Collisions around the Coulomb barrier induced by halo and/or weakly bound nuclei: experimental results at INFN-LNS Catania

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Outline of the talk

- Motivations & Experimental methods
- Collisions induced by halo nuclei
- Collisions induced by stable weakly bound nuclei
- Note on two specific experimental problems in:
  measuring charged particle with segmented Si detectors;
  measuring fusion with the stack activation technique
- Summary and perspectives
Collisions around the barrier induced by halo and/or weakly bound nuclei

Characteristics of the projectiles:
- Low break-up thresholds, diffuse tails
  └──────────────────────────────┘
  Coupling to continuum effects expected to be important.

Direct mechanisms (e.g. break-up, transfer) expected to be important.

What do we expect for fusion reactions?

a) Static effects:
- Diffuse tail affects the shape of the potential

b) Dynamic effects:
- Coupling not only to bound states but also to continuum

c) Contribution of Incomplete Fusion (ICF) can be important
Experimental techniques for elastic and direct reaction measurements

**Aim:** measure charged particles in single and coincidence with low intensity beams

**Need for:** large solid angles + good granularity ⇒ wide use of segmented Si detectors

**Experimental techniques for \( \sigma_{\text{FUS}}(E) \) measurements**

**General problems:** low \( \sigma_{\text{Fus}} \) and beam intensities.

**Very Heavy Targets** → fusion-fission → FF detection

**Other targets** → direct ER detection impossible → Activation techniques widely used!

In our fusion studies

Detection of atomic X rays following EC decay of the ER.

By measuring the activity curves associated to the different \( K\alpha \) lines cross section of the different ER identified in \( Z \) and \( A \) can be extracted.
$^4,^6\text{He}+^{64}\text{Zn} @ \text{LLN: elastic and transfer + break-up}$

$^6\text{He}+^{64}\text{Zn} E=18\text{MeV}$

$^4\text{He}+^{64}\text{Zn} E = 18 \text{ MeV}$

$^6\text{He}+^{64}\text{Zn}: \text{conclusions.}$

- Presence of large alpha particle yield due to transfer and B.U. events.
- Transfer+B.U cross section dominates ($\sim 80\%$) total reaction.
- From coincidence data: 2n transfer important.

**10,11Be+^{64}Zn elastic scattering angular distributions**

**10,11Be+^{64}Zn @ Rex-Isolde, CERN**

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**11Be + ^{64}Zn: OM analysis adopted procedure:**
- Volume potential for the core-target interaction obtained from the 10Be+^{64}Zn scattering fit.
- DPP potential is a surface term having the shape of a W-S derivative with a very large diffuseness (a_i=3.5 fm).

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**Reaction cross-sections:**
- $\sigma_R^{9}\text{Be} \approx 1.1 \text{b}$
- $\sigma_R^{10}\text{Be} \approx 1.2 \text{b}$
- $\sigma_R^{11}\text{Be} \approx 2.7 \text{b}$


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**CDCC calculations (A.M. Moro)**
- Experimental elastic A.D. reproduced only taking into account coupling to continuum via the Coulomb and nuclear interactions.
$^{11}\text{Be} + ^{64}\text{Zn}$ Transfer+B.U. angular distributions

Which is the origin of the $^{11}\text{Be}$ total reaction enhancement?

Conclusions on $^{10,11}\text{Be} + ^{64}\text{Zn}$

\[ \sigma_{\text{REACT}}^{(11\text{Be})} \approx 2 \sigma_{\text{REACT}}^{(9,10\text{Be})} \]

- $\sigma_{\text{TR+BU}} \approx 40\% \sigma_{\text{REAC}}$
- Measured elastic AD reproduced considering Coulomb and nuclear coupling to continuum.

n halo nuclei scattering and direct processes: additional results from literature

- Most of the existing results are with $^6$He Beams $\rightarrow$ similar conclusions

- Separation of 1n, 2n transfer and B.U. processes with $^6$He in some experiments e.g.: A.Chatterjee et al. PRL 101, 032701 (2008), P.A.De Young et al: Phys.ReV. C71,051601,(2005)
  2n transfer is the dominant reaction channel with $^6$He at the barrier.

- First data with different n-halo beams different than $^6$He, qualitatively similar results

- Data with n halo nuclei different than $^6$He would help in building up a wider systematics

What do we expect for p-halo nuclei?

p in the halo feels Coulomb interaction $\rightarrow$ is dynamics different then for n halo case?

Elastic scattering data $^8$B+$^{58}$Ni suggests enhancement in $\sigma_R$ as with $^6$He.
(E.Aguilera et al PRC 79,021601,(2009)
  New p halo data needed.

Example

$^9,^{11}$Li + $^{238}$Pb elastic scattering
(M. Cubero et al., PRL 109, 262701, (2012))
Fusion with n halo nuclei

When we talk about suppression or enhancement is with respect to what?

**EXAMPLE**

\(^6\text{He} + ^{209}\text{Bi}\)

Data:
J.J. Kolata et al PRL 81,4580,(1998)
Figures:

Comparison with \(^4\text{He}\)
Activation technique used. Off-line measurement of X-rays.

Enhancement of $\sigma_{\text{FUS}}$ for $^6\text{He}$ with respect to $\sigma_{\text{FUS}}$ for $^4\text{He}$

Reduced excitation functions to eliminate static effects.

$V_B$ and $R_B$ from double folding potential.

The observed enhancement can be explained as due to static effects.

V.Scuderi et al. PRC 84, 064604, (2011)
Fusion with n-halo nuclei: additional examples from literature

\[4,6,8^{\text{He}}+^{197}\text{Au}\]
A. Lemasson et al., PRL 103, 232701, (2009)
Yu. E. Penionzhkevich et al., EPJ A31, 185, (2007)

\[13,14,15^{\text{C}}+^{232}\text{Th}\]
M. Alcorta et al., PRL 106, 172701 (2011)
Fusion of halo nuclei: can we reach some conclusions?

- There is an effect of the halo structure on fusion
- Static effects appears to be important but not the only ones
- CF appears to be dominant over ICF
- Few data below barrier

No clear conclusions can be reached for p-halo nuclei see e.g.:

- $^8\text{B}+^{58}\text{Ni}$ - E.F. Aguilera et al.: PRL 107,092701,(2011)
- $^8\text{B}+^{28}\text{Si}$ - A.Pakou et al.: PRC87,014619,(2013)

Systematics for fusion with halo nuclei

Main ingredient:

reduce $\sigma_{\text{Fus}}(E)$ to eliminate static effects

$$E \rightarrow x = \frac{E - V_B}{\hbar \omega} ; \quad \sigma_F \rightarrow F(x) = \frac{2E}{\hbar \omega R_B^2} \sigma_F$$

Further transformation eliminates coupling to bound state effects

Collisions around the barrier induced by the stable weakly bound nuclei $^6$Li, $^7$Li.

Question: effects of weakly bound cluster structure?
Stable beams $\Rightarrow$ better data quality.

Elastic scattering, possible motivations:
- Total reaction cross section
- Coupling to continuum effects
- O.P. Threshold anomaly (TA);

Is usual threshold anomaly in O.P. present in collisions involving weakly bound nuclei?

$^6,^7\text{Li}+^{64}\text{Zn} \text{ Elastic scattering A. D.}$

Elastic A.D. measured at several energies around the barrier
OM fits with renormalized DF potential
Absence of usual threshold anomaly appears to be present on both systems

M. Zadro et al., PRC 80, 064610, (2009) and to be published
$^6,^7\text{Li} + ^{64}\text{Zn}$ elastic scattering
CDCC calculations (preliminary)
(J.P. Fernandez & A.M. Moro)

Coupling to continuum effects more important for $^6\text{Li}$ than for $^7\text{Li}$
$^6,^7\text{Li}+^{64}\text{Zn}$ Q.E. barrier distributions

$4 \Delta E(10\mu m)-E(200\mu m)$ telescopes around $170^0$

$$D_{qel}(E) = -\frac{d}{dE} \left[ \frac{d\sigma_{qel}}{d\sigma_{Ruth}}(E) \right]$$

CC calculations including inelastic excitations of projectile and target do not reproduce the data especially for the $^6\text{Li}$ case.

Fusion of weakly bound nuclei with heavy targets

- CN evaporates only neutrons →
  CF and ICF reactions can be easily separated via ER charge identification

- Main Experimental findings:
  $\sigma_{CF}$ suppression above the barrier of about 30% with respect to SBP or CC not including continuum.
  $\sigma_{TF} = \sigma_{CF} + \sigma_{ICF}$ not suppressed

Example: the $^{6,7}$Li+$^{120,119}$Sn collision @ LNS

![Diagram of nuclear reactions and energy levels](image)

Complete Fusion:

- $^{6}$Li + $^{120}$Sn → $^{126}$I$^*$
- $^{7}$Li + $^{119}$Sn

Incomplete Fusion:

- d + $^{120}$Sn → $^{122}$Sb$^*$
- $^{120}$Sn
- $^{119}$Sn
- α + $^{120}$Sn → Te$^*$
- I$^*$ → Te
The $^6,^7\text{Li}+^{120,119}\text{Sn}$ collision @ LNS

ER relative yield for CF well reproduced by statistical model.

Example: $^6\text{Li}+^{120}\text{Sn}$ CASCADE DATA

Measured $\sigma_{\text{FUS}}(E)$ show the usual suppression above barrier with respect to SPB or CC.
Fusion of WB nuclei with light/medium mass targets

- CN evaporates charged particles →

CF and ICF reactions produce the same ER and cannot be easily separated

Experimental data refer to total fusion cross sections $\sigma_{TF} = \sigma_{CF} + \sigma_{ICF}$

Example: the $^6,^7\text{Li}+^64\text{Zn}$ collision @ LNS

Which is the relative importance of CF, ICF and other mechanisms in the HR production?

Enhancement with respect to SBP or CC calculations for CF

Is there an important contribution of processes different than CF?
Fusion of WB nuclei with light/medium mass targets

- CN evaporates charged particles \( \rightarrow \)

CF and ICF reactions produce the same ER and cannot be easily separated

Experimental data refer to total fusion cross sections \( \sigma_{TF} = \sigma_{CF} + \sigma_{ICF} \)

Example: the \(^{6,7}\text{Li}^{64}\text{Zn} \) collision @ LNS

Which is the relative importance of CF, ICF and other mechanisms in the HR production?

Ratio of the HR excitation functions shows larger yield for \(^6\text{Li} \) below barrier already observed for other systems.

Which is the origin of such a relative enhancement?
$^6\text{Li}+^{64}\text{Zn}$ heavy residue relative yields

Is $d$ or $\alpha$ capture from $^6\text{Li}$ important?

- ICF: $E^* \sim (E_{cm} - S_\alpha) \times (m_{\text{clus}} / m_{\text{proj}}) + Q(\text{Clu} + ^{64}\text{Zn})$
- Cluster transfer: $E^* \sim Q_{gg} - Q_{opt}$

$E_{cm} = 28.34 \text{ MeV}$

1$n$ or 1$p$ transfer leading to $^{65}\text{Zn}$ and $^{65}\text{Ga}$ can also contribute

Above barrier CF dominates
Below the barrier different processes dominate

7Li+64Zn heavy residue relative yields

Is t or α capture from 7Li important?

- ICF \( E^* \sim (E_{cm} - S_\alpha) x (m_{clu}/m_{proj}) + Q(Clq+64Zn) \)
- Cluster transfer \( E^* \sim Q_{gg} - Q_{opt} \)

1n transfer leading to 65Zn is also contributing

Once more above barrier CF dominates
Below the barrier different processes dominate

For the study of collisions induced by halo and weakly bound nuclei, one finds in the literature wide use of

- **Segmented Si detectors** for detecting charged particles
- **Stack activation techniques** for measuring fusion cross sections

Some related experimental problems are usually not deeply discussed in the literature...
Full energy efficiency for charged particles in DSSSD detectors

Well known from the literature:
Particles hitting the interstrip region can generate signals with reduced amplitude or inverted polarity (e.g.: Yorkston, NIM A262 (1987) 353; Blumenfeld NIM A421 (1999) 471 and many others)

Is the full energy efficiency equal to the geometric one?
Various tests performed on MICRON W1 DSSSD 1000,500, 75 $\mu$m (D. Torresi et al. NIM A713, 11, (2013) and NIM A to be published)

In the back side interstrip events give a charge sharing between the two neighboring strips.

For front strips this is no more valid and inverted polarity signals are generated.
Efficiency for full energy detection can be different than geometrical one and can depend on particle energy and detector operating conditions. If we are interested in knowing the absolute efficiency detector has to be characterised.
The effective interstrip width is different than the geometrical one and depends on particle energy and detector operating conditions.
Drawbacks of the activation technique for $\sigma_{\text{Fus}}$ measurements

Several thick targets $\rightarrow$ average $\sigma$ measured.

To which effective energy $E_{\text{eff}}$ do we have to associate the measured $\sigma$?

- **a) Easy solution**
  
  \[ E_{\text{eff}} = \frac{(E_i + E_f)}{2} \]

- **b) A bit more complete**

  \[ E_{\text{eff}} = \frac{\int_{E_i}^{E_f} E \cdot \sigma(E) \cdot D(E)dE}{\int_{E_i}^{E_f} \sigma(E) \cdot D(E)dE} \]

(See e.g. R.Wolski et al.: EPJA 47,111(2011))

But things can be even more complicate because…
Beautiful looking targets can be not really uniform....

$^{64}$Zn target $\sim$ 0.4 μm average thickness, exagonal grains 0.2 μm

Target non uniformity effects have to be taken properly into account when irradiating a multiple stack of targets.

Related information should be reported in the corresponding papers.
Summary and some perspectives

**Halo Nuclei**

- Most of the halo experiments performed with $^6$He beams on different targets
  - Suppression of $\sigma_e$ with enhancement of $\sigma_R$ due to direct processes
  - There is an effect of $n$ halo structure on fusion

- New data with $n$ halo beam different than $^6$He needed
  - $p$-halo $n$-halo differences on reaction dynamics? $\Rightarrow$ new data needed
  - New sub barrier fusion data with halo nuclei needed.

**Stable weakly bound**

- Coupling to continuum effects observed with elastic scattering in AD and OP
- CF and ICF easily separated on heavy targets $\Rightarrow$ observed CF suppression above barrier
- CF and ICF not separated on light/medium mass targets, CF appears to dominate above barrier whereas different processes such as ICF or transfer dominate below barrier.

What else can we understand with elastic scattering?
New fusion data studying CF-ICF-Transfer competition?

**Experimental problems**

Special care has to be used in extracting DSSSD efficiencies and fusion cross sections with the stack activation technique.
Collaboration