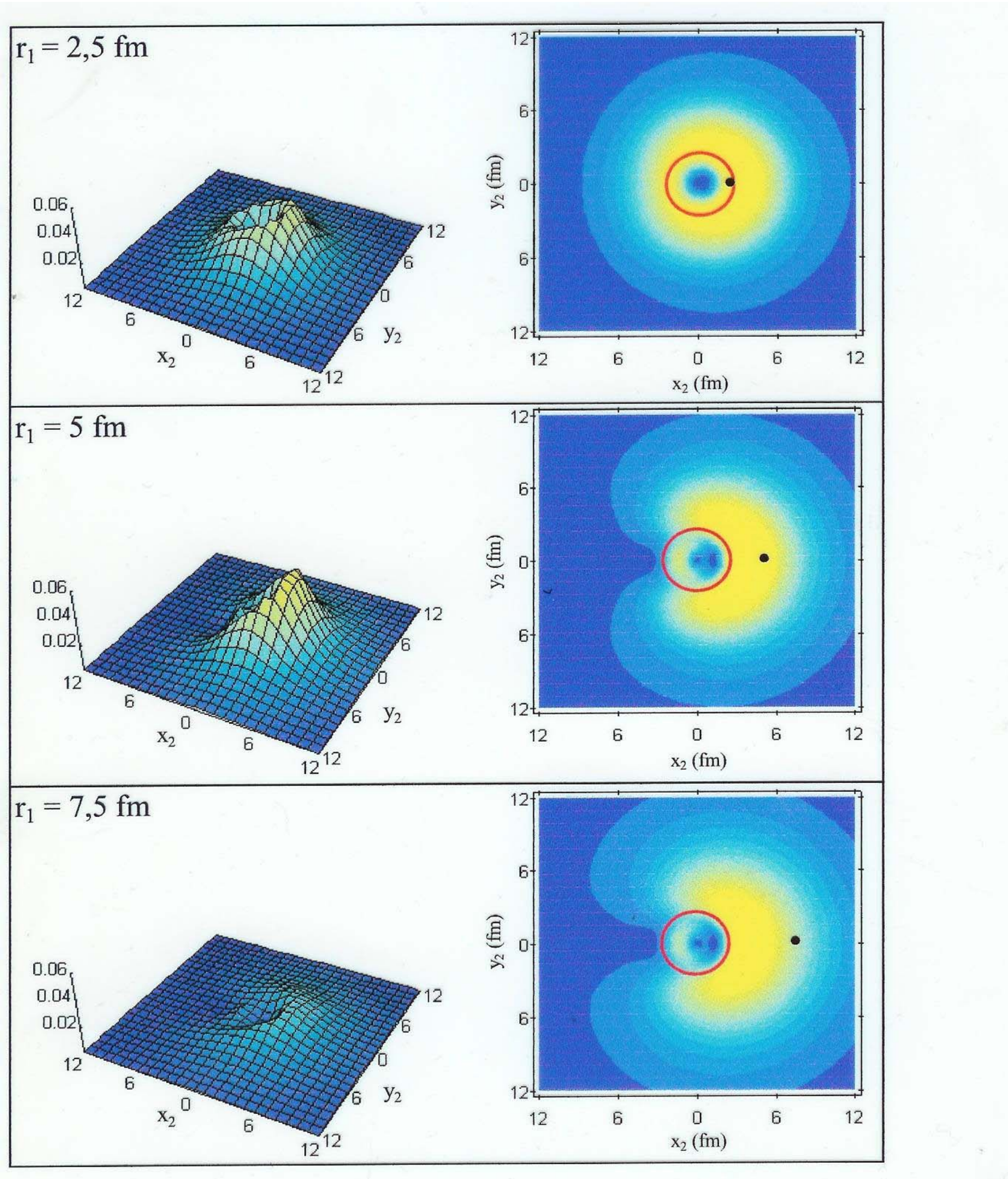


Eur. Phys. J. A11(2001)385

Comparison with experiment

		Exper.	Theory	
			particle-vibration +Argonne	mean field
$^{10}_{3}Li_7$ (not bound)	s	0.1 – 0.2 MeV	0.2 MeV (virtual)	≈ 1 MeV (virtual)
	p	0.5 – 0.6 MeV	0.5 MeV (res.)	-1.2 MeV (bound)
$^{11}_{3}Li_8$ (bound)	S_{2n}	0.294 ± 0.03 MeV	0.33 MeV	2.4 MeV
	s^2 , p^2	50 % , 50 %	41% , 59 %	0% , 100%
	$\langle r^2 \rangle^{1/2}$	$3.55 \pm 0.1\ fm$	$3.9\ fm$	
	$\sigma_\perp$	$48 \pm 10\ \frac{\text{MeV}}{c}$	$55\ \frac{\text{MeV}}{c}$	

Spatial correlations between the two halo neutrons



ADVANTAGES OF THE MODEL:

- Standard mean-field potential, without adjustments of the spin-orbit force or l-dependent terms; the same parametrization for Li and Be isotopes

- Coupling with continuum states is taken into account

- Bare interaction between the valence neutrons, without ad-hoc density dependent terms

- Limited amount of phenomenological input: strength of low-lying vibrations

- Consistent treatment of the Pauli principle (Nuclear Field Theory)

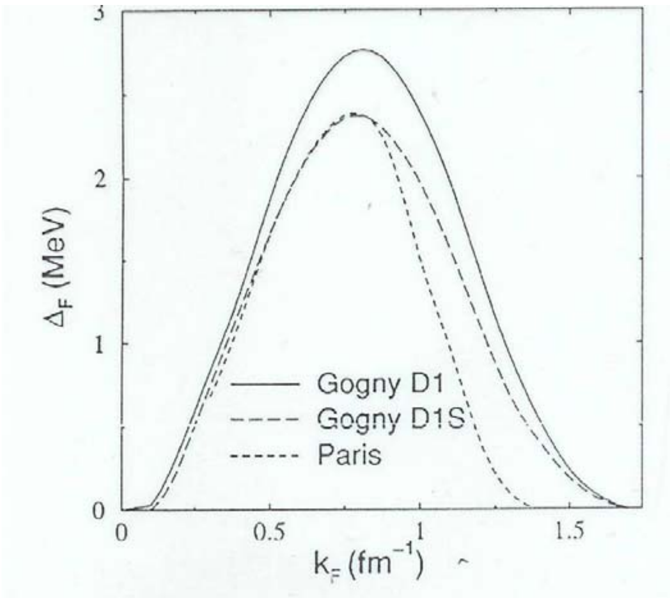
- SOME LIMITATIONS OF THE MODEL :

- One-phonon configurations

- Harmonic vibrations of the core

- Tamm-Dancoff treatment of pairing vibrations

Pairing gaps in uniform matter calculated with effective and bare interactions look similar…



However, in ^{120}Sn Argonne potential reproduces experiment only taking into account renormalization effects