Exotic nuclei at high energies

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AGATA Workshop

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A New In-Flight Exotic Nuclear Beam Facility

I High intensity primary beams from SIS 200 (e.g. $10^{12} \ ^{238}\text{U} / \text{sec}$ at 1 GeV/u)

II Superconducting large acceptance Fragment separator

III Three experimental areas

- Optimized for efficient transport of fission products

[Diagram of the layout of the facility]
Experiments

- knockout
- quasi-free scattering
- electromagnetic excitation
- charge-exchange reactions
- fission
- fragmentation

Physics goals

- shell structure, resonances beyond the drip lines
- single-particle occupancies, spectral functions, correlations, clusters
- shell structure, astrophysical reactions (S factor),
  soft coherent modes, giant resonance strength, B(E2)
- Gamov-Teller strength, spin-dipole resonance, neutron skins
- shell structure, dynamical properties
- \(\gamma\)-ray spectroscopy, isospin-dependence in multifragmentation

The high-energy branch of the Super-FRS:
A versatile setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams
Secondary Beams and High-Energy Scattering

**Physics Aspects:**
- Short interaction time ➔ sudden process
- $\sigma_{NN}$ lowest at ~ 300 MeV ➔ reduced re-scattering
- Low transverse momentum ➔ eikonal approximation

⇒ reaction dynamics and nuclear structure less entangled

**Experimental Aspects:**
- Thick targets (g/cm²) ➔ increased luminosity
- Lorentz boost ➔ full solid angle coverage
- Mixed secondary beams ➔ 100% detection efficiency

⇒ compensating low beam intensity (1 - 10000 s⁻¹)

**GSI:** Up to 1 GeV/A

**Other Laboratories** (up to ~ 0.1 GeV/A):
- GANIL / France
- MSU / U.S.
- RIKEN / Japan
Scattering of Light Neutron-Rich Nuclei Investigated at LAND@GSI

Knockout
- single-particle structure
- unbound states

Electromagnetic excitation
- dipole response
- single-particle structure
- collective excitations (soft modes, GDR)

Neutron skin
- $S_n \sim 16$ MeV
- $S_n \sim 4-7$ MeV

Halo nuclei

$S_{2n} (^{11}\text{Li}) = 0.3$ MeV
Reaction:

\[ ^{23}\text{O} (938 \text{ MeV/u}) + \text{C} \rightarrow ^{22}\text{O} + \gamma + \chi \]

\[ \Rightarrow I^\pi = 1/2^+ \]

\[ \Rightarrow S (\nu_s \otimes ^{22}\text{O}(0^+)) \approx 0.9(2) \]

D. Cortina-Gil et al., in preparation
Low-Lying E1 Strength as Spectroscopic Tool

Wave function: e.g. $|^{11}\text{Be}> = \alpha |^{10}\text{Be}(0^+) \otimes 2s_{1/2}> + \beta |^{10}\text{Be}(2^+) \otimes 1d_{5/2}> + ...$

$$d\sigma(I_c)/dE_{rel} = \frac{16\pi^3}{9hc} N_{E1}(E^*) S(I_c, nlj) \sum_m |<q| \frac{Ze}{\Lambda} rY_m | \Phi_{nlj}>|^2$$

Density distribution

Differential cross section

Shape of differential cross section $\Rightarrow$ angular momentum $l$

$\gamma$-ray coincidence $\Rightarrow$ identification of core state

Cross section $\Rightarrow$ spectroscopic factor
Coulomb Breakup of $^{11}\text{Be}$: The Classical One-Neutron Halo

\[ |^{11}\text{Be}\rangle = \sqrt{S(2^+)} |^{10}\text{Be}(2^+)\otimes 1d_{5/2} \rangle + \sqrt{S(0^+)} |^{10}\text{Be}(0^+)\otimes 2s_{1/2} \rangle + \ldots \]
Coulomb Breakup of $^{21}\text{O}$

$^{208}\text{Pb}(^{21}\text{O},^{20}\text{O}+n+\gamma_1+\gamma_2)X$

Dominant ground state configurations

$\sqrt{S(0^+)} |^{20}\text{O}(0^+)\otimes\nu 1d_{5/2} > + \sqrt{S(4^+)} |^{20}\text{O}(4^+)\otimes\nu 1d_{5/2} >$

Confirms the ground state spin of $^{21}\text{O}$ as $J^\pi = 5/2^+$

Shell model: $C^2S(4^+) = 2.59$

R. Palit et al., to be published
Sensitivity of Coulomb Breakup and Knockout

Reaction probabilities

Halo-Neutron Densities

Sensitivity to low-density tail of the wave function

Overlap with continuum wave function
Quasi-free scattering

- Knockout reactions (Be, C targets) and Coulomb breakup reactions are surface dominated (similar transfer)
- \((e,e'X)\) knockout reactions will be feasible in the future at the \((e,A)\) collider, restriction to light nuclei due to luminosity reasons
- \((p,pX)\) reactions: knockout also from deeply bound states possible
  
  but: problem of final state interaction

  -> high beam energy
The high-energy branch of the Super-FRS:
A versatile setup for kinematical complete measurements of

**Reactions with Relativistic Radioactive Beams**

**Goal:**

- Fully exclusive measurement of quasi-elastic scattering reactions (p,pX)
- Precise measurement of momentum / energy for both nucleons
- Identification and high-resolution momentum measurement of A-x fragment
- Gamma-coincidence measurement
- High beam energy: both nucleons in the minimum N-N cross section region
- Minimization of final-state interaction
- Less absorption
- Background-free measurement
Electromagnetic excitation of secondary beams

Semi-classical theory:
\[
d\sigma_{elm} / dE = N_\gamma(E) \sigma_\gamma(E)
\]

Absorption of ‘virtual Photons’

\[\sigma_{elm} \sim Z^2\]

High velocities \(v/c \approx 0.6-0.9\)
\[\Rightarrow\] High-frequency Fourier components

\[E_{\gamma,\text{max}} \approx 25\ \text{MeV} \ (\text{at} \ 1\ \text{GeV/u})\]

Determination of ‘photon energy’ (excitation energy) via a kinematically complete measurement of the momenta of all outgoing particles (invariant mass)
Dipole Strength Distribution of n-Rich Nuclei

$^{16}\text{O}$ ($\sim$500 MeV/u) + Pb $\rightarrow A-x\text{O} + \gamma + xn$

$\Rightarrow$ Photo-neutron cross sections from virtual photons

$\Rightarrow$ Low-lying dipole strength

$\Rightarrow$ Fragmentation of GDR strength

? Collective soft mode?

Large-scale shell model calculation

H. Sagawa, T. Suzuki,

Data: LAND-FRS@GSI
Onset of collective low-energy dipole resonances in medium mass nuclei: predictions

Relativistic mean field calculations: Vretenar, Paar, Ring, Lalazissis (NPA 692 (2001) 496)

- Dipole strength functions
- Transition densities

Collective low-energy state at 9 MeV characterized by a coherent superposition of many ph configurations exhausting 4.3% of the EWSR.

16.4 MeV

- Neutron transitions
- n-p in phase
- Soft mode
- GDR
- n-p out of phase

Oscillation of excess neutrons at the surface (soft mode, 'Pygmy' resonance)
Dipole strength below threshold

- see MSU measurement (Eric Tryggestad et al.)
- see Angela Bracco et al. (RISING experiment)
- see measurements with stable nuclei at the S-DALINAC (A. Zilges et al.)

Beam energy needed:
- several hundred MeV/u
- 100 MeV (adiabatic cutoff ~7 MeV)
Summary: γ spectroscopy and high-energy reactions

- Knockout reactions: spectroscopic factors for valence nucleon single-particle states (~500 MeV/u)
- Quasi-free scattering (p,pX): deeply bound states (~700 MeV/u)
- Coulomb breakup: loosely bound states (~500 MeV/u)
- Virtual photon scattering: low-lying dipole modes (~500 MeV/u)

- Fragmentation reactions: higher-spin states (>50 MeV/u)
- Electromagnetic excitation of the GDR populating excited states in the daughter nucleus (>500 MeV/u)
Other high-energy reactions and γ-ray spectroscopy

- Fragmentation (>50 MeV/u)
  + few-proton knockout leads to more exotic nuclei
  + population of high-spin states possible
  - low cross section

\(^{230}\)O:

- Electromagnetic excitation of the GDR (>500 MeV/u)
  (plus neutron decay populating excited states)
  + large cross section (~barn)
  - only low spin states
  - final nucleus less exotic than projectile
The New Accelerator Facility for Beams of Ions and Antiprotons at GSI
Four major research areas:

- **Nuclei far from stability**
- **Hadron spectroscopy (\(\overline{p}\))**
- **Compressed nuclear matter**
- **Plasma and Atomic Physics**

The New Accelerator Facility for Beams of Ions and Antiprotons at GSI

SIS 100/200

High-Intensity Synchrotron
Fast cycling superconducting magnets
- 60 GeV protons
- 23 GeV/u \(U^{92+}\)
- 30 GeV/u \(Ne^{10+}\)
- 1 GeV/u \(U^{28+}\)

Existing

Planned
Production cross sections
## Conclusion

- Experiments at the FRS have demonstrated the large research potential of high-energy radioactive beams produced by in-flight fragmentation and fission
  - experimental methods coping with the low beam intensities and large phase space of secondary beams were successfully developed and applied

## The future Super-FRS project at GSI

- **higher intensities**
  - (primary beam intensity, efficient separation, transport and injection of radioactive beams in storage rings)

- **new experimental methods and concepts**
  - (e.g. reactions in storage rings, scattering of light hadrons, $e^-$ - scattering, …)
Experiments with Low-energy and Stopped beams

- Decay spectroscopy
- Reactions near the Coulomb barrier
- Laser spectroscopy
- Ion traps
Experiments at Storage Rings

- Mass measurements
- Reactions with internal targets
  - Elastic p scatt.
  - \((p,p') (\alpha,\alpha')\)
  - transfer
- Electron scattering
  - elastic scattering

TOF Detector

MCPs anode

Ion C + CsI foil

Electron cooler

Degrader for fast slowing down

Exotic nuclei from Super-FRS

Gas Target and Detector

Tagging of reaction products

Si strip array Scintillator

Gas jet Beam

Schottky pickup

Electron spectrometer

eA-collider

Reaction zone

Heavy ions

Elastic p scatt.
External target – R3B collaboration

GSI
IN2P3/IPN Orsay, France
Univ. de Santiago de Compostela, Spain
University of Keele, UK
Physik Department, TU München
Instituto de Estructura de la Materia, CSIC, Spain
Department of Physics, University of Surrey, UK
Department of Physics, University of Liverpool, UK
Kurchatov Institute, Moscow, Russia
University of Manchester, UK
CEA, Saclay, France
University of Birmingham, Edgbaston, UK
Inst. of Phys. and Astronomy, Univ. of Aarhus, Denmark
II. Physikalisches Institut, Universität Giessen
Chalmers Tekniska Högskola, Göteborg, Sweden
Fizyki, Uniwersytet Jagellonski, Krakow, Poland
Universität Mainz
Institute of Nuclear Research (ATOMKI), Debrecen, Hungary
CLRC Daresbury, UK
GANIL, France
Institut für Kernphysik, TU Darmstadt
Institut für Kernphysik, Universität zu Köln,
Michigan State University, USA
Forschungszentrum Rossendorf

Light-ion scattering – Storage ring

GSI
KVI Groningen, Netherlands
IPN Orsay, France
Physik Department, TU München
Chalmers Tekniska Högskola, Göteborg, Sweden
Univ. Milano, Italy
The Svedberg Lab., Uppsala, Sweden
Univ. Basel, Switzerland
Inst. Kernchemie, Universität Mainz, Germany
Institute of Nuclear Research, Debrecen, Hungary
Institut für Kernphysik, TU Darmstadt
FZ Jülich, Germany
Kurchatov Institute, Moscow, Russia
Intensities expected behind the Super-FRS
Experimental Scheme:
II. Separation in FLIGHT

FRagment Separator (FRS)

Separation in Flight: \( v_{\text{Frag.}} = v_{\text{Beam}} \)

Transport efficiency \( \sim 50\% \); \( \Delta p/p \sim 2\% \)

Magnetic separation only: mixed beam \( (Z/A \sim \text{const.}) \)

H. Geissel et al., NIM B 70 (1992) 286
One-Nucleon Knockout: a Spectroscopic Tool

**Sudden process**

Reaction: \( \Delta t \approx 10^{-22} \) s

Internal motion: \( \approx 10^{-21} \) s

\[ \Rightarrow P_{\text{frag}} = -P_n \]

\[ \Rightarrow \text{measurement of wave function (at the surface: } b_c > r_c) \]

**Measurement**

<table>
<thead>
<tr>
<th>Example:</th>
<th>Momentum distribution</th>
<th>Carbon isotopes</th>
<th>( {^A}_C + C \rightarrow {^A-1}_C + x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma )-ray coincidence</td>
<td>Cross section</td>
<td>FRS@GSI</td>
<td>T. Baumann et al</td>
</tr>
<tr>
<td>( E \approx 900 ) MeV/u</td>
<td>( \sigma_{ln}(J^\pi) = S )</td>
<td>Wavefunction</td>
<td></td>
</tr>
</tbody>
</table>

\[ 12C \text{ stable} \]

\[ 17C \text{ Halo} \]

\[ 19C \]
Neutron removal from individual single-particle states:

$^{11}\text{Be} \rightarrow ^{10}\text{Be} (I^{\pi}) + \gamma + X$

$\gamma$-ray coincidences

Partial cross sections

Data: S800@MSU, T.Aumann et al., PRL 84 (2000) 35
Ground state configuration of $^{14}\text{Be}$

⇒ Mixed ground-state configuration
⇒ $s$, $p$, and $d$ waves contribute
⇒ Occupation probabilities: $s \gg d > p$

H. Simon et al., to be published
Quasi-free cluster knockout

$^6\text{He} + p \rightarrow \alpha + p' + X$

Experiment S174: Proton elastic scattering (P. Egelhof et al.)

Momentum distribution

L. Chulkov et al.
Low-Lying E1 Strength of n-Rich Oxygen Isotopes

⇒ Integrated strength below the GDR

low-lying strength mainly related to single neutron particle-hole excitations

→ but: collective soft mode predicted for heavier nuclei, e.g., Ni and Sn isotopes
Nuclear structure and \textbf{Reactions with Relativistic Radioactive Beams}

<table>
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<th>Experiments</th>
<th>Physics goals</th>
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<td>total absorption measurements</td>
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<td>knockout reactions</td>
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<td>Gamov-Teller strength, spin-dipole resonance, neutron skins</td>
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<tr>
<td>fission in complete kinematics</td>
<td>shell structure, dynamical properties</td>
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<tr>
<td>fragmentation</td>
<td>$\gamma$-ray spectroscopy, high-spin states</td>
</tr>
</tbody>
</table>

$\rightarrow$ Exploring heavier nuclei and more exotic isotopes with established reactions
$\rightarrow$ Development of new experimental schemes for reactions in inverse kinematics
$\rightarrow$ Higher intensities, better resolution, detector and spectrometer developments
The ground state structure of $^{23}$O

dominant g.s. configuration: $|^{22}$O$(0^+)$ $\otimes$ \nu_s >

in conflict with the recently proposed g.s. configuration $(s^{1/2})^2 (d^{5/2})^{-1}$ by Kanungo et al., PRL 88 (2002) 142502

C. Nociforo, K.L. Jones et al., to be published