Shape coexistence in exotic Sr isotopes

CAP Congress, Tuesday 17th June 2014.

Steffen Cruz

UBC and TRIUMF

On behalf of the S1389 experimental team
Theory

- Shape deformation enables the nucleus to minimize its energy.

- FRDM calculation below shows expected deformation across nuclear chart.

Quadrupole deformation is a measure of nuclear shape.

Nilsson model: Different deformations have different single particle configurations.


Plot source: R.F. Casten
• This calculation of $^{186}\text{Pb}$ shows how the potential surface has minima close in energy at different shapes.

• The potential minima are produced using different single particle configurations.

• Shape coexistence in nuclei occurs between states with different deformations which can have very close energies.

Onset of deformation is driven by single particle levels

State of the art (beyond mean field) calculations predict binding energy as a function of deformation. Measurements of single particle levels in $^{95,96}$Sr essential for a detailed description of this transitional region.

Beyond mean field calculations of quasi-particle states

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

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

Source: R.F. Casten

Observed neutron drip line $A > 107$
**Experiment**

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

**Aims**

- Measure energies of excited states (single particle energies).
- Measure angular momentum transfer of $^{95}\text{Sr}$ states ($d\sigma/d\Omega$).
- Measure cross section, which gives an orbital occupation number.

*Neutron populates one of the single particle orbitals*
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 15$^+$. 

Ionized beam (Q=22$^+$) was delivered at 5.5 MeV/u to the experiment.
Experiment

**SHARC**
- A Silicon detectors.
- Efficiency $\approx 80\%$.
- Coverage $\approx 80\%$ of $4\pi$.
- Ang. res. $\approx 1^\circ$.

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

$^{94}\text{Sr}$ with an intensity of approximately 30,000 pps was impinged upon a 0.5 mg/cm$^2$ deuterated polyethylene target (CD2).
Experiment

SHARC
- A Silicon detectors.
- Efficiency $\approx 80\%$.
- Coverage $\approx 80\%$ of $4\pi$.
- Ang. res. $\approx 1^\circ$.

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

$^{94}\text{Sr}$ with an intensity of approximately 30,000 pps was impinged upon a 0.5 mg/cm$^2$ deuterated polyethylene target (CD2).
• TIGRESS and SHARC detectors used to enable proton–gamma coincidence measurements.

• Inverse kinematics and other energy losses gives excited state energy resolution $\sim 200$ keV.

Individual $^{95}$Sr states cannot be resolved using SHARC only
Proton intensities are different between states and vary with \( \theta \).
- Reaction code (FRESCO) predicts \( \frac{d\sigma}{d\Omega} \).
- \( \frac{d\sigma}{d\Omega} \) can be used to determine angular momentum transfer, \( \ell \).

Angular distributions can be measured in shaded angular ranges by SHARC.

This predicts the cross section depending on the single particle properties.
SHARC calibrated using triple alpha ($^{241}\text{Am} / ^{239}\text{Pu} / ^{244}\text{Cm}$) source, >15,000 segments.

2mm beam collimator gives SHARC position uncertainty, so fit using data.

Calibration challenges

- Energy loss of beam in target
- Energy loss of ejectile in target
- Energy loss SHARC dead layers and sensitive regions

(x,y,z)

Comparison of expected energy measured with data to determine position of target during experiment.
We want to select transfer protons only, so need to characterize particles and reactions.

Particle identification used through dE-E detector arrangement
• Use PID and kinematic cuts to select transfer protons for analysis.

• Reconstruct excitation energy using kinematics.
Ongoing analysis

- Doppler corrected gamma spectra gated on transfer protons.

- Evidence for direct population of $^{95}\text{Sr}$ states.

Adapted from [NNDC.bnl.gov](http://NNDC.bnl.gov)
Gate on transfer proton states using gamma coincidences.
Ongoing analysis

Gate on transfer proton states using gamma coincidences.

We see both direct population of 352 keV state and feeding from higher states.
Looking to the future

- Extract angular distributions.

- Measure absolute cross sections.

- Determine single particle occupations and compare to theoretical calculations.

- Continue high mass Sr(d,p) campaign with $^{95}\text{Sr}$ beam (begins next week!).
THANK YOU FOR LISTENING

many thanks to;

R. Krücken$^{1,2}$, P. C. Bender$^2$, K. Wimmer$^3$, F. Ames$^2$, C. Andreoiu$^4$, C. S. Bancroft$^3$, T. Drake$^5$, R. Braid$^6$, T. Bruhn$^2$, W. Catford$^7$, D. S. Cross$^4$, A. Garnsworthy$^2$, G. Hackman$^2$, A. Knapton$^7$, K. Kuhn$^6$, J. Lassen$^2$, R. Laxdal$^2$, M. Marchetto$^2$, A. Matta$^7$, D. Miller$^2$, M. Moukaddam$^2$, N. Orr$^8$, A. Sanetullaev$^7$, C. Unsworth$^2$, P. Voss$^4$

• 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.

(a) Magnetic substate energy dependence in a deformed nucleus

(b) SPE shifts as a function of deformation
A dramatic occurrence of evolving shape is seen around $Z = 40, N = 60$ [1].

The sudden change in radius suggests competing shapes in ground states of Sr isotopes [2].

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.
The rotational band built on top of the third $0^+$ states at 1465 keV indicates deformation.

The strong $0^+ (1465 \text{ keV}) \rightarrow 0^+ (1229 \text{ keV})$ transition is characteristic of coexisting shapes.

Coexistence is next seen in $^{98}\text{Sr}$. 

*Shape coexistence in atomic nuclei [Rev. Mod. Phys. 83, 1467 (2011)]*
15\(^+\) A/Q minimises contamination of beam.

Anticipated (on target);
- \(2\times10^5\) p.p.s. of \(^{94}\text{Sr}\)
- \(1\times10^5\) p.p.s. of \(^{94}\text{Rb}\)
- \(1\times10^6\) p.p.s. of \(^{94}\text{Mo}\)

Measured (on average);
- \(^{94}\text{Sr}\) 50\% of total beam
- approx. 30,000 p.p.s. \(^{94}\text{Sr}\)
The main component in the spectrum is the radioactive $^{94}$Sr beam, the major contaminant is $^{119}$Sn.

The measurement of the beam composition has been repeated several times during the experiment, the composition of the beam was stable throughout the experiment.
Beam contaminants with $A>94$ or $Z>38$ were suppressed using a scintillator–degrader configuration called the trifoil.

If trifoil detects a signal, search for signals in TIGRESS and SHARC.

During analysis we can use timing gates to make use of this veto.