Outline
Shell Structure – Collective Structure:

• Experimental methods:
  
  *Coulomb excitation*
  
  *Knockout reactions*

• Magic Numbers in exotic nuclei
• New modes of collectivity?

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The existence of magic numbers is the most important thing to know about atomic nuclei.

Protons and neutrons act almost like independent systems.

Is this true for really exotic nuclei?
Very neutron-rich nuclei are expected to exhibit diffuse surfaces, which leads to a reduced spin-orbit coupling and "melting" of the shell structure.
Nuclei with N,Z near closed shells can be successfully described as many-body systems.

Interactions of valence- protons and neutrons lead to collective correlations, so that

Nuclei far away from closed shells are also described through a (deformed) mean field.
Quadrupole - Deformation

ISF rate limit for mass measurements (Penning trap, 50 keV uncertainty)

Proton dripline

Quadrupole deformation

Neutron dripline

Color scale:
- < - 0.2
- 0.2 – - 0.1
- 0.1 – 0.1
- 0.1 – 0.2
- 0.2 – 0.3
- 0.3 – 0.4
- > 0.4

Neutron number
- electric **Quadrupole moment** leads to electric Quadrupole (E2) transitions.
- Measure E2 transition probability $\Rightarrow B(E2) = \text{measure Quadrupole deformation}$

\[
\frac{Q}{2/5ZR^2}
\]
Even simpler: Grodzins Rule:
Quadrupole transitions
Quadrupole deformation = lower 2+ energy

\[ E(2^+_1) \times B(E2) \uparrow = 2.57 Z^2 A^{-2/3} \]

If we want to investigate shell structure of exotic nuclei, we need

- Exotic nuclei
- Methods to measure excited states
- Methods to measure Quadrupole transition rates
- Methods to measure “single-particle” character
• Superconducting cyclotrons and magnets
• Rare isotope separation by physical means
• Flight path few hundred ns (depends on vault)
• Event-by-event beam particle isotopic identification
• Largest acceptance fragment separator
• Can track beam momentum event-by-event

D.J. Morrissey et al, NIM B 204 (2003) 90
Segmented Germanium Array (SeGA)
Highly-segmented HPGe detectors for fast beams

Intermediate Energy Coulomb Excitation

- Only e.m. excitations?

Shape coexistence in the $N=20$ isotones

Shell-model calculation

      f_{7/2}: X. Campi et al. Nucl. Phys. A 251 (1975) 193

32\(^{\text{Mg}}\) + 209\(^{\text{Bi}}\)

32\(^{\text{Mg}}\): 
B(E2↑) = 447(54)e^2fm^4 (deformed)

34\(^{\text{Mg}}\) + 209\(^{\text{Bi}}\)

34\(^{\text{Mg}}\): 
B(E2↑) = 541(102)e^2fm^4 (deformed)
Investigation of magic numbers close to the drip-line

- Modification of the shell structure may be most easily detected around the neutron magic numbers.
- N=20 is broken in the “island of inversion” at $^{32}\text{Mg}$.
- N=28 is the lightest magic number generated by the spin-orbit coupling.
- N=28 is the heaviest magic number, for which the drip-line can be reached in the foreseeable future.
- Knockout reactions allow us to measure particle structure.
The $N=28$ magic number below Ca

- $T_{1/2}^{(44S)}$ too short to be spherical

- Microscopic calculations
    - strong deformation for $N \approx 28$
    - $f_{7/2} \rightarrow fp$ core breaking

- Measurement of B(E2), collectivity

- Mass measurements at GANIL
Explanation for collectivity in $^{44}$S:
Proton Shell Structure

- As the $\nu(f_{7/2})$ fills from 0 to 8, the $E(\pi d_{3/2})$ is depressed due to $\nu f_{7/2} - \pi d_{3/2}$ interaction
- Explains difference between $^{36}$S and $^{44}$S
- Explains $^{34}$Si
- Explains $^{38}$Ar and $^{46}$Ar ($\pi d_{3/2})^2$
- Predicts $Z=14$ shell closure for $^{42}$Si

Single proton hole energies from Ca($d,^3$He) [P. Doll et al, Nucl. Phys. A 263 (1976) 210]

R.K. Bansal, J.B. French, Phys. Lett. 11 (1964) 145
F. Pellegrini, Phys. Rev. C 19 (1979) 2412
New magic nucleus $^{42}\text{Si}$


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**Nature 435, 922 (2005)**

- **Two experiments** at the Coupled Cyclotron Facility.
- **Primary beam:** $^{48}\text{Ca}$, 140 MeV/u
- **Secondary beams:** $^{44}\text{S}$, 98.7 MeV/u 300 s$^{-1}$
  $^{46}\text{Ar}$ (setup and test) delivered by A1900 fragment separator
Experiments

- Two and one proton-knockout on exotic beams.
- Identify secondary reaction products in S800.
- Measure coincident $\gamma$-rays in SeGA.

$^{46}\text{Ar} \rightarrow ^{44}\text{S}$
$^{44}\text{S} \rightarrow ^{42}\text{Si}$
$^{44}\text{S} \rightarrow ^{43}\text{P}$
Particle Identification: “In and Out”

- Spectrograph selects rigidity $B_\rho \approx v A/q$
- Reaction product's $Z$ are identified by energy loss.
- Mass number $A$ is identified by path-corrected $\text{tof}$.
Single-Proton Knockout $^{44}\text{S} \rightarrow ^{43}\text{P}$

$^{44}\text{S} : \pi \left( \alpha (d_{3/2})^2 + \beta (s_{1/2})^2 + \gamma (d_{5/2})^2 \right) \otimes \nu (xyz)$

$\sigma_{sp}(j, S_p)$

$\sigma(I^\pi) = \sum c^{2S}(j, I^\pi) \sigma_{sp}(j, S_p)$

- Calculate eikonal-approach cross section (J. Tostevin) to knock-out either (here) $d_{5/2}, d_{3/2}, s_{1/2}$ proton
- Measured cross section allows determination of spectroscopic factors
- Large cross sections mean single particle wave functions
Example: Neutron-knockout

- Example: $^{34}\text{Ar} - n \rightarrow ^{33}\text{Ar}^+ \gamma$
- Multiple final states populated
Counting nucleons in single-particle orbits in exotic nuclei: 1-nucleon removal reactions

Measured spectroscopic factor $C^2S$ relates to the occupation number of the orbit involved.

Reduction factor with respect to the shell model $R_s = C^2S_{\text{exp}} / C^2S_{\text{th}}$

$^{32}\text{Ar}$ and $^{22}\text{O}$ have the same neutron configuration but the reduction $R_s$ is very different.

Measured spectroscopic factor $C^2S$ relates to the occupation number of the orbit involved.

- Determination of the occupancies probes the foundations of the nuclear shell model and provides information on the presence of correlation effects beyond effective-interaction theory.
- Reduction has strong dependence on binding energy.
**Single-p knockout:** $^{44}\text{S} \rightarrow ^{43}\text{P}$

- **Total production cross section:** 7.6(11) mb,
- **Only two final states** are populated at large cross sections
- **Exp. upper limit** on $d_{5/2}$ strength up to 4 MeV: <2 mb
- **SM:** expect $5/2^+$-strength 2.2 mb at 1.5 MeV, 7.2 mb at 2.2 MeV
Proton shell structure at N=28

- **Calculation** of pure single particle ka cross-section (J. Tostevin):
  - $d_{3/2}$: 7.7 mb
  - $s_{1/2}$: 6.1 mb
  - Total: 13.8 mb

- **Experiment**:
  - Total: 7.6(11) mb

- 55% of the “single particle” strength “single proton” character for both states

- Degenerate $d_{3/2}$ and $s_{1/2}$ states.

- No significant $d_{5/2}$-strength observed below 4 MeV

- $Z=14$ is a magic number at N=28
2p -Knockout as direct reaction


Indirect 2p-removal would go through neutron-unbound region
=> would rather evaporate a neutron and not produce the product in question

- Characteristics of “direct” reactions: excitation of few degrees of freedom in nuclei
- Knowledge of initial and final wavefunction allows quantitative characterization of the reaction
- Relatively strong reaction leading to exotic nuclei
2p-Knockout

- Cross sections in previous examples:
  Bazin et al PRL 91,1 (2003):
  \[ ^{28}\text{Mg} \rightarrow ^{26}\text{Si}, \sigma = 1.5 \text{ mb} \]
  \[ ^{34}\text{Si} \rightarrow ^{32}\text{Mg}, \sigma = 0.76(10) \text{ mb} \]

- Our experiments:
  \[ ^{46}\text{Ar} \rightarrow ^{44}\text{S}, \sigma = 0.23(2) \text{ mb} \]
  \[ ^{44}\text{S} \rightarrow ^{42}\text{Si}, \sigma = 0.12(2) \text{ mb} \]

- Calculations: (Brown / Tostevin)
  \[ ^{46}\text{Ar} \rightarrow ^{44}\text{S}, \sigma = 0.36 \text{ mb} \]
  \[ ^{44}\text{S} \rightarrow ^{42}\text{Si}, \sigma = 0.17 \text{ mb} \]

- Reduced cross sections are result of \( Z=14 \) shell closure:
  Few valence nucleons available for reaction.
Shell-model + Eikonal theory

- Calculation using parameters derived from Nowacki PRC63, 44316, (2001)
- Model space $\nu: (0f_{7/2}, 1p_{3/2}) \pi (0d_{3/2}, 1s_{1/2}, 0d_{5/2})$
- Calculate both $^{46}\text{Ar} \rightarrow ^{44}\text{S}$ and $^{44}\text{S} \rightarrow ^{42}\text{Si}$ 2p-knockout
2p-Knockout: $^{42}\text{Si} \gamma$-spectrum

- Data from ~500 $^{42}\text{Si}$ nuclei
- Number of gammas counted $N(\gamma) / N(^{42}\text{Si}) = 0.25(3)$
- $\gamma$-spectrum is consistent with no peaks observed
"Microscopic correction" - energy

\[ m_{\text{micro}} = m_{\text{exp}} - m_{\text{FRLDM}} \]

- N=28 shell closure washed out in \(^{44}\text{S}\)
- N=28 shell closure clearly visible in \(^{42}\text{Si}\)
- \(S_N\) in \(^{42}\text{Si}\): 5.9(7) MeV

B. Jurado, W. Mittig et al., to be published

- Two-proton knockout identifies low-energy 770 keV gamma-ray in $^{42}$Si.

- Breakdown of N=28 shell closure?

- or new mode of collective excitation?
What's “exotic” about neutron-rich nuclei

- Many (?) examples for modification of shell structure in neutron-rich nuclei are known (N,Z<50)

- What may be the more interesting question: What are the collective excitations of neutron matter?
Inelastic excitation of $^{16}$C
- extremely low $B(E2) = 0.26$ (W.u.)
- Far off systematics of $E(2^+)$ vs $B(E2)$
Riken: Neutron – Structure of $^{16}$C

- Inelastic proton-scattering selectively populates neutron-states
- Cross section corresponds to neutron deformation $\beta_{pp'} = 0.47(5)$
- $2^+$ energy expected from Neutron deformation
C16 – Neutron collectivity?

- 2N+core cluster model

Three-body model calculations for the $^{16}$C nucleus

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A new type of collectivity?

- How to explain small B(E2): “Decoupling” of neutrons or “Destructive Interference”?
- The B(E2) strength has to be somewhere! Barrier energy Coulomb excitation
- Do protons contribute at all? Proton-knockout study: $^{17}$N $\rightarrow$ $^{16}$C (+\gamma?) (NSCL)
- What is the neutron-wavefunction? Pair transfer $^{16}$C(p,t)$^{14}$C (+\gamma?)
- Are there more, heavier nuclei with this behaviour?
- Is this what we have to expect at the dripline?
- Neutron-rich nuclei have \textit{shell structure different} from their “stable” siblings and their proton-rich mirrors!

- New collective excitations have to be expected: Neutron-only collectivity?

- We need more detailed experiments than the $E(2^+)$ $B(E2)$ of the first excited state!