• Nuclear structure and reactions far from stability
• Collective phenomena and symmetries
• Dynamics and thermodynamics of light and heavy nuclei
• Sub- and near-barrier reactions
• Fusion and Fission dynamics
• Ab initio calculations, cluster models and shell model
• Nuclear energy density functionals
• Nuclear astrophysics
• Fundamental interactions
Experiment
Nuclear structure via mass measurements

Nuclides measured with JYFLTRAP

JYFLTRAP:
- Over 340 nuclides measured
  ~100 neutron-deficient
  ~220 neutron-rich
  ~20 stable
- More than 50 isomeric states
- Typical precisions: ~10 ppb

THIS TALK

Anu Kankainen
Neutron-rich rare-earth isotopes

- 21 rare-earth isotopes measured
- 14 masses measured for the first time
- Mainly TOF-ICR, recently also PI-ICR
- Campaign I: M. Vilén et al., PRL 120, 262701 (2018)
- Campaign II: in preparation

Motivated by the rare-earth abundance peak in the astrophysical r process

F.G. Kondev

Masses & Beta-Decay Spectroscopy of Neutron-Rich Nuclei: Isomers & Sub-shell Gaps with Large Deformation

CARIBU & ANL
Isospin symmetry in the heavier mass region

- Precision measurements of $T_z=+1$ nuclei: $^{82}\text{Zr}$, $^{84}\text{Nb}$, $^{86}\text{Mo}$, and $^{88}\text{Tc}$

- $^{88}\text{Tc}^m$ and $^{89}\text{Ru}$ ($T_z=+1/2$) measured for the first time

- $^{89}\text{Ru}$ more bound than predicted in AME16

- MDE predictions for $^{82}\text{Mo}$ and $^{86}\text{Ru}$ also more bound and more precise than AME16 extrapolations

M. Vilen et al., to be submitted
Isospin Symmetry of the $A=46$ $T=1$ triplet studied with AGATA

M.A. Bentley

Isospin Symmetry and $T=1$ Triplets

\[
T_z = \frac{(N-Z)}{2}
\]

-5/2 -3/2 -1/2 1/2 3/2 5/2

-2 -1 0 1 2

ground states

excited states

forbidden states

proton rich

neutron rich

Isospin

isospin

T

Scott Alexander Milne, sam519@york.ac.uk (and Alberto Boso, alberto.boso@pd.infn.it)

IOP Conference 2015

Lifetime and Coulex Measurements performed across the $T=1$ $A=46$ Triplet of Nuclei

A Boso, S.A. Milne, M.A. Bentley, F. Recchia, S.M. Lenzi, M. Labiche et al. (on behalf of AGATA, PRESPEC and LYCCA Collaborations)
• High precision measurement of B(E2)s in T=1 triplet
• Heaviest triplet for which this has been done (so far!)
• No evidence for non-linear behaviour with $T_z$
GANIL-VAMOS Campaign: Ongoing

GANIL Intense Stable Beams
AGATA coupled to VAMOS
MNT reactions

2014-2018

Collectivity along the N=50 neutron-magic
$^{92}$Mo, $^{94}$Ru
C. Domingo-Pardo, A.Gadea, R.Perez-Vidal

Study of quadrupole correlations in $^{106,108}$Sn via lifetime measurements.
J.J.Valiente-Dobon M.Siciliano

Due to the optimum Q-value condition with stable beams mostly p-stripping and n-pick-up occur in MNT processes →populates n-rich nuclei.

With p-rich beam and target possible to populate p-rich ejectiles with
$\sigma$ = few to ~1mb in +2p pick-up reactions
R.Broda et al., PRC 49, R575

Andres Gadea
Lifetime Measurements in \(^{106,108}\text{Sn}\).

- Direct population of the states, avoiding the experimental limitations due to the “seniority” isomers
- Complementary information to Coulomb-excitation measurements
- Extend the investigation above the \(2_1^+\) excited state
Evidence of octupole-phonon at high spin in $^{207}$Pb: Study of the octupole phonon in the $^{208}$Pb region.

- Case of the $^{207}$Pb: 1 neutron hole in $^{208}$Pb
- The first excited states of $^{207}$Pb are part of the $\nu p^{-1} 1/2 \times 3^{-}$ multiplet with slightly reduced B(E3) with respect to $^{208}$Pb due to the $p_{1/2}$ blocking effect
- The $\nu (i_{13/2})^{-1}$ state band structure: strong coupling effect of the $i_{13/2}$ and $f_{7/2}$: enhanced B(E3) with respect to $^{208}$Pb

D. Ralet, E. Clément et al, submitted to PLB
Pear-shapes and EDMs

CP-violation (matter-antimatter asymmetry in universe)

Schiff Moment

$$ S = -2 \frac{J}{J+1} \frac{\langle \hat{S}_z \rangle}{\Delta E} $$

related to $Q_3$, P,T-violating interaction

atomic EDM

$\Delta E \sim 50$ keV

$Q_3$ known for $^{224,226}$Ra

$^{225}$Ra [Argonne]

$^{223}$Rn [TRIUMF]

$\Delta E$ not known

$Q_3$ known for $^{220}$Rn

ACME 2018 $e^-$

$^{225}$Ra [Argonne]

$\Delta E \sim 50$ keV

$Q_3$ known for $^{224,226}$Ra

$^{223}$Rn [TRIUMF]

$\Delta E$ not known

$Q_3$ known for $^{220}$Rn

Peter Butler
Level schemes Rn

NEW!

Peter Butler
Structure of $^{70}$Fe: Single-particle and collective degrees of freedom

**Experiment**
- $^9$Be($^{71}$Co,$^{70}$Fe+$\gamma$)X at 87 MeV/u; typical $^{71}$Co rate: 65/second
- $^{70}$Fe unambiguously identified in the S800, coincident $\gamma$ rays event-by-event Doppler reconstructed from GRETINA's interaction points

**Results**
- Inclusive cross section for the reaction to happen: 11.0(8) mb
- Three $\gamma$ rays observed, one is new, two agree with previous results
- All three are in coincidence $\rightarrow$ level scheme established
- A catch – Shell model predicts a $^{71}$Co $7/2^-$ ground state and a $1/2^-$ isomer

Alexandra Gade
The experiment – One-proton knockout from $^{43}\text{P}$

- Again, one-proton knockout is a direct reaction $\rightarrow$ probes the single-particle degree of freedom
- $^{43}\text{P}$: ground state is $1/2^+$
  - L. A. Riley et al., PRC 78, 011303(R) (2008)
- This means, knockout of sd-shell protons cannot populate $J \geq 4$
- All $\gamma$-ray transitions except for the 2743 keV line had been reported in the RIBF two-proton removal experiment

- $^9\text{Be}(^{43}\text{P},^{42}\text{Si}+\gamma)\text{X}$ at 81 MeV/u
- Gamma rays in GRETINA and projectile-like reaction residues in the S800
Doubly-magic $^{78}\text{Ni}$

- $^{78}\text{Ni}$ is the only neutron-rich doubly-magic nucleus with unknown $E(2^+)$
- within the predicted neutron drip-line
  
- magicity inferred from $\beta$-decay measurements
  
- prediction $E(2^+) = 2 - 4 \text{ MeV}$
Towards high-resolution in-beam $\gamma$-ray spectroscopy at the RIBF

Kathrin Wimmer

The University of Tokyo

14 May 2019

$\gamma$-ray spectra for $^{78}$Ni

$^{79}$Cu$(p,2p)^{78}$Ni, $M_\gamma < 6$

- inclusive cross section $\sigma = 1.7(4)$ mb
- highest intensity peak $\rightarrow E(2^+) = 2600(33)$ keV
- 583(10) keV transition:
  $4^+ \rightarrow 2^+$ candidate, $R_{4/2} = 1.22(2)$
  similar to other doubly magic nuclei

$^{79}$Cu$(p,2p)^{78}$Ni

- 583(10) keV transition:
  similar to other doubly magic nuclei

Shape coexistence in the vicinity of $^{78}\text{Ni}$

Complete $\beta$-delayed $\gamma$-spectroscopy of $^{83}\text{Ge}$

Excited states lifetime measurement of $^{85}\text{Se}$ (better precision) and $^{83}\text{Ge}$ (first time)

First observation of a 2p-1h state in a N=51 isotone far from stability: shape coexistence towards N=50
one-proton knockout reaction at RIKEN: 
75Cu and 77Cu 
SEASTAR Level schemes
Collectivity in the vicinity of $^{78}\text{Ni}$: Coulomb excitation of neutron-rich Zn at HIE-ISOLDE

A. Illana Sison

On behalf of the IS557 collaboration

Andres Illana Sison
NSD Venezia - May 2019

B(E2; $2^+ \rightarrow 0^+$) [e$^2$ fm$^4$]

B(E2; $4^+ \rightarrow 2^+$) [e$^2$ fm$^4$]

Neutron Number N
Silvia Leoni

Revealing microscopic origins of shape coexistence in the Ni isotopic chain

Lifetime Measurements (Plunger)
Comparison with Monte Carlo SHELL Model

Preliminary

64Ni

1.0(1) W.u.
5(1) W.u.
0.01 W.u.
2.1 W.u.
12.4 W.u.

MCSM
Heavy ion transfer reactions

- Neutron rich nuclei
- Heavy nuclei

Correlations
- Nucleon - nucleon
- Mass - mass

Reaction mechanism
- Above the barrier
- Below the barrier

Studies of pairing in nuclei
- Instrumental: coincident detection of partners

Studies of production of heavy neutron-rich nuclei

Recent studies of heavy ion transfer reactions using large solid angle magnetic spectrometers

Suzana Szilner
Ruđer Bošković Institute, Zagreb
PRISMA collaboration
The experimental transfer probabilities are well reproduced, in absolute values and in slope by microscopic calculations which incorporate nucleon-nucleon correlations:

✓ a consistent description of (1n) and (2n) channels

✓ the formalism for (2n) incorporates the contribution from both the simultaneous and successive terms (only the ground-to-ground-state transition has been calculated)

✓ character of pairing correlations manifests itself equally well in simultaneous and in successive transfers due to the correlation length
Synthesis of heavy neutron rich nuclei in labs

$^{197}$Au+$^{130}$Te: coincident detection of binary partners

Multinucleon transfer reactions are suitable tool for the production of the heavy neutron-rich nuclei $^{130}$Te isotopes with “more” neutrons than in $^{130}$Te and $^{197}$Au isotopes with “more” neutrons than in $^{197}$Au
Y.X. Watanabe

Nuclear production around $N = 126$ by MNT reaction

KEK Isotope Separation System (KISS)

Experimental results

- $\beta-\gamma$ spectroscopy at KISS
- Laser spectroscopy at KISS

Element

- Au, Pt, Ir, Os, Re, W, Ta, Hf, Lu, Yb

Neutron number

- $N = 126$

Lifetime known

Charge radius known

- $136\text{Xe}$ (9.4 MeV/nucleon)
- $198\text{Pt}$ (12.5 mg/cm$^2$)

Ar gas, 100 kPa

Element selection

- Laser resonance ionization

Detection system

- Tape transport system
- $\beta$-ray detector
- Clover HpGe detectors for $\gamma$-rays

Extraction chamber

- HV (~20 kV)

KEK Isotope Separation System (KISS)

- Construction at RIKEN since 2011
- Online test since 2013
- Open for users since 2016

ISOL (Mass selection)

-$\mu$Q Known

$\beta-\gamma$ spectroscopy at KISS
Laser spectroscopy at KISS
The system $^{12}\text{C} + ^{30}\text{Si}$ has a $\zeta$ parameter very near to the lighter systems important for stellar evolution. Its Q-value for fusion is positive ($Q=+14.1$ MeV).

$^{12}\text{C} + ^{24}\text{Mg} (Q=+16.3$ MeV) is even closer to the light systems and has been measured very recently.

The case of $^{12}\text{C} + ^{20}\text{Ne}$ raises questions....

N.B. (the points of C+C and O+O are obtained only from extrapolations)
Pushing the $^{12}\text{C}+^{12}\text{C}$ cross-section to the limits with the STELLA experiment at IPN Orsay

David Jenkins

...measurement of the S-factor with particle-gamma coincidence.
An increase in the $^{12}\text{C} + ^{12}\text{C}$ fusion rate from resonances at astrophysical energies

A. Tumino$^{1,2*}$, C. Spitaleri$^{2,3}$, M. La Cognata$^{2}$, S. Cherubini$^{2,3}$, G. L. Guardo$^{2,4}$, M. Gulino$^{1,2}$, S. Hayakawa$^{2,5}$, I. Indelicato$^{2}$, L. Lamia$^{2,3}$, H. Petracca$^{4}$, R. G. Pizzone$^{2}$, S. M. R. Puglia$^{2}$, G. G. Rapisarda$^{2}$, S. Romano$^{2,3}$, M. L. Sergi$^{2}$, R. Spartà$^{2}$ & L. Trache$^{4}$
Recent results on heavy-ion induced reactions of interest for neutrinoless double beta decay

**A new experimental tool**

Nuclear reactions

**Heavy-Ion induced Double Charge Exchange reactions (DCE)**

to stimulate in the laboratory the same nuclear transition (g.s. to g.s.) occurring in 0νββ

The dream:

Extraction from measured cross-sections of "data-driven" information on NME for all the systems candidate for 0νββ
Hiroyuki Sagawa

Single and Double Charge exchange excitations of Spin-Isospin mode
Theory
3H(d,n)4He with chiral NN+3N(500) interaction

\[ \frac{\partial \sigma_{\text{pol}}}{\partial \Omega_{\text{c.m.}}} (\theta_{\text{c.m.}}) = \frac{\partial \sigma_{\text{unpol}}}{\partial \Omega_{\text{c.m.}}} (\theta_{\text{c.m.}}) \left( 1 + \frac{1}{2} p_{z2} A_{z2}^{(0)} (\theta_{\text{c.m.}}) + \frac{3}{2} p_{z2} q_{z2} C_{z2} (\theta_{\text{c.m.}}) \right) \]

\[ \sigma_{\text{unpol}} = \sum_{\lambda} \frac{2\lambda+1}{(2\lambda_D+1)(2\lambda_T+1)} \sigma_\lambda \]

\[ \approx \frac{1}{3} \sigma_2^\text{ss} + \frac{2}{3} \sigma_3^\text{ss} \]

\[ \sigma_{\text{pol}} \approx 1.5 \sigma_{\text{unpol}} \]

NCSMC calculation demonstrates impact of partial waves with \( l > 0 \) as well as the contribution of \( l = 0 J^p = \frac{1}{2}^+ \) channel
NCSMC wave functions of $^{11}$Be used as input for other studies

**Physical Review C 98, 054602 (2018)**

Systematic analysis of the peripherality of the $^{10}$Be($d,p$)$^{11}$Be transfer reaction and extraction of the asymptotic normalization coefficient of $^{11}$Be bound states

J. Yang$^{1,2,4}$ and P. Capel$^{1,3,1}$

**Physical Review C 98, 034610 (2018)**

Dissecting reaction calculations using halo effective field theory and ab initio input

P. Capel$^{1,2,3,4,5}$, D. R. Phillips$^{5,3,4,1}$ and H.-W. Hammer$^{3,4,1}$

Reliable extraction of the $dB(E1)/dE$ for $^{11}$Be from its breakup at 520 MeV/nucleon

L. Moschini$^{5,6}$, P. Capel$^{1,4}$

Neutron transfer reactions in halo effective field theory

M. Schmidt$^{1,2}$, L. Platter$^{2,3}$ and H.-W. Hammer$^{1,4}$

---

- *Ab initio* calculations of nuclear structure and reactions becoming feasible beyond the lightest nuclei
- Make connections between the low-energy QCD, many-body systems, and nuclear astrophysics
Comparison with theory

- $\chi$EFT calculations of $B(M1; 1^+ \rightarrow 0^+)$ and $\mu(1^+)$ in the no-core shell model

- SRG-evolved next generation chiral NN+3N interactions up to N4LO+N3LO
  D.R. Entem, R. Machleidt, Y. Nosyk, PRC 96 (2017)

- Unevolved M1 operator, evolved M1 operator at LO, and evolved M1 operator at NLO

→ First complete chiral calculation of these observables

High experimental precision crucial to test state-of-the-art theory!
Chiral three-body force and monopole properties of shell-model Hamiltonian

Chiral $N^2$LO 3NF for shell model

3-body MEs with nonlocal regulator

Benchmark test for $p$-shell

Monopole properties of $fp$-shell

→ Our RSM calculations with 3NF are satisfactorily comparable to the ab initio results.


→ The 3NF-induced monopole Hamiltonian is essential to explain the measured shell evolution.

Y. Z. Ma et al., arXiv:1812.03284.
Microscopic optical potential from chiral forces

Paolo Finelli

![Graphs showing microscopic optical potential](image)
Coexisting shapes in neutron-deficient Nd and Sm isotopes

Tamara Nikšić

University of Zagreb

Nuclear structure studies based on energy density functionals


Coexisting shapes in neutron-deficient Nd and Sm isotopes

The new complex configurations 2q+2phonon included for the first time enforce fragmentation and spreading toward higher and lower energies, thus, modifying both giant and pygmy dipole resonances;


RQTBA\(^3\) demonstrates an overall systematic improvement of the description of nuclear excited states heading toward spectroscopic accuracy without strong limitations on masses and excitation energies.
Time-Dependent Hartree-Fock Theory for Multinucleon Transfer Reactions:

Kazuyuki Sekizawa

Production cross sections for N=126 isotones

Isotonic distributions for various systems

$N=126$, primary

- Watanabe et al. ($E_{c.m.}=645\text{MeV}$)
PRL115(2015)172503
- Barrett et al. ($E_{c.m.}=450\text{ MeV}$)
PRC91(2015)064615

- $^{136}\text{Xe}+^{198}\text{Pt}$
- $^{144}\text{Xe}+^{198}\text{Pt}$
- $^{132}\text{Sn}+^{208}\text{Pb}$
- $^{134}\text{Xe}+^{208}\text{Pb}$
- $^{204}\text{Hg}+^{198}\text{Pt}$
Quasifission – $^{48}$Ca + $^{249}$Bk – orientation and shell effects

- Most comprehensive QF calculation
- All $\beta$ in range $(0^\circ, 180^\circ)$ $\Delta\beta=15^\circ$
- Entire L range for each $\beta$
- Each ($\beta$,L) run takes 1-3 days on 20 core CPU

Light

Heavy

Deep inelastic Quasielastic
Quantum equilibration dynamics

### Mass

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Time to Equilibrium</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40,48}\text{Ca}+^{238}\text{U},^{249}\text{Bk}$</td>
<td>~ 10 zs</td>
</tr>
<tr>
<td>Cr+W and many others</td>
<td>~ 1 zs</td>
</tr>
<tr>
<td>Slowed by shell effects</td>
<td>~ 1.5 zs</td>
</tr>
</tbody>
</table>

### Isospin

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Time to Equilibrium</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{78}\text{Kr}+^{208}\text{Pb}$</td>
<td>~ 1.5 zs</td>
</tr>
</tbody>
</table>

### Energy

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Time to Equilibrium</th>
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</thead>
<tbody>
<tr>
<td>$^{78}\text{Kr}+^{208}\text{Pb}$</td>
<td>~ 1.5 zs</td>
</tr>
<tr>
<td>$^{58}\text{Ni}+^{60}\text{Ni}$</td>
<td>~ 3 zs</td>
</tr>
</tbody>
</table>

### Mass Fluctuations

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Time to Equilibrium</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{58}\text{Ni}+^{60}\text{Ni}, \text{Xe}+\text{Pb}$</td>
<td>~ 3 zs</td>
</tr>
<tr>
<td>SMF, TDRPA</td>
<td></td>
</tr>
<tr>
<td>Williams et al., PRL 120, 022501 (2018)</td>
<td></td>
</tr>
</tbody>
</table>
Agreement with observations is pretty good and without any fitting parameters, as long as the basic nuclear properties (saturation, surface tension, symmetry energy, Coulomb, spin-orbit, pairing) are well described!

How important is pairing?

\(^{238}\text{Pu} \text{ fission in the normal pairing gap}

\(^{238}\text{Pu} \text{ fission in a larger pairing gap}

Normal pairing strength
Saddle-to-scission 14,000 fm/c

Enhanced pairing strength
Saddle-to-scission 1,400 fm/c !!!
Symmetry-guided and algebraic approaches:

Jerry Draayer

Systematic Search for Tetrahedral and Octahedral Symmetries

‘Symmetry Adapted’ NCSM Campaign

A. Leviatan

Intertwined Quantum Phase Transitions in the Zr Isotopes

Kosuke Nomura

Coexistence and evolution of shapes:
mean-field-based interacting boson model

Nobuo Hinohara

Pairing rotation and pairing energy density functional
G. de Angelis (INFN Legnaro) - Chair
L. Corradi (INFN Legnaro) - Chair

E. Fioretto (INFN Legnaro)
F. Galtarossa (INFN Legnaro)
T. Marchi (INFN Legnaro)
M. Mazzocco (Uni. and INFN Padova)
D. Mengoni (Uni. and INFN Padova)
J.J. Valiente-Dobón (INFN Legnaro)

A. D’Este (INFN Legnaro) - Secretary
A. Schiavon (Uni. Padova) - Secretary