Storage-ring experiments for nuclear astrophysics at GSI

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Facility overview

Experimental opportunities

Future directions

Emphasis on data for nuclear astrophysics:

• decay spectroscopy
• mass measurements
• reaction studies
• half-lives
Nucleosynthesis of the chemical elements

Nucleosynthesis in binary systems

Nucleosynthesis in AGB stars

Nucleosynthesis in supernovae

Fusion up to iron

Big Bang nucleosynthesis

Heavy nuclei (A>56) are mainly produced by s-process (~50%) and r-process (~50%)

OMEG-10, Osaka (Japan), March 8th-10th, 2010

Christoph Scheidenberger (GSI)
The need for reliable nuclear physics data

Consistent nuclear theory and/or experimental data needed!
Nuclear astrophysics in the laboratory

- SHE, masses, decay properties, half-lives, level energies, $\beta$-delayed $n$-emission
- LAND / R3B: photo-dissociation rates, $(n, \gamma), (p, \gamma)$ cross sections, $B(GT)$
- SHIP-Trap: masses, half-lives, $(p, \gamma)$ rates, $B(GT)$
- Theory: nuclear rates, nucleosynthesis
Nuclear astrophysics in the laboratory

**FRS**
- half-lives
- level energies
- $\beta$-delayed n-emission

**ESR**
- masses
- half-lives
- $(p,\gamma)$ rates
- $B(GT)$

**SHIP-Trap**
- SHE, masses
- decay properties

**LAND / R3B**
- photo-dissociation rates
- $(n,\gamma)$, $(p,\gamma)$ cross sections
- $B(GT)$

**Theory**
- nuclear reaction rates
- nucleosynthesis network calculations
Elementary reactions for the production of exotic nuclei

1GeV/u U + H

Experimental data:

V Ricciardi et al.,
PRC 73 (2006) 014607
Production of very neutron-rich isotopes

**Cold fragmentation**

\[
\sim 1\text{GeV/u } \text{Au} + \text{Be}
\]

**Fission**

\[
\sim 1\text{GeV/u } \text{U} + \text{Pb}
\]

**Fragmentation**

\[
\sim 1\text{GeV/u } \text{U} + \text{Be}
\]

J. Benlliure et al., NPA 660 (1999) 87

M. Bernas et al., Phys. Lett.


and to be published
Spectroscopy and β-decay studies at FRS

$Q_\beta$-measurement (I. Dillmann et al., PRL91, 162503 (2003))

$^{130}\text{Cd}$ less bound than expected → "quenching" of N=82 shell closure?

Detailed spectroscopy, unambiguous identification, high granularity, high γ-efficiency
no indication of "shell quenching", no weakening of N=82-shell observed
Agreement with SM-calculations:
• level sequence
• energies
• transition rates

A. Jungclaus et al., PRL 99, 132501 (2007)
**Storage, cooling, measurement**

- Fast injection of fragments (bunch~400ns)

- Stochastic and electron cooling

- Relative momentum spread $\delta p/p$

- Schottky-noise detection

- Storage times: min. .... days
Storage, cooling, measurement

Fast injection of fragments (bunch~400ns)

Revolution-frequency measurement

Mass determination

Mass accuracy $5 \cdot 10^{-8}$ up to $5 \cdot 10^{-7}$
Masses of more than 1100 nuclides measured
Results: ~ 350 new mass values
~ 300 improved mass values
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Mapping the mass surface: predictive power of mass models

HFB (BSk2)
S. Goriely, et al.,

$\sigma_{\text{rms}} = 650$ keV

In explosive szenarios (Novae, X-ray bursts, and SN) masses play a crucial role
- energy "generation" (→ light curves)
- pathways (→ final abundances)

Few data exist
- mass models (→ predictive power?)

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H. Geissel, B. Pfeiffer, et al.,
β⁻- decay to bound states of the released electron

New radioactive decay mode


First experimental observation at ESR: $^{163}\text{Dy}/\text{Ho}^{66+}$
M. Jung et al., PRL 69, 2164 (1992)

Applications

Neutrino mass

$^{187}\text{Re}/\text{Os}$ cosmochronometer

Galactic age

$\nu < 265$ eV

$T_G = (15 \pm 1)$ Ga
Time-resolved decay studies: bound-state beta decay

T. Ohtsubo et al., PRL 95, 052501 (2005)
Branching ratio $\frac{\lambda_{\beta_b}}{\lambda_{\beta_c}}$

Theory

Decay rate of continuum beta decay:

$$\lambda_{\beta_c} = \sum_i \frac{g_i^2}{2\pi^3} |M_i|^2 f_i \quad \text{with} \quad f_i = \int_0^{W_0} pW(W_0 - W)^2 F(Z,W)S_i(W)dW$$

Decay rate of bound-state beta decay:

$$\lambda_{\beta_b}^{(k)} = \sum_i \frac{g_i^2}{2\pi^3} \frac{\pi}{2} |M_i|^2 \left|\Psi_e^{(k)}(R)\right|^2 q_{v,k}^2$$

Branching ratio: for allowed transitions:

$$S_i(W) \equiv 1$$

Experiment

T. Ohtsubo et al.,
PRL 95, 052501 (2005)

Calculation

$$\lambda_{\beta_b} / \lambda_{\beta_c}$$

0.171 ± 0.001

Experiment

0.188 ± 0.018
Isomer decays are altered: half-life measurement of bare $^{151m}$Er$^{68+}$


Decay rate for bare ions

$$\lambda_{\text{bare}} = \lambda_{\text{neutral}} \times \left( \sum_i \frac{b_{i,\beta^+ + e}}{(1 + \varepsilon/\beta^+) * s^i} + \sum_j \frac{b_{j,\text{IT}}}{1 + \alpha_{\text{tot}}^j} \right)$$

- $b_r$ = branching ratio
- $\varepsilon/\beta^+$ = ratio of electron capture and $\beta$-decay
- $s$ = screening = $F(Z,W)_{\text{neutral}} / F(Z,W)_{\text{bare}} \sim 1\%$

Calculated half-life: $15.3 \pm 1.0$ s

Measured half-life: $19 \pm 3$ s

Hindrance factor: $33 \pm 5$
Newly observed decay-properties in H-like iodine

- Orbital electron capture of highly-charged exotic ions
- Exhibits modulated exponential behaviour
- Explanation presently under discussion

Fit:
\[ \frac{dN_{EC}}{dt} = N_0 \lambda_{EC} \exp(-\lambda t) \left[ 1 + a \cos(\omega t + \phi) \right] \]
Origin of ‘p-nuclei’ – abundant n-deficient isotopes, e.g. \( ^{92,94}\text{Mo} \), \( ^{96,98}\text{Ru} \)

Supernova shock passing through O-Ne layers of progenitor star

(p,γ) or (α,γ) rates in the Gamow window of the p-process in inverse kinematics

Pilot experiment performed with stable beams:
- direct proton capture of $^{96}$Ru in H gas target: $^{96}$Ru(p,γ)$^{97}$Rh
- in-ring particle detectors for recoiling reaction products (low background, high efficiency)

R. Reifarth, M. Heil, P. Woods
to be published
Scattering of stored exotic nuclei off light hadronic probes

- Inverse kinematics
- Thin gas target (~$10^{15}$/cm$^2$)
- Kinematic complete measurements
  - Elastic scattering ($p,p$) ...
  - Inelastic scattering ($p,p'$), ($\alpha,\alpha'$) ...
  - Charge-exchange reactions ($p,n$), ($^3$He,t), ($d,^2$He) ...
  - Quasi-free scattering ($p,pn$), ($p,2p$), ($p,p\alpha$) ...

→ Excitation energy and form factors from recoil ions with small energy/small momentum

Feasibility study ($p,p$) with 350 MeV/u $^{136}$Xe ions in ESR

Nuclear matter radius:
$R_m = 4.89 \pm 10$ fm

S. Ilieva et al.,
Summary and conclusion

Experimental data are needed for stellar nucleosynthesis

These data can be obtained (to some extent) in the laboratory.

Storage ring is a unique instrument, experiments provide data for highly-charged ions

Complementary approaches exist...
  - exotic nuclei at low and high energies
  - spectroscopy
    - reaction studies (stable and secondary beams \(\rightarrow\) FAIR)
...which yield
  - masses, half-lives, \(P_n\)-values, fission yields, cross sections, etc. .....  
...needed to understand the state of affairs