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Study of the Dynamical Dipole Resonance Mode with the SPES Radioactive Beams

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Study of the Dynamical Dipole Resonance mode with the SPES radioactive beams

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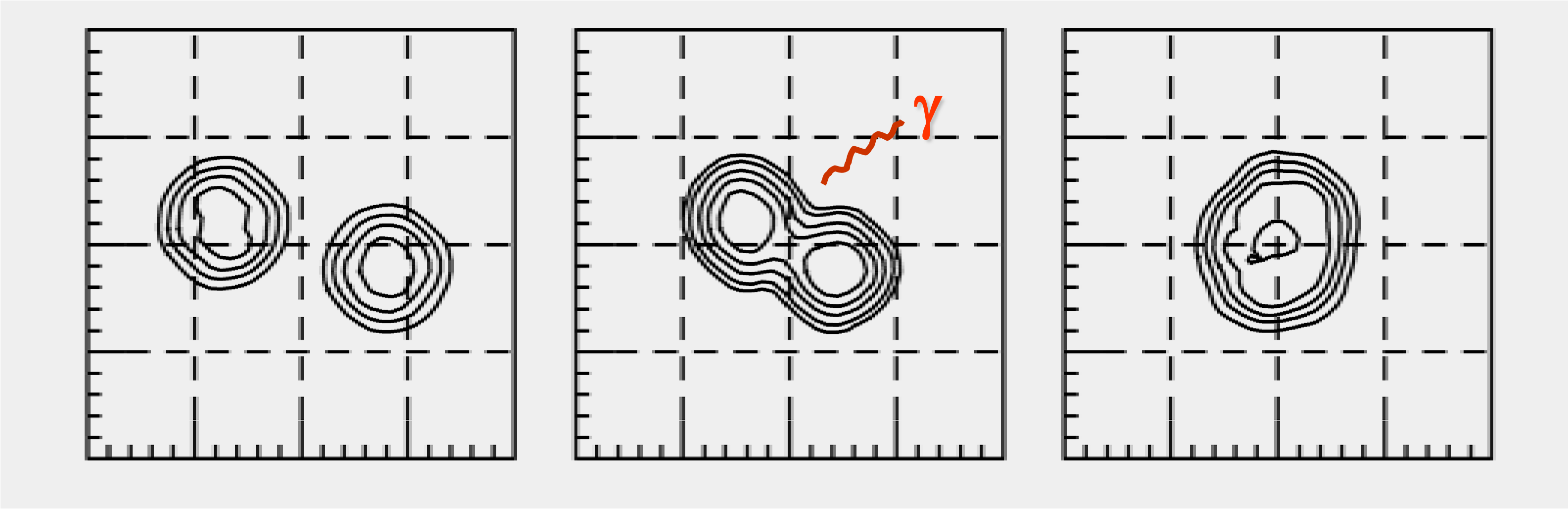
Dynamical Dipole: the physical problem

Dynamical Dipole: a collective dipole oscillation along the symmetry axis of the dinuclear system in charge asymmetric heavy-ion reactions

Prompt dipole γ-ray emission

- $E_{dd} < E_{GDR,stat}$
- anisotropy



$$D_0 = \frac{Z_1 Z_2}{A}\left(\frac{N_1}{Z_1} - \frac{N_2}{Z_2}\right)(R_1 + R_2)$$

Initial Dipole Moment

D(t) : prompt dipole radiation

CN: stat. GDR

Dynamical Dipole: the physical problem

The intensity of the prompt γ radiation depends on the:

✓Initial dipole moment

✓Reaction dynamics (centrality, mass asymmetry, E_{lab})

✓Symmetry term below saturation that is acting as a restoring force: informations on the density dependence of the nuclear matter EOS at $\rho < \rho_0$

The dynamical dipole mode could be a new cooling mechanism of the dinuclear system in fusion reactions

→ superheavy elements

Dynamical Dipole in fusion reactions: model independent observation

Experimental method:

Comparison of the energy spectra and the angular distributions of the γ-rays emitted in two reactions with different charge asymmetry that populate the same CN with identical excitation energy and identical spin distribution

Evidence of the dynamical dipole mode:

1) Extra yield γ (prompt dipole radiation) for the charge asymmetric system at $E<E_{GDR}$

2) anisotropic γ-ray excess angular distribution

DD: incident energy dependence in fusion reactions

Compound Nucleus ⇒ ^{132}Ce

E_{lab} ~ 6 MeV/nucleon	E_{lab} ~ 9 MeV/nucleon	E_{lab} ~ 16 MeV/nucleon
$E^* = 117$ MeV, $L_{fus} \sim 83\hbar$	$E^* = 174$ MeV, $L_{fus} \sim 83\hbar$	$E^* = 284$ MeV, $L_{fus} \sim 83\hbar$
$^{32}S + {}^{100}Mo$ D(t = 0) = 18.2 fm	$^{32}S + {}^{100}Mo$ D(t = 0) = 18.2 fm	$^{36}Ar + {}^{96}Zr$ D(t = 0) = 20.6 fm
$^{36}S + {}^{96}Mo$ D(t = 0) = 1.7 fm	$^{36}S + {}^{96}Mo$ D(t = 0) = 1.7 fm	$^{40}Ar + {}^{92}Zr$ D(t = 0) = 4.0 fm
(LNL, SERPE)	(LNL, SERPE)	(LNS, MEDEA)

Experimental technique

γ-ray and charged particles in coincidence with evaporation residues

evaporation residues in singles (γ-ray e particle multiplicity)

First systematic study of the dynamical dipole in fusion reactions
Saturated CN spin: identical spin distribution
Experimental evaluation of the effective E^* and A of the CN
Absence of normalization factors in the γ-ray and particle spectra
γ–ray angular distributions

EPJA 17 (2003) 71, PRC 71 (2005) 054605, PLB 664 (2008) 47, PRC 80 (2009) 024612

SERPE at LNL

high energy γ-rays :

6 clusters of 7 BaF_2 d=28 cm $\Delta\Omega$=1.6 sr

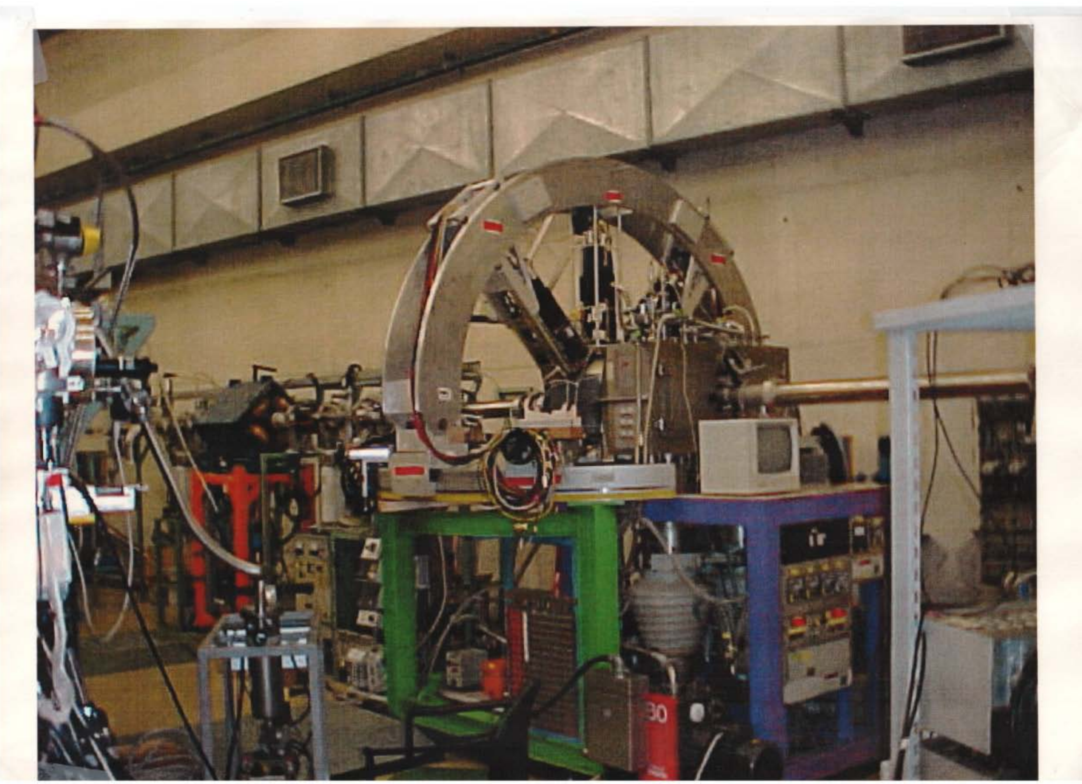
reaction products:

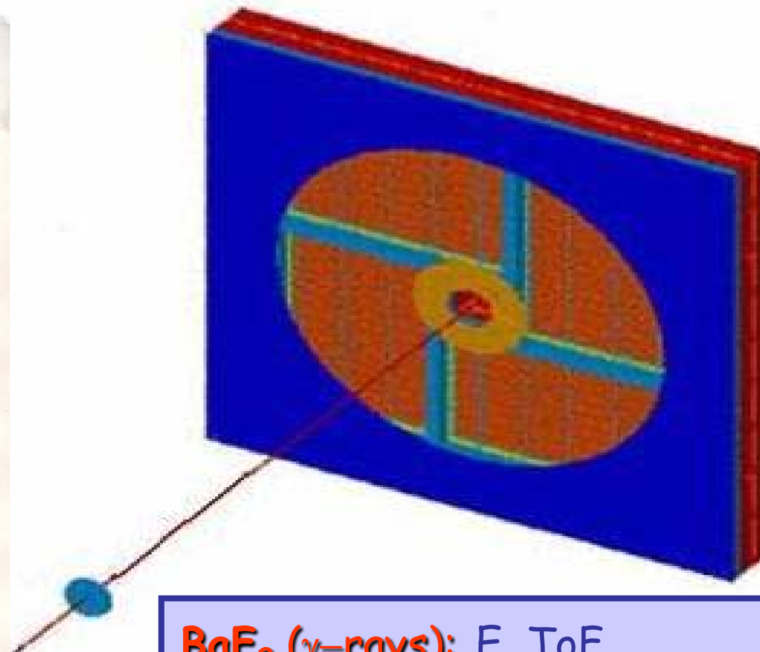
4 position sensitive PPAC at θ= 7°, d=70 cm $\Delta\Omega$=0.089 sr (fusion-evaporation)

4 position sensitive PPAC at θ= 50°, d=15 cm $\Delta\Omega$=0.16 sr (fission)

4 two-stage telescopes at d=7.8 cm $\Delta\Omega$=0.1 sr (peripheral collisions)

12 three-stage telescopes at θ= 11-37° d=35 cm $\Delta\Omega$= 0.144 sr (periph. collisions)





BaF_2 (γ–rays): E, ToF

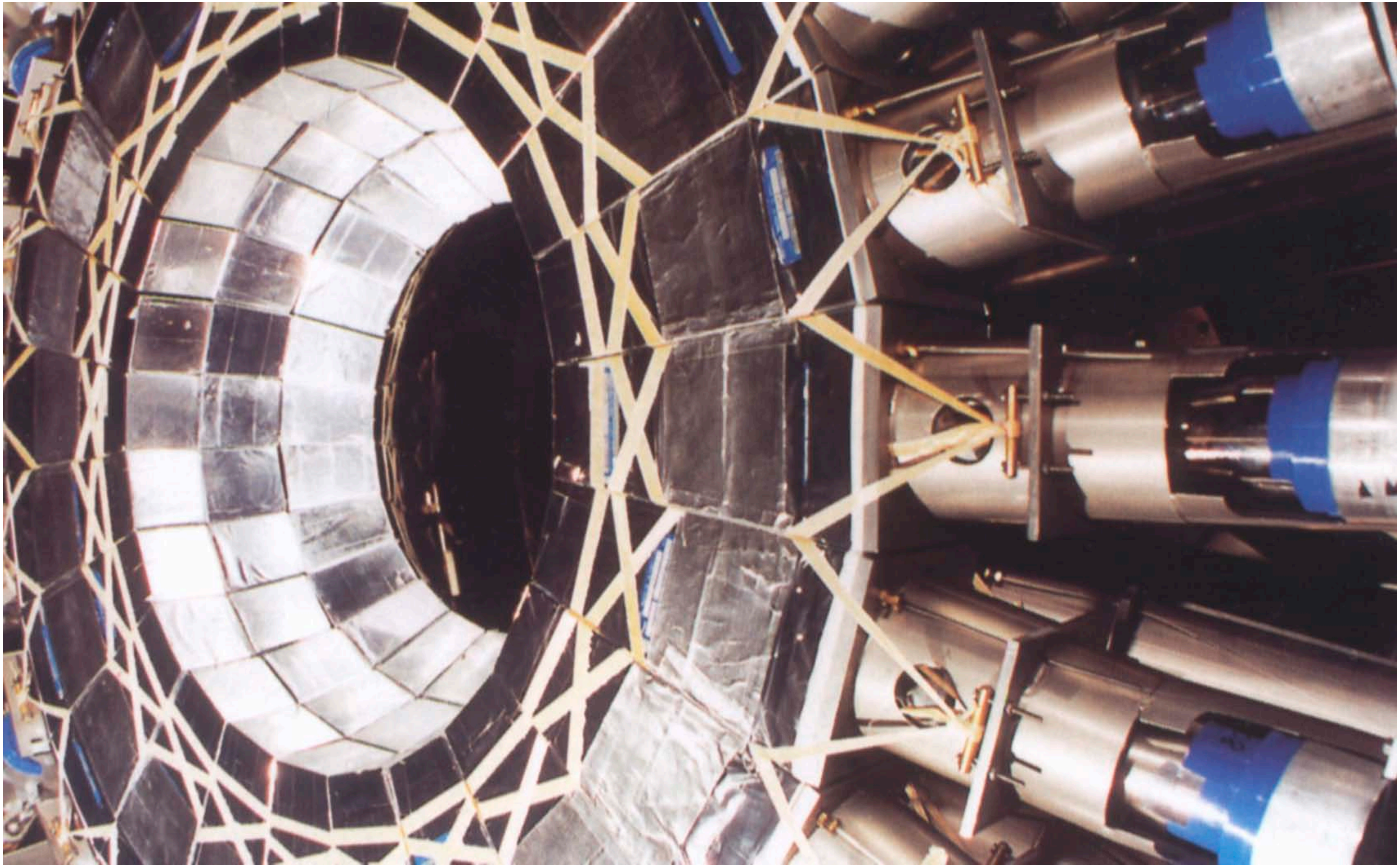
PPAC (reaction products):

ΔE,ToF

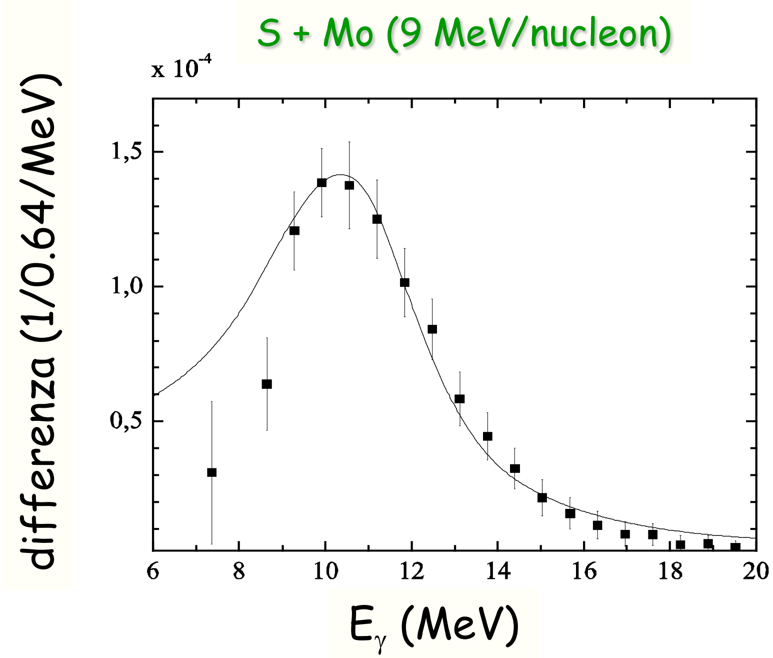
MEDEA (LNS)

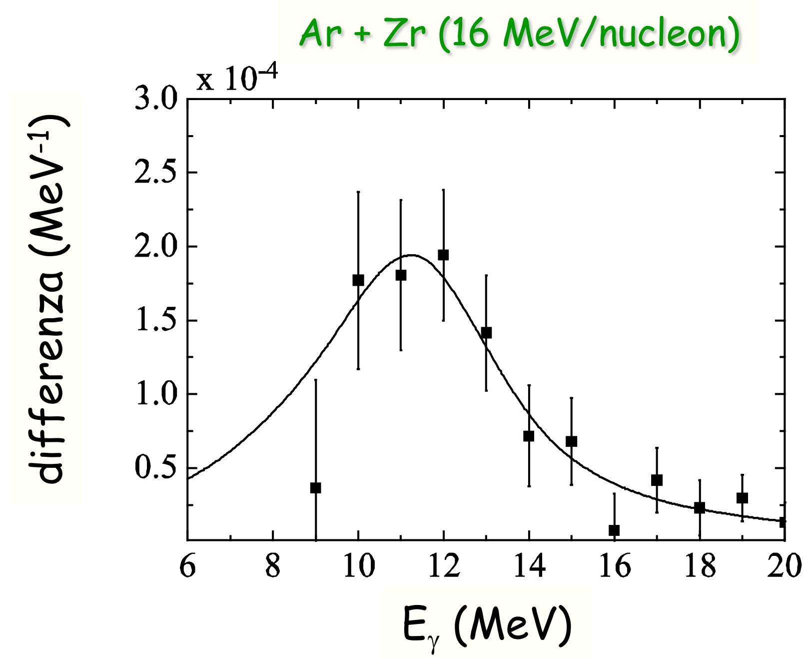
γ–rays, particles with Z=1,2 (E, ToF)

180 BaF_2 d=22 cm $\Delta\Omega$=3.7 π sr



^{132}Ce : $^{32,36}S+^{100,96}Mo$ 9 MeV/nucleon
$^{36,40}Ar+^{96,92}Zr$ at 16 MeV/nucleon





E_{dd}= (11.4 ± 0.3) MeV

Γ_{dd} = (3.0 ± 0.5) MeV

E_{dd}= (12.0 ± 0.6) MeV

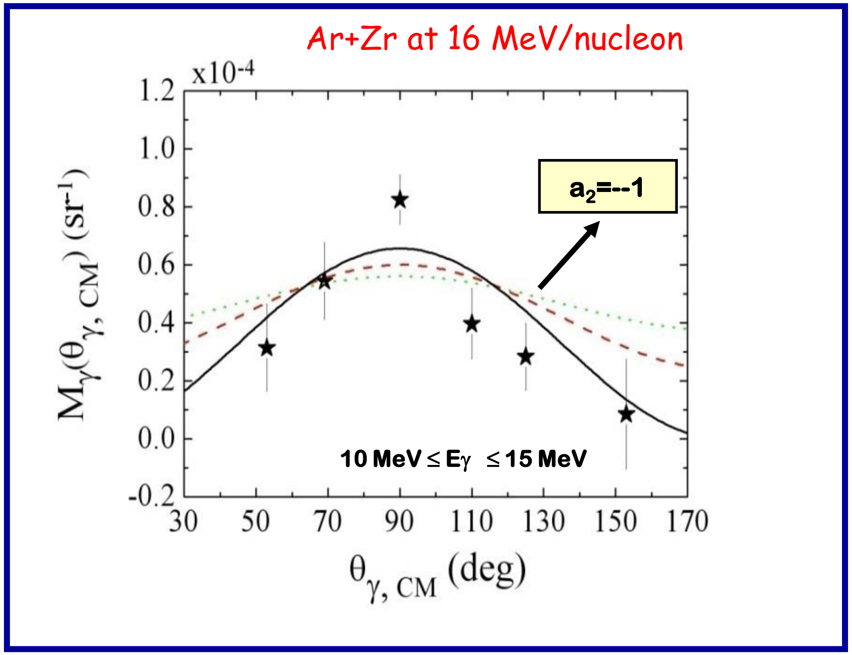
Γ_{dd}= (3.7 ± 1.4) MeV

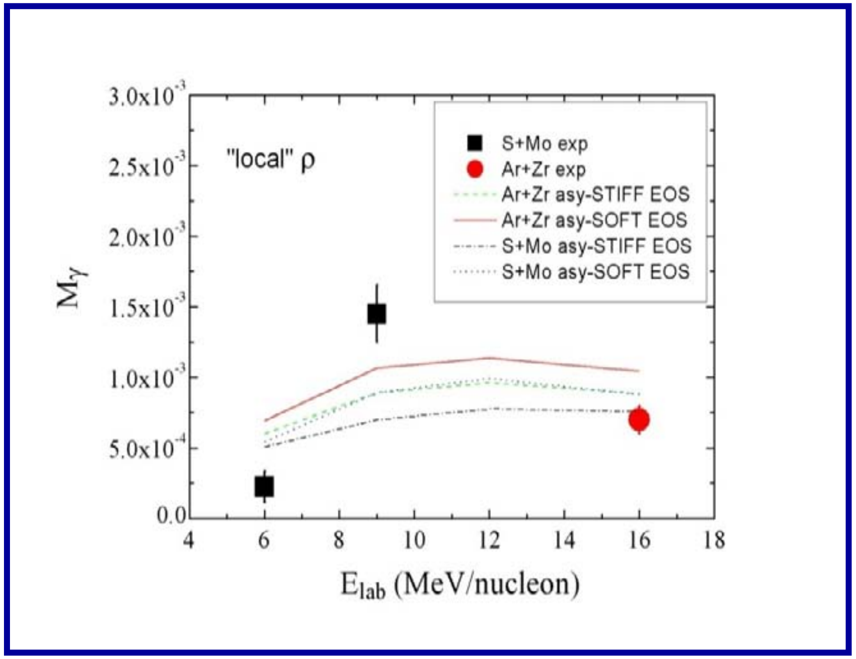
E_{dd}<E_{GDR}=14 MeV → large deformation of the emitting source

Edd, Γ_{dd}: independent of incident energy within errors

EPJA 17 (2003) 71, PRC 71 (2005) 054605, PLB 664 (2008) 47, PRC 80 (2009) 024612

^{132}Ce : $^{32,36}S+^{100,96}Mo$ at 6 and 9 MeV/nucleon
$^{36,40}Ar+^{96,92}Zr$ at 16 MeV/nucleon





Large anisotropy of the γ-rays excess angular distribution around 90° with respect to the beam direction compatible with a dipole oscillation along the beam axis

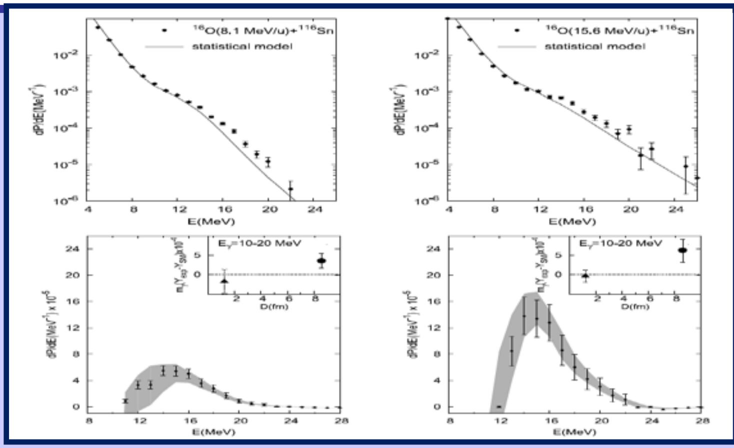
The DD yield shows a pronounced maximum at E_{lab}~ 9 MeV/nucleon while the BNV calculations done with in medium NN cross sections and a "local" density display a smoother behaviour with E_{lab}

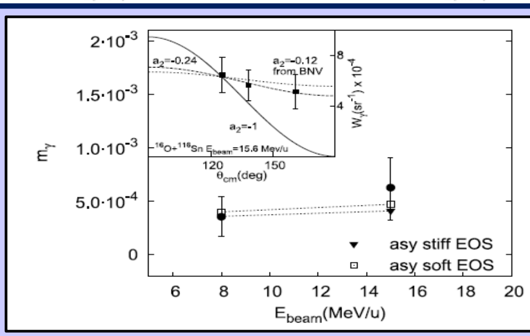
EPJA 17 (2003) 71, PRC 71 (2005) 054605, PLB 664 (2008) 47, PRC 80 (2009) 024612

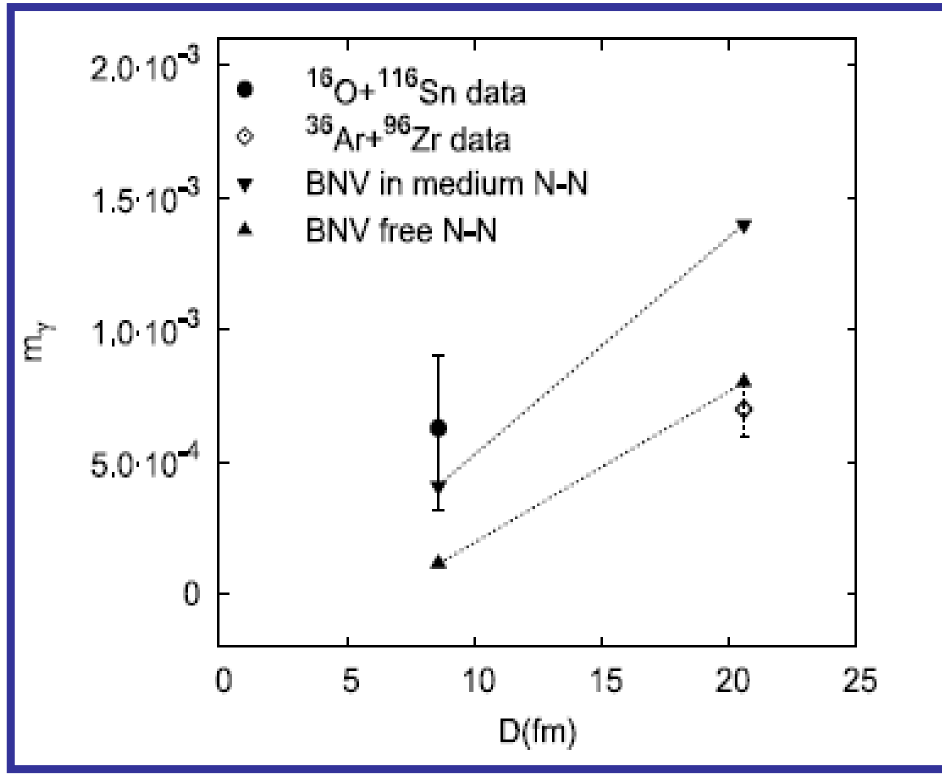
^{132}Ce : $^{16}O + ^{112}Sn$ at 8 and 16 MeV/nucleon

A. Corsi et al., PLB 679 (2009) 197

Different method: The dynamical dipole yield was obtained by subtraction of the statistical γ yield (calculated with CASCADE at a CN E^* deduced from the charged particle energy spectra) from the $^{16}O + ^{112}Sn$ experimental γ yield $E_{dd} = E_{GDR} = 14$ MeV $\Gamma_{dd} = 5\text{-}6$ MeV







1)The DD centroid obtained experimentally is larger than that expected from BNV calculations: difficulty in extracting the DD yield below a stiff exponential. Slightly anisotropic ang. distribution
1)DD yield reproduced well by BNV calculations using in medium NN cross sections
3) Rather flat dependence of the DD yield on the initial dipole moment. No possibility to reproduce simultaneously both data obtained at 16 MeV/nucleon by using the same NN cross sections

Dynamical dipole
in
Peripheral Reactions

Prompt dipole γ-ray emission in peripheral heavy-ion collisions: $^{32}S+^{58,64}Ni$ at 10 MeV/nucleon

$^{32}S + ^{64}Ni$
E_{lab} = 288 MeV
D(t = 0) = 11.46 fm

$^{32}S + ^{58}Ni$
E_{lab} = 320 MeV
D(t = 0) = 3 fm

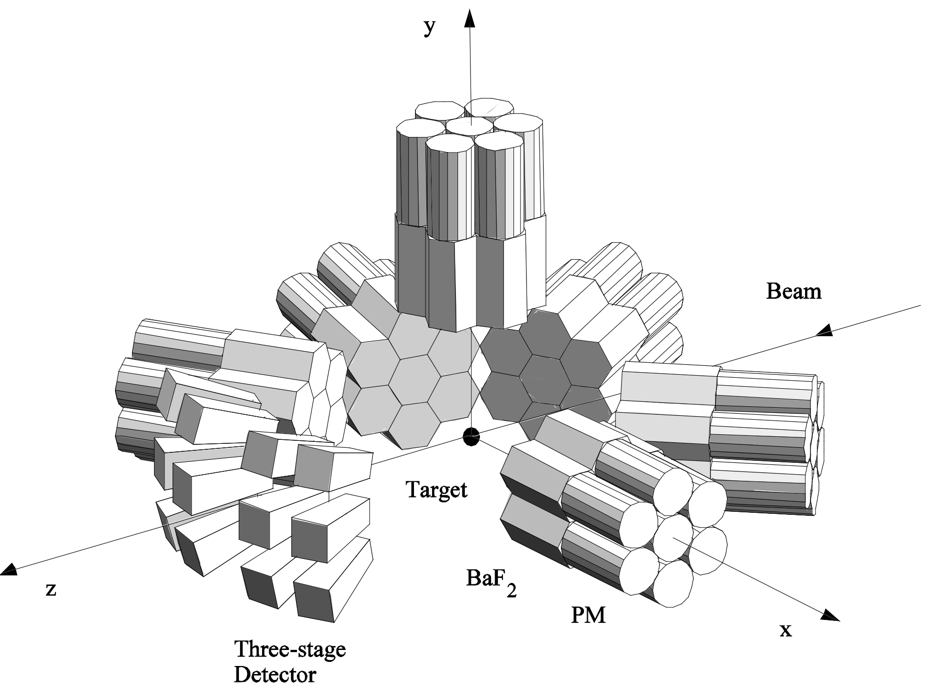


Fig. 1

Detection of γ-rays in coincidence with complex fragments

γ - ray detectors

8 clusters of 7 BaF_2

d = 28 cm $\Delta\Omega_{tot}$ = 2.14 sr

Complex fragment detectors

12 three-stage detectors (ionization chamber, Si detector, CsI(Tl) scintillator)

θ = 11° - 37°

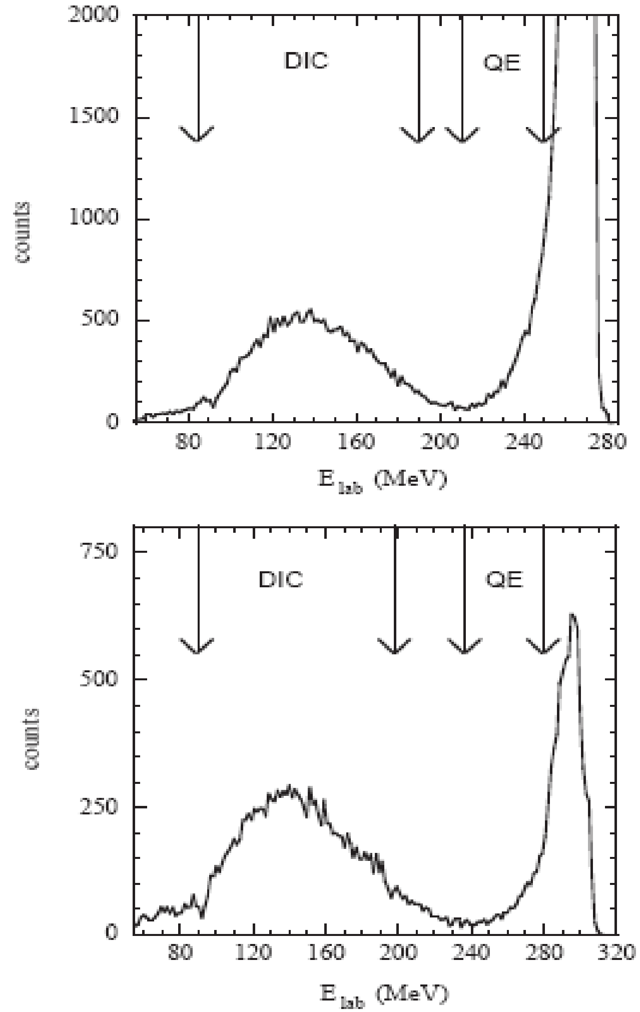
d = 35 cm $\Delta\Omega_{tot}$ = 0.144 sr

D. P. et al., EPJA 16 (2003) 423

Prompt dipole γ-ray emission in peripheral heavy-ion collisions: : $^{32}S+^{58,64}Ni$

θ_{lab}=19°, Z=16

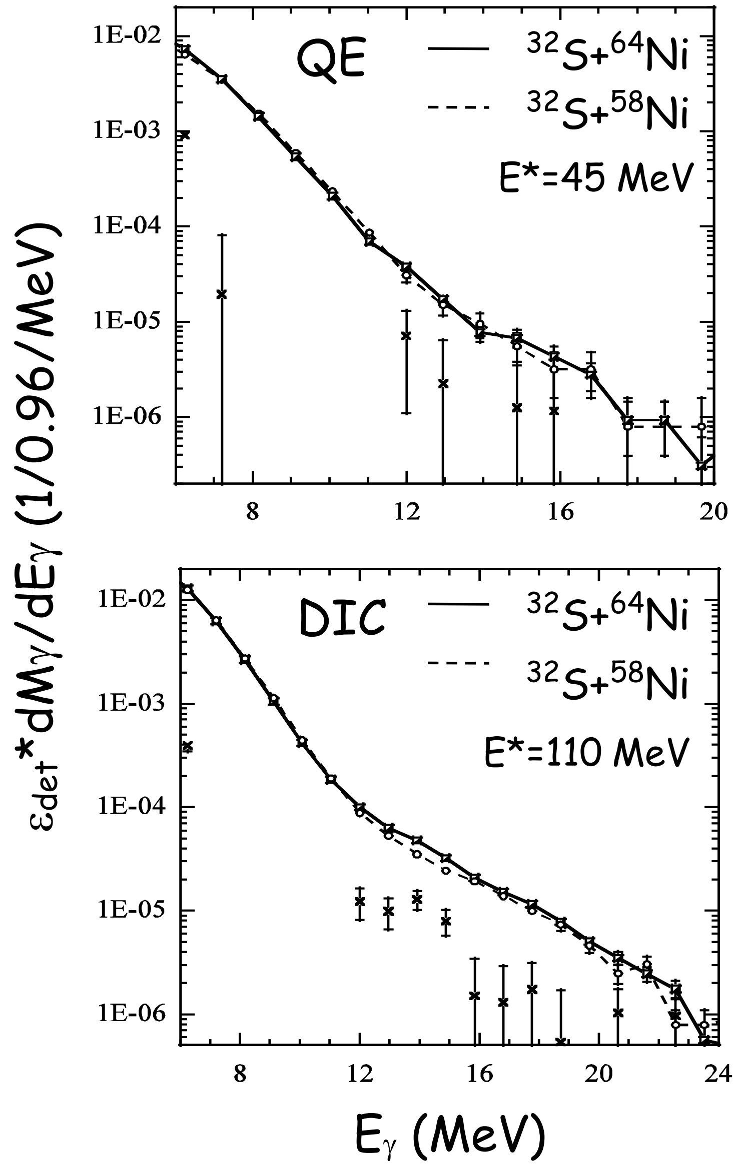
$^{32}S + ^{64}Ni$



$^{32}S + ^{58}Ni$

Fig. 1. Laboratory kinetic energy spectrum of the $Z = 16$ secondary fragments emitted at $\theta = 19°$ for the $^{32}S + ^{64}Ni$ (upper panel) and the $^{32}S + ^{58}Ni$ (lower panel) reaction. The arrows on the left hand side of the figure delimit deep-inelastic events, while those on the right hand side quasi-elastic events.

Prompt dipole γ-ray emission in peripheral heavy-ion collisions: : $^{32}S+^{58,64}Ni$

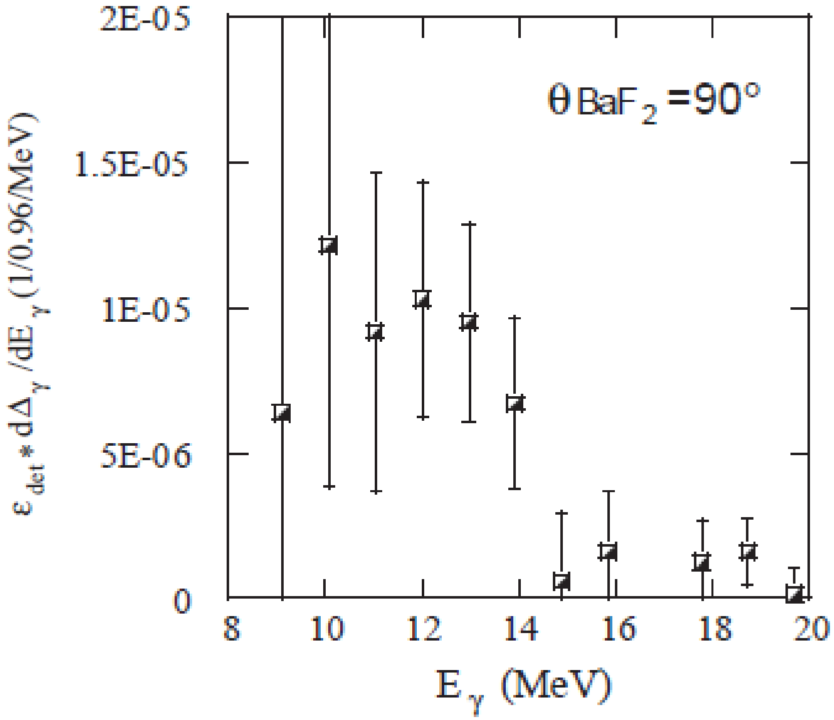


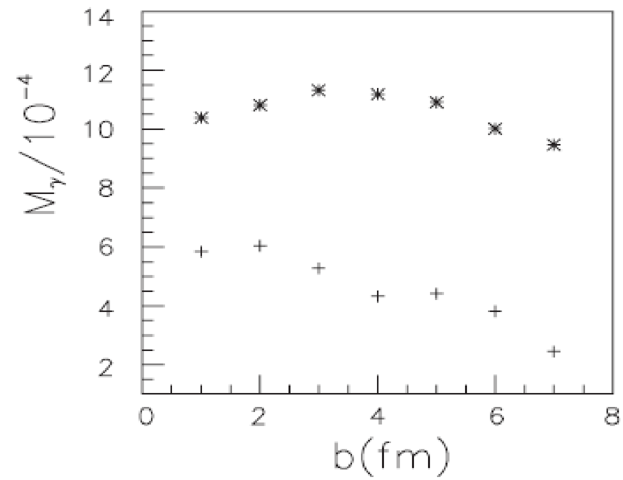
For fast quasi – elastic events the γ-ray multiplicity is identical for both reactions within the experimental uncertainties over the whole energy range: no prompt dipole radiation

For deep inelastic events the γ–ray multiplicity increases for the more N/Z asymmetric system in the composite system GDR energy range.

D. P. et al., EPJA 16 (2003) 423

Good agreement between theory and BNV calculations experiment: $^{32}S+^{58,64}Ni$ system





$M_{\gamma,\,exp} \sim 3.10^{-4}\gamma \;\; (\theta=90^{\circ})$

The DD mode develops in peripheral collisions with a yield that inreases with centrality in agreement with BNV calculations.

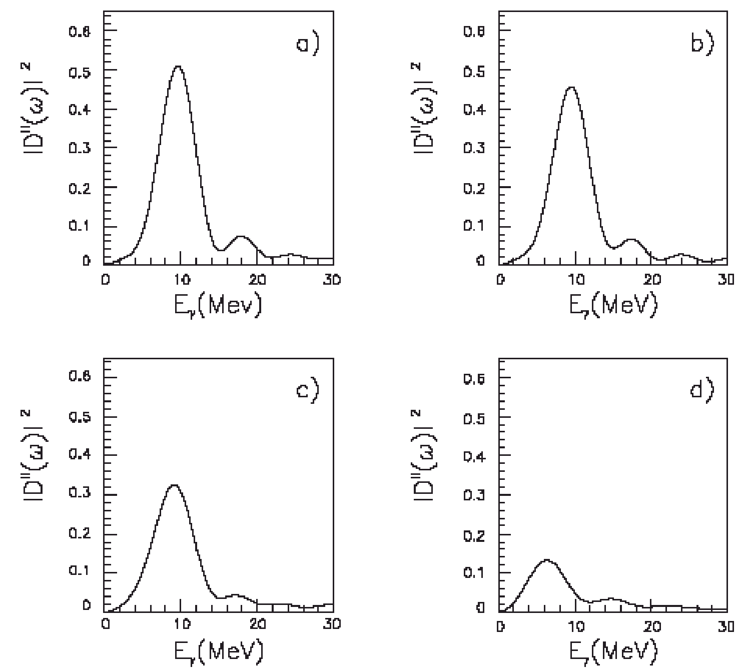


Fig. 10. System $^{32}S + ^{64}Ni$ at 10 A MeV. Power spectrum $|D''(\omega)|^2$ (in c^2 units): a) impact parameter $b = 1$ fm; b) $b = 3$ fm (fusion dominance, see text); c) $b = 5$ fm; d) $b = 7$ fm (deep-inelastic dominance).

Prompt dipole γ-ray emission in peripheral heavy-ion collisions: other works

The prompt dipole radiation was observed in peripheral reactions from a highly deformed composite system also in other works:

L. Campajola et al., Zeit. für Phys. 352 (1995) 421, M. Sandoli, Z. Phys. A357 (1997) 67 and EPJA6 (1999) 275,

M.Papa et al., PRC 68 (2003) 034606 and PRC 72 (2005) 064608, F. Amorini et al., PRC 69 (2004) 014608 ($^{40}Ca+^{48}Ca$ and $^{40}Ca+^{46}Ti$ at 25 MeV/nucleon)

Dynamical dipole
in
Heavier Composite Systems

Dynamical Dipole: cooling in fusion reactions

As a fast cooling mechanism of the composite system the prompt dipole radiation could be used to favour the super heavy element formation through hot fusion reactions

Cold fusion reactions → larger CN survival probability

Hot fusion reactions → larger CN formation probability

V. Baran *et al.*, PRL 87(2001) 182501
C. Simenel *et al.*, PRC 76(2007) 024609

Does the dynamical dipole yield decrease with increasing the mass of the reaction partners as TDHF calculations predict???

C. Simenel *et al.*, PRL 86(2001) 2971

Interesting: to investigate the existence of the dynamical dipole mode in heavier composite systems

Dynamical Dipole in ^{192}Pb at Elab ~ 11 MeV/nucleon

Existence of the dynamical dipole mode in heavier compound nuclei: simultaneous investigation in fusion-evaporation and fission events (experiment performed at LNS)

$^{40}Ca + {}^{152}Sm$	$^{48}Ca + {}^{144}Sm$
E_{lab} = 440 MeV	E_{lab} = 485 MeV
$D(t=0) = 30.6\ fm$	$D(t=0) = 5\ fm$
$\Delta = 0.22$	$\Delta = 0.18$

^{192}Pb E*=236 MeV

$$L_{fus} = 74\hbar$$

$$L_{fus,evap} = 36\hbar$$

$$B_f(l=0) = 10.4\ MeV$$

σ_{Bass} = 1804 mb
$\sigma_{fusion-fission}$ = 251 mb
$\sigma_{fusion-evap}$ = 77 mb

σ_{Bass} = 1966 mb
$\sigma_{fusion-fission}$ = 213 mb
$\sigma_{fusion-evap}$ = 64 mb

PACE 2 calculations

Dynamical Dipole in ^{192}P: Observables

Evaporation events

Detection of evaporation residues in singles and in coincidence with γ-rays (charged particles)

γ-ray multiplicity spectra

γ-ray angular distribution with respect to the beam axis

Fission events

Detection of the two fission fragments in singles and in coincidence with γ-rays (charged particles)

γ-ray multiplicity spectra

γ-ray-fragment angular correlation with respect to the spin axis

fragment mass and TKE distribution

Experimental set up

γ-ray and charged particle detectors

MEDEA : 180 BaF_2 (48 at θ=90°), d=22 cm ($\Delta\Omega$= 3.37π sr)

Evaporation residue detectors

4 position sensitive PPAC's symmetrically around the beam

θ=7° ± 3.75° at d=70 cm from the target ($\Delta\Omega_{total}$= 0.089 sr)

Fission fragment detectors

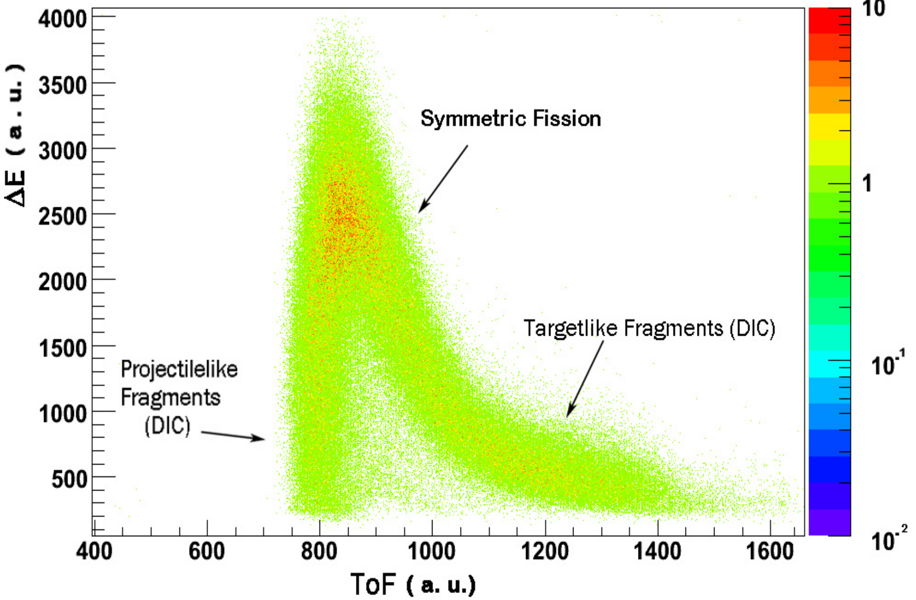
4 position sensitive PPAC's symmetrically around the beam
θ = 50° ± 11° ($\Delta\phi$=22°) at d=15 cm from the target ($\Delta\Omega_{PPAC}$= 0.16 sr)

They define a plane perpendicular and a plane collinear to the 90° BaF_2 detectors

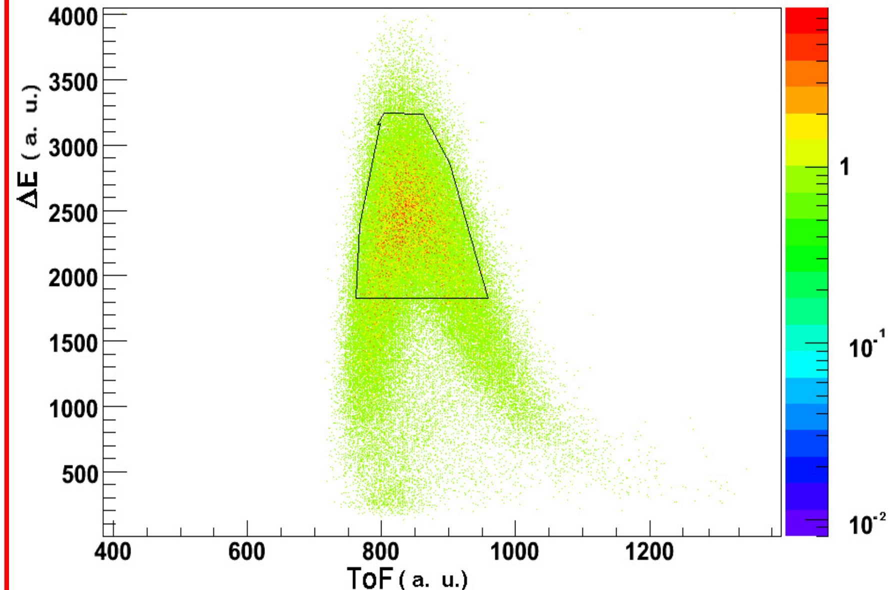
γ-ray-fragment angular correlations at θ=0° and 90° with respect to the spin axis

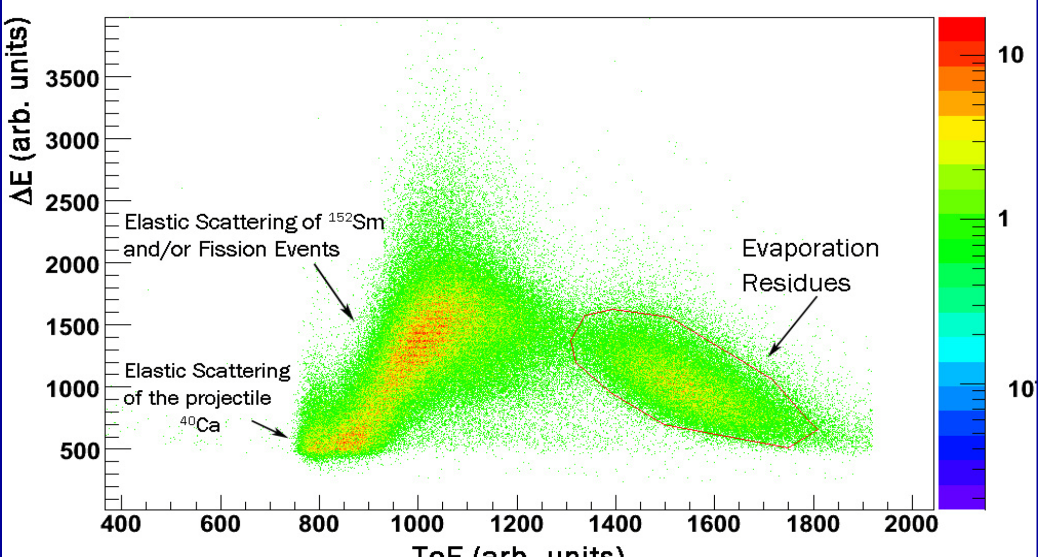
Reaction Products

Fission



Fission Coincidences between PPACs





Fusion – evaporation

$^{40,48}Ca$ + $^{152,144}Sm$ reactions at E_{lab}= 11 MeV/nucleon

Preliminary results by analyzing a part of the collected statistics for BaF_2 situated at $\theta = 82^\circ, 97^\circ, 112^\circ$

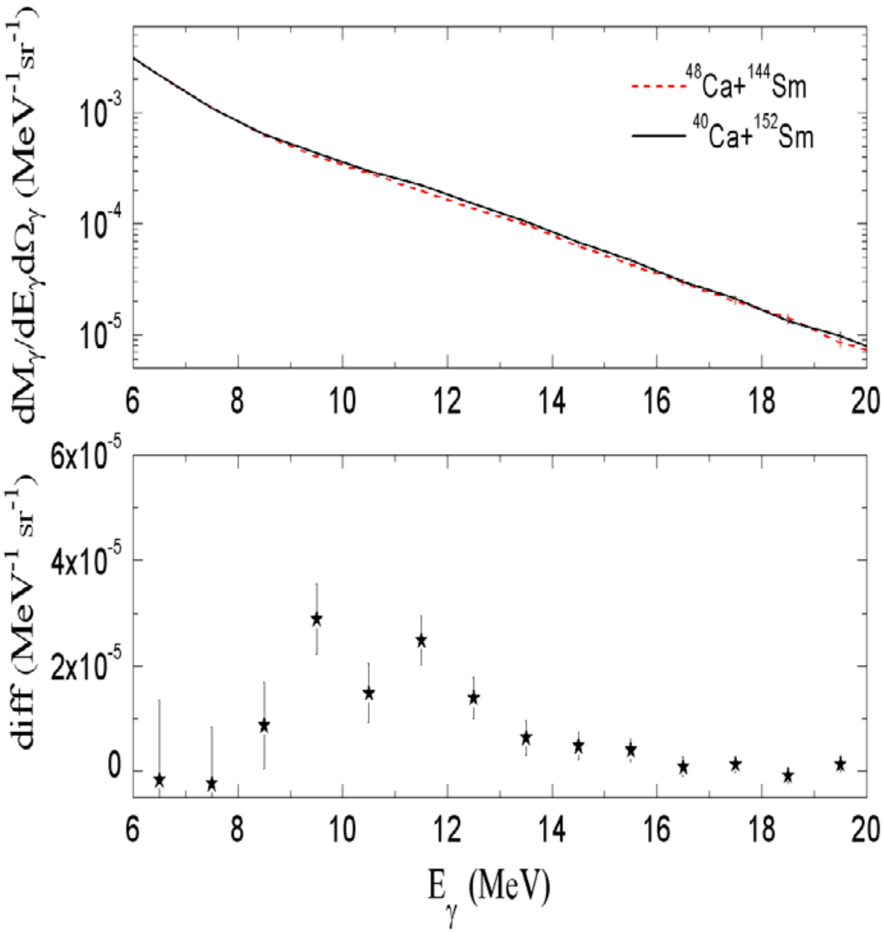
Evaporation and fission γ spectra at θ_γ=90° and 112°

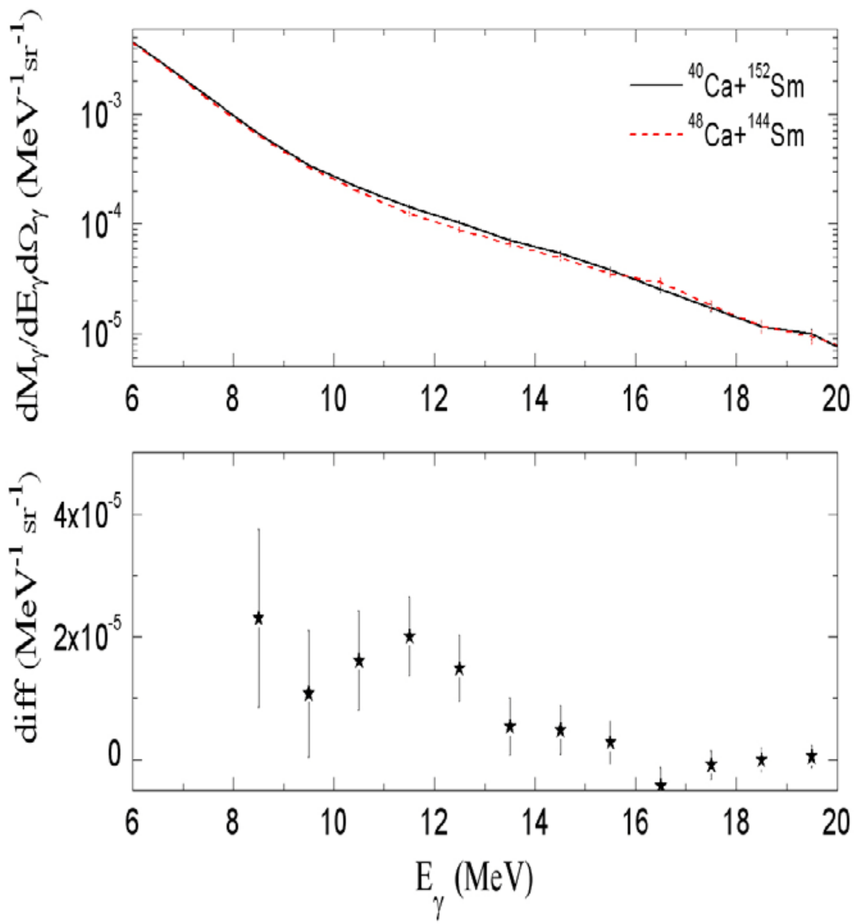
Fusion-evaporation

$M_\gamma(\theta_\gamma)$ =(1.3 ± 0.2) 10^{-4} γ/ sr

Fission

$M_\gamma(\theta_\gamma)$ =(1.2 ± 0.3) 10^{-4} γ/ sr

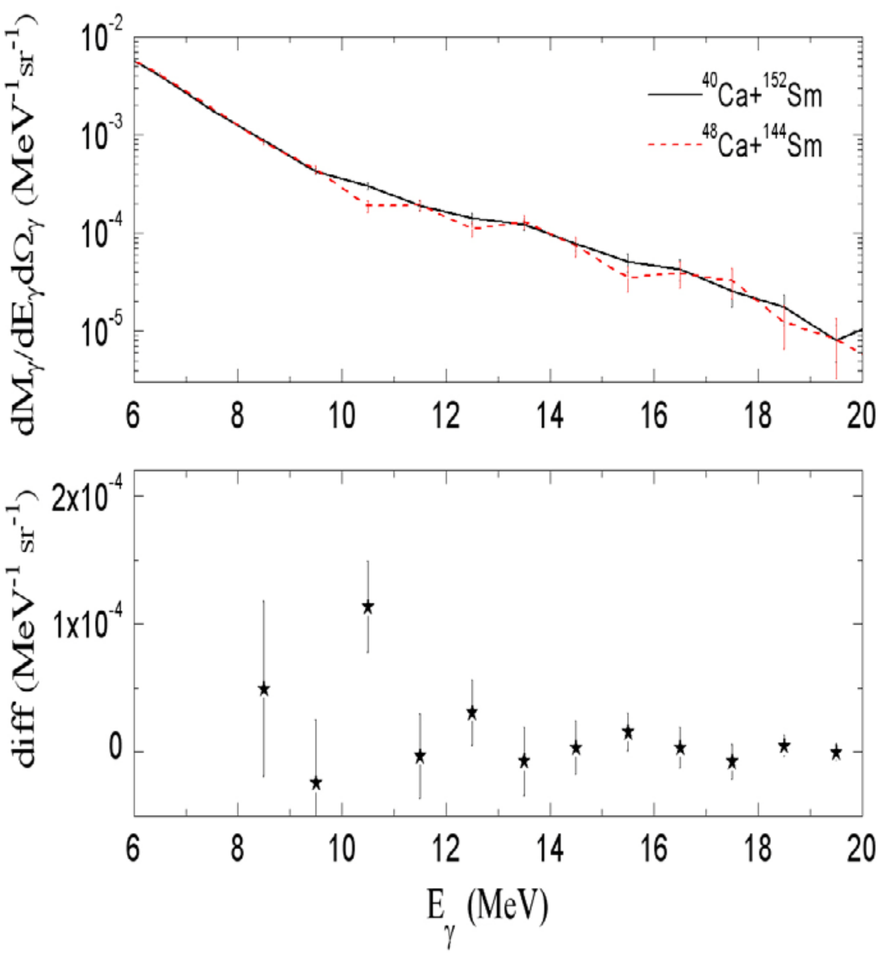


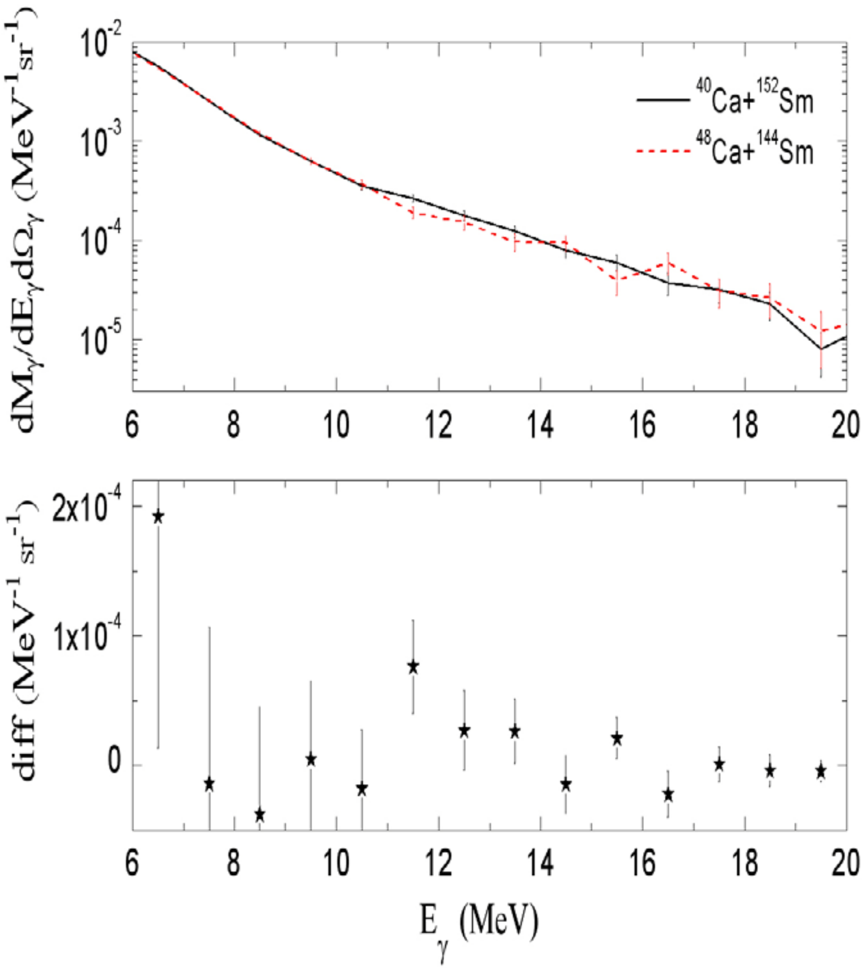


Fission γ–ray spectra: θ_{spin}=0° and 90°

At θ_{spin}=0° the DD yield should be maximum:
$M_\gamma(\theta_{spin})$ = (2.3± 1.3) 10^{-4} γ/ sr

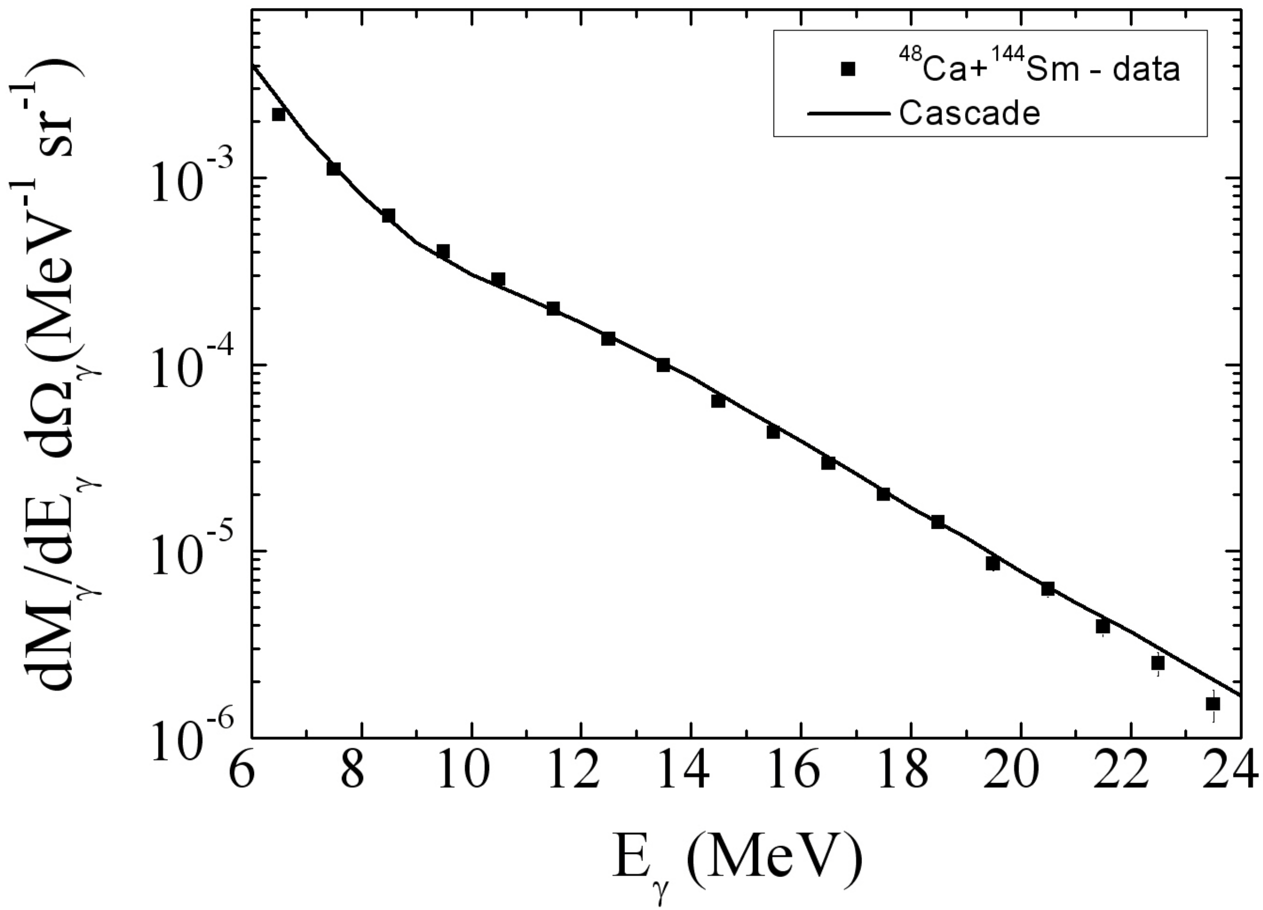
At θ_{spin}=90° the DD yield should be minimum:
$M_\gamma(\theta_{spin})$ = (0.7± 1.6) 10^{-4} γ/ sr



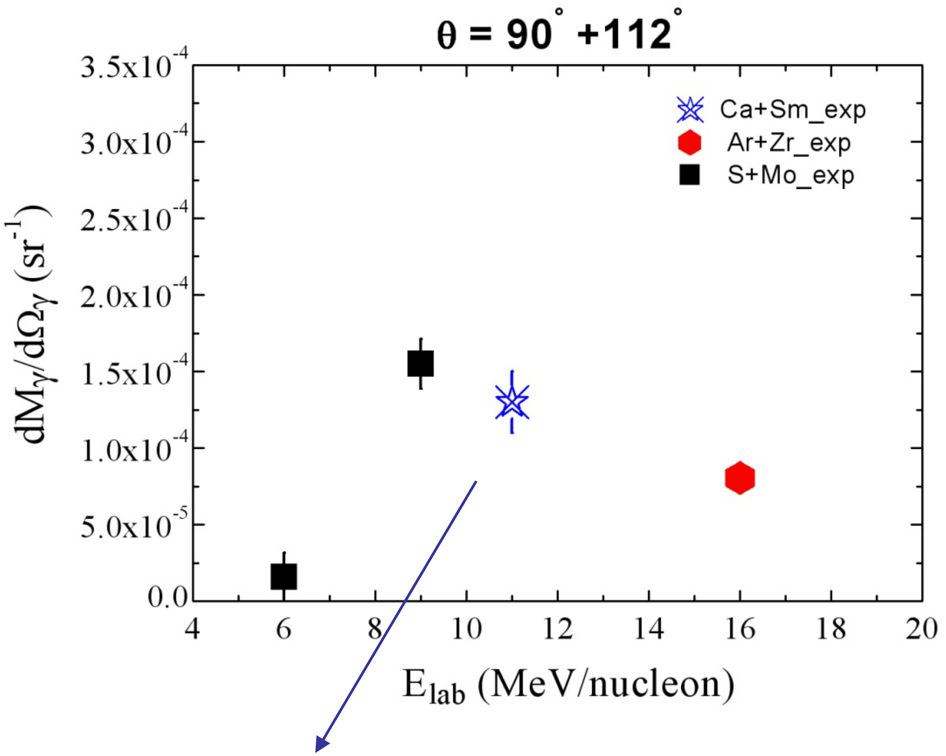


Fusion-evaporation γ–ray spectra at θ=90° and 112°

CN: ^{192}Pb, E^{*}= 236 MeV, a=A/11 MeV^{-1}
E_{GDR}=13 MeV, Γ_{GDR}= 12 MeV, F_{GDR}= 1 TRKSR
E_{dd} ~ 10-11 MeV < E_{GDR} = 13 MeV



Fusion-evaporation: θ_γ=90° e 112°



CN: ^{192}Pb

^{40,48}Ca+^{152,144}Sm: D(t=0) =(30.6-5) fm

Preliminary results

CN: ^{132}C

^{32,36}S+^{100,92}Mo D(t=0) =(18.2-1.7)fm

^{36,40}Ar+^{96,92}Zr D(t=0)= (20.6-4)fm

Preliminary result

The dynamical dipole yield of the Ca+Sm reaction pair at 11 MeV/nucleon is comparable with that of the S+Mo pair at 9 MeV/nucleon despite its larger initial dipole moment. The heavier mass of the Ca+Sm partners should play a role.

Summary: $^{40,48}Ca + ^{152,144}Sm$ reactions

1. The DD mode survives also in heavier composite systems being centered at an energy E_{dd}~10-11 MeV lower than that of the statistical GDR, E_{GDR}= 13 MeV, in agreement with expectations.

2. The DD yield obtained in fusion-evaporation events is comparable with that obtained in mass symmetric fission events as expected for a pre-equilibrium γ emission

3. At the same angular range the DD yield of the Ca+Sm reaction pair at 11 MeV/nucleon

$$M_{\gamma}(\theta_{\gamma}) = (1.3 \pm 0.2)\ 10^{-4}\ \gamma /\ sr$$

is comparable with that of the S+Mo reaction pair at 9 MeV/nucleon despite its larger initial dipole moment.

The role of the mass should be important, in agreement with TDHF calculations (C. Simenel *et al*, PRL 86 (2001) 2971)

Dynamical Dipole mode
Perspectives with stable and radioactive beams

Perspectives with stable and radioactive beams

- ✓ More efforts should be done from both a theoretical and an experimental point of view to shed light on the interplay between the different parameters that influence the dynamical dipole features.

- ✓ Systematic study of the DD with charge asymmetry, incident energy, mass asymmetry and mass by using stable and radioactive beams produced by SPES. Radioactive beams maximize the initial dipole moment between interacting ions. Moreover, the combination of stable and radioactive beams allow to have a large variety of target-projectile combinations.

DD with stable and radioactive beams

Proj	Target	Beam	I (pps)	CN	D(t=0) fm	Δ (t=0)
^{112}Cd	^{80}Se	Stable		^{192}Pb	1.8	0.06
^{48}Ca	^{144}Sm	Stable		^{192}Pb	5.3	0.18
^{86}Kr	^{106}Pd	RIB	10^{8}	^{192}Pb	8.0	0.03
^{110}Cd	^{82}Se	Stable		^{192}Pb	11.2	0.05
^{88}Kr	^{104}Pd	RIB	8.08×10^{7}	^{192}Pb	17.4	0.03
^{93}Sr	^{99}Ru	RIB	4.26×10^{8}	^{192}Pb	19.0	0.01
^{94}Sr	^{98}Ru	RIB	2.54×10^{8}	^{192}Pb	23.6	0.01
^{32}S	^{160}Dy	Stable		^{192}Pb	24.1	0.26
^{90}Kr	^{102}Pd	RIB	8.74×10^{7}	^{192}Pb	26.8	0.02
^{40}Ca	^{152}Sm	Stable		^{192}Pb	30.6	0.22
^{96}Sr	^{96}Ru	RIB	3.14×10^{5}	^{192}Pb	33.0	0.00

Study of the Symmetry Energy energy dependence on ρ at $\rho<\rho_0$ by studying the DD in $^{132,124}Sn+{}^{58}Ni$ at E_{lab}= 10A MeV

Asysoft EOS with respect to Asystiff EOS

E_{sym} larger at $\rho < \rho_0$
Larger isovector restoring force

DD parameters: Asysoft with respect to Asystiff EOS

Larger centroid, larger width, larger yield, different angular distribution for high impact parameters

The differences in the dynamical dipole parameters can be observed experimentally for the more "exotic" system **$^{132}Sn+{}^{58}Ni$**

DD yield larger by 30% with the Asysoft EoS choice

V. Baran, M. Di Toro, M. Colonna *et al.*, PRC79(2009) 021603

Reactions to study with the SPES RIBs:

$^{132}Sn+{}^{58}Ni$ (I)= 3.11*10^7 pps (D=45 fm) and $^{48}Ca+{}^{142}Ce$ (D=3.13 fm)

$^{132}Te+{}^{58}Ni$ (I)= 8.4*10^8 pps (D=38.5 fm) and $^{48}Ca+{}^{142}Nd$ (D=2.2 fm)

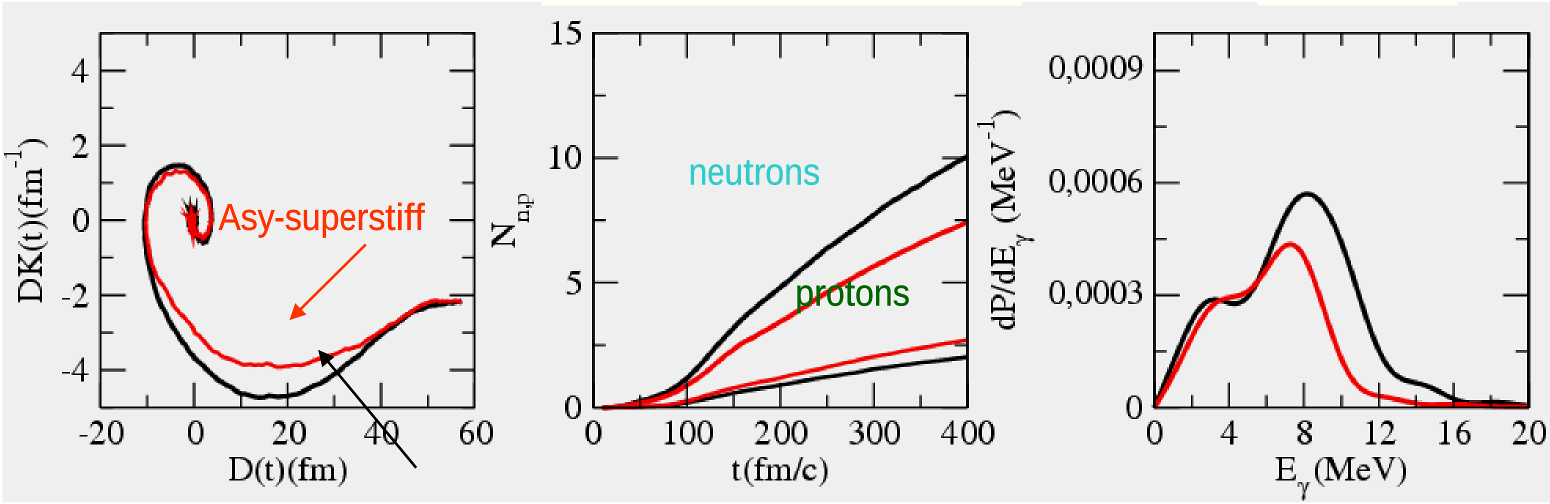
The "Monster" Dynamical Dipole $^{132}Sn + ^{58}Ni$ at E_{lab}= 10A MeV

V. Baran, M. Di Toro, M. Colonna *et al.*, PRC79(2009) 021603

$^{132}Sn + ^{58}Ni$

Fast emitted nucleons

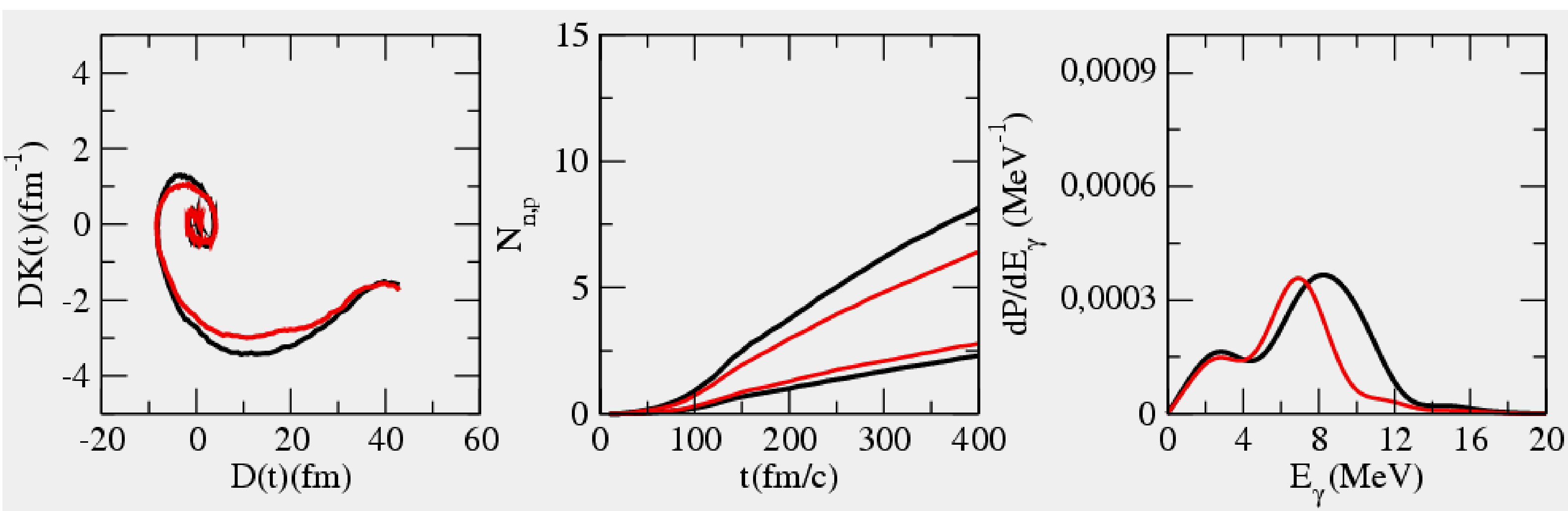
Spectra



Asy-soft

$^{124}Sn + ^{58}Ni$

ASYSOFT: *Larger energy integrated ield by 30%*
Larger Centroid Energy
Larger Width



The "Monster" Dynamical Dipole $^{132}Sn + ^{58}Ni$ at E_{lab}= 10A MeV

Angular distributions

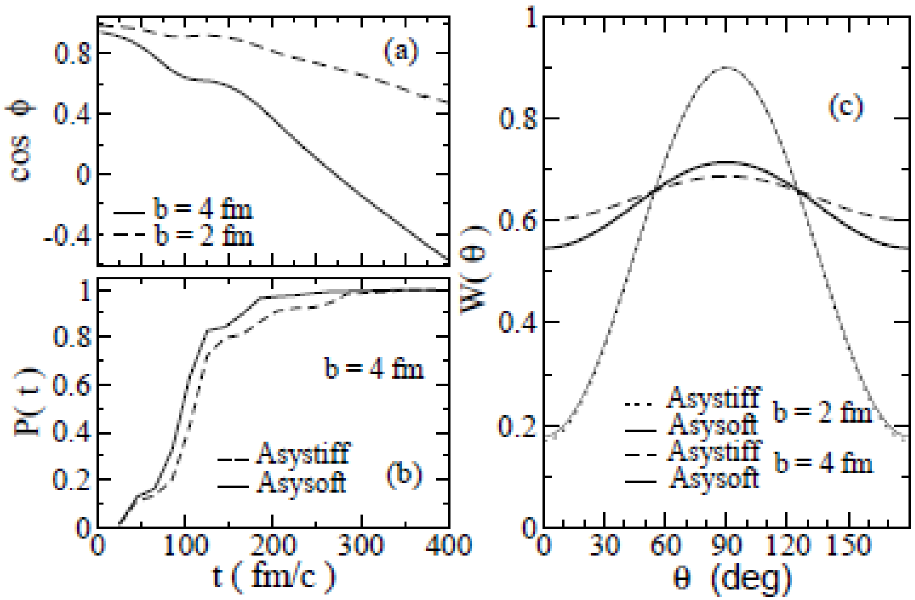


FIG. 3: "132" system. (a) panel: time dependence of the rotation angle at b=2fm (dashed line) and b=4fm (solid line). (b) panel: time evolution of the emission probability $P(t)$, see text, for $b = 4fm$ impact parameter. (c) panel: weighted angular distributions for $b = 2fm$ and $b = 4fm$ centralities for different symmetry term choices. Dashed lines for the Asystiff choice, solid for Asysoft. The Iso-Eos effects on the rotation angle are negligible.

Calculations predict that angular distribution measurements at relatively high impact parameters could allow us to disentagle between the two EoS density dependences

V. Baran, M. Di Toro, M. Colonna *et al.*, PRC79(2009) 021603

Requests for an experimental set up to use with RIBs

γ–ray detection :

Energy resolution~ 7% at 1 MeV,

Time resolution~ 1 ns

High efficiency for high energy γ rays

Detection of eveporation residues, fission fragments, complex fragments

In case of incident energy larger 8 MeV/nucleon, particle preequilibrium emission sets in : detection of light charged particles and neutrons

SERPE apparatus

γ-rays

6 clusters of 7 BaF_2 (hexagones of TAPS standard type
d_{inner}= 5.9 cm, L= 25 cm= 12 X_o, X_o = radiation length,) all faces optically polished
at 28 cm from the target in and out of plane
$\varepsilon_\gamma \sim 5.10^{-3}$ for E_γ = 15 MeV, $\Delta\Omega_{cluster}$ = 0.27 sr
$\Delta\Omega_{tot}$ = 1.62 sr

reaction products

4 position sensitive PPACs at θ= 7°, d=70 cm, $\Delta\Omega$=0.089 sr (for evaporation residues)
ε_{PPAC} = 0.4 to 0.67 for E_{lab}= 5 to 11 MeV/nucleon

4 position sensitive PPACs at θ= 50°, d=15 cm, $\Delta\Omega$=0.16 sr (for fission fragments)
$\varepsilon_{PPAC,pair}$ = 0.18 for E_{lab}= 10 MeV/nucleon and θ = 50°

4 two-stage telescopes (IC+Silicon Strip detectors) at d=7.8 cm , $\Delta\Omega$=0.1 sr
(for peripheral reaction fragments)
12 three-stage telescopes (IC+ Silicon Strip detectors +CsI (Tl) crystals)
at θ= 11-37°, d=35 cm, $\Delta\Omega$= 0.144 sr (for peripheral reaction fragments)

A beam intensity of 10^7 pps is needed to have a relative error of the DD yield integrated over energy and over solid angle of 5-6% while a beam of 10^8 - 10^9 pps is necessary for decreasing this error down to 1-2% and for performing DD angular distribution studies

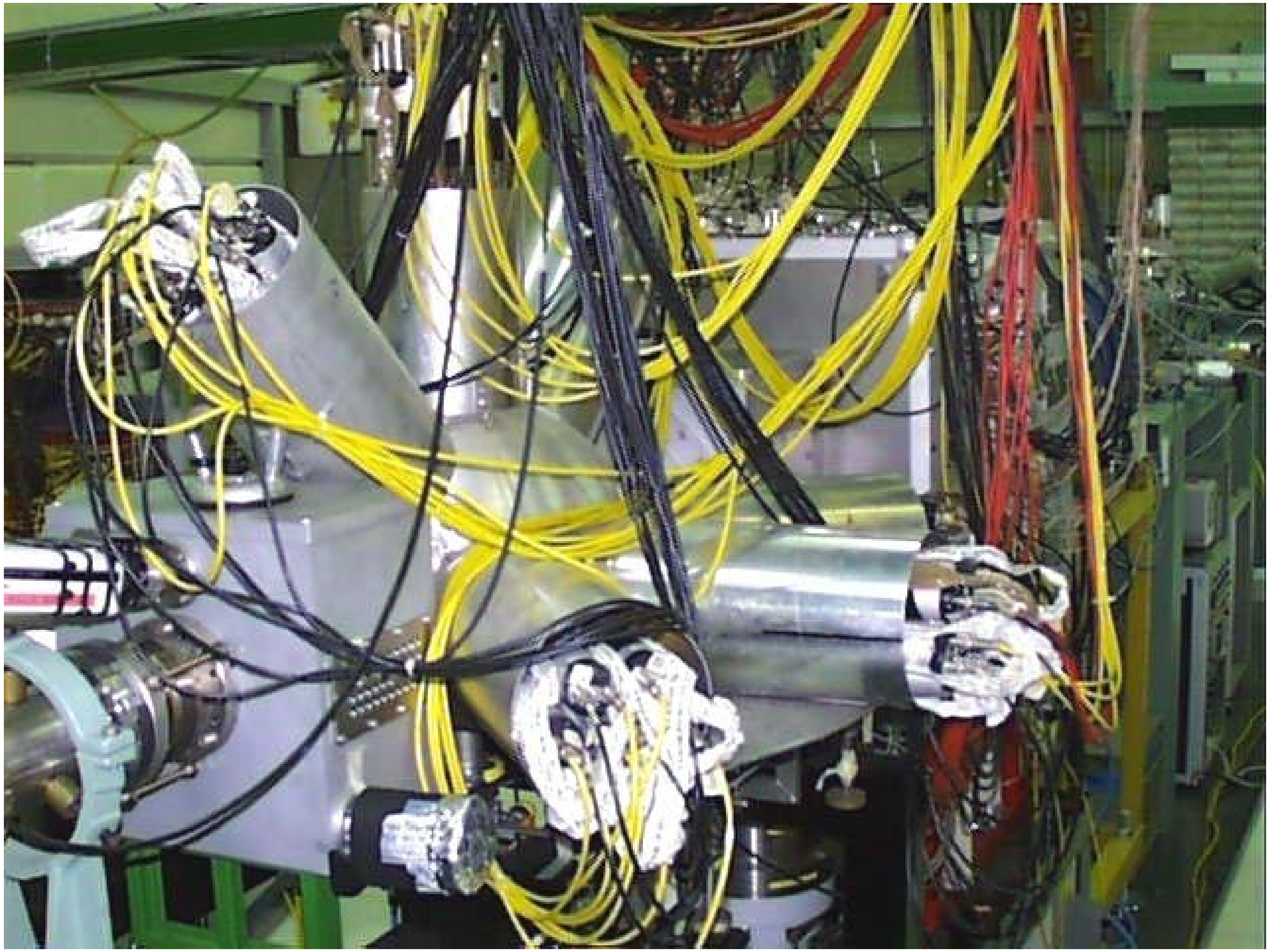
TRASMA apparatus at LNS

9 clusters of 7 BaF_2 identical with those of the SERPE apparatus

$\Delta\Omega_{cluster}$ = 0.27 sr

$\Delta\Omega_{tot}$ = 2.43 sr

SERPE+TRASMA $\Delta\Omega_{tot}$ = 4.05 sr (32% of 4π)



Conclusions

✓Investigation of the DD in peripheral heavy-ion collisions: DD yield increasing with centrality

✓A systematic study of the DD features as a function of the beam energy in the S+Mo and Ar+Zr fusion reactions leading to the ^{132}Ce compound nucleus: evidence that the prompt dipole radiation is confined at the first moments of the reaction

✓ Investigation of the DD in both fusion-evaporation and fission events in the Ca+Sm reactions at 11 MeV/nucleon leading to a ^{192}Pb compound nucleus: data analysis in progress

Open Problems & Perspectives

✓Better understanding of the interplay of the different parameters influencing the dynamical dipole features in fusion and peripheral collisions

✓Cooling of the composite system in fusion reactions to facilitate the formation of superheavy elements

✓Information of the density dependence of the nuclear matter EoS at $\rho < \rho_0$ by taking advantage of the use of radioactive beams