Structure of unstable nuclei studied by Monte Carlo shell model

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Outline of the talk

The title of the workshop is “Past, Present and Future of the Nuclear Shell Model”.

We would like to survey how the understanding of unstable nuclei in the N~20 region has been advanced.

- **Past**
  - Early studies of multi *hw* shell model
- **Present**
  - Performance of unrestricted calculation by the Monte Carlo shell model and a finding of exotic shell structure
- **Future**
  - How to make effective interactions for regions with lack of experimental data

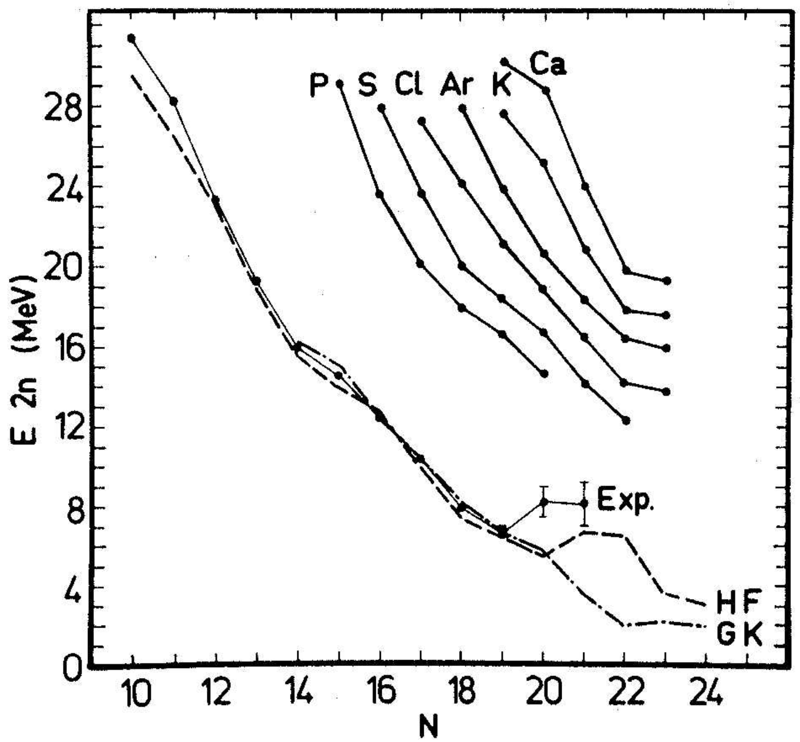
Brief history of realistic shell model calculations in light nuclei

0*hw* model space

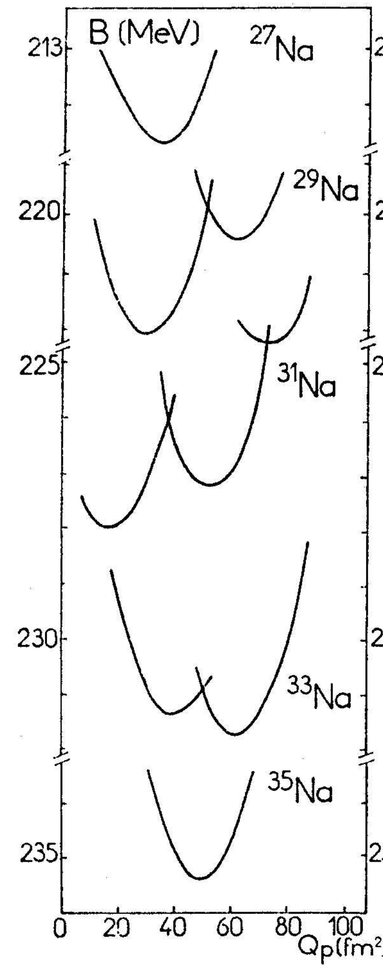
- 1960's: complete study of the p-shell region (Cohen-Kurath)
- 1970's-1980's: realistic sd-shell calculation (Wildenthal-Brown)
- 1990's: Full pf shell calculations turned out possible. (Nakada-Sebe-Otsuka, Caurier et al., Honma-Mizusaki-Otsuka)

- Beyond 0*hw* calculation had been developed slowly. (due to large model space)

Finding of mass anomaly and breaking of magicity



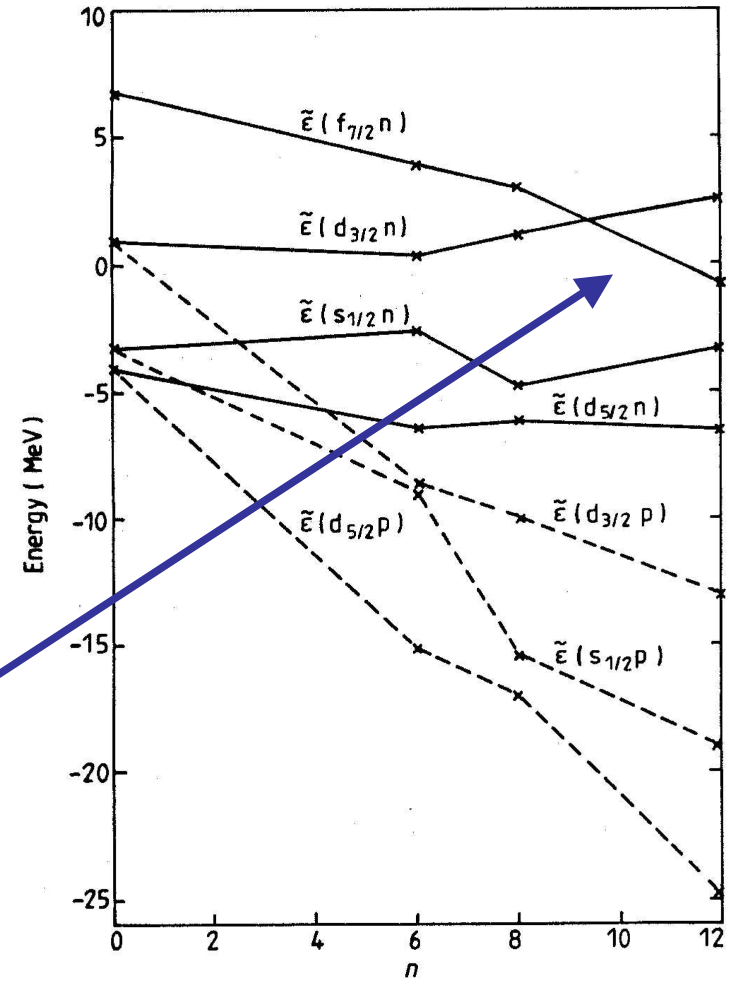
C. Thibault et al., Phys. Rev. C 12, 644 (1975).



X. Campi et al., Nucl. Phys. A251, 193 (1975).

Early study of shell model calculation in the N~20 region

- up to early 1980's
  - sd shell calculation only
  - possible nuclei of intruder dominance are pointed out, leading to later "island of inversion"
- inclusion of the $f_{7/2}$ orbit
  - intruder dominance can be reproduced
  - leading to an unrealistic situation

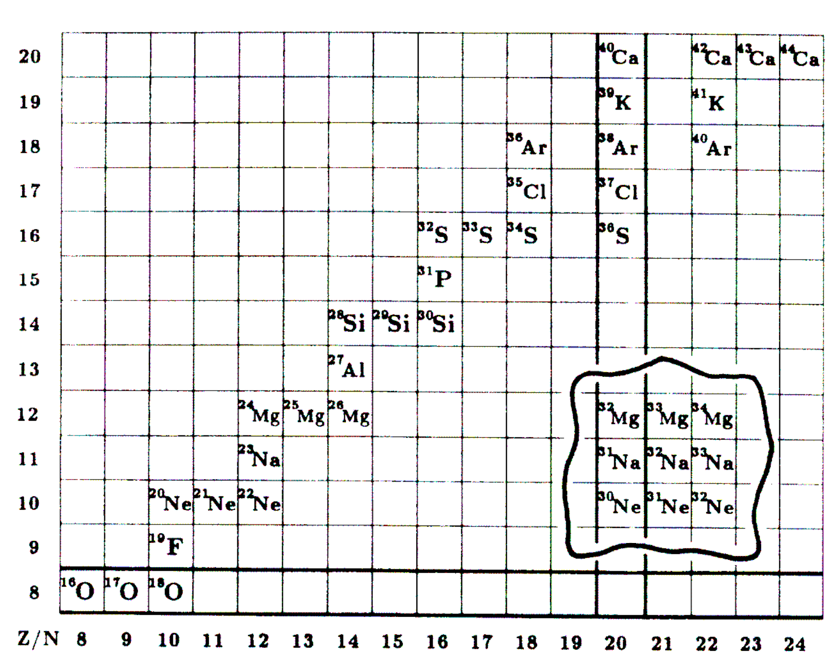


Too small model space do not result in the correct answer.

M.H. Storm et al., J. Phys. G 9, L165 (1983).

Former standard picture "island of inversion"

- Interaction by Warburton, Becker, Miller and Brown in 1990 (hereafter referred to as WBMB)
- Systematic mass calculation in this region
- By comparing the lowest energies between the 0hw and 2hw space, the region, called "**island of inversion**", where the intruder state is the ground state is determined.
- Weak-coupling approximation is also adopted to evaluate the energy that cannot be directly calculated.



Further development

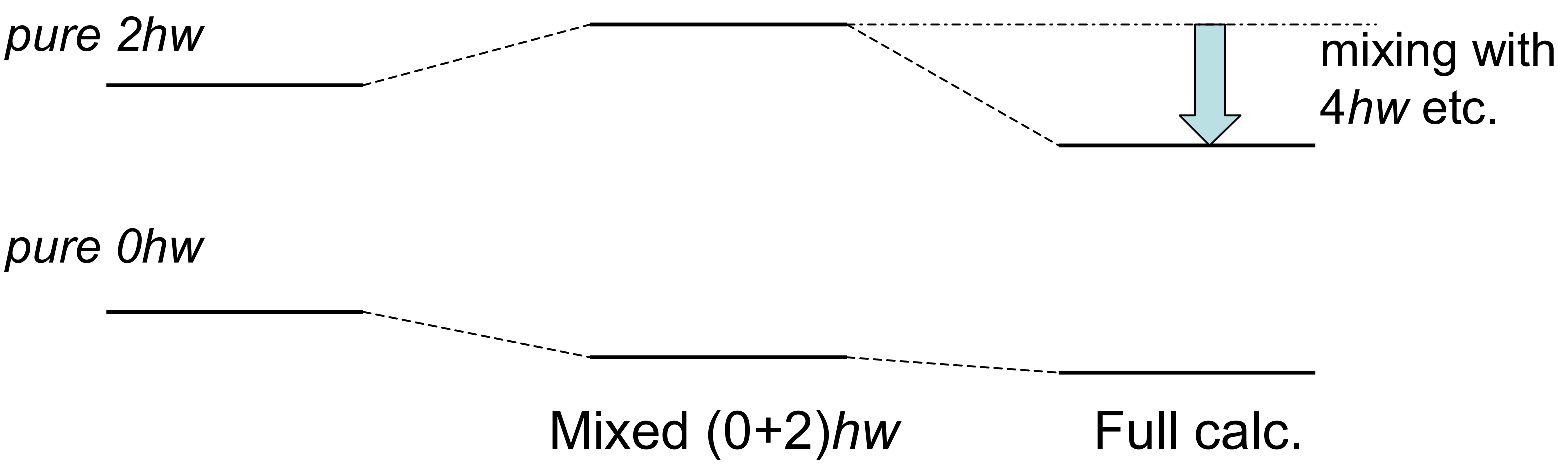
- **Conventional shall model diagonalization**
  Caurier et al.; full sd-pf model space, but the same truncation scheme as WBMB.
- **Shell model Monte Carlo (SMMC)**
  Dean et al.; full sd-pf model space with full mixing, but only ground-state properties
- **Monte Carlo shell model (MCSM)**
  Utsuno et al.; full sd + lower pf model space with full mixing, and calculate lower several states including non-yrast states

What is progress from WBMB?

- **Computational aspect**
  - fully mixed calculation has been performed by Monte Carlo shell model (MCSM).
  - its importance in the nuclear structure?
- **New understanding of exotic shell strcuture**

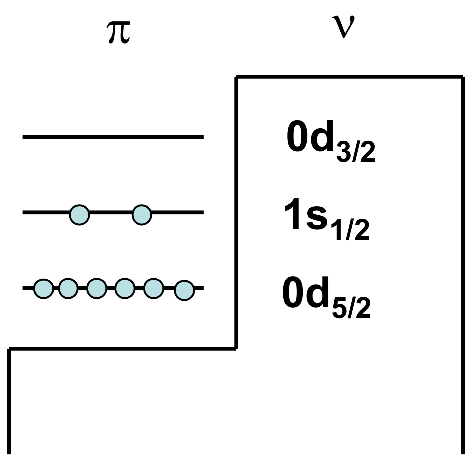
Computational point of view

- WBMB (and Caurier et al.) does not mix the 0*hw* eigenstate with the 2*hw* state. Why?
- Since the 0hw space is much smaller than the 2hw space, the computational limit is not the reason.
- Warburton et al. mentioned "*nhw* catastrophe".



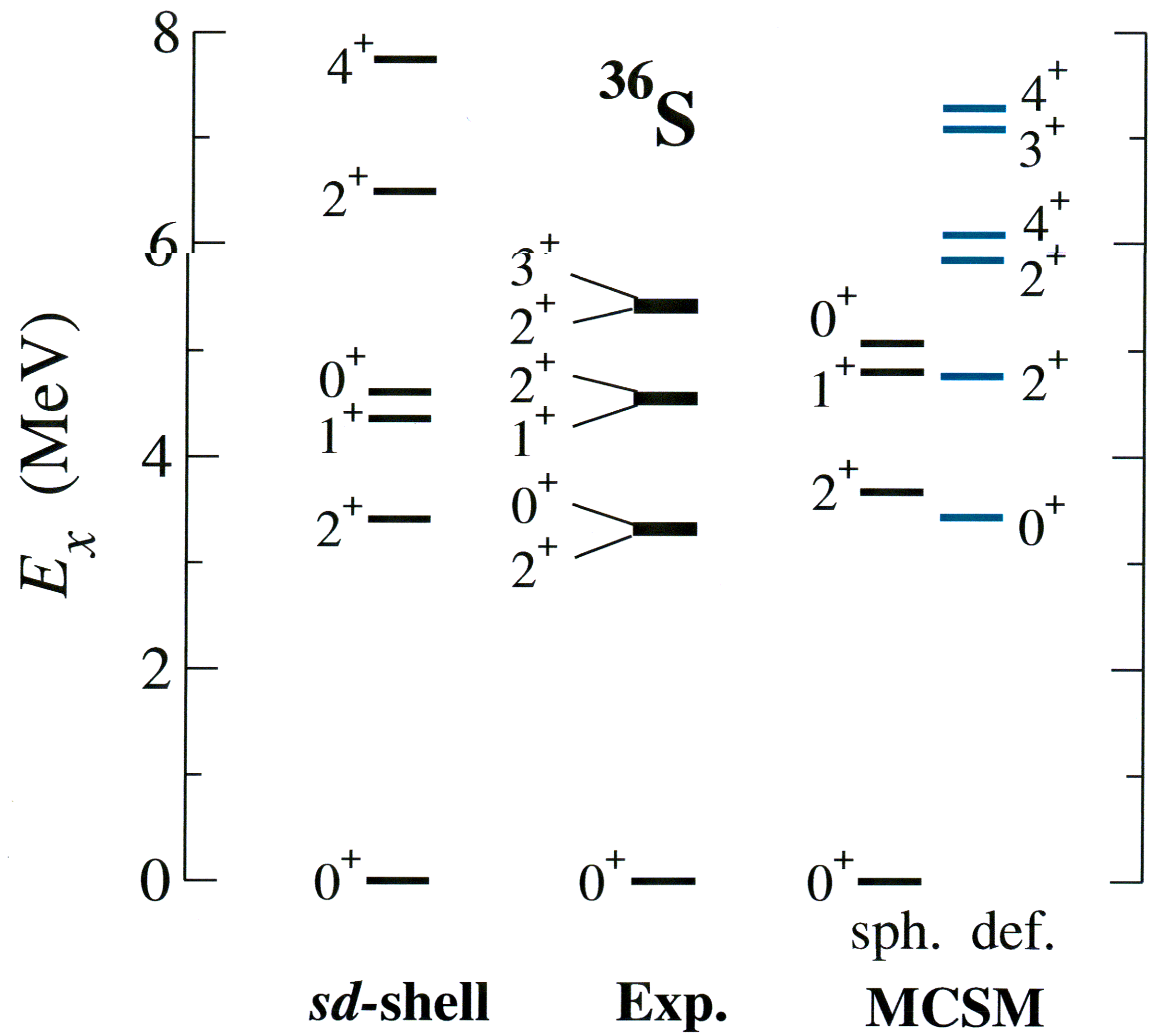
It is speculated that the spacing of the pure calculation is similar to that of the full calculation. Is it true?

Example: ^{36}S



sd-shell : Z=16 closure
- Vacuum : 0^+
- $(1s_{1/2})^{-1}(0d_{3/2})^1$: 2^+, 1^+
- $(1s_{1/2})^{-2}(0d_{3/2})^2$: 0^+, 2^+

Deformed state:
(quasi) K=0 and 2 band
- 5.46 MeV state: 3^+ ?

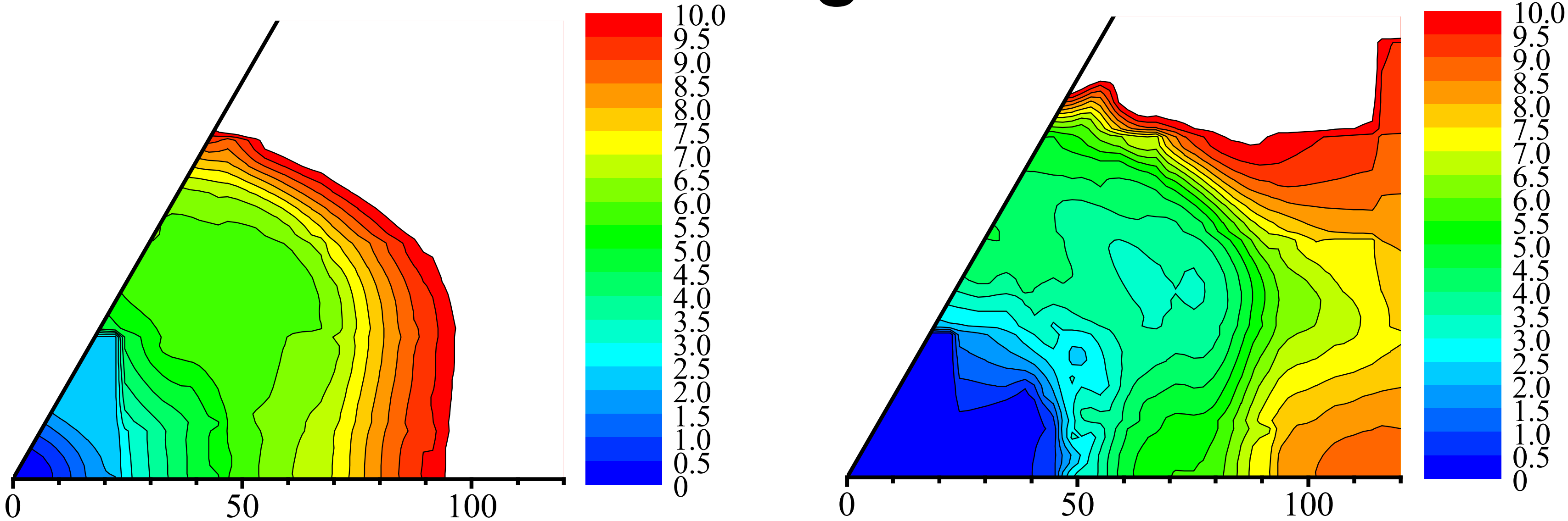


Potential energy surface

- Shell model : development of deformed band

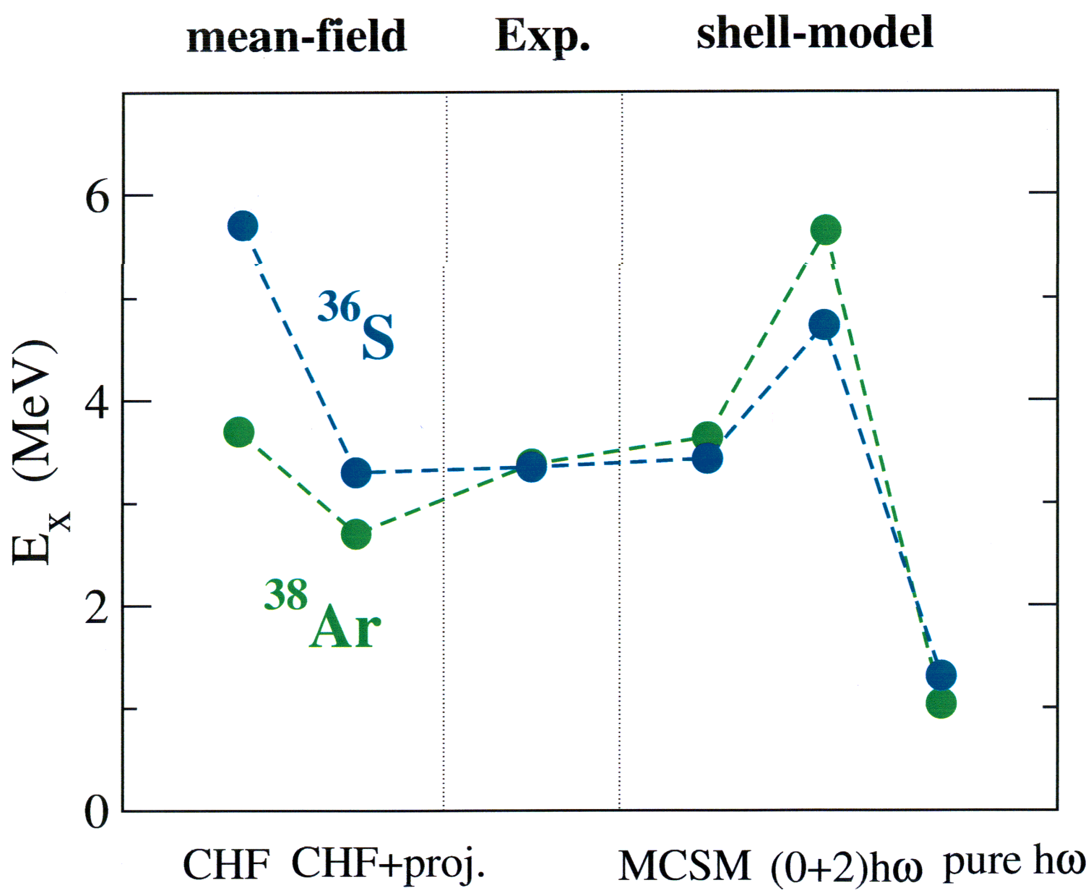
How about the mean-field picture?

(a) unprojected ^{36}S (b) projected onto J=0



- Pure 0p0h and 2p2h states for spherical and deformed minima, respectively

Band-head energies of ^{36}S and ^{38}Ar



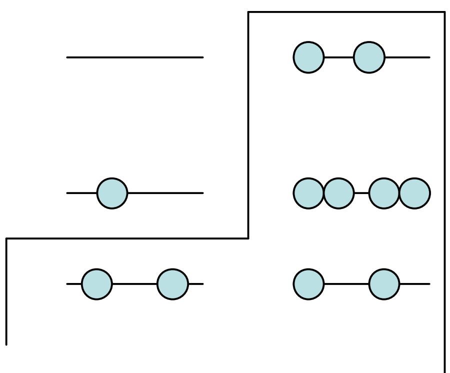
np-nh decomposition of the MCSM state (%)

hw	^{36}S		^{38}Ar	
	0^+_1	0^+_2	0^+_1	0^+_2
0	74	7	66	5
2	24	81	30	79
4	2	11	4	15

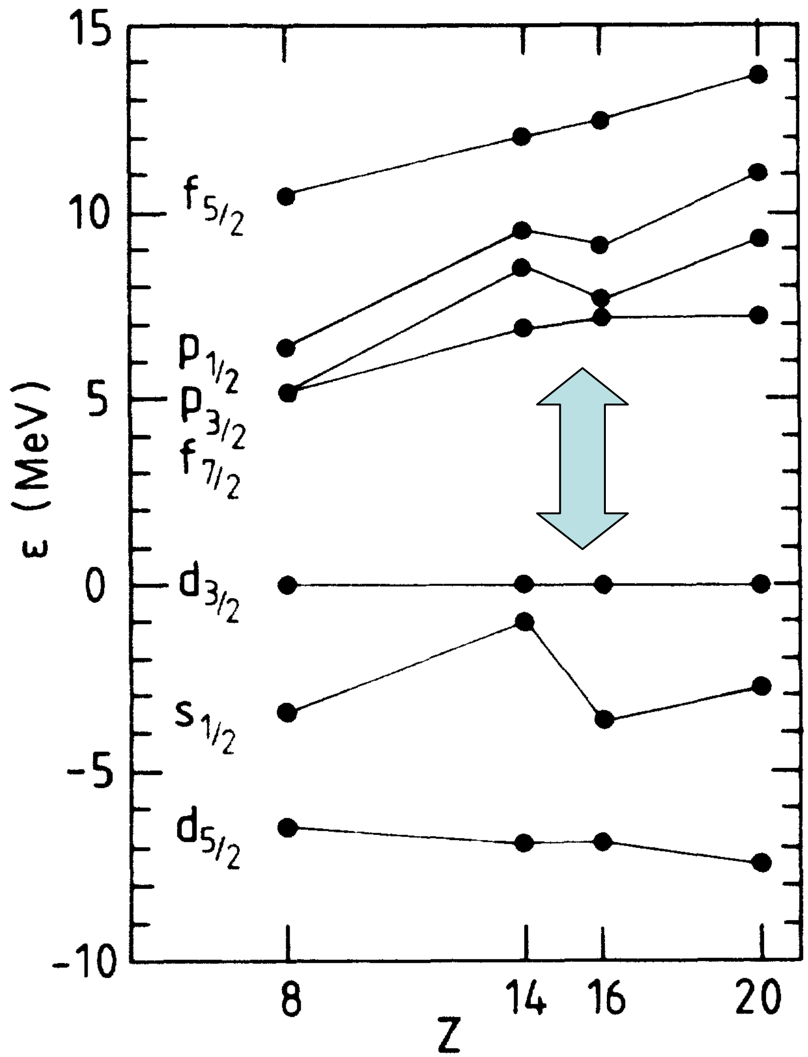
- Effect of J and parity projection in mean field
- Importance of the full mixing in shell model

Shell structure in shell model

- Effective single-particle energy (ESPE)
  - pick up a sub-shell closed nucleus (Z, N = 8, 14, 16, 20, ...) and calculate the energy with the filling configuration
  - add or remove a nucleon in a designated orbit and calculate the total energy
  - energy difference between those nucleus is called ESPE
- EPSE corresponds to the spherical single-particle energy for each nucleus.
- ESPE can be generalized for open-shell nuclei by evaluating energy with the monopole interaction (Utsuno et al., 1999).



ESPE by WBMB



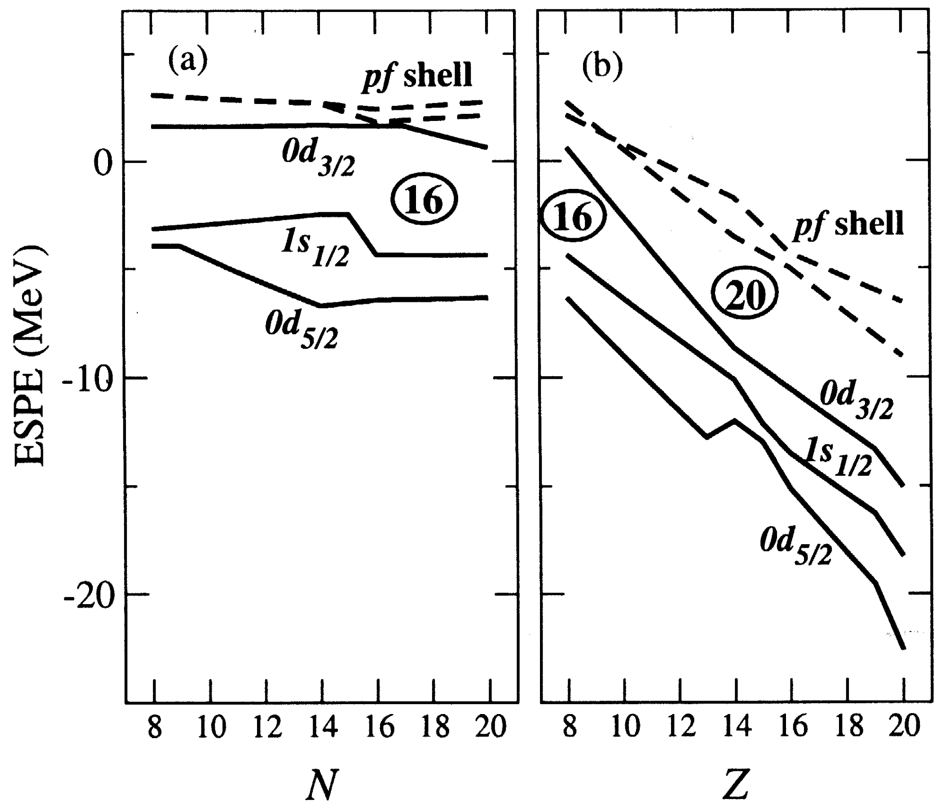
Warburton et al. said,
“we conclude that the decrease in the sd-fp gap contributes but is not the primary cause of the inversion”.

It may be true if only the N=20 isotones are considered.

Exotic shell structure

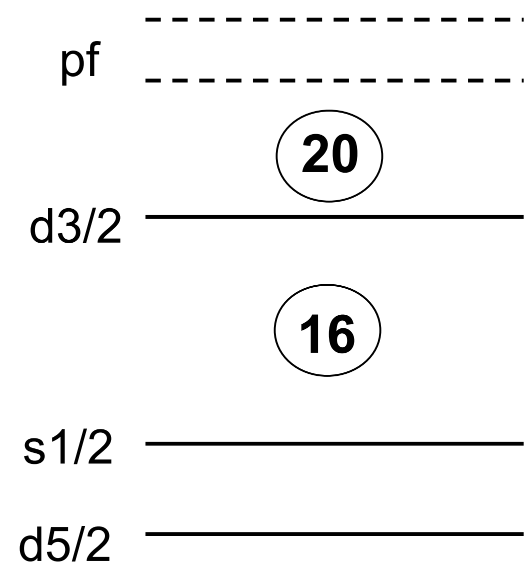
- Driven by non-existence of O isotopes with N=18 and 20 and the large S_{2n} of the last O isotope.
- The N=20 shell gap gets smaller for small Z accordingly.
- Does it affect the structure of isotopes other than O?

neutron shell structure
by SDPF-M interaction



Nuclear structure reflecting a new shell structure

- **Up to N=16**
  - high-lying intruder states
- **N=17**
  - low-lying negative-parity states
- **N=18**
  - strong mixing between 0p0h and 2p2h
- **N=19**
  - "inversion" takes place earlier than previous predictions.

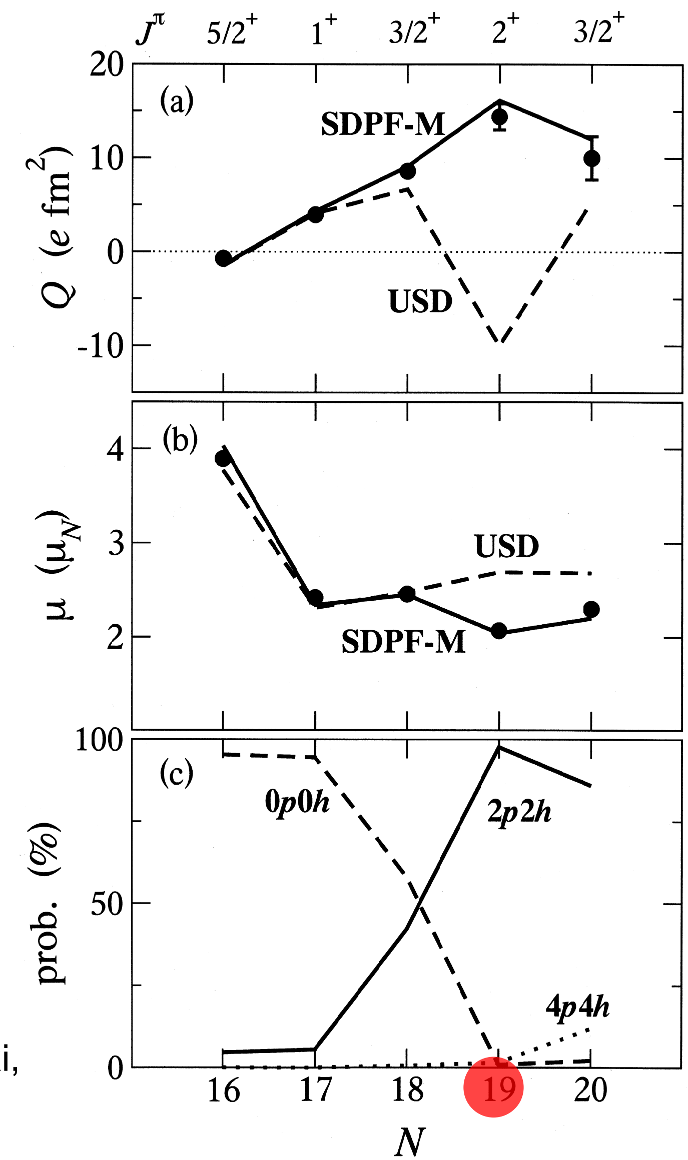


Na isotopes

- **Electromagnetic moment**
  — Sensitive probe for g.s. property
  — Odd-*Z* : non-vanishing value
- **Comparison with exp. data**
  Both quadrupole and magnetic moments are reproduced.
  - **intruder dominance at N=19**
  - **large mixing at N=18 consistent with the enhanced Q moment**

earlier onset than “island of inversion” picture (at N=20)

Y. Utsuno, T. Otsuka, T. Glasmacher, T. Mizusaki, and M. Honma, Phys. Rev. C **70**, 044307 (2004).



^{30}Na: from mass systematics

- It had been considered a normal nucleus.
  - mass in agreement with USD
  - the ground-state spin same as the prediction of USD
  - magnetic moment: deviation is not very large

USD interaction in the sd shell

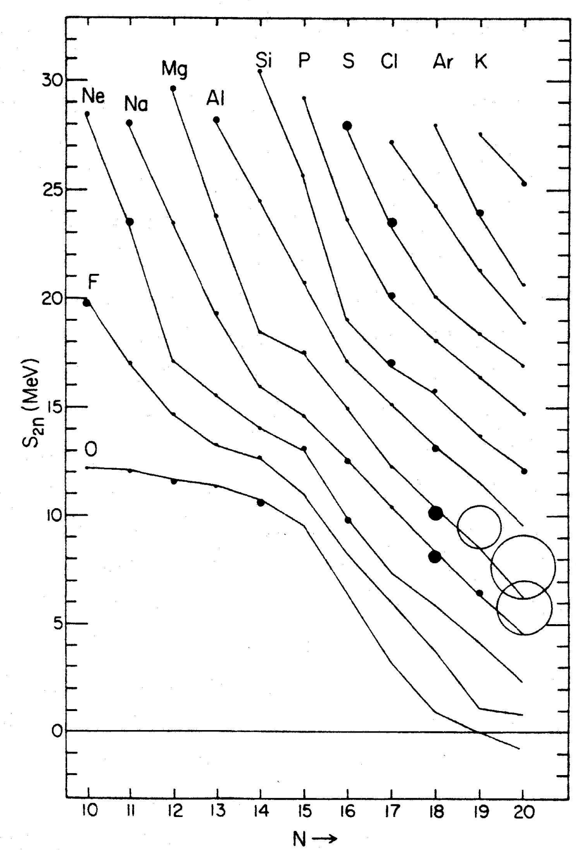


Figure 4 Two-neutron separation energies as a function of the neutron number N (see Section 2.1).

Understanding the mass of ^{30}Na as an intruder state

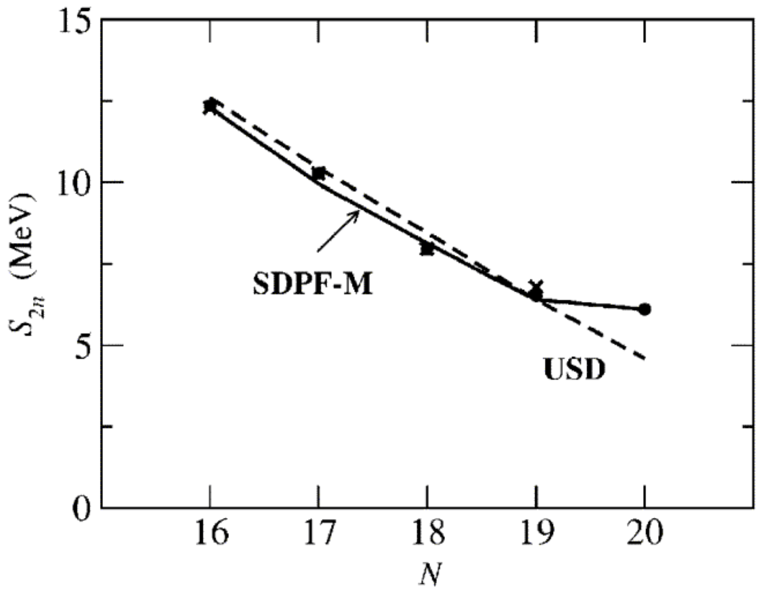


FIG. 2. Two-neutron separation energies of Na isotopes, as a function of the neutron number, N. The circles and the crosses are the experimental values taken from the mass table by Audi *et al.* [34] and a new measurement by Lunney *et al.* [21], respectively. The solid line denotes the MCSM calculation with the SDPF-M interaction, while the dashed line the USD-model calculation.

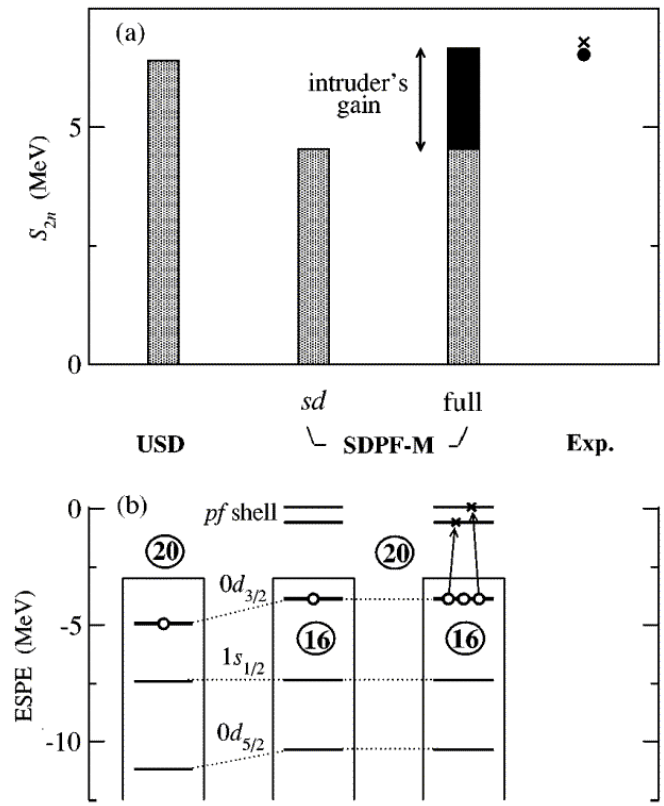
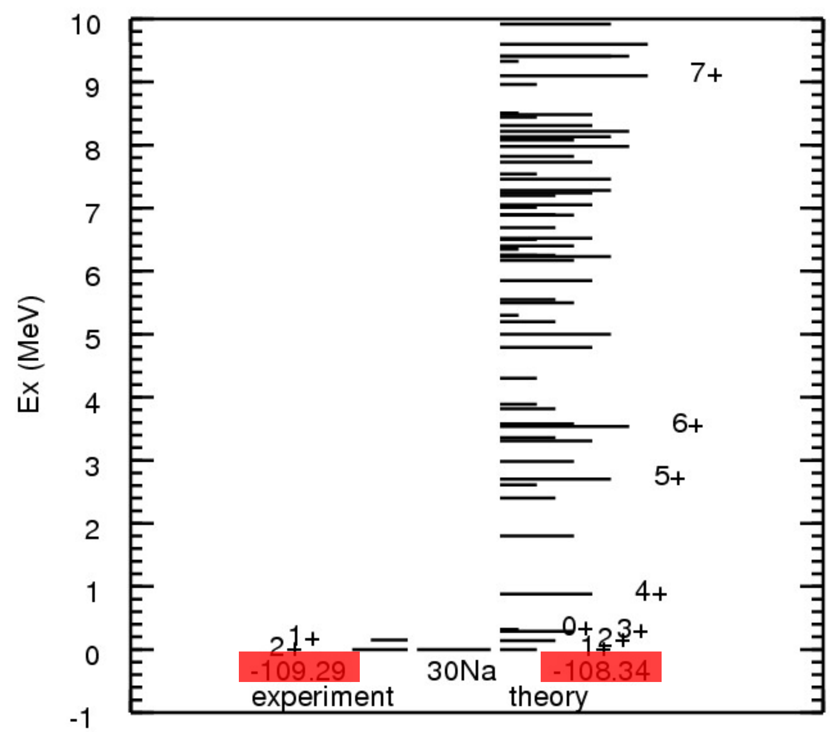


FIG. 3. (a) S_{2n} of ^{30}Na compared among the shell-model calculations (with the USD interaction and the SDPF-M one) and experiment. For the SDPF-M interaction, a truncated calculation within the *sd* shell and the full one by the MCSM are compared, too. The circle and the cross are experimental data taken from Refs. [34] and [21], respectively. (b) Corresponding dominant neutron configurations of the ground state and the ESPE's obtained from each interaction. All the ESPE's are obtained by assuming the filling configuration.

How about a new sd interaction?

- **Original USD**
  - ^{26}O (N=18) is a bound nucleus: N=16 shell gap is not so large.
- **New USD** (B.A. Brown et al., 2005)
  - ^{26}O is unbound, which means larger N=16 shell gap.
  - At the same time, $d_{3/2}$ in Na isotopes is higher than the original.
  - The B.E. of ^{30}Na within the sd shell is accordingly reduced.

USD-05A



http://www.nscl.msu.edu/~brown

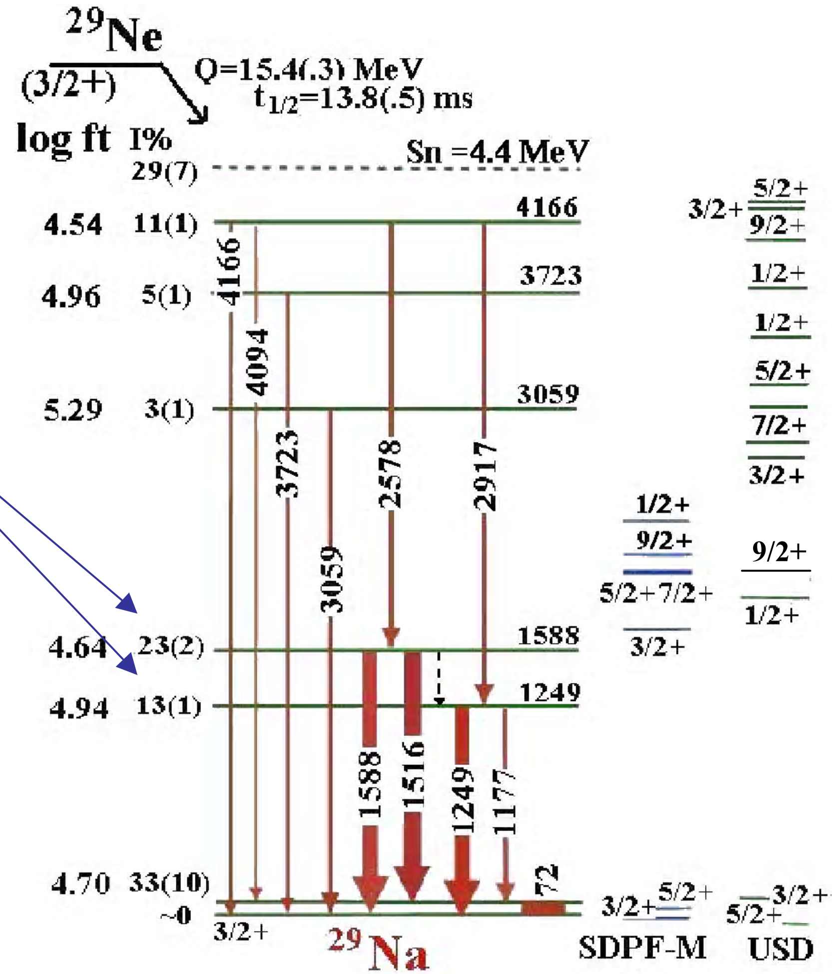
Position of intruder states at N=18

- Only fully mixed calculation can predict the position of the intruder states.
- Thus, the position is a good measure for the shell gap for smaller Z because it cannot be determined well from nuclei dominated by the intruder configurations (such as ^{32}Mg).

^{29}Na—competition and mixing

- ^{29}Na (N=18): new excited states from the β decay

no corresponding level in USD



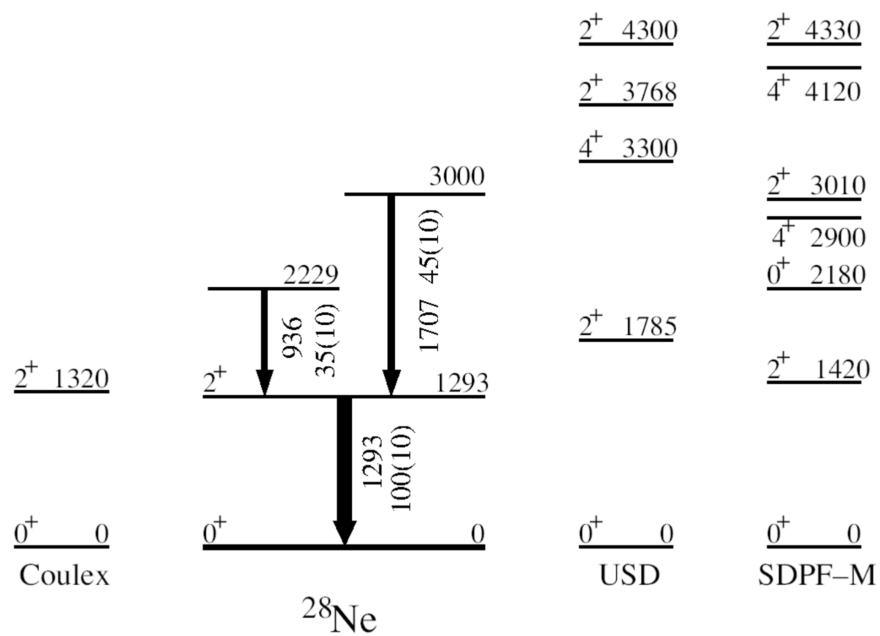
These levels should originate from the intruder state (having strong mixing with the normal state).

The appearance of these states is consistent with the strongly mixed ground state suggested by the enhanced Q moment.

V. Tripathi et al., Phys. Rev. Lett. 94, 162501 (2005).

^{28}Ne—an N=18 isotone

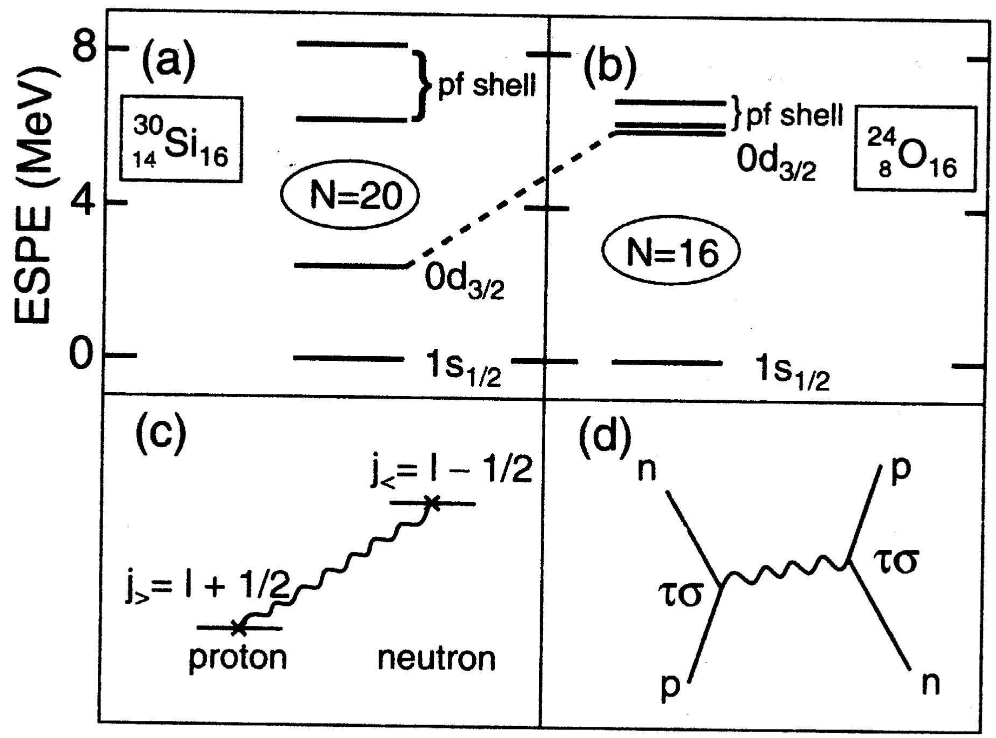
- Similarly to the Na case, low-lying states having large intruder component is predicted to appear.
- Recent experiment: Gamma-ray was observed, but spin-parity has not been assigned.



M. Belleguic et al. Phys. Rev. C 72, 054316 (2005).

From present future about shell evolution

The discussion has been generalized:



In SDPF-M, this effect is included in a phenomenological way.

T. Otsuka et al., Phys. Rev. Lett. **87**, 082502 (2001).

Quantitative discussion? Application to other region?

Microscopic point of view — tensor interaction

- Shell evolution by tensor interaction
  (T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005))
- Spin-tensor decomposition
  All the shell-model interaction can be decomposed into central, spin-orbit and tensor contributions.

Comparison of T=0 tensor monopole interaction (in MeV)

	d3d3	**d3d5**	d5d5
USD	+0.36	-0.30	+0.17
Kuosd	+0.72	-0.60	+0.34
$\pi+\rho$	+0.69	-0.57	+0.33
MK	+0.26	-0.22	+0.13

Summary

- Recent development on the structure of unstable nuclei around N=20 is surveyed.
- The full mixed calculation with large model space makes it possible to trace the nuclear structure back to the shell structure.
- The effective N=20 shell gap must be narrowed as the proton number decreases due to the strong monopole interaction of $d_{3/2}$-$d_{5/2}$, which appears to originate from the tensor interaction. Its universality should be investigated more by extending the mass region.