Coupled-Channel Effects in Collisions between Heavy Ions near the Coulomb Barrier
C. Beck (IPHC Strasbourg)

- Introduction: Role of neutron-transfer and/or breakup channels below the Coulomb Barrier
- Semi-classical fusion model of Zagrebaev
- Coupled Channel analysis: new NTFus code (transfer) and CDCC calculations (breakup)
- Enhanced cross sections for $^6$Li+$^{56}$Co (Sao Paulo)
- Multi-neutron Transfer Coupling for $^{32,36}$S, $^{28}$Si+$^{94,96}$Zr (Beijing data), $^{40}$Ca+$^{96}$Zr and $^6$He+$^{64}$Zn fusion
Fusion Enhancement: $^{40}\text{Ca} + ^{96}\text{Zr}$ typical example
Grazing Calculations: need Transfer Coupling
G. Pollarolo and A. Winther, Phys. Rev. C 62, 054601 (2000)

Transfers taken into account in GRAZING code
Semi-classical Fusion Model of V. Zagrebaev and NTFus code (A. Richard et al.)

![Graph showing fusion cross section vs. center-of-mass energy (MeV) for different isotopic combinations.](image-url)
NTFus code with Transfer Couplings

Transfers with positive Q-values enhance Fusion below Barrier

### Table 2. Q-values in MeV for neutron pickup transfer channels from ground state to ground state for $^{32}$S+$^{90}$Zr and $^{32}$S+$^{96}$Zr, respectively.

| System       | +1n  | +2n  | +3n  | +4n  |
|--------------|------|------|------|------|
| $^{32}$S+$^{90}$Zr | -3.33 | -1.229 | -6.59 | -6.319 |
| $^{32}$S+$^{96}$Zr | 0.788 | 5.737 | 4.508 | 7.655 |

\[ \sigma_F(E_{c.m.}) = \frac{\pi \hbar^2}{2 \mu E_{c.m.}} \sum_{l=0}^{l_n} (2l + 1) T_j(E_{c.m.}) \]

\[ T_j(E_{c.m.}) = \int f(B) \frac{1}{N_{tr}} \sum_k \int_{-E_{c.m.}}^{Q_0(k)} \alpha_k(E_{c.m., l, Q}) \times P_{HW}(B, E_{c.m.} + Q, l) dQ dB \]

B: Barrier height, \( f(B) \): Barrier distribution (Gaussian or CCFull), \( P_{HW} \): Hill-Wheeler formula

\( \alpha_k \): k-transfer probability, \( Q_0(k) \): Q-values of k-transfers
LNL Electrostatic Deflector (Legnaro)

Detector set-up and experimental matrix $\Delta E$-ToF

(lowest measurable cross section $\approx 0.5$-$1 \mu b$)
Experimental setup: CIAE Electrostatic Deflector (Beijing, China)

H.Q. Zhang et al.

2010 Chinese Phys. C 34 1628

Fig. 1. The layout of the electrostatic deflector and the MCP+Si detection system.
Time-of-Flight Spectrum and Angular Distributions

130 MeV $^{32}\text{S}^{+6}\text{Zr}$

$\sigma(\theta)$ vs. $\theta_{lab}$ (deg)

BLP

ER

$^{32}\text{S}^{+6}\text{Zr}$
ER Excitation Functions for $^{32,36}\text{S} + ^{90}\text{Zr}$ and $^{32,36}\text{S} + ^{96}\text{Zr}$

High-precision fusion (ER) data from CIAE Beijing (China) or LNL (Italy).
Fusion enhancement below Coulomb Barrier

- Universal Fusion Function (Canto & Gomes)
Coupled Channel Analysis of $^{32}\text{S} + ^{90}\text{Zr}$

$V_B$: 1D-BPM Coulomb Barrier

 includes inelastic channel couplings
Coupled Channel Analysis of $^{32}\text{S}+^{96}\text{Zr}$

--- : includes de multi-neutron channel couplings
FIG. 4. $^{28}\text{Si} + ^{92}\text{Zr}$ fusion excitation function along with the theoretical calculations using CCFULL. The results of exact coupled-channels calculations including various inelastic states of target as well as projectile and two-neutron pickup transfer channel along with the 1-d BPM calculations.

FIG. 5. $^{28}\text{Si} + ^{94}\text{Zr}$ fusion excitation function along with the theoretical calculations using CCFULL. The results of exact coupled-channels calculations including various inelastic states of target as well as projectile and two-neutron pickup transfer channel along with the 1-d BPM calculations.
NTFus Analysis of $^{28}$Si+$^{90}$Zr (Dehli)
NTFus Analysis for $^{28}\text{Si}+^{94}\text{Zr}$ (Dehli)
Fig. 6 (color online) The excitation functions of $^{32}\text{S} + ^{90,96}\text{Zr}$ systems measured at $\theta_{\text{Lab}} = 165.17^\circ$ and $154.83^\circ$, respectively versus the centre-of-mass energies.
Quasi-elastic Barrier Distributions

\[ T = 1 - R \]

\[ D^{\text{qel}}(E) = -\frac{d}{dE}\left[\frac{d\sigma^{\text{qel}}}{d\sigma^R}(E)\right] \]

Fig. Quasi-elastic barrier distributions of \( ^{32}\text{S}+^{90,96}\text{Zr} \) systems
Barrier distributions in agreement with CC including n-Transfer Coupling
$^4,^6\text{He}+^{64}\text{Zn}$ Fusion: Transfer Coupling

Fisichella et al., JP 282 (2011) 012014

$^6\text{He}+^{64}\text{Zn}$

$^4\text{He}+^{64}\text{Zn}$

$^6\text{He}+^{64}\text{Zn}$: $V_0=-110$ MeV, $R_V=4.65$ fm, $a=0.85$ fm, $B=9.0$ MeV

$^4\text{He}+^{64}\text{Zn}$: $V_0=-100$ MeV, $R_V=4.30$ fm, $a=0.85$ fm, $B=9.5$ MeV
Conclusions on Transfer Coupling

- Investigation of the Role of Transfers in Sub-barrier Fusion Reactions
- Fusion and Quasi-elastic data of $^{32}\text{S} + ^{90,96}\text{Zr}$
- Semi-classical model of Zagrebaev used in NTFus code
- Need of Multi-neutron Transfer (with positive Q-values) Coupling for $^{32,36}\text{S} + ^{96}\text{Zr}$ and $^{40}\text{Ca} + ^{96}\text{Zr}$. Same effect for $^6\text{He} + ^{64}\text{Zn}$. 
Notre Dame experiments: E.F. Aguilera et al. Phys. Rev. lett. 107 (2011); Phys. Rev. C 79,021601(R)(2009).
Breakup Coupling in $^6$Li, $^7$Be, $^8$B + $^{58}$Ni

Recent data for $^6$Li, $^7$Be & $^8$B + $^{58}$Ni elastic scattering [Aguilera et al., PRC 79 (2009) 021601(R)] allow an interesting comparison of breakup coupling effects.

Optical model fits already find much larger $\sigma_R$ for $^8$B than for either $^7$Be or $^6$Li, even when “geometric” and “Coulomb” effects are accounted for:

Note that $^8$B $\sigma_R$ is similar to $^6$He $\sigma_R$. Both significantly larger than for other weakly-bound systems.

Figure from Aguilera et al., PRC 79 (2009) 021601(R)
Total Reaction cross sections systematics
J.J. Kolata and E.F. Aguilera, PR C 79 (2009).
ALPHA PARTICLE SYSTEMATICS for $^6$Li and $^6$He induced Reactions

F.A. Souza et al., Nucl. Phys. A 821, 36 (2009).
Exclusive data for $^6\text{Li} + ^{59}\text{Co}$: Breakup Coupling

- CDCC Method: alpha core + x clustering configurations and $^7\text{Be} + p$ ($^7\text{Be}$ inert core)
  Global alpha, d, 3He, 6Li (surrogate of 7Be) optical potentials for cluster folding

- CDCC analysis of $^6\text{Li}, ^7\text{Be}, ^8\text{B} + ^{58}\text{Ni}$ with FRESCO
  $^6\text{Li} = \text{alpha} + d$ ; $^7\text{Li} = \text{alpha} + t$ ; $^7\text{Be} = \text{alpha} + ^3\text{He}$
  $^8\text{B} = ^7\text{Be} + p$ ; $^6\text{He} = \text{alpha} + 2n$ as two-body cluster models

Study of $^6\text{Li} + ^{59}\text{Co}$ as a test case
$^{6}\text{Li} + ^{59}\text{Co}$

\[ \sigma_{\text{mb}}(\text{MeV}) \]

- $\sigma_{\text{F}}$ (TOTAL)
- $^{60}\text{Ni} (\alpha n)$
- $^{63}\text{Cu} (\text{pn})^+$
- $^{63}\text{Zn} (3n)$
- $^{62}\text{Cu} (\text{p2n})$
- $^{64}\text{Cu} (\text{p})^+$
- $^{60}\text{Co} (\alpha \text{pn})$
- $^{62}\text{Zn} (3n) +$
- $^{63}\text{Ni} (2p) +$
- $^{62}\text{Ni} (2\text{pn})$

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C. Beck et al.
PRC 67 (2003) 54602
$^{7}$Li + $^{59}$Co

$\sigma (\text{mb})$

$E_{\text{c.m.}}$ (MeV)

$\sigma_F$ (TOTAL)

$^{64}$Zn (2n)

$^{61}$Ni ($\alpha n$)

$^{64}$Cu (pn) +

$^{60}$Co ($\alpha pn$)

$^{63}$Cu (p2n) +

$^{63}$Zn (3n)

$^{60}$Ni ($\alpha 2n$)

$^{62}$Cu (p3n) +

$^{63}$Ni (2pn) +

$^{62}$Ni ($\alpha$) +

$^{59}$Ni ($\alpha 3n$)

1BPM

C. Beck et al.
PRC 67 (2003) 54602
$^6$Li+$^{59}$Co breakup (2003 status)

$^6$Li breakup (2011 status)
Breakup Influence (CDCC Calculations)

A. Diaz-Torres, C. Beck and J. J. Thompson, Phys. Rev. C 67, 054602 (2003).
$^6\text{Li} + ^{59}\text{Co} @ E_{\text{lab}} = 29.6 \text{ MeV} \quad \text{F.A. Souza et al. EPJ A 44, 181 (2010).}$
Incomplete Fusion vs Breakup

Sequential Breakup cross sections larger than Direct Breakup cross sections
Sequential Breakup vs Direct Breakup

PRELIMINARY ANALYSIS (2011)
C. Beck, N. Keeley and A. Diaz-Torres, Phys. Rev. C 75, 054607(2007).
**CDCC $^6$He+$^{59}$Co: [di-neutron+alpha] cluster model for $^6$He**

![Graph showing the fusion cross section for $^6$He+$^{59}$Co, compared to data and $^4$He+$^{59}$Co](image)

C. Beck, N. Keeley, A. Diaz-Torres, Phys. Rev. C 75, 054605 (2007).
CDCC Calculations for $^6\text{Li} + ^{58}\text{Ni}$

$^6\text{Li} + ^{58}\text{Ni}$, data from Aguilera et al., Phys. Rev. C 79 (2009) 021601(R)

- $E_{\text{lab}} = 9.85$ MeV
- $E_{\text{lab}} = 11.21$ MeV
- $E_{\text{lab}} = 12.13$ MeV
- $E_{\text{lab}} = 13.04$ MeV
- $E_{\text{lab}} = 14.04$ MeV

Blue dashed curve: no coupling
Solid red curve: full CDCC breakup coupling

Additional data (filled circles) from: Nucl. Phys. A206 (1973) 545
CDCC Analysis of $^8\text{B}+^{56}\text{Ni}$ Elastic Scattering

N. Keeley, R.S. McIntosch and C. Beck, Nucl. Phys. A 824, 792c (2010).
CDCC Analysis of $^7$Be + $^{58}$Ni Elastic Scattering

![Graphs showing elastic scattering results at different energies](image-url)
Conclusions on Breakup Coupling

- Measurements (inclusive and exclusive) elastic scattering, fusion, breakup: for $^6\text{Li} + ^{59}\text{Co}$ collisions

- CDCC analysis
  a) exclusive $^6\text{Li} + ^{59}\text{Co}$ data
  b) fusion of $^6\text{He} + ^{59}\text{Co}$ (“neutron halo”)
  c) elastic $^7\text{Be}, ^8\text{B} + ^{58}\text{Ni}$ (“proton halo”)

- FUTURE
  Experimental programme with RIB
    R&D ex.: $^{11}\text{Be}, ^8\text{B} + ^{40}\text{Ar}$ with a TPC act. targ.
    CDCC analysis with Four-Body Model
Active-target time-projection chamber
R&D Notre-Dame/MSU J.J. Kolata et al.
List of “Breakup” Collaborators

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List of “Transfers” Collaborators

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- H.Q. Zhang and H.M. Jia
  
  *China Institute of Atomic Energy, Beijing, China*

  - *Experiment performed at CIAE Beijing by*: H.Q. Zhang, H.M. Jia, C.J. Lin, F. Yang, C.L. Bai, N. Yu, X.X. Xu, X.Z. Zhang, C.L. Zhang and A. Richard

  - *Semi-classical model calculations by*: V. Zagrebaev (JINR Dubna, Russia)
Announcement of a Nuclear Theory School

"MODERN METHODS IN COLLISION THEORY"
Applications in Nuclear Physics and in Few-Body Physics
Organizing committee: C. Beck, M. Dufour, R. Lazauskas, H. Molique

December 5-9, 2011 - Institut Pluridisciplinaire Hubert Curien (IPHC)
Sponsors: IN2P3, IPHC, Université de Strasbourg, Consortium de Physique Théorique de Strasbourg

Dear Colleagues,

We are pleased to announce the First Theory School entitled "MODERN METHODS IN COLLISION THEORY - Applications in Nuclear Physics and in Few-Body physics", which will be held at the "Institut Pluridisciplinaire Hubert Curien" (IPHC) in Strasbourg (France) on December 5-9, 2011.

This School pursues the tradition of the "Nuclear Theory Workshops" organized by the IPHC theory group since 2001. It aims to provide to students doing theoretical or experimental work a solid background in different physical methods that have been quite successful over the last few years.

The specificity of the school is to mix academic lectures with computational/tutorial sessions. Indeed some of the lecturers have agreed to give not only introductory lectures on the physics principles, but also to make some computer codes available to the participants to train on during tutorial sessions. Seminars on open subjects related to these methods are also planned.