The Strong Force

One of the four basic interactions, playing among others an essential role for:

- Quark – Gluon - Plasma
- Formation and development of stars
- Development of the universe
- Synthesis of the chemical elements
- Structure of the atomic nuclei
The Strong Force

Shell strength parameter $\delta_{2n}$ of nobelium isotopes ($Z = 102$)

SLy4 - prediction

exp. values

$\delta_{2n}$ / MeV

Neutron Number

0,0 0,5 1,0 1,5 2,0

Neutron shell $N = 152$

HFB - SLy4
(Chatillon et al. EPJ A30, 397 (2006))

$E^* / \text{keV}$

experiment

1/2-[521]

294+x3

7/2-[514]

253+x2

210+x1

0+x1 0+x2 0+x3

3/2-[521]

7/2+[633]

243{Es} 245{Es} 247{Es} 249{Es} 251{Es} 253{Es}
Superheavy Nuclei (SHN) - Chemical Elements:

- Group of nuclides ('isotopes') with same proton but different neutron numbers,
- Having equal chemical properties, nearly identical atomic properties ('Coulomb force'),
- But different nuclear structure ('strong force') - not a proper concept for nuclear physics.

R.Smolanczuk, A. Sobiczewski
Proc. EPS Conf. 'Low Energy Nucl. Dyn.'
St. Petersburg, Russia, 1995 & priv. comm.

Macroscopic – Microscopic Predictions of Shell Effects

Shell effects \(-E_{sh}/\text{MeV}\)

- Proton number
- Neutron number

Stability limit of a droplet against prompt fission
**Tin – region:**
- All parametrizations predict the same shell closures, $Z=50$, $N=50$ and $N=82$
- High shell correction energies in narrow regions around the shell closures

**SHN region:**
- Shell closures are strongly dependent on the parametrization,
  - $Z = 114$, 120 or 126, $N = 172$ or 184
- Wide regions of high shell correction energies are predicted

Physics Motivation for Synthesis and Nuclear Structure Investigations of SHN

Understanding nuclear structure of SHN is essential for understanding their properties and stability, i.e. the 'strong force' and thus the 'limits of our world'.

Topic Questions
- Are there proton and neutron shells at all?
  - How strong are they?
  - Where are they located?

Shell structure determines nuclear mass excess, which determines Q-values for α- and β-decay.
Expected Decay Modes and Halflives of SHN

- **α-decay**
- **β-decay**
- SF

**Expected decay modes and halflives**

**Proton number**

- **Z=114**
- **Z=108**

**Neutron number**

- **N=162**
- **N=184**

**Nuclear Structure**

**Synthesis**

- <1
- <10^{-4}
- <10^{-8}
- >10^4
- <1
- <10^{-4}
- <10^{-6}
- <10^{-9}
- >10^9

Expected decay modes and halflives by Karpov et al. [2012], Smolanczuk [1995], Smolanczuk et al. [1995], and Poenaru et al. [1980].
Velocity separator SHIP

**SHIP**

- **Separation time:** 1 – 2 µs
- **Transmission:** 20 – 50 %
- **Background:** 10 – 50 Hz
- **Det. E. resolution:** 18 – 25 keV
- **Det. Pos. resolution:** 150 µm
- **Dead time:** 25 µs
Nuclear structure investigations require a large amount of events, but production rates of SHN are low (ca. 240 /d/nb)

- **Nuclear structure of odd-A even Z nuclei** is similar along isotone line

- **Nuclear structure of odd-A even Z nuclei** is similar along isotope line

- Study of systematics of (low lying) Nilsson levels in odd A nuclei

- Study of K - isomers
Decay Study of $^{259}$Sg

Production by $^{206}$Pb($^{54}$Cr,n)$^{259}$Sg; $\sigma \approx 1$ nb; $\alpha$-decay from two states $^{259g}$Sg ($T_{1/2} \approx 410$ ms) and $^{259m}$Sg ($T_{1/2} \approx 250$ ms) observed.

CE not in coincidence with 9610 keV and 9035 keV lines!!
CE in coincidence with 9545 keV;
no gammas or K X-rays observed in del. coincidence with $\alpha$ – particles;
first decay scheme of $^{259}$Sg based on $\alpha$, $\alpha$-$\gamma$, $\alpha$-CE measurements and systematics for N=153 isotones

S. Antalic et al. subm. to EPJ A
Decay schemes of the N=153 Isotones $^{255}$No, $^{257}$Rf, $^{259}$Sg

$^{255}$No

- (1/2+[620])
- (3/2+ ?)
- (1/2+[631])
- (7/2+[624])

$^{257}$Rf

- (1/2+[620])?
- (3/2+ ?)

$^{259}$Sg

- (1/2+[620])
- (1/2+[620])

References:
- B. Streicher et al. EPJ A 45, 275 (2010)
- S. Antalic et al. subm. to EPJ (2014)
Nilsson-Levels in N=151 Isotones
Nilsson-Levels in N=153 Isotones
1. deceleration
2. cooling
3. accumulation
4. purification
5. storage
6. detection

Masses Measured
252, 253, 254, 255$_{\text{No}}$
255, 256$_{\text{Lr}}$
Masses of N-Z = 48, 50 even-even nuclei

Determination of 2n binding energy
Shell strength towards $N = 162$

$S_{2n}$ - separation energies

- exp.
- Mac.-Mac., Smolaczuk et al.
- Mac.-Mac. Möller et al.
- SkP Dobaczewski et al.

$N = 162$ – shell more localized or weaker than predicted ??

Neutron number $N$
Z – Identification of SHE

- α-chains terminated by sf
- sf of o-o – nuclei strongly hindered
- maybe no sf of o-o nucleus observed; but sf of e-e daughter af EC
- EC is a 'certain' source for K-X-rays
- Z – identification by delayed coincidences between K – X-rays and sf

→ test-case: $^{258}\text{Db}$

Predict. SF - halflives

$^{266}\text{Rf}$: 23s
$^{268}\text{Rf}$: 1.4s
$^{270}\text{Rf}$: 20 ms
Direct Prove of EC of $^{258}$Db

γ–spectrum (coinc. CE) preceeding sf within $\Delta t < 39$ ms

From delayed coincidences $T_{1/2}(sf) = 13 \pm 11$ ms
Implantation depth of ER < range of SF products
p(sf1+sf2) \approx 40\%
large PHD due to high ionisation density

\[ \text{Implantation depth ER} \approx 6-10 \, \mu m \]

\[ \text{range of sf products} \approx 22 \, \mu m \]

\[ p sf1 + sf2 \approx 40\% \]

\[ \approx 7 \, \mu m \text{ for } ^{258}\text{Db} \]
configuration
- **stop detector**: $1 \times$ DSSD ($60 \times 60$ strips)
- **box detectors**: $4 \times$ SSSD (32 strips)
- overall particle - $\gamma$-efficiency $\approx 40$

chamber
- **compact** (overall length 35 cm)
- Al-cap with thin $\gamma$ window (1.5 mm)
- compatible due to 150 mm standard flange
- electronics partly integrated (vacuum)

**DSSD**
- integrated cooling (Cu-frame) and connection (flex-PCB)
- $60 \times 60$ strips/mm (pitch 1 mm)
- 300 $\mu$m

D. Ackermann, J. Maurer, M. Vostinar, J. Piot, N. Kurz, P. Wieczorek, J. Hoffmann et al.
Enhanced Focal Plane Detector Set-up for SHE Spectroscopy

First on-line test at LISE – Wienfilter GANIL, November 2014

$^{40}\text{Ar}$ (4.66 AMeV) + $^{174}\text{Yb}$ → $^{209,210}\text{Ra}$

DSSD – analog signal processing

Energy resolution ≈ 20 keV (FWHM)
Enhanced Focal Plane Detector Set-up for SHE Spectroscopy

Digital signal processing → FEBEX + conventional PA
DSSD, Ge-detectors, .....  
• fast timing • deadtime free • pulse shape analysis options

![Graph showing energy distribution and FWHM](image)

\[ \text{Ra}_{209,210} \]
FWMH = 45 keV

![Single trace graph](image)
**Summary and Conclusions**

- Macroscopic – microscopic models did a great job in predicting a region of 'relative' high nuclear stability above the actinides (superheavy elements) at $Z = 114$ and $N = 184$.

- Selfconsistent models using effective NN – interaction put the 'old' shell predictions in question, $Z = 120$, 126 and also $N = 172$ appear as possible candidates for proton and neutron shells.

- Nuclear spectroscopy is a suited method to obtain detailed information about the nuclear structure and the underlying nuclear force and to test the predictive power of models with respect to location and strengths of nuclear shells (even without reaching the 'center').

- Precise mass and $Q_\alpha$ – value measurements allow to determine the strength of nuclear shells in the region of SHE.

- Nuclear spectroscopy is also an unambiguous method to determine the atomic number by measuring K – X-rays either from deexcitation of nuclear levels populated by $\alpha$ – decay or from EC.

- On long-term view a general (or common) parametrization of the 'strong force' to decribe commonly evaluation of the universe and the stars as well as the atomic nuclei is desired; investigation of superheavy nuclei are hopefully a valuable tool to reach that aim.
Collaboration

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