Exploring the Onset of Shape Coexistence using (d,p) with Exotic Sr Isotopes

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On behalf of the TRIUMF S1389 experimental team
Quadrupole Deformation

- Shape deformation enables the nucleus to minimize its energy.

- HFB calculation (left) shows expected quadrupole deformation across nuclear chart.

Quadrupole deformation is a measure of nuclear shape.

Nilsson model: Different deformations have different single particle configurations.
State of the art (beyond mean field) calculations predict binding energy as a function of deformation.

Measurements of single particle levels in $^{95,96,97}\text{Sr}$ essential for a detailed description of this transitional region.

**Predicted**

*Binding energy curves predict almost degenerate potential minima at $N = 60$.***

**Shape Coexistence at $Z \sim 40$ $N \sim 60$**

- **$^94\text{Sr}$**
- **$^{95}\text{Sr}$**
- **$^{96}\text{Sr}$**
- **$^{97}\text{Sr}$**
- **$^{98}\text{Sr}$**
- **$^{99}\text{Sr}$**
- **$^{100}\text{Sr}$**
- **$^{101}\text{Sr}$**
- **$^{102}\text{Sr}$**
- **$^{103}\text{Sr}$**

**Neutron drip line $A > 107$**

- **$^{87}\text{Rb}$**
- **$^{88}\text{Rb}$**
- **$^{89}\text{Rb}$**
- **$^{90}\text{Rb}$**
- **$^{91}\text{Rb}$**
- **$^{92}\text{Rb}$**
- **$^{93}\text{Rb}$**
- **$^{94}\text{Rb}$**
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- **$^{96}\text{Rb}$**
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- **$^{98}\text{Rb}$**
- **$^{99}\text{Rb}$**
- **$^{100}\text{Rb}$**
- **$^{101}\text{Rb}$**
- **$^{102}\text{Rb}$**

**Stable Neutrons**

- **$^{88}\text{Sr}$**
- **$^{90}\text{Sr}$**
- **$^{91}\text{Sr}$**
- **$^{92}\text{Sr}$**
- **$^{93}\text{Sr}$**
- **$^{94}\text{Sr}$**
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Shape Coexistence at $Z \sim 40 \ N \sim 60$

- State of the art (beyond mean field) calculations predict binding energy as a function of deformation.

- Measurements of single particle levels in $^{95,96,97}$Sr essential for a detailed description of this transitional region.

Predicted Binding energy curves predict almost degenerate potential minima at $N = 60$.

Observed Sudden drop in first $2^+$ excitation energy indicates transition to deformed shape

neutron drip line $A > 107$
State of the art (beyond mean field) calculations predict binding energy as a function of deformation.

Measurements of single particle levels in $^{95,96,97}$Sr essential for a detailed description of this transitional region.
• The strong $0^+_3 (1465 \text{ keV}) \rightarrow 0^+_2 (1229 \text{ keV})$ E0 transition is characteristic of coexisting shapes.

• The deformed $0^+_3$ state at 1465 keV is expected to be the same structure as the $^{98}\text{Sr}$ ground state.

Shape coexistence in atomic nuclei [Rev. Mod. Phys. 83, 1467 (2011)]
The strong $0^+_3 \rightarrow 0^+_2$ (1465 keV $\rightarrow$ 1229 keV) E0 transition is characteristic of coexisting shapes.

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\[ \rho^2(E0) = \frac{Z^2}{R_0^4} a^2 (1 - a^2) [\Delta \langle r^2 \rangle]^2 \]

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Shape Coexistence at $Z \sim 40 \, N \sim 60$

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\[ \begin{array}{cc}
8^+ & 3125 \\
6^+ & 2466 \\
4^{(o)} & 2120 \\
4^+ & 1975 \\
4^+ & 1793 \\
2^+ & 1628 \\
0^+ & 1465 \\
0^+ & 1229 \\
\end{array} \]

\[ 96^{38}_{58} \]

Shape coexistence in atomic nuclei [Rev. Mod. Phys. 83, 1467 (2011)]

$^{94,95,96}$Sr(d,p)Sr reactions to study evolution of structure in Sr through low energy single particle states.

**Aims**

- Measure angular momentum transfer of Sr states ($d\sigma/d\Omega$).
- Measure cross section, which gives an orbital occupation number.
- Compare occupation numbers to large scale shell model calculations that will be carried out in collaboration with shell model experts.
Experimental Campaign

\(^{94,95,96}\text{Sr}(d,p)\text{Sr}\) reactions to study evolution of structure in \(\text{Sr}\) through low energy single particle states.

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**Neutron populates one of the single particle orbitals**


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A 500 MeV proton beam was impinged on a UCx target.

Extracted isotopes were laser ionized, mass separated and transported to the Charge State Booster where the isotopes were charge bred to 16⁺.

Ionized beam (Q=22⁺) was delivered at 5.515 MeV/u to the experiment.
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Ionized beam (Q=22⁺) was delivered at 5.515 MeV/u to the experiment.

Composition of radioactive beam was ~80% $^{95}\text{Sr}$.

$^{95}\text{Sr}$ with an average intensity of $\sim 10^7$ pps was impinged upon a 0.5 mg/cm² deuterated polyethylene target (CD$_2$).
TIGRESS and SHARC detectors used to enable proton-gamma coincidence measurements.
Experimental Station

**SHARC**
- Highly pixelated Si Detectors
- Efficiency $\approx 80\%$
- Coverage $\approx 80\%$ of $4\pi$
- Ang. Res. $\approx 1$ degree.

**TIGRESS**
- 12 HPGe Clovers.
- Efficiency (1 MeV) $\approx 10\%$.
- Coverage $\approx 2\pi$.
- Energy res. (1 MeV) $\approx 2$ keV.

**TIGRESS and SHARC detectors used to enable proton-gamma coincidence measurements.**
- Right: kinematics of measured particles.
- Below: Excitation energy.
- Poor energy resolution makes extracting $^{96}$Sr states difficult.
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- Use proton-gamma coincidences to identify states.
- Right: Gamma singles
- Below: Gamma-gamma
- Corner: Excitation-gamma.
TIGRESS Data

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$S_n = 5.8 \text{ MeV}$
$^{96}\text{Sr}$

TIGRESS Data

$S_n=5.8 \text{ MeV}$
TIGRESS Data

Q = 3.65 MeV
$S_n = 5.87$ MeV

All protons

Gate on 414 keV gamma-ray

$S_n=5.8$ MeV
- Assume pure $v[s_1/2]$ state for the $^{95}$Sr ground state and calculate angular distributions using FRESCO.

- Spectroscopic factors for $0^+$ states will tell us about the $[s_1/2]^2$ component of their single particle configurations.

\[ \text{4}^+ \text{ state} \]
\[ (s_{1/2} - g_{7/2}) \text{ configuration} \]

\[ \text{2}^+ \text{ state} \]
\[ (s_{1/2} - d_{3/2}) \text{ configuration} \]

\[ \text{0}^+ \text{ state [g.s.]} \]
\[ (s_{1/2})^2 \text{ configuration} \]
**96Sr 0+ Ground State**

- Clear $\ell=0$ character.
- Spectroscopic factor of $\sim0.29$ tells us that the $^{96}$Sr ground state is not pure $[s_{1/2}]^2$ configuration.
- Pair scattering of neutrons in $^{95}$Sr would affect the cross section for this reaction.
- Shell model calculations for $^{95,96}$Sr to follow shortly.

![Ground State $l=0$ Angular Distribution](image)

- Experimental Data
  - FRES: $L = 0$, SF = 0.290(8)

![Shell Model Configuration](image)
96Sr 0+ Ground State

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![Graph showing angular distribution and differential cross section](image-url)
1229 keV 0⁺ State

- TIGRESS gate used on 414 keV transition to select 1229 keV state.
- Clear ℓ=0 character in angular distribution.
- Spectroscopic factor determined to be 0.456(3).
1229 keV $0^+$ State

- TIGRESS gate used on 414 keV transition to select 1229 keV state.
- Clear $\ell=0$ character in angular distribution.
- Spectroscopic factor determined to be 0.456(3).
1465 keV $0^+$ State

- $0^+$ state populations strengths can be compared in UQQQ detector.

- Spectrum can be fit using known resolutions and measured cross sections in this angular range.

- $0_3^+$ cross section indicates much smaller $[s_{1/2}]^2$ contribution.

- This suggests a different structure.

\[ \rho^2(E0) = \frac{Z^2}{R_0^4} a^2 (1 - a^2)[\Delta \langle r^2 \rangle]^2 \]
Additional Populated States

- Spectroscopic factor and $\chi^2$ extracted for each state assuming $\ell=0,2,4$.
- Preliminary SFs and spin assignments shown below.

* State spin assigned in previous studies. Our results are in agreement.
Summary and Outlook

- $^{94,95,96}\text{Sr}$ are first high mass (A>30) accelerated beam at TRIUMF.
- Population strengths of low energy $0^+$ states in $^{96}\text{Sr}$ have been measured.
- $0_1^+$ and $0_2^+$ strongly populated, while $0_3^+$ not observed.
- We have begun working with SM experts towards large scale calculations.
- $^{94}\text{Sr}(d,p)$ and $^{96}\text{Sr}(d,p)$ analysis in progress
- $^{94}\text{Sr}(t,p)$ next month at TRIUMF.
THANK YOU FOR LISTENING

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Theory (changes in radii)

- A dramatic occurrence of evolving shape is seen around $Z = 40, N = 60$ \[1\].

- The sudden change in measured radius suggests competing shapes in ground states of Sr isotopes.

- We are investigating how changes in occupations of orbitals affect this transitional region in Sr.

Theory (Sr calculations)

- Relativistic mean-field Skyrme-Hartree-Fock calculations of the structure of strontium predict coexisting shapes.

- The dots denote the corresponding Fermi energy levels.
Elastic Channels

$^{95}\text{Sr}(d,d)$ data provides distorted waves in **incoming** $^{95}\text{Sr}(d,p)$ channel

$^{95}\text{Sr}(p,p)$ data provides distorted waves in **outgoing** $^{95}\text{Sr}(d,p)$ channel

Assume $^{95}\text{Sr}(p,p)$ has ~ the same optical model parameters as $^{96}\text{Sr}(p,p)$
All OM parameter sets predict similar angular distributions for (p,p).

Optical potentials for DWBA

All OM parameter sets predict similar angular distributions for (d,d).

Optical potentials for DWBA

[1] Lohr-Haeberli (A>40 8<E<13 MeV)
   see: ADNTD 17 (1976) p6
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(d,p) Cross Sections

- All OM parameter sets predict similar angular distributions for (d,p).

Theory is in good agreement with data.

Optical potentials for DWBA

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- Occupations from K. Sieja’s $^{98}$Zr calculations shows dominant $(s_{1/2})^2$ character in ground state $0_1^+$ and dominant $(g_{7/2})^2$ character with some $s_{1/2}$ component in first excited $0_2^+$.

- Conclusion: 1465 keV $^{96}$Sr state is likely the equivalent state as the $0_2^+$ state in $^{98}$Zr.
SM Calculations

\[ ^{98}\text{Zr} \]

**neutron occupation numbers**

- \[ 0^+ \]
- \[ 1^+ \]
- \[ 2^+ \]
- \[ 3^+ \]

- \[ v_{2h11/2} \]
- \[ v_{1g7/2} \]
- \[ v_{2d3/2} \]
- \[ v_{3s1/2} \]
- \[ v_{2d5/2} \]

\[ [1] \text{A Holt}^{88}\text{Sr core} \]

\[ [2] \text{K. Sieja}^{78}\text{Ni core} \]

\[ ^{96}\text{Sr} \]

**neutron occupation numbers**

- \[ 0^+ \]
- \[ 1^+ \]
- \[ 2^+ \]
- \[ 3^+ \]

- \[ v_{1g7/2} \]
- \[ v_{2d3/2} \]
- \[ v_{3s1/2} \]
- \[ v_{2d5/2} \]

Preliminary
A Number of other states were also strongly populated and so the angular distributions were also extracted.

Example shown is analysis for 1995 keV state (spin unassigned).

Normalized data is shown with DWBA calculations.

Gamma gated on 1176 keV transition to 815 keV (2+) first excited state.

Strong $\ell=2$ character.
Detector Coverage

SharcCoverageLab

SharcCoverageCm : sr95(d,p)sr96 @ 5.378 MeV/u

SharcCorrectionLab

SharcCorrectionCm : sr95(d,p)sr96 @ 5.378 MeV/u
In the presence of a deformed mean field potential, single particle energies are shifted.

The delicate energy balance between spherical and deformed configurations depends crucially on the size of these energy gaps and the occupations of the single particle levels.