What are limits of stability?

Which new phenomena emerge at the drip lines (halo, clustering, breaking mirror symmetry... )?

How do nuclear structure and shape evolve along the chart of nuclides?

How does nuclear structure change with Temperature and Spin value?

How to unify nuclear structure and reaction approaches?

How to probe the density and isospin dependence of the nuclear equation of state?

What are nuclear processes that drive the evolution of stars and galaxies in the universe?

How / where are nuclei synthesized in the universe?

Find a universal interaction, based on fundamental principles, that can model nuclear structure and reactions in nuclei and in stars (i.e. from the \( fm \) to \( 10^4 \) km, over \( 10^{22} \) orders of magnitude)
Accelerators, reactions and instrumentation

Facilities:
GANIL, GSI, Dubna, RIKEN, Licorne
Stable / radioactive beams
5 - 500 MeV/A

Detectors:
Charged particles: GRIT, ACTAR-TPC
γ-rays: AGATA, nu-ball, PARIS

Reactions:
Fusion, transfer, Fission, knockout...

A wide variety of phenomena to understand
Magic nuclei
Fission, pear shapes
GDR
Soft GMR
Exotic decays
2n halo
molecular cluster
rotation-deformation

Implantation
Residual nuclei
β, α-decay, isomeric decay

Scientific council IN2P3- June 26th
Nuclear physics impact many astrophysical processes.

X-ray bursts

Stable nuclei

p-process

i-process

r-process

Supernova EC process

Stellar fusion

rp-process

vp-process

Neutron star crust process

Normal star H surface

Neutron star

Mass Number

Number of Protons

Log solar (Abundance)

Number of Neutrons

Sneden & Cowan 2003

Price & Rosswog

H. Schatz (2016)
Nuclear astrophysics
Energy profile of X-ray burst and nuclear physics

Departure from Hot CNO cycle depends crucially on $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ reaction. It is followed by $(\alpha,p)$, $(p,\gamma)$ reactions and $\beta$-decays.
Determination of the $^{15}$O($\alpha,\gamma$)$^{19}$Ne reaction rate

$^{15}$O + $\alpha \rightarrow ^{19}$Ne + $\gamma$ mainly through $3/2^+$

$N_A <\sigma v> \propto \omega \gamma [\text{MeV}] \exp (-11.6 E_\alpha [\text{MeV}] / T_9)$

$\omega \gamma = (2J_r + 1) / (2J_\gamma + 1) \times \frac{\Gamma_\alpha \Gamma_\gamma}{(\Gamma_\alpha + \Gamma_\gamma)}$

Branching $\Gamma_\alpha$ and $\Gamma_\gamma$ are needed

Use $^{15}$O ($^7$Li,t) $^{19}$Ne transfer reaction to simulate $\alpha$ capture

$^{15}$O (4.7 MeV/A) beam at $10^7$ pps from SPIRAL1

Tritons in segmented charged particle detector (MUGAST)

$\gamma$-rays in high efficiency/resolution (AGATA)

Recoil $^{19}$Ne at focal plane of VAMOS spectrometer

World-leading experience in charged-particle arrays -> GRIT

Diget et al., To be performed at GANIL/VAMOS July 2019
Magic nuclei and shell evolution far from stability
The neutron numbers 8, 20 and 28 were considered as magic over several decades.

- Large gap between occupied and valence states

Increase of $2^+$ energy at $N=8, 20, 28$
Assuming our world was more neutron-rich

While removing protons, the same loss of magicity occurs for all magic numbers.

No sign of shell closure and magic nuclei

While deformation appears at relatively low energy, the measured $2^+$ of $^{78}\text{Ni}$ reveals that magicity is kept at $N=50$.

Shell evolution and transfer reactions

The change of magicity comes from the reduction of shell gaps and increase of correlations.

Probe the evolution of proton and neutron orbits far from stability using various transfer reactions.

Need of charged particle detectors, gamma-arrays, as well as cryogenic targets in same cases.

Understand shell evolution at N=82 below $^{132}\text{Sn}$ for the building of the r process peak.

See talk Beaumel
Super Heavy Elements
Motivation for studying super-heavy elements

Discover the heaviest elements whose location is likely connected to spherical shell gaps whose location is unknown (Z=114, 120, 126 ?)

Study their decay properties:
$\alpha$ & fission competition

Study the structure of the heavy nuclei:
- Ascertain the discovery of SHE
- Confront experiment to models for better predictivility of shell structure in the region
Motivation for studying super-heavy elements

Identify orbits in deformed nuclei to trace back to the amplitudes of the spherical shell gaps
Spectroscopy of the very heavy nucleus $^{254}$No

$^{208}$Pb($^{48}$Ca,2n)$^{254}$No

at the target

Two isomers discovered (study at the focal plane)

$^{254}$No recoil-gated

unpublished, see also: S.Eeckhaudt,P.T.Greenlees et al., EPJA 26 (2005) 227

$^{254}$No 266ms isomer-gated

C. Gray-Jones, PhD theis (2008)

266 ms decay

184 μs decay

Combine in-beam and delayed spectroscopy

Herzberg et al., Nature 442 (2006)

Tandel et al., PRL. 97 (2006)
Spectroscopy of very heavy nuclei at Dubna
Spectroscopy of very heavy nuclei at Dubna

K=8
8⁻ 1293 KeV
266 ms

Band on top of 8⁻ isomer not observed in γ-ray spectrum

π² or ν² state?
Spectroscopy of very heavy nuclei at Dubna

Hyperfine splitting in $^{253}\text{No}$: $I(^{253}\text{No})=9/2$

$g_K=-0.22(5)$

(confirming results from prompt & decay spectroscopy of $^{253}\text{No}$)

K=8

8$^-$ 1293 KeV

266 ms

Band on top of 8$^-$ isomer not observed in $\gamma$-ray spectrum

See talk Hauschild

Laser spectroscopy of the long-lived 8$^-$ isomer foreseen in 2020 @ GSI/SHIP

See talk Jurado / Lescene
Spectroscopy of very heavy nuclei at Dubna

Hyperfine splitting in $^{253}$No: $I(^{253}$No)$=9/2$
$g_K=-0.22(5)$
(confirming results from prompt & decay spectroscopy of $^{253}$No)

Laser spectroscopy of the long-lived 8⁻ isomer foreseen in 2020 @ GSI/SHIP

See talk Jurado / Lescene
Nuclear fission

Licorne (nu-ball), SOFIA & Cryring@GSI, GANIL/VAMOS
Selected features related to fission

Fission yields needed for societal applications
Fission allows to produce neutron-rich nuclei at high J

Fission competes with the synthesis of the heaviest and hyperdeformed nuclei (see talk Hauschild)

Evolution of fission yields show that:
- Fission is mostly asymmetric
- No yield enhancement at (magic) Z=50
- One fragment keeps the same Z!

Amount of Lanthanide produced in Binary Neutron Stars depends on the fission yields of very heavy nuclei

No fully microscopic description so far
The dynamics of nuclear fission

Fission probabilities
- Sensitive to structural evolution to fission barrier
- Most direct way to determine fission barriers
- Neutron-induced fission cross sections are highly important for societal applications

Fission-fragment yields
- Sensitive to evolution from the barrier to scission
- Role of shell effects and pairing at extreme deformation
- The decay of the fission fragments determine the residual power of a nuclear reactor in an accidental configuration.
High-precision decay-probability measurements at CRYRING

Beam: $10^7$-$10^8$ stored $^{238}$U$^{92+}$ at 10 A MeV

- Beam cooling & ultra-thin gas-jet target
  - Excellent energy and position resolution of the beam, negligible straggling effects
- Pure targets & beams
- $E^*$ resolution $\sim 200$ keV, $\approx 100\%$ efficiency
- Simultaneous measurement of fission, $\gamma$- and $n$-emission probabilities of many short-lived nuclei

see talk Jurado
High-precision fission-fragment yields with SOFIA


- Outstanding Z and A resolution
- Full identification of both fragments event-by-even
- Measurement of prompt neutron mult. with Z & N
- Access to a wide range of exotic fissioning systems

See talk Jurado
Nuclear deformation

> Shell evolution
> Hyperdeformation
Nuclear shapes and deformation at $N=60$
Does deformation persist at N=60 at Z=36?

Specific role of the tensor $g_{9/2} - g_{7/2}$ pn interactions to induce deformation

See Grévy
Search for hyperdeformation in atomic nuclei

Find the best way to produce a maximally elongated nucleus
-> high angular momentum

Competition between hyperdeformation / Jacobi shapes / fission

Find a needle in a haystack -> requires extremely high sensitivity

Expected gain in sensitivity with AGATA 4π

See talk Lopez-Martens
Soft and giant excitations in nuclei

> Symmetry energy
> Nuclear matter incompressibility
Pigmy and giant dipole excitations in neutron-rich nuclei

Challenges:

Prove the appearance of PDR at large N/Z (few cases so far)

Prove its E1 character.

Study its configuration using Nuclear and Coulomb Probes

Determine %EWSR of the total E1 strength in the PDR

General interest:

Information on the size of neutron skin in nuclei, on neutron star’s radii and the EOS of asymmetric nuclear matter

PDR may considerably speed-up neutron captures in rapid capture nucleosynthesis (if present at suitable energies and with large E1 strengths).
Pigmy and giant dipole excitations in $^{34}\text{Si} @ \text{GANIL/LISE}$

Use a radioactive beam of $^{34}\text{Si}$ at $5 \times 10^4$ pps in CH$_2$, C and Pb targets

-> Use of Nuclear and Coulomb probes to study the E1 response to both excitations

**PARIS**: 8 modules of Phoswich NaI & LaBr$_3$

- High-efficiency up to 30 MeV
- Good granularity ($\approx 4.5 \text{ cm} \times 4.5 \text{ cm}$)
- Good energy resolution (4%)
- Excellent timing resolution ($\approx 150\text{ps}$)
Soft and giant monopole modes in exotic nuclei

\[ K = 9 \rho_0^2 \left( \frac{\partial^2 E^{sym}}{\partial \rho^2} \right) \rho = \rho_0 \]

Incompressibility modulus of nuclear matter

Low-energy modes involve only neutrons over the entire volume of the nucleus

-> Incompressibility modulus of almost pure neutron matter -> CC Supernovae

-> Experimental evidence and characterization of this mode (M. Vandebruck PRL (2014))
Physics at the drip line

Mild changes / almost same models applied

Drastics change / new models and concepts needed
Evolution of nuclear pairing close and beyond the drip line at RIKEN

Study of 1n and 2n decays of unbound B nuclei at RIKEN allows rather accurate determinations of $S_n$ values beyond the drip line.
Exotic decay of borromean systems: the $^{19}$B case

Sequential decay of $^{19}$B through the virtual state in $^{18}$B

J. Gibelin, M. Marques et al.

Other systems under study, e.g. $^{16}$Be decay

B. Monteagudo, M. Marques

See talk N. Orr
Study of 2n and 4n correlations in atomic nuclei at FAIR/GSI

Means:
Study of all step of the reaction with full kinematics for ions and neutrons

Program:
Use of quasi-free proton knockout mechanism to promote 1n, 2n or 4n in the continuum

Spectroscopy of drip-line nuclei with excellent energy resolution -> shell evolution

Study of 2n or 4n correlations as a function of nuclear structure and the proximity of the drip line -> Evolution of nuclear superfluidity

Planned studies 2020 (core+4n, haloes, drip-line)

Very good neutron energy resolution (NEULAND)
Highest efficiency worldwide

Good $\gamma$ energy resolution and efficiency (CALIFA)

See talk Jurado / Sorlin
Understanding the 1p & 2p radioactivity processes require proper modeling of the nuclear structure and the dynamics.
The end – backup slides after
Study of $2n$ correlations in atomic nuclei at GSI/R3B

Use quasi-free proton knockout reaction from to
suddenly promote neutron pairs in the continuum

$^{19}\text{N}(-p)$ $\rightarrow$ $^{18}\text{C}^*$ $\rightarrow$ $^{16}\text{C}+2n$

$S_{2n}$ $\rightarrow$ doorway state $\rightarrow$ $E_d$

$^{19}\text{N} \ (400 \text{ MeV/A})$
Use quasi-free proton knockout reaction from to suddenly promote neutron pairs in the continuum

$$^{19}\text{N}(-p) \rightarrow ^{18}\text{C}^* \rightarrow ^{16}\text{C} + 2n$$

Small relative n-n momentum $\rightarrow r_{nn} \approx 4$ fm

Neutrons decay by pair in 85% cases, even up to $E_d=12$ MeV

Revel et al. PRL120 (2019)
Pigmy and giant dipole excitations in neutron-rich nuclei

\[ \alpha_d = \sum \frac{B(E1)}{E} \text{ dipole polarizability} \]

Nuclear EOS. : \[ E/A (\rho, \delta) = E/A(\rho,0) + S(\rho) \delta^2 \]

Symmetry energy: \[ S(\rho) = J + \frac{L}{3\rho_0} \times (\rho-\rho_0) + ... \]

J: Symmetry energy at saturation density
L: Slope at the saturation density
\( \rho=\rho_n+\rho_p, \delta=(\rho_n-\rho_p) / (\rho_n+\rho_p) \)
At the scission point, octupole shapes are preferred for one of the fragment. Maximum fission yield around Z=52-56 where octupole-deformed nuclei are found.

Pigmy and giant dipole excitations in neutron-rich nuclei

Nuclear EOS: \[ E/A(\rho,\delta) = E/A(\rho,0) + S(\rho) \delta^2 \]

Symmetry energy: \[ S(\rho) = J + L/(3\rho_0) \times (\rho-\rho_0) + ... \]

- \( J \): Symmetry energy at saturation density
- \( L \): Slope parameter

\[ \rho = \rho_n + \rho_p, \ \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) \]

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Inakura et al. PRC 84 (2011) 021302

Tsang et al. PRC 86 (2012)
Pigmy and giant dipole excitations in neutron-rich nuclei

**Nuclear EOS**

\[ E/A (\rho, \delta) = E/A(\rho,0) + S(\rho) \delta^2 \]

**Symmetry energy:**

\[ S(\rho) = J + L/(3\rho_0) \times (\rho - \rho_0) + \ldots \]

- \( J \): Symmetry energy at saturation density
- \( L \): Slope parameter

\[ \rho = \rho_n + \rho_p, \quad \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) \]

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Carbone et al., PRC 81 (2010)
Pigmy and giant dipole excitations in neutron-rich nuclei

Link between slope parameter and Neutron Star radius

Ling between the energy and strength of the PDR and neutron capture rates

GDR

PDR can enhance the neutron capture rate for the \( r \) process by orders of magnitude (A.C. Larsen et al., PPNP in press)
<table>
<thead>
<tr>
<th>Structure nucléaire</th>
<th>Comment évoluent les effets de couches (nombres magiques, formes) ? Quelles sont les limites d’existence des noyaux en isospin et masse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astrophysique nucléaire</td>
<td>Comment sont synthétisés les éléments chimique dans l’Univers Quelle est l’équation d’état de la matière nucléaire ? (lien avec explosions stellaires, étoiles à neutrons, NSM …)</td>
</tr>
<tr>
<td>Mécanismes de réaction</td>
<td>Comment parvenir à une description microscopique des processus de fusion, fission et collisions nucléaires rapprochées ?</td>
</tr>
<tr>
<td>Interactions fondamentales</td>
<td>Peut-on trouver des indices de la physique BSM ?</td>
</tr>
</tbody>
</table>

**Introduction to nuclear physics with accelerated beams**

*O. Sorlin (GANIL)*

**Physics at the femtometer scale**

- **Coupling to continuum**
- **Lattice Effective Field Theory**
- **2p radioactivity**
- **π-ν pairing**
- **Equation of state**
- **Fission dynamics**
- **Super Heavies**
- **New magic numbers**
- **Exotic Shapes**
- **Clusters**
- **Shape coexistence**
- **Neutron halos**

---

**Z**

**N**
Motivations for studying $^{36}$Ca

Influence of the rapid proton capture rates

Study of $^{36}$Ca using $^{37}$Ca(p,d) and $^{38}$Ca(p,t) reactions

$^{37,38}$Ca beams produced with LISE spectrometer at 50MeV/A

Detection of the charged particles with MUST2
Experimental set up to study $^{36}\text{Ca} – \text{Preliminary results}$

$^{37}\text{Ca}$

5000 pps
50 A.MeV
± 1.45 %

LISE

22m

CHIO

CATS

$\Delta E_x, y, t$

$\text{Liq H}_2$

7mg.cm$^{-2}$

$\Delta E, E, x, y$

IC+DC+plast

$\Delta E_{XY}, E, t$

MUST2

$\Delta E_{IC}$

$^{37}\text{Ca}$

$^{36}\text{K}$

$^{35}\text{Ar}$

MUST2 array (8 modules)

Kinematics in MUST2 gated on outgoing $Z$

Gated on $\text{Ca}$

Gated on $K$

Preliminary

$E_d (\text{MeV})$

$\theta_d (\text{deg.})$

$E^*_d (\text{MeV})$

$E^*_{^{36}\text{Ca}} (\text{MeV})$

$1^+$

$0^+, 2^+, 4^+$
Nuclear shapes and deformation at N=60

Specific role of the tensor attractive $g_{9/2} - g_{7/2}$ and repulsive $g_{9/2} - d_{5/2}$ proton-neutron interactions to cluster the neutron orbits and induce deformation.
Assuming our world was more neutron-rich

While removing protons, the same loss of magicity occurs for all magic numbers

role of proton-neutron interactions, poorly known far from stability

No sign of shell closure and magic nuclei (no increase of $2^+$ energy at $N=8, 20, 40$)

Magic numbers in the valley of stability

The neutron numbers 8, 20 and 28 were

Increase of $2^+$ energy at N=8, 20, 40