Investigations of reaction dynamics and structure of exotic nuclei: fusion, haloes and exotic decays


Universidad de Huelva (Huelva, Spain)
The development of intense low energy radioactive beams has opened the opportunity to “fabricate” nuclei at extreme (N,Z) combinations.

Spectroscopic tools: Direct Nuclear Reactions
- not too many degrees of freedom
- precise knowledge of theoretical framework
- well tested with stable nuclei

Elastic/inelastic  p,n transfer  Breakup

6Li (stable)  6He (exotic)

E.g.: “Di-nucleon” cluster models

1) Halo → extended neutron distribution
   → larger overlap of target-projectile WFs
   → should lower the barrier and increase fusion

2) Weak binding → should greatly increase breakup → reduce fusion yields

3) Coupling to soft dipole modes, transfer, breakup → doorway states → increase fusion yields

4) Coupling to continuum

5) Polarization effects due to the different forces between halo/core and target

A complicated dynamical scenario!
Scattering of $^6\text{He}$ at energies around the coulomb barrier

$^6\text{He}$:
- Two loosely bound neutrons orbiting an alpha-core
- Halo nucleus with Borromean structure: \((4\text{He} + n + n)\)
- NO bound excited states
- weakly bound $S_{2n}=0.97$ MeV, $S_{1n}=1.87$ MeV

$J^\pi=0^+ // T_{1/2}=0.807$ s

Most studied halo nucleus $\rightarrow$ consistent sets of experimental data are available at Coulomb barrier energies

TWINSOL (USA), CRC (Belgium), GANIL (France), RIBRAS (Brasil)

FLR-JINR (Russia) $\rightarrow$ ACCULINNA-1 facility (ACCULINNA-2, in construction)


Nuclear reaction measurements

Cyclotron Research Center (UCL, Louvain la-Neuve, Belgium) →
- Reaction & fusion $^6$He+$^{208,206}$Pb at energies around the Coulomb barrier

Angular distributions and fusion at E=14, 16, 18, 22, 27 MeV with $^{206,208}$Pb targets, 27 MeV with $^{197}$Au,…

Channels: $^6$He (Elastic)
  $^4$He (breakup/transfer)
  2n + $^{210}$Po (fusion/2n-evap)

Hall experimental


- Typical beam intensity $10^6$ pps
- Beam spot ~ 2 mm on target
- Target: $^{206}$Pb, 1-2 mg/cm$^2$
Elastic cross sections: $^6\text{He} + ^{208}\text{Pb}$

CRC-Louvain la-Neuve (Belgium) Experiments PH189, PH215

CDCC calculations describe the data (2n-model)

OM calculations:
- Full OM
- No C. Dipole
- Bare (J. Cook)

Strong absorption up to small scattering angles, rainbow dissapears. → Long range reaction mechanisms → Strong dipole Coulomb couplings

CDCC calculations:
- Full CDCC
- No continuum
- Dipole coupling

Scattering process dominated by:
- Dipole couplings (coulomb + nuclear)
- Coupling to continuum
The role of breakup/transfer

- Large alpha yields even well below the barrier
- CDCC calculations → Direct break-up (dashed line) - Not consistent with energy distributions

DWBA calculations →
1n - transfer gives some contribution
2n- transfer gives main contribution (solid line). → Consistent with energy distribution.

Dynamical scenario consistent with Zagrebaev expectations for FUSION ENHANCEMENT
The scattering system $^{6}\text{He}+^{208}\text{Pb}$ exhibits interesting regularities in the angular distributions of elastic and alpha production cross sections.

**Scaling parameters:**
- Cross section: \( \frac{d\sigma(\theta)}{d\Omega} = \left( \frac{Z_1 Z_2 e^2}{4E} \right)^2 \frac{1}{\text{sen}(\theta/2)^4} \)
- Scatt. angle \( \rightarrow \) distance of closest approach in coulomb trajectory
  \( D(\theta) = e^2 (Z_p Z_t / 2 E) (1 + 1/\text{Sin}(\theta/2)) \)
- Semi-classical picture of the reaction process

- "Universal" function for $^6\text{He}$ scattering: Deduce $^4\text{He}$ yield as: \( (1 - \text{Elastic}) \)
- Reaction dominated by alpha production channels (n-transfer, breakup…)
- Semi-classical picture: reactions “localized” at turning point
Sub-barrier fusion: the $^6\text{He} + ^{206}\text{Pb}$ system

Fusion measurements at Flerov Laboratory (Dubna) - RIB Complex (U400M+U400 cyclotron)

**In-beam measurements**

$^6\text{He} + ^{206}\text{Pb} @ 10 \text{ MeV/A}$

**Activation technique:**

- Stack of 10-14 targets + enriched $^{206}\text{Pb}$ foils + Al degraders

TWO measurements:

Y.E. Penionzhkevich et al., PRL96 (2006) 162701


LARGE fusion cross sections found for $^{206}\text{Pb}(^6\text{He},2n)^{210}\text{Po}$ at deep sub-barrier energies.

-> Consistent with sequential 2n transfer (V. Zagrebaev, Phys. Rev. C 67 (2003) 061601)
Most recent sub-barrier fusion investigations of the $^6\text{He} + ^{206}\text{Pb}$ system

Centre de Recherches du Cyclotron (UCL, Belgium): reaction & activation process

→ mainly production of $^{210}\text{Po}$ (~ 138 d)

→ Radiochemistry analysis: Detector Lab – University of Huelva (Spain)
Extract $^{210}\text{Po}$ by chemistry: solution in acid medium + calibrated radiotracer ($^{209}\text{Po}$, 102y)

Measurement of alpha decay over ~3-4 weeks

Self-deposition of Polonium on silver disks

Main advantages:
- Improved energy resolution ~30keV
- Removal of contaminants
- Relative yield to radiotracer: $Y = \frac{^{210}\text{Po}}{^{209}\text{Po}}$
Our results show a sizeable sub-barrier enhancement with respect to the $^4$He+$^{208}$Pb system. This effect might be related to the presence of strong sub-barrier transfer channels.


Full CRC → J.P. Fernández-García, PRC2011-in preparation
NEW DUBNA-HUELVA PROPOSAL AT MSU (USA)

A lay-out of new common proposal

Beam-off~nT_{1/2}  Measuring of $\alpha$

$^{211}\text{Po}$
$E_a = 7.4\text{MeV}$

$^{212}\text{Po}$
$E_a = 8.7\text{MeV}$

To repeat $^6\text{He} + ^{206}\text{Pb}$

$^{208}\text{Pb}$
thin target

$^{208}\text{Pb}$
thick targets

Si strip detectors

Plastic scintillator

25s|0.56s

45s|17ns|0.3us

Courtesy of Prof. S. Lukyanov
Study of $^8$He+$^{208}$Pb scattering at 16 and 22 MeV-Proposal E587S

**PROPOSED SETUP: GLORIA**

(Glogal Ion Reaction Array)

- 6 DSSSD-telescopes 50x50 mm$^2$
- DE: 40 mm (16 x 16), 1000 mm (16 x 16)
- Strip pitch: 3 mm
- **26% Solid angle**
- Distance to target (center square): 60 mm
- Angular range: 15 - 165 degrees Lab
- $E_{\text{resolution}} \sim 40$ keV

**GANIL**

(Caen, France)

- **Beam time**
  - $^8$He @ 2.0 MeV/u, 2 x $10^5$ pps
  - $^8$He @ 2.75 MeV/u, 2 x $10^5$ pps
GLORIA SETUP: Beam line G22/GANIL
The HYbrid DEtector concept (HYDE)

Detector for charged particles:

Physics at the low energy branch $< 100$ MeV/u
Direct Nuclear Reactions, Clustering, Fusion Evaporation, Transfer, Deep Inelastic, etc.

Beam properties:
- Large emittance and energy spread
- Low intensity $<10^7$ pps.

Goals:
- Detection of Charged particles.
- Good charge and mass identification.$\rightarrow$ S, Cl isotopes
- Efficiency ($>60\%$).
- Good energy resolution ($<150$ keV).
- Angular resolution ($<1^\circ$).

Constraints:
- Use with other detectors:
  - Subsystem of AGATA array
- Use at other RIB facilities (SPIRAL2, HIE-ISOLDE, SPES,…. ACCULINA2)
- Modularity and portability
Scientific Framework

Nuclear instruments: the HYDE detector for FAIR
at the Low Energy Branch

International collaboration:
Univ. Huelva (I. Martel)/Coordination
CRC-Louvain la Neuve
CSIC-IEM, Madrid (M.J.G. Borge)
Univ. Surrey (W. Catford)
IKS-University of Leuven (P. Van Dappen)
Flerov Laboratory Nucl. Reac.- Dubna (A. Fomichev)
GSI-Darmstadt (J. Gerl)
Univ. Sevilla (J. Gómez-Camacho)
A. Soltan Inst. Nucl. Studies, Warsaw (K. Rusek)
Instytut Fizyki Jądrowej PAN, Krakov (A. May, A. Czermak)
Rudjer Boskovic Institute, Zagreb, Croatia (N. Soic)

Project Steering Committee
A. Fomichev, (JINR-Flerov, Dubna)
W. Catford (Univ. Surrey)/GASPARD
R. Bougault (LPC-Caen)/FAZIA
O. Tengblad (IEM-CSIC-Madrid)
A. Gadea (LN-Legnano)/AGATA+TRACE
K. Rusek (A.Soltan-Warsaw)
J. Gerl (GSI-Darmstad)
J. Gómez-Camacho (Univ. Sevilla)
I. Martel (Univ.Huelva)

The new FAIR facility at GSI (Darmstadt., Germany)

The HYbrid DEtector concept (HYDE)

Detector for charged particles:

Physics at the low energy branch < 100 MeV/u
Direct Nuclear Reactions, Clustering, Fusion Evaporation, Transfer, Deep Inelastic, etc.

HYDE detector is also a natural framework for DUBNA-HUELVA collaboration in particle detector instrumentation and future experimental physics activity at FAIR.
Mechanical design of HYDE

Characteristics:
- ~ 4 PI ARRAY
  - Detection of charged particles.
  - Particle ID using PSA, DE/E and TOF.
  - Energy & angular resolution (< 150 keV, 1°/0.1°).
  - Large multiplicity (> 3)

Design constraints:
- Subsystem of AGATA array
- Use at other RIB facilities (SPIRAL2, HIE-ISOLDE, LEGNARO-SPES)
- Modularity and portability

Construction:
- Chamber < 380 mm diameter
- 49 DETECTOR CELLS
- 3 different shapes: square
  + 2 trapezoids fitting 4" wafer.
- Cylindrical symmetry/10 sides

Mechatronics
- FFE on air
- 31.360 channels
- High density feedthroughs
- Multiplexing.

Detector cell (Silicon)
- 4 inches, NTD silicon wafers
- Strip size 0,4 mm, Multilayer (5 layer)
HYDE - PARTICLE IDENTIFICATION

Results from FAZIA collaboration (G. POGGI, Spiral2 Week January 2010)/LNS-Catania experiments.

- Good identification up to Z~25 with ~5GeV
- 100MS/s 14 bit digitizer
- Highly uniform Si: NTD
- Silicon doping uniformity ~1% (TOPSIL)
- Channeling
- Voltage stability

- Last PSA test at Orsay Tandem for light particles/500um NTD looks promising → test thin silicon (20um/100um)

TOF simulation for HYDE/A. Sánchez-Benítez) Limited by Si response ~1ns

Challenging developments in SILICON materials, as well as fast digital FEE
Road map for ACCULINNA–2

Andrey Fomichev, FLNR JINR

Dubna
Radioactive Ion Beams
DRIBs-I → DRIBs-III 2010-2016

Production target and ECR source

Acculinna-2

Combos

Acculinna

U400M cyclotron
stable ion beams: \(^{7}\text{Li} @ 34\ \text{AMeV}\), \(^{11}\text{B},^{18}\text{O} @ 33\); \(^{6}\text{Li},^{15}\text{N} @ 46\); \(^{20}\text{Ne},^{32}\text{S} @ 52\ \text{AMeV}\)

Courtesy of Prof. A. Fomichev
LI\-\text{NAC RESEARCH FACILITY (LRF)} at University of Huelva

The Linac Research Facility (LRF) is foreseen to be a user oriented facility for producing intense HEAVY ION BEAMS for basic research on nuclear physics and applications.

POSSIBLE COLLABORATIONS USING STABLE NUCLEI:
- Machine and detector construction
- Physics: Superheavies, astrophysics, sub-barrier fusion, …
Summary and Conclusions

Relevant collaborations have been realized between Huelva-Dubna framework on 6He (and other light helium isotopes):

- Elastic and alpha production angular distributions, fusion and reaction cross sections can be described using “universal functions”.

- Fusion cross sections at deep sub-barrier energies show a sizeable sub-barrier enhancement; this effect might be related to the presence of strong sub-barrier transfer channels. New direct measurements are foreseen at MSU (USA).

- Collaboration in detector development for HYDE array at FAIR are already under discussion.

- The new radioactive beam facility DRIBS/ACCULINA-2 at Dubna and stable beam facility LRF at Huelva open new possibilities for our collaboration in nuclear spectroscopy and instrumentation.