The EXPERT project at the Super-FRS fragment separator

Vratislav Chudoba

FLNR, JINR
NUclear STructure, Astrophysics and Reactions

SuperFRS Experiments

EXPERT (EXotic Particle Emission and Radioactivity by Tracking)
Physical case of EXPERT

- unknown exotic nuclear systems
- new types of radioactivity
- resonance decays
- beta-delayed decays
- exotic excitation modes
Why exotic?

- far from stable nuclei
- complicatedly available

too heavy

or

strange in other way
Nuclear halo
Nuclear halo

- tunneling to the forbidden regions
- extended size of nucleus

Soft dipole mode (SDM) of Giant dipole resonance (GDR)

- protons vs. neutrons
- $E_{\text{GDR}} \sim 14 - 24$ MeV
- induced by EM excitation
Soft dipole mode (SDM) of Giant dipole resonance (GDR)

**GDR**
- protons vs. neutrons
- $E_{\text{GDR}} \sim 14 - 24 \text{ MeV}$
- induced by EM excitation

**SDM**
- halo vs. core
- $E_{\text{SDM}}$ lower than $E_{\text{GDR}}$
- induced by EM excitation and charge-exchange reaction
Soft dipole mode (SDM) of Giant dipole resonance (GDR)

**GDR**
- protons vs. neutrons
- \( E_{\text{GDR}} \sim 14 – 24 \) MeV
- induced by EM excitation

**SDM**
- halo vs. core
- \( E_{\text{SDM}} \) lower than \( E_{\text{GDR}} \)
- induced by EM excitation and charge-exchange reaction
Radioactivity and decays

- **α decay**: E. Rutherford, 1899
- **β⁻ decay**: H. Becquerel, 1886
- **β⁺ decay**: F. and I. Joliot-Curie, 1932

- **p radioactivity**: S. Hoffman, 1982
- **2p radioactivity**: M. Pfützner, 2002
- **n radioactivity**: still waiting
Proton radioactivity

p-radioactivity
natural generalization
of α-radioactivity
Proton radioactivity

p-radioactivity
natural generalization of α-radiactivity

2p-radioactivity
genuine quantum mechanical phenomenon
Proton radioactivity

**p-radioactivity**
Natural generalization of α-radiactivity

**2p-radioactivity**
Genuine quantum mechanical phenomenon

\[ S_p < 0 \]
\[ E_T \]
\[ E_{2r} \]
\[ (A-1) + p \]
\[ (A-2) + 2p \]

\[ ^{45}\text{Fe}, \, ^{19}\text{Mg}, \, ^{54}\text{Zn}, \, ^{48}\text{Ni}, \, ^{67}\text{Kr}, \, ^{94m}\text{Ag} \]
Neutron radioactivity

2n decays

\[ E_T = -S_{2N} > 0 \]

\[ S_{2N} < 0 \]

\[ (A-1)+N \]

\[ (A-2)+2N \]

\[ A \]

4n decays

\[ E_T = -S_{4N} > 0 \]

\[ S_{3N} > 0 \]

\[ S_{2N} > 0 \]

\[ (A-1)+N \]

\[ (A-2)+2N \]

\[ (A-3)+3N \]

\[ (A-4)+4N \]

\[ A \]

\[ 5^5 \text{H}, \ 10^{10} \text{He}, \ 26^{26} \text{O}, \ ... \]

\[ 7^7 \text{H}, \ 18^{18} \text{Be}, \ 28^{28} \text{O}, \ ... \]
Available experimental methods

- ion-implantation method
- decay-in-flight by tracking technique
  - information on life-time accessible
  - identification of 2p-decay channels by correlations
Decay-in-flight by tracking

fragmentation in target

decay vertex

2p-decay in flight

Intensity

Distance from target to decay vertex

successfully used in series of experiments (e.g.)

- I. Mukha et al., PRC 77 (2008) 061303
- I. Mukha et al., PRC 82 (2010) 054315
- I. Mukha et al., PRL 115 (2015) 202501
Life-time measurement by tracking

- characteristic shape of vertices distribution
- suitable for lifetimes $10^{-7} – 10^{-12}$ s
Identification of 2p-decay channels
Identification of 2p-decay channels

(a) A-1 → A → A-2
(b) A-1 → A → A-2
(c) A-1 → A → A-2
Identification of 2p-decay channels

- transition $k_{\text{p-HI}} \rightarrow \theta_{\text{p-HI}}$
- without measurement of proton energies

Identification of 2p-decay channels

- transition $k_{p-HI} \rightarrow \theta_{p-HI}$
- without measurement of proton energies


true 2p decay

$\theta_{p_{14}^{14}O}$ (mrad)

$\theta_{p-HI}$
Hardware
EXPERT: Experimental setup

- Secondary beam
- γ-ray detector with LaBr₃, CsI crystals, GADAST
- Very thick secondary target
- High-resolution spectrometer for heavy-ion (HI) fragments $A-2(Z-1)$
- HI identification detectors
- OTPC for decays of implanted HI
- Stopped HI
- Monte Carlo simulation framework in data analysis
- Proton- or neutron-radioactive precursors
- Si beam detectors
- μSi tracking detectors for protons
- NeuRad, high-resolution neutron detector
EXPERT: Experimental setup

- **Very thick secondary target**
- **$A_Z$**
- **Secondary beam**
- **$A_{-1}(Z-1)$**
- **$A_{-1}Z$**
- **Proton- or neutron-radioactive precursors**
- **Si beam detectors**
- **$\gamma$-ray detector with LaBr$_3$, CsI crystals, GADAST**
- **High-resolution spectrometer for heavy-ion (HI) fragments $A^{-2}(Z-1)$**
- **HI identification detectors**
- **Stopped HI**
- **OTPC for decays of implanted HI**
- **Monte Carlo simulation framework in data analysis**
- **NeuRad, high-resolution neutron detector**
- **$\mu$Si tracking detectors for protons**
EXPERT: Experimental setup
EXPERT: Experimental setup

- Very thick secondary target
- Secondary beam
- Si beam detectors
- Proton- or neutron-radioactive precursors
- μSi tracking detectors for protons
- High-resolution spectrometer for heavy-ion (HI) fragments $A^2(Z-1)$
- HI identification detectors
- OTPC for decays of implanted HI
- Neurad, high-resolution neutron detector
- Monte Carlo simulation framework in data analysis
- γ-ray detector with LaBr₃, CsI crystals, GADAST
- Stopped HI
EXPERT: Experimental setup

- VERY THICK secondary target
- γ-ray detector with LaBr₃, CsI crystals, GADAST
- High-resolution spectrometer for heavy-ion (HI) fragments A-2(Z-1)
- HI identification detectors
- OTPC for decays of implanted HI
- Stopped HI

Secondary beam

A-Z

A-1Z

A-1(Z-1)

p

n

Proton- or neutron-radioactive precursors

μSi tracking detectors for protons

NeuRad, high-resolution neutron detector

Monte Carlo simulation framework in data analysis
EXPERT: Experimental setup
OTPC
Optical Time Projection Chamber

lifetime range: 100 ns – 1 s
Optical Time Projection Chamber

lifetime range: 100 ns – 1 s


45Fe

31Ar

beam
GADAST

- tagging of gammas from 2p-radioactivity
- $E_g \sim 100$ keV – 2 MeV
- CsI(Tl) crystals more than 15° in LAB
- LaBr$_3$(Ce) crystals around the beam

in the middle of SuperFRS in FMF2
128 CsI(Tl) modules
32 LaBr$_3$(Ce) modules
GADAST

- tagging of gammas from 2p-radioactivity
- $E_g \sim 100$ keV – 2 MeV
- CsI(Tl) crystals more than 15° in LAB
- LaBr$_3$(Ce) crystals around the beam

in the middle of SuperFRS in FMF2

128 CsI(Tl) modules
32 LaBr$_3$(Ce) modules
NeuRad
NeuRad

- neutron radioactivity studies
- $E_n \sim 200 – 800$ MeV in LAB
- low transverse momenta 0.1 – 100 keV
- precise information on angular correlations of decay neutrons with a charged fragment
- angular resolution $\sim 0.1 – 0.2$ mrad

28 m from the target in FMF2
at least 36 modules
$30 \times 30 \times 100$ cm$^3$
NeuRad

bundles
- 3 x 3 mm scintillation fibers BCF12
- 48 x 48 x 1000 mm
- 2 MAPMT from both sides

- longitudinal coordinate of the n interaction along the fiber
- determination the very first hit
- avoid neutron cross-talk
NeuRad
NeuRad

**bundles**
- 3 x 3 mm scintillation fibers BCF12
- 48 x 48 x 1000 mm
- 2 MAPMT from both sides

**neutron beam**

- **longitudinal coordinate** of the n interaction along the fiber
- **determination the very first hit**
- avoid **neutron cross-talk**
EXPERT software

- **MC generator of events**
  - decay and reaction mechanism

- **ExpertRoot**
  - simulation of experiment
  - data analysis

http://er.jinr.ru
Outlook

• two experimental proposals for FAIR phase-0
• 4 of 5 detectors will be commissioned in 2018
• looking forward to SuperFRS
Appendix: Nuclear halo

Stable nuclei

\[ < r_n^2 >^{1/2} - < r_p^2 >^{1/2} \approx 0.1 \text{ fm} \]

Exotic nuclei

\[ < r_n^2 >^{1/2} - < r_p^2 >^{1/2} \gtrsim 1.5 \text{ fm} \]

neutron halo

one neutron: \(^{11}\text{Be}, \^{19}\text{C}\)

two neutron: \(^6\text{He}, \^{11}\text{Li}, \^{17}\text{B}, \^{19}\text{B}, \^{22}\text{C}\)

neutron skin: \(^8\text{He}\) and \(^{14}\text{Be}\)

proton halo

g.s. of \(^8\text{B}, \^{13}\text{N}, \^{17}\text{Ne}, \^{26}\text{P}, \^{27}\text{S}\)

the first e.s. of \(^{17}\text{F}\)
Appendix: Borromean nuclei

M.V. Zhukov et al., Bound state properties of Borromean halo nuclei: $^6$He and $^{11}$Li. Physics Reports, 231(4):151–199, 1993

$^6$He

$^5$He

$^2n$
Appendix: Dipole modes

- **property of particular nucleus**
- **its population does not depend on reaction mechanism**

- **characteristic for specific reaction**
- **its population is given by reaction mechanism**

**resonance** vs. **mode**

- **6He**
  - \( \Delta T = 0 \)
  - SDM: Soft (cluster) \( \Delta S = 0 \)

- **6Li**
  - \( \Delta T = 1 \)
  - IVSDM: Soft (cluster) \( \Delta S = 0, 1 \)
  - SDR: Collective \( \Delta S = 1 \)

- **GDR**
  - Collective \( \Delta S = 0 \)

- **6Be**
  - \( \Delta L = 1 \)
  - IVSDM: Soft (cluster) \( \Delta S = 0, 1 \)
Appendix: microStrip detectors
Appendix: GADAST

- CsI(Tl)

\[ \Delta E/E = 7.5\% \text{ at } E_\gamma = 1.17 \text{ MeV} \]

\[ ^{60}\text{Co} \]

- LaBr\(_3\)(Ce)

\[ ^{137}\text{Cs} + ^{60}\text{Co} \]

\[ \Delta E/E = 4.0\% \text{ at } E_\gamma = 662 \text{ keV}; \]
\[ \Delta E/E = 2.9\% \text{ at } E_\gamma = 1.33 \text{ MeV} \]
Appendix: NeuRad status

- collimated beam - $^{60}$Co
- only one fiber of the bundle selected
- Time resolution: 2.9 ns
- comparison with simulations needed

Very preliminary results!!!
Appendix: Proposed experiments

1) Si TOF DSSD
2) μSi tracker, 4) GADAST
3) OTPC
5) NeuRad

+ simulation and data analysis framework
ExpertRoot
(http://er.jinr.ru)
Appendix: Theoretical model

- PWIA in combination with 3-body problem
- task reduced to solving of Schroedinger equation with source

\[(\hat{H}_3 - E_T)\Psi^{JM(+)}_{{6Be}} = \hat{O}_{\mu'\mu}\Psi^{(in)}_{{6Li}}M^{(in)}\]

- transition operator contains information about population of $^6$Be from $^6$Li

\[\hat{O}_{\mu'\mu} = \sum_{i=1,2} \sum_{lm} f_l(q, r_i) Y_{lm}(\hat{r}_i) Y^*_{lm}(\hat{q}) \tau^{(i)}_\nu \sum\nu (-1)^\nu \sigma^{(i)}_\nu C^{1/2}_{\mu'\mu} \frac{1}{\mu_1\nu}\]

- Transition operator takes a “simple” analytical form thanks to the choice of the N-N potential used in PWIA

\[\hat{V}_{ir}(r_{ir}) = (\sigma_i \cdot \sigma_r)(\tau_i \cdot \tau_r) V_0 \exp \left[ - \left( \frac{(r + r_i)^2}{r_0^2} \right) \right] \]
NUSTAR

NUclear STructure, Astrophysics and Reactions

- HISPEC/DESPEC (High-Resolution Spectroscopy/Decay Spectroscopy)
- R3B (Reactions with Relativistic Radioactive Beams)
- MATS (Precision Measurements of very short-lived nuclei with Advanced Trapping System)
- LaSpec (Laser Spectroscopy)
- ILIMA (Isomeric Beams, Lifetimes and Masses)
- ELISe (Electron-Ion Scattering in a Storage Ring)
- EXL (Exotic nuclei studied in light-ion induced reactions at the NESR storage ring)

- **Super-FRS Experiments**
- SHE (Super-Heavy Element Research)
SuperFRS Experiments

- **Mass and charge resolution**
  - Search for new isotopes and ground-state properties
  - Atomic collisions

- **Unique experiments at Super-FRS as high-energy high-resolution spectrometer**
  - Spectroscopy of meson-nucleus bound system
  - Exotic hypernuclei and their properties
  - Importance of tensor forces in nuclear structure
  - Delta resonances probing nuclear structure

- **Experiments taking advantages of multi-stages and high-resolution of the Super-FRS**
  - Nuclear radii and momentum distributions
  - EXPERT (EXotic Particle Emission and Radioactivity by Tracking)
  - Low-q experiments with an active target
  - Nuclear reaction studies and synthesis of isotopes with low-energy RIBs