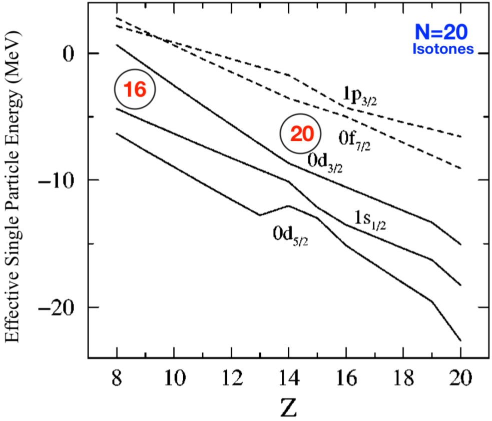
Shell evolution in nuclei

Matthias Heinz



[Utsuno et al., 1999]

Outline

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- Overview of the Shell Model
- Motivation
- Disappearance of $N = 20$ Shell Closure
- Appearance of the $N = 16$ Shell Closure
- Modern Frontiers for Shell Evolution
- Summary

Nuclear Shell Model

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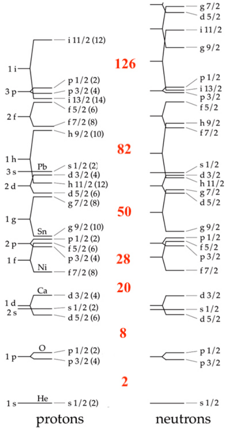
- Mean field and NN correlations
- Valence space for “active nucleons”
- Shell gaps and correlations (configuration mixing)
- Magic nuclei: closed shells for protons and/or neutrons



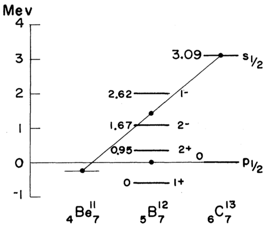
[Amsler, 2015]

Shell Evolution

- Monopole drift
- Consider interaction between $p_{3/2}$ protons and the single neutron

$$\left\langle j^2 (J=0) j' \middle| V_{1n} + V_{2n} \middle| j^2 (J=0) j' \right\rangle = 2 \sum_{J=|j-j'|}^{j+j'} (2J+1) \left\langle j j' J \middle| V \middle| j j' J \right\rangle \Big/ \sum_{J=|j-j'|}^{j+j'} (2J+1)$$

- Spin and isospin dependence
- Monopole vs. multi-pole correlations

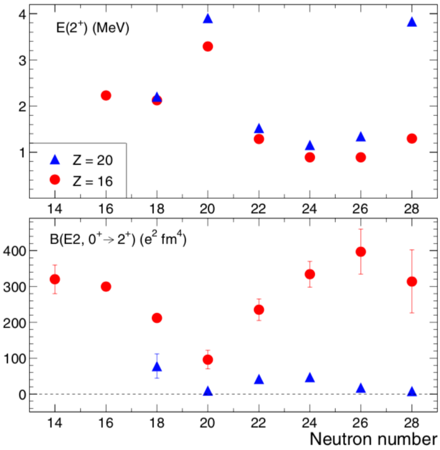


[Talmi and Unna, 1960]

Properties of “Magic Nuclei”

Properties of “magic nuclei”:

- Large binding energy
- Long lifetime
- High excitation energy
- Low $B(E2)$
- Spherical $\rightarrow$ small r_{rms}



[Alamanos and Gillibert, 2004]

Motivation

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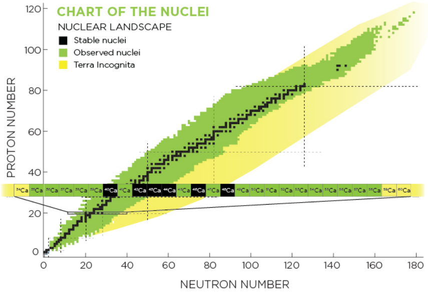
Historical example:

- N = 20 shell disappearance
- N = 16 shell appearance

Experimental challenges:

- Large range of unstable, bound nuclei
- Beam intensity quickly drops to 0



[NSCL, 2018]

Observable: $B(E2)$

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- Reduced electric quadrupole transition probability

$$B(E2 : J_i \rightarrow J_f) = \frac{1}{2J_i + 1} \left| \langle \psi_f | E2 | \psi_i \rangle \right|^2$$

- Measured via intermediate Coulomb excitation
  - Required intensity: ~100 pps
  - Precision: ~10–15%
- Alternative: low-energy Coulomb excitation
  - Required intensity: several thousand pps
- Alternative: lifetime measurement
  - Required intensity: several thousand pps

Coulomb Excitation of ^{32}Mg

Motobayashi et al.

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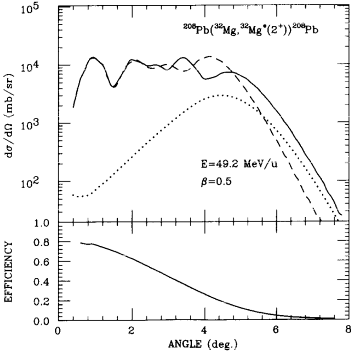
- ^{32}Mg beam on ^{208}Pb target
- Beam energy 49.2 MeV/u
- Measure only forward angles
- Extract $B(E2)$ from cross section

$$\sigma_{E2} \approx \left(\frac{Ze^2}{\hbar c}\right)^2 \frac{\pi}{e^2 b_{\text{min}}^2} B(E2)$$

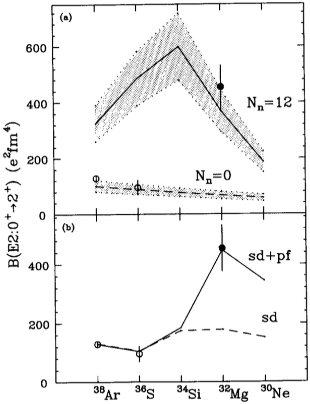
- σ = 91.7 $\pm$ 14.4 mb
- $B(E2)$ = 454 $\pm$ 78 e^2fm^4



[Motobayashi et al., 1995]

Measured Value of $B(E2)$

Motobayashi et al.



[Motobayashi et al., 1995]

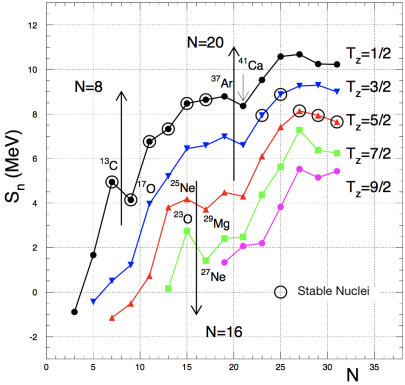
Observable: S_n

Ozawa et al.

- Neutron separation energy
- Determined by nucleus mass

$$S_n(^{40}Ca) = M(^{39}Ca) + M(n) - M(^{40}Ca)$$

- Mass measured by Penning traps and time-of-flight methods
- Penning traps:
  - Required intensity: ~10 pps
  - Precision: ~1 keV
- Time-of-flight:
  - Required intensity: ~0.1 pps
  - Precision: ~100 keV



Data: [Ozawa et al., 2000]
Base figure: [Obertelli, 2018]

Observable: $E_x(2^+)$

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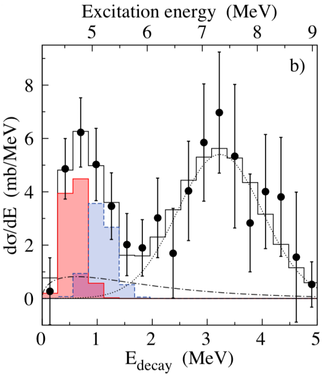
- Excitation energy to $J^P = 2^+$ state
- First excited state is 2^+ in almost all even-even nuclei
- Near stability, measured via β-decay
- For exotic nuclei, measured via in-beam gamma spectroscopy
  - Required intensity: ~10 pps
  - Precision: ~1–10 keV

Measuring $E_x(2^+)$ of ^{24}O

Tshoo et al.

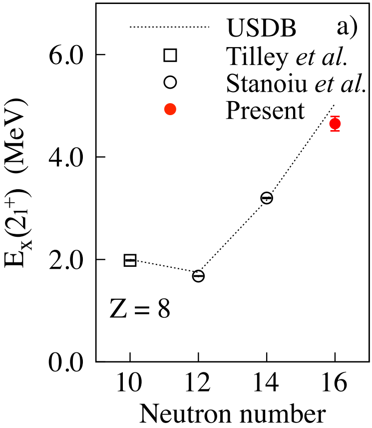
- Proton inelastic scattering
- $^{24}O(p, p')^{24}O* \rightarrow\ ^{23}O + n$
- Excited states are unbound
- Measure ^{23}O and n invariant mass
- Determine decay energy
  - $E_{decay} = 0.56 \pm 0.05$ MeV
- Compute excitation energy
- Need to know S_n
  - $S_n = 4.09 \pm 0.13$ MeV
- $E_x(2^+) = 4.65 \pm 0.14$ MeV



[Tshoo et al., 2012]

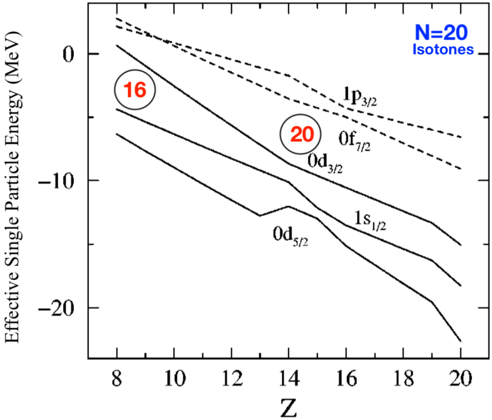
Measuring $E_x(2^+)$ of ^{24}O

Tshoo et al.



[Tshoo et al., 2012]

$N = 20$ and $N = 16$ Recap



[Utsuno et al., 1999]

Modern Frontiers for Shell Evolution

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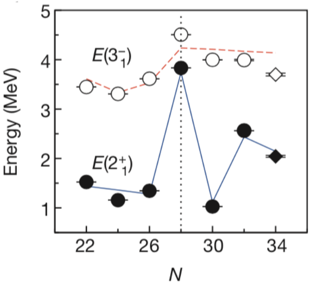
- Are N = 32 and N = 34 “magic numbers” for *Ca*?
- What are the properties of ^{78}Ni and ^{100}Sn?
- What are shell closures for super heavy elements?



[Steppenbeck et al., 2013]

Summary

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- Shells evolve and shell closures are not universal across the nuclear landscape
- Observable signs of shell closure:
  - Low $B(E2)$
  - Large binding energy
  - High $E(2^+)$
  - Small r_{rms}
  - Long lifetime
- Still many unexplored regions
- New facilities currently being constructed to explore these effects

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