Projectile Break-Up *and* Compound Nucleus Decay

with light *n*-poor beams provided by SPES
(*targets different from UC_x*)
A GARFIELD +RCo Letter of Intents

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F. Gulminelli, A. Bonaccorso, M. Bruno, M. D'Agostino, L. Morelli, A. Bracco, L. Bardelli, S. Barlini, M. Bini, A. Brondi, F. Camera, F. Cannata, L. Campajola, S. Carboni, G. Casini, M. Cinausero, M. Degerlier, A. Di Nitto, S. Dogan, N. Gelli, F. Gramegna,G. Guastalla, V. L. Kravchuk, G. La Rana, T. Marchi, R. Moro, A. Olmi, A. Ordine, G. Pasquali, G. Poggi, G. Prete, Ad. Raduta, G. Vannini, E. Vardaci, O. Wieland

SPES 2010 International Workshop - 16^{th} November 2010

Physics Framework & Cases

SPES Beams

Reactions - MCHF Simulations

Conclusion & Perspectives

Reactions involving weakly bound nuclei

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✓ Physical ingredients:

- available energy

  $\longrightarrow$ Coulomb barrier
- initial state separation energy

  $\longrightarrow$ structure effects (cluster, halo $_{(RAD.)}$)
- size of the system, *e.g.* charge state of TARGET

  $\longrightarrow$ nature of the interaction with the TG (Coul/nucl)

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A. Di Pietro, Journ. of Phys.: Conference Series 205 (2010) 012042
F.A. Souza *et al.*, Brazilian Journ. of Phys., vol.35, no.3B, (Sept. 2005)

- coupling to bound states

  no or at most one bound excited state

  coupling to the CONTINUUM, inelastic channel

  (th. & exp.) → enhancement of σ_{FUS} for $E \leq E_{barrier}$
- coupling to Break-Up states

  gs close to particle emission threshold

  BU, BU + Incomplete Fusion, Complete Fusion

  (th. & exp.) → reduction of σ_{CF} for $E \geq E_{barrier}$

  (heavy TG)

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► **(medium) and light TG ?**

Break-Up reactions with radioactive nuclei

short lifetime $\Longleftrightarrow$ small binding energy (peripheral)

A.Bonaccorso, "Reazioni nucleari con fasci radioattivi", 2010 Congress of the Italian Physics Society.

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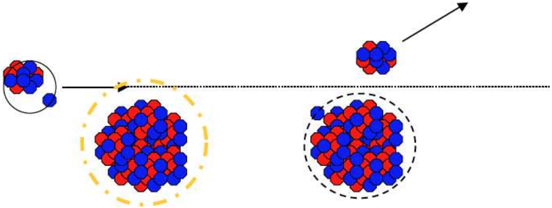

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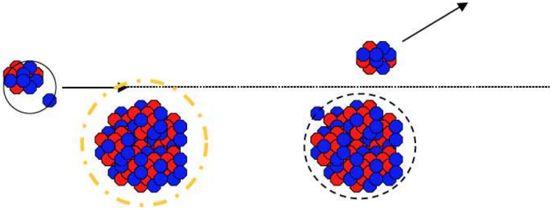
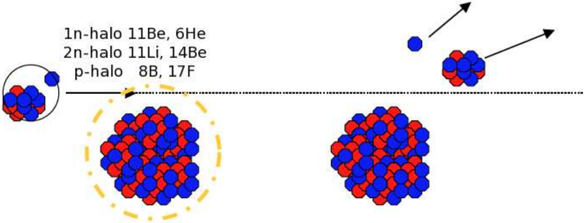


- EXCLUSIVE BU - projectile fragmentation

  coincident measurement of PROJ fragments



Fusion-Evaporation react. with radioactive nuclei

focus on light systems ($A \sim 20$), exclusive measurements (central)
$\longrightarrow$ access to the nuclear level density

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- cluster - structure of some excited states in this mass region
  - $\longrightarrow$ exotic non-statistical decay
  - $\longrightarrow$ α-clustered excited states close to multi-α decay thresholds in all even-even $N = Z$ nuclei
  - $\longrightarrow$ modification of clustering along the isotopic chain (N/Z) for $\mathbf{N}\cdot\alpha$ nuclei (Ne, Mg)

T.Neff, H.Feldmeier, Nucl.Phys. A738 (2004) 357
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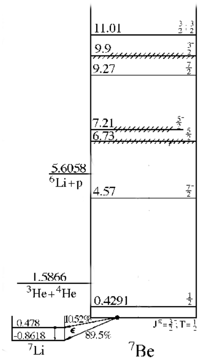
- hot light nuclei, in this A region and excitation energy $\epsilon^* \sim 3\ A.MeV$ are produced in multifragmentation in a wide range of N/Z (excited unstable nuclei)
  understanding of their statistical behaviour
  $\rightarrow$ properties of heavy excited sources at break-up time
  M.D'Agostino et al., CSYM experiment, LNL, February 2010

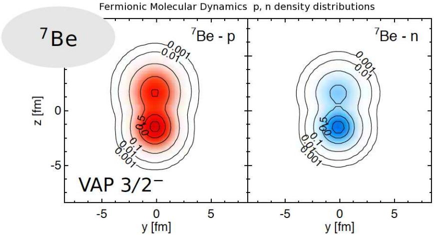
^{7}Be - Features

SPES beam · B_4C target oxides

- *gs* unstable against β^+ decay ($T_{1/2} = 53.22\ d$);
- 1 bound state at $E^* = 429.08\ keV$;
- low α separation threshold: $S_\alpha = 1.587 \leq S_p,\ S_n$;

$\rightarrow$ cluster structure and interaction





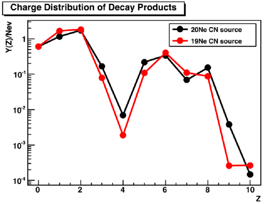
Cluster Break-up
$^7Be^* \rightarrow \alpha + ^3He$
can absorb
an important part of σ_r!

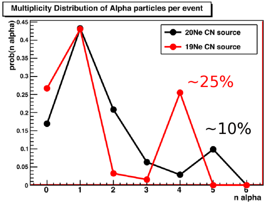
T.Neff, WS "Limits of Existence of Light Nuclei ", ECT^* Trento, October 2010

Reactions · Fusion-evaporation

Reaction	E_{Beam} MeV	θ_{gr} deg	A_{CN}	Z_{CN}	v_{CN} cm/ns	E^*_{CN} A.MeV	σ_{CN} mb
$^7Be + \, ^{12}C$	67.9	4.6	19	10	1.6	3	348
$^7Be + \, ^{13}C$	51.8	6.0	20	10	1.33	3	356

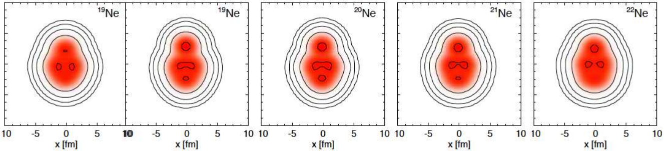
and $^7Be(@60\ MeV) + ^{179}Au$
reference reaction to isolate the contribution of Coulomb BU



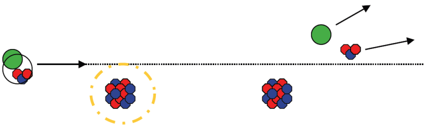


^{19}Ne: ^{3}He, α clustering

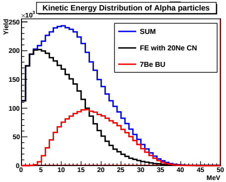
$^{20-22}$Ne: α clustering

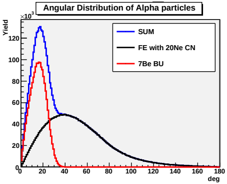


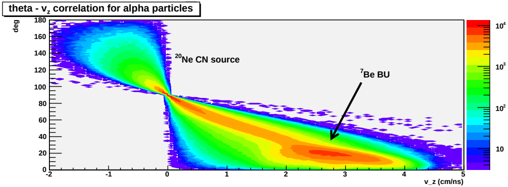
Reactions · Projectile Fragmentation



binary decay of $^7Be^*$ QP source, peripheral collisions:
$\epsilon^* = gauss(\epsilon^*_{med} = 1, \sigma_{\epsilon^*} = 0.5)\ A.MeV,\ v_{QP} = v_{proj} - 1\ cm/ns$







non-physical condition $\sigma_{CN} = \sigma_{BU}$

Experimental Set-Up

GARFIELD (μstrip G.C.-$CsI(Tl)$) +
Ring-Counter (RCo) (I.C.-$Si(nTd)$ $reverse\ mounted$-$CsI(Tl)$)

nearly-4π coverage, now fully equipped with digital electronics

- high granularity and θ-resolution: $\Delta\theta \approx 1^\circ$ for $5^\circ \leq \theta_{RCo} \leq 18^\circ$;
- $\Delta E/E$ of Si-strips and new CsI(Tl) detectors given by 0.3% and 2-3%;
- low E detection thresholds, (RCo) A id. up to $Z = 14$ with digital psa!

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$\longrightarrow$ up to <u>20% efficiency</u> for the detection of Z_{CN}!!

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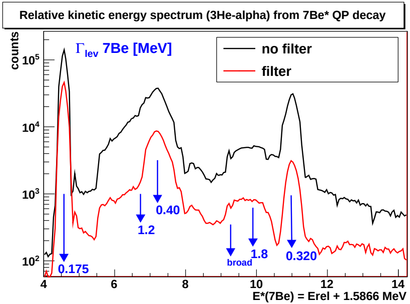
$\longrightarrow$ up to 20% efficiency for the detection of Z_{CN}!!

$\longrightarrow$ up to 22% efficiency for the detection of resonant $(\alpha, {}^3He)$!!



Letter of Intents - Summary

We propose to measure:

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$^7Be + ^{13}C$	51.8	6.0	20	10	1.33	3	356
$^{17}F + ^7Li$	100.0	3.4	24	12	2.4	2.5	417
$^{12}C + ^{12}C$	95	4	24	12	2.0	2.6	430

$+$ reference reactions on ^{179}Au

$E_{beam} = (6 - 10\ A.MeV)$

$i_{beam} \geq 10^7\ pps$

to study:

- the competition of different reaction mechanisms, projectile Break-Up and Fusion-Evaporation
  $\leftarrow$ radioactive (weakly bound) projectiles
- the statistical behaviour of hot light nuclei

feasible with our present set-up GARFIELD+RCo

$\rightarrow$ possible upgrades of the set-up!

$\rightarrow$ **preparatory experiments on the decay of light sistems could be of great help!!**

...thank you for your attention!

Back-slides

^{17}F *lightest particle−stable fluorine isotope*;

- $S_p = 0.6\ MeV$;
- only one bound excited state $(1/2^+)$ at $E^* = 0.5\ MeV\ l = 0$,
  $\rightarrow 5/2^+\ gs$ via γ, large $B(E2) = 66.4\ e^2 fm$;
- good proton halo candidate:
  study of $^{16}O(p,\gamma)$: spatial extension of 5.33 fm for $1/2^+$
  compared to 3.7 fm for $5/2^+\ gs$!
- astrophysical interest: $\sigma_{coul\ BU} \propto \sigma_{(p,\gamma)}$ radiative capture
  $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\alpha,p)^{21}Na$
  explosive nucleosyinthesis in x-ray bursts and novae

$\rightarrow$ increase of σ_{FUS} because of the lowering of the Coulomb barrier (larger radius of the excited state);

$\rightarrow$ BU effects.

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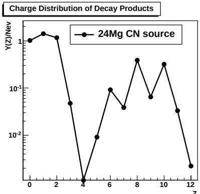
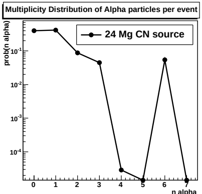
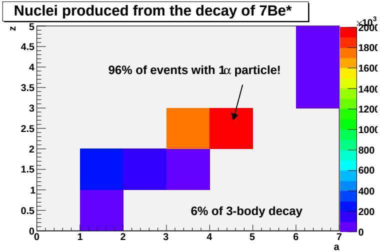
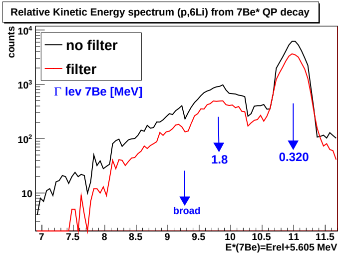




$^7Be^*$ QP Decay

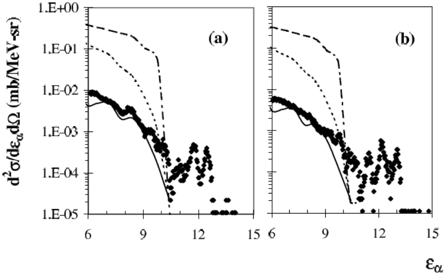




$\sim 60\%$ efficiency for the detection of $(p, ^6Li)$ resonant couples!!

Entrance channel dependence in FE reactions

S.Adhikari *et al.*, Phys.Rev. C74 (2006) 024602



Inclusive α-spectrum measured at 175° from the reaction
$^7Li(@14,16\ MeV) + ^6Li \rightarrow ^{13}C$
symmetric

- deformation effects (RLDM) included in the calculations
  NOT necessary in the case of $n + ^{12}C \rightarrow ^{13}C$
  asymmetric
- shell effects in the level density parameter;

$\rightarrow$ σ_{FUS} NOT suppressed in the above-barrier energy range!

FE/BU with weakly bound

PHYSICAL REVIEW C **74**, 024602 (2006)

Reaction mechanisms with loosely bound nuclei ^{7}Li+^{6}Li at forward angles in the incident energy range 14–20 MeV

S. Adhikari,[1,*] C. Samanta,[1,2] C. Basu,[1] B. J. Roy,[3] S. Ray,[4] A. Srivastava,[3] K. Ramachandran,[3] V. Tripathi,[3] K. Mahata,[3] V. Jha,[3] P. Shukla,[3] S. Rathi,[1] M. Biswas,[1] P. Roy Chowdhury,[1] A. Chatterjee,[3] and S. Kailas[3]
[1]*Nuclear & Atomic Physics Division, Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Kolkata-700064, India*
[2]*Physics department, Virginia Commonwealth University, Richmond, Virginia 23284-2000, USA*
[3]*Nuclear Physics Division, BARC, Mumbai-400085, India*
[4]*Department of Physics, University of Kalyani, Kalyani, West Bengal-741235, India*
(Received 8 March 2006; published 14 August 2006)

Emission of charged particles from the ^{7}Li+^{6}Li reaction at $E(^7\text{Li}) = 14$–20 MeV is studied at forward angles. Analysis of the inclusive spectra are performed in terms of the statistical model for compound nuclear process and Serber model for inclusive breakup reactions. Compound nuclear calculations better reproduce the experimental data in comparison to the projectile breakup calculations even at extreme forward angles and above barrier energies.

"From the model analysis at least it may be concluded that the higher energy emissions are mainly from an equilibrated compound nucleus rather than from a fragmented projectile even at such forward angles. A detailed **exclusive** *measurement is therefore required for a more conclusive picture."*

HF formalism and Level Density

$$\Gamma_i = \frac{1}{\rho_{parent}} \cdot \int_{K_{min}}^{K_{max}} dK$$

$$\left[\sum_{J_d=J_{low}}^{J_{plus}} \sum_{j=|J-J_d|}^{J+J_d} \sum_{l=|j-s_p|}^{l+s_p} \cdot TC_{(A,Z,A_i,Z_i,K,l)} \rho(E^* - Q - K, Jd, A_{res}, Z_{res}) \right.$$

$$\left. + \sum_{[lev]=gs}^{lev_{max}} \sum_{j=|J-J_{d[lev]}|}^{J+J_{d[lev]}} \sum_{l=|j-s_p|}^{l+s_p} (2J_{d[lev]}+1) TC_{(A,Z,A_i,Z_i,K,l)} BW(K, E^* - Q - en_{[lev]}], \Gamma_{[lev]}) \right]$$

Physical ingredients:

- Binding Energies (experimental)
- parametrization of Coulomb Barriers and Transmission Coefficients
- angular momentum (total conservation and changes due to evaporation)
- level density parametrization for the continuum and equivalent convolution of Breit Wigner distributions for the levels in the discrete

  $\longrightarrow$ need of a Match!

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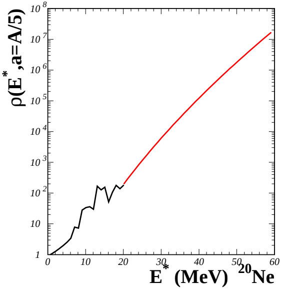


Populations of all the discrete levels are predicted by the code!
...and at the last but one step:

→ can be EXPERIMENTALLY reconstructed via correlation function

^{20}Ne $PACE4$

```
************ Fusion xsection taken from Bass model
Bass fusion xsection for E =  52.0 MeV  is 599.3 mb
Fusion radius =  3.65 fm. Barrier height is   4.25 MeV
Transmission probability for a one-dimens.barrier: Quantum-Mechanical
h_omega (curvature parameter) = 5.0 MeV
```

Starting conditions

	Z	N	A	Spin
Projectile	4	3	7	0.0
Target	6	7	13	0.0
Compound nucleus	10	10	20	

Bombarding energy (MeV)	52.00
Center of mass energy (MeV)	33.80
Compound nucleus excitation energy (MeV)	59.737
Q-value of reaction (MeV)	25.937
Compound nucleus recoil energy (MeV)	18.200
Compound nucleus recoil velocity (cm/ns)	1.326e+00
Compound nucleus velocity/c	4.420e-02
Beam velocity (cm/ns)	3.789e+00
Beam velocity/c	1.263e-01

Experimental fusion cross section (mb)	599
Yrast spin at maximum excitation energy	16
Compound nucleus formation cross section (mb)	356

^{19}Ne *PACE4*

```
************ Fusion xsection taken from Bass model
Bass fusion xsection for E =  68.0 MeV  is 525.6 mb
Fusion radius =  3.55 fm. Barrier height is   4.32 MeV
Transmission probability for a one-dimens.barrier: Quantum-Mechanical
h_omega (curvature parameter) = 5.0 MeV
```

Starting conditions

	Z	N	A	Spin
Projectile	4	3	7	0.0
Target	6	6	12	0.0
Compound nucleus	10	9	19	

Bombarding energy (MeV)	68.00
Center of mass energy (MeV)	42.95
Compound nucleus excitation energy (MeV)	56.966
Q-value of reaction (MeV)	14.019
Compound nucleus recoil energy (MeV)	25.053
Compound nucleus recoil velocity (cm/ns)	1.596e+00
Compound nucleus velocity/c	5.321e-02
Beam velocity (cm/ns)	4.333e+00
Beam velocity/c	1.444e-01

Experimental fusion cross section (mb)	526
Yrast spin at maximum excitation energy	15
Compound nucleus formation cross section (mb)	348

Fermionic Molecular Dynamics · 1

from the presentation of T.Neff,

Workshop "Limits of Existence of Light Nuclei, *ECT** Trento, October 2010

FMD

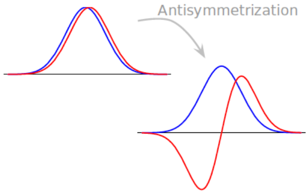
Fermionic Molecular Dynamics

Fermionic

Slater determinant

$$|Q\rangle = \underset{\sim}{\mathcal{A}}\Big(|q_1\rangle \otimes \cdots \otimes |q_A\rangle\Big)$$

- antisymmetrized A-body state



Molecular

single-particle states

$$\langle \mathbf{x}|q\rangle = \sum_i c_i \exp\left\{-\frac{(\mathbf{x}-\mathbf{b}_i)^2}{2a_i}\right\} \otimes |\chi^{\uparrow}_i, \chi^{\downarrow}_i\rangle \otimes |\xi\rangle$$

- Gaussian wave-packets in phase-space (complex parameter $\mathbf{b}_i$ encodes mean position and mean momentum), spin is free, isospin is fixed
- width a_i is an independent variational parameter for each wave packet
- use one or two wave packets for each single particle state

Feldmeier, Schnack, Rev. Mod. Phys. **72** (2000) 655

Neff, Feldmeier, Nucl. Phys. **A738** (2004) 357

Fermionic Molecular Dynamics · 2

FMD

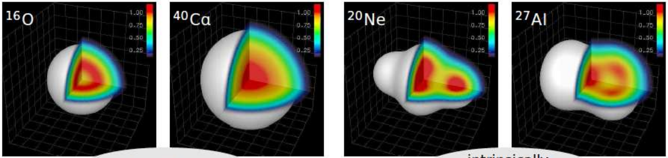
Mean-Field Calculations

Minimization

- minimize Hamiltonian expectation value with respect to all single-particle parameters q_k

$$\min_{\{q_k\}} \frac{\langle Q | \underset{\sim}{H} - \underset{\sim}{T}_{cm} | Q \rangle}{\langle Q | Q \rangle}$$

- this is a Hartree-Fock calculation in our particular single-particle basis
- the mean-field may break the symmetries of the Hamiltonian



spherical nuclei

intrinsically deformed nuclei

Thomas Neff — ECT. 10/25.

Thermodynamics of **light** systems

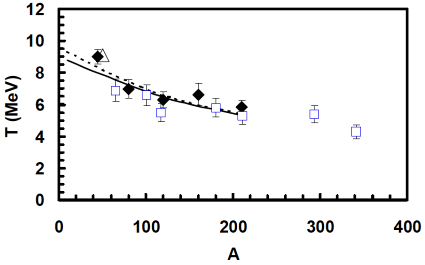


Figure: Limiting Temperatures vs Mass. Limiting temperatures derived from double isotope yield ratio measurements are represented by solid diamonds. Temperatures derived from thermal bremsstrahlung measurements are represented by open squares. Lines represent limiting temperatures are calculated using interactions proposed by Gogny (dashed) and Furnstahl.

J. B. Natowitz *et al.*, Phys.Rev.Lett. 89 (2002) 212701