

# Nuclear Structure Physics with Advanced $\gamma$ -detector Arrays

10-12 June 2013 - Palazzo del Bo', Padova, Italy

*dedicated to the memory of Enrico Farnea*

## In memoriam of Enrico Farnea

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[nsp13@pd.infn.it](mailto:nsp13@pd.infn.it)  
<http://nsp13.pd.infn.it>

Dino Bazzacco



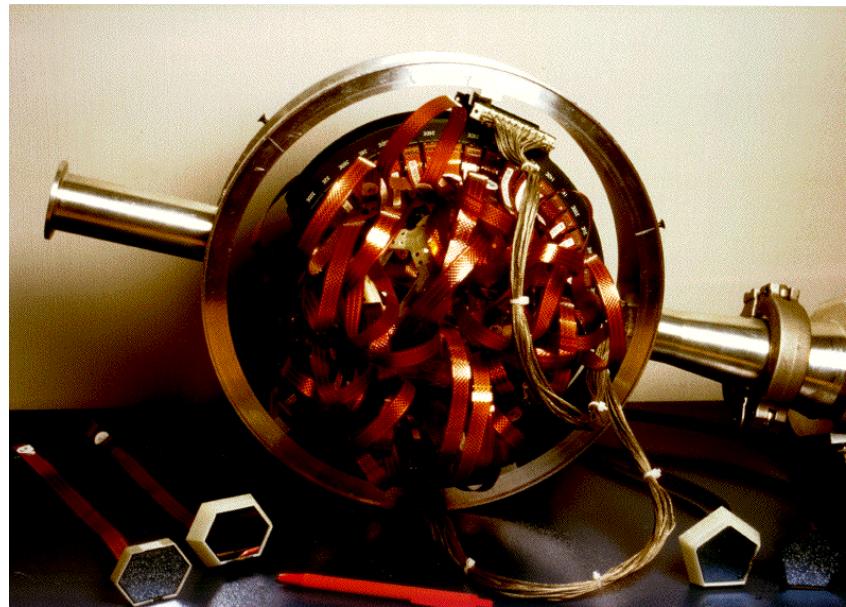
- Born in Verona on August 29, 1970
- 1995: graduation in Physics at the University of Padova with a thesis done at Legnaro on the development and use of the LCP detector ISIS for GASP.
- Continued working in our group with an INFN scholarship
- 1998: “Marie Curie” research grant for a two-year stint at University of Valencia
- 2000: Back to Italy with a research fellowship of University of Padova to work on the development of the LCP detector EUCLIDES for Euroball
- 2001: PhD at University of Surrey with the thesis *Spectroscopic Studies of Isospin Mixing in  $^{64}$*  based on experiments done with EUROBALL III (LNL) and EUROBALL IV (IReS)
- 2001: permanent position at INFN Padova, strengthening the  $\gamma$ -ray spectroscopy group and contributing to: GASP, EUROBALL, CLARA, AGATA, GALILEO, ...
- With us until April 14, 2013

# ISIS

## 40 $\Delta E+E$ Si telescopes for GASP



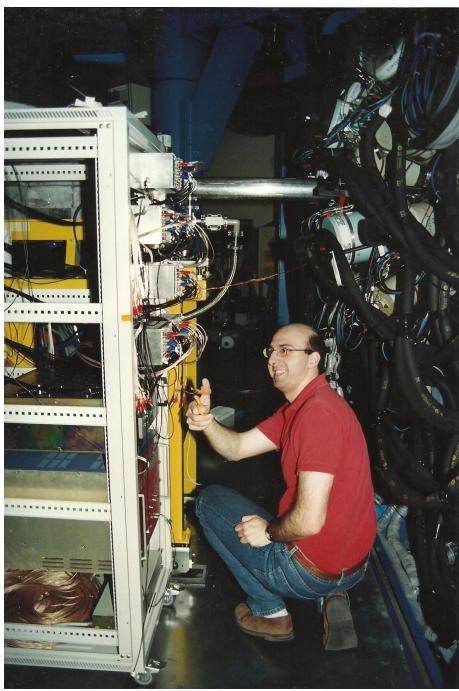
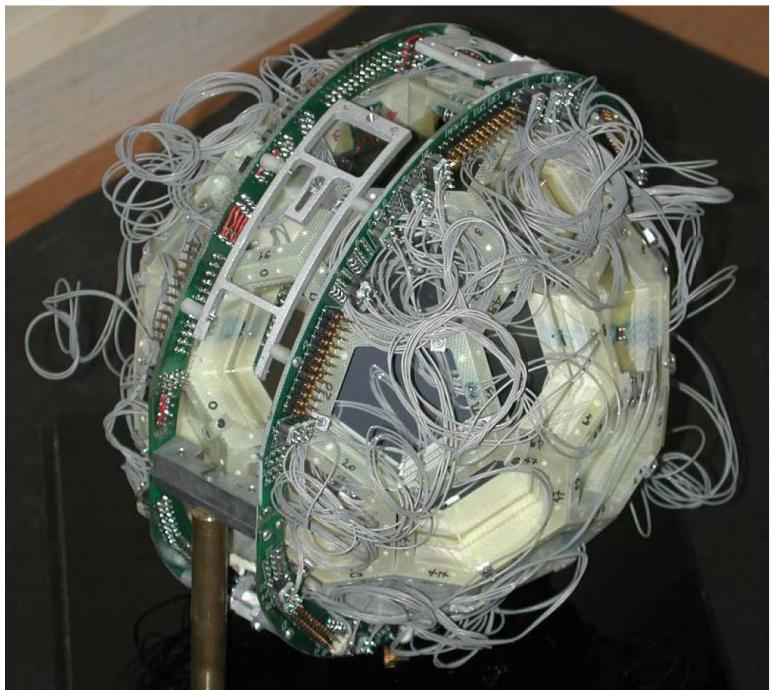
# Working on ISIS with Andres and Alejandro



# EUCLIDES



40  $\Delta E$  (130 $\mu m$ , mounted in reverse configuration)+E(1mm) telescopes  
The detectors of the forward ring are segmented in 4 parts  
Used in EUROBAL III, EUROBALL IV, GASP and GALILEO



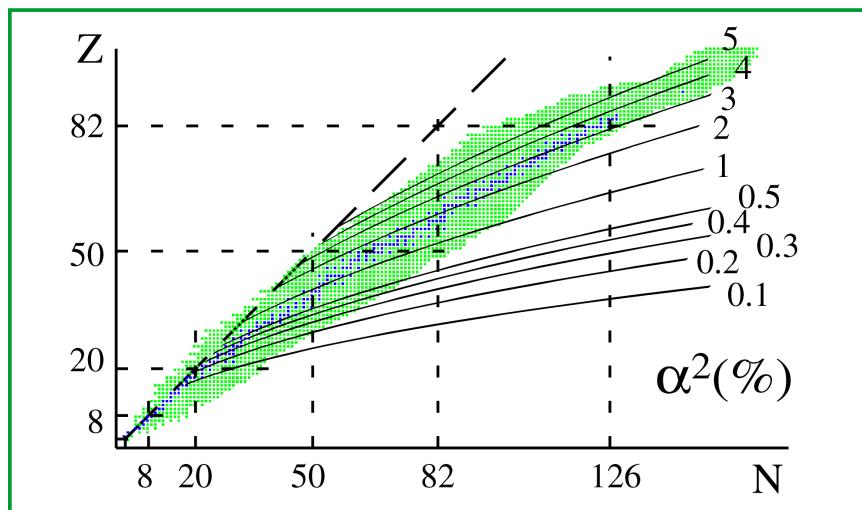


# Isospin Mixing from the in-beam study of $^{64}\text{Ge}$

Isospin mixing

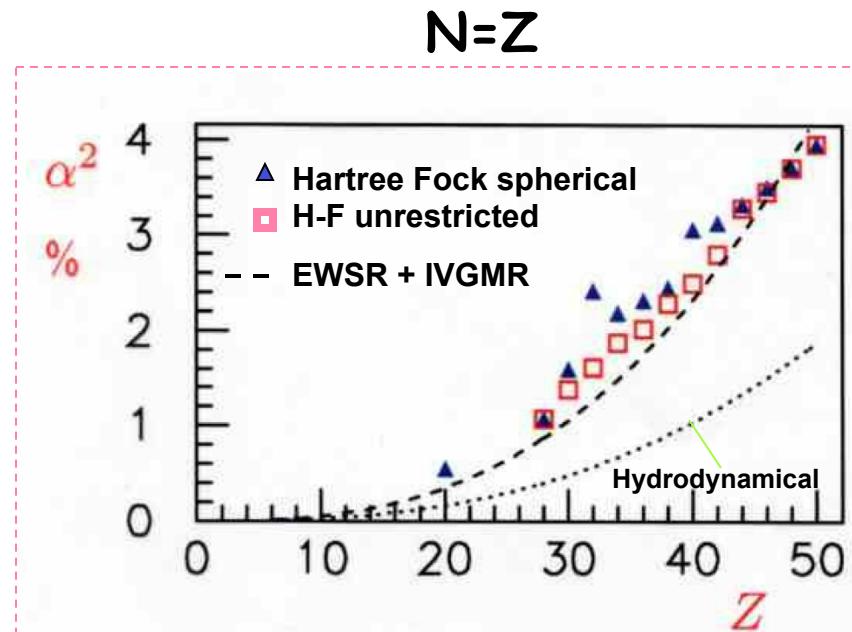
- Nuclear structure
- Unitary test of the CKM in nuclear  $\beta$ -decay

$\alpha^2$  in the ground state of even-even nuclei



Estimated isospin mixing via the IVGMR

G. Colò et al., Phys. Rev. C 52 (1995) R1175



$$\alpha^2 = \frac{1}{2} \langle N = Z | T_- T_+ | N = Z \rangle$$

J. Dobaczewski and I. Hamamoto, PLB 345 (1995) 181  
I. Hamamoto and H. Sagawa, PRC 48 (1993) R960

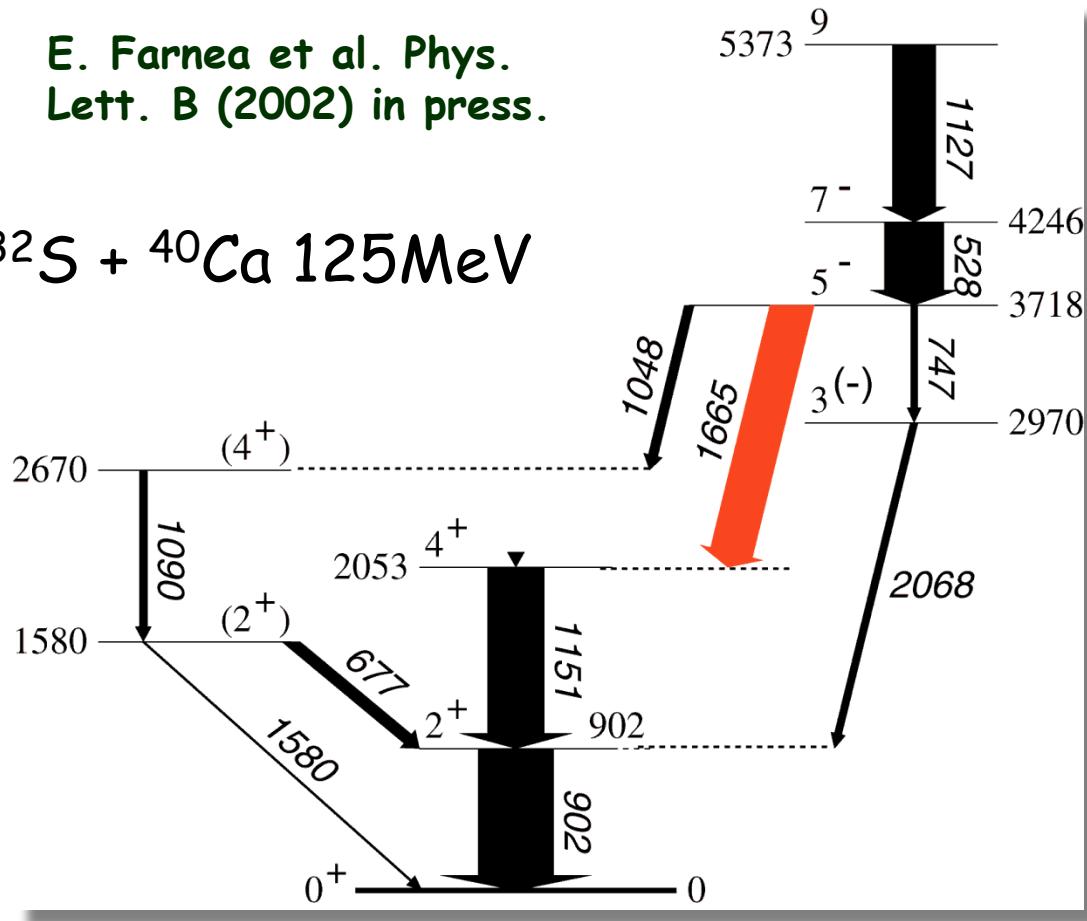
# Forbidden E1 transitions in $^{64}\text{Ge}$

Level scheme completed with  
GASP and  
EUROBALL III.

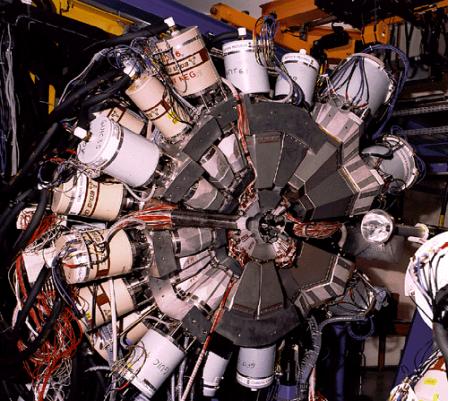
Lifetime from  
EUROBALL IV +  
EUCLIDES +  
Plunger  
measurement

E. Farnea et al. Phys.  
Lett. B (2002) in press.

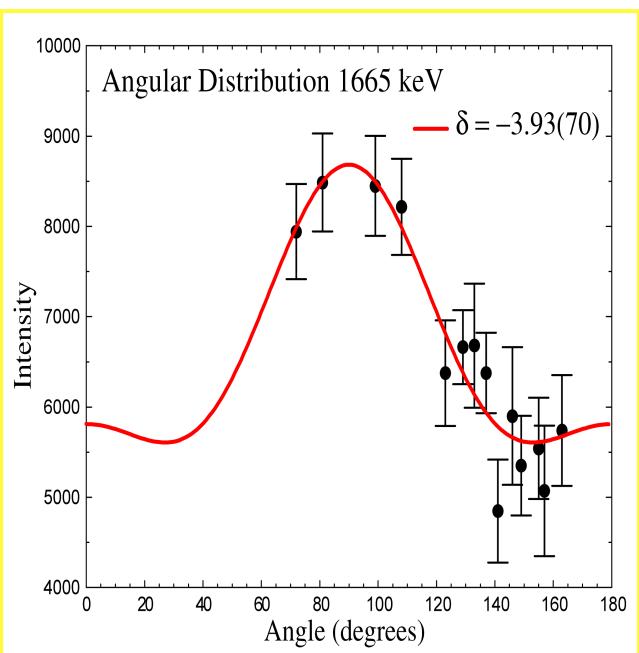
$^{32}\text{S} + ^{40}\text{Ca}$  125 MeV



Previous work on  $^{64}\text{Ge}$ : P.J. Ennis et al., Nucl. Phys. A 535 (1991) 392



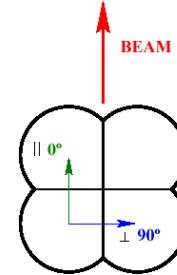
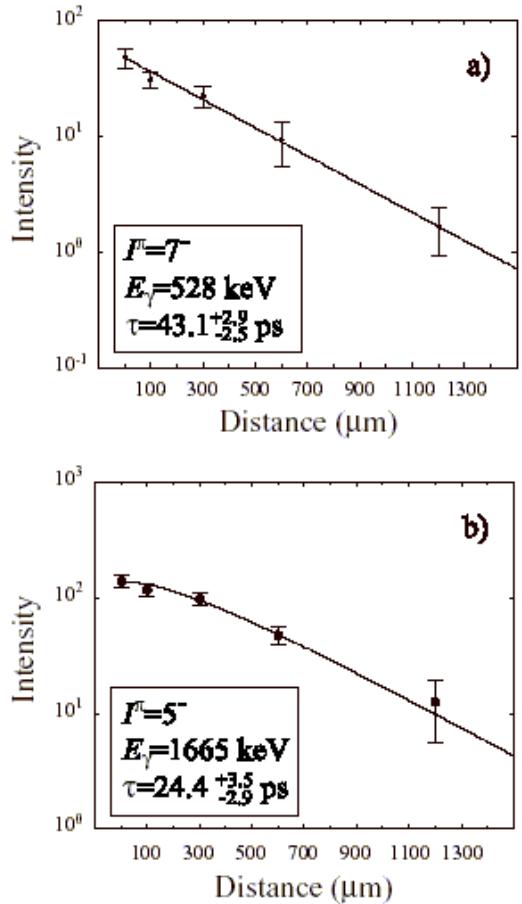
## Angular distribution



$\delta = -3.93(70)$   
 $B(M2) = 6.1(1.6) \text{ W.u.}$   
 $B(E1) = 2.3 (1.3) 10^{-7} \text{ W.u.}$



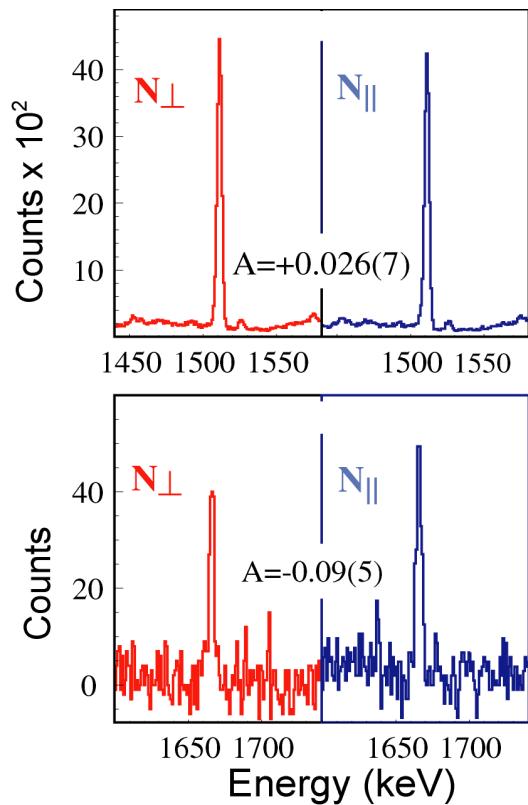
## Lifetime



$$A = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel}$$

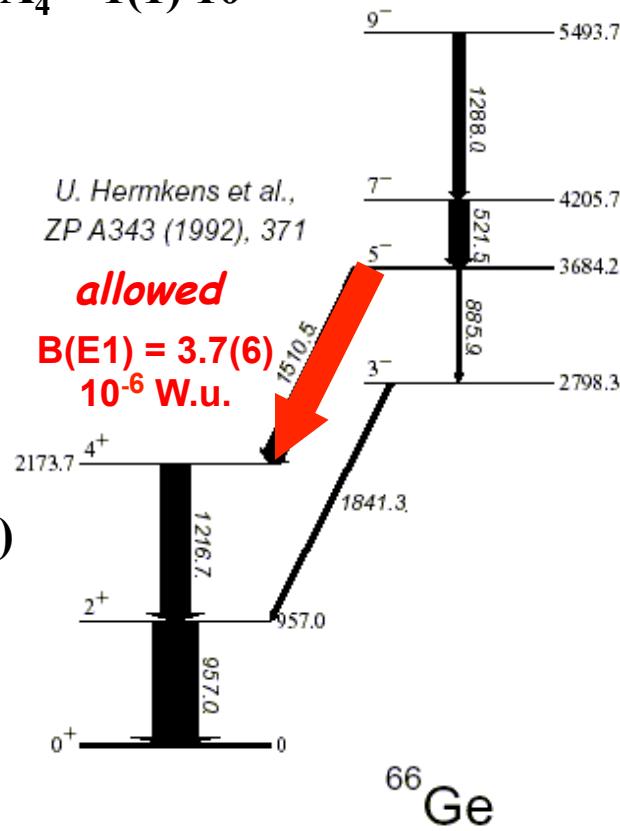
## Asymmetry and polarization

$$A = N_\perp - N_\parallel / (N_\perp + N_\parallel)$$

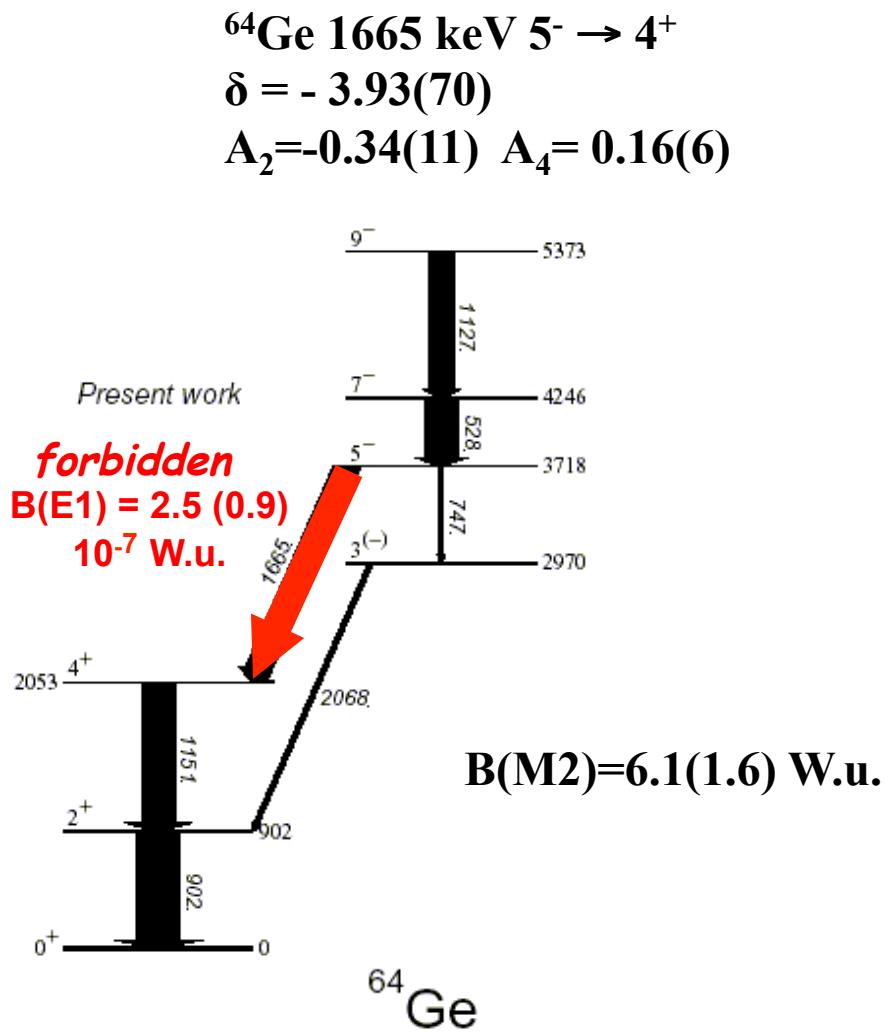


The 1665 keV transition mixed E1/M2 character ~93% quadrupole contents

$^{66}\text{Ge}$  1510 keV  $5^- \rightarrow 4^+$   
 $\delta = -0.021(0.009)$   
 $A_2 = -0.28(8)$   $A_4 = 1(1) 10^{-4}$



$$B(M2) = 3.7(6) 10^{-2} \text{ W.u.}$$



$$B(M2) = 6.1(1.6) \text{ W.u.}$$

$$B(M2)_{^{68}\text{Ge}} = 0.71(11) \text{ W.u.}$$

Other large  $B(M2)$  values in this mass region  $^{59}\text{Cu}$  (1.8 W.u.),  $^{63}\text{Cu}$  (0.5 W.u.),  $^{65}\text{Ga}$  (0.7 W.u., 23 W.u.)

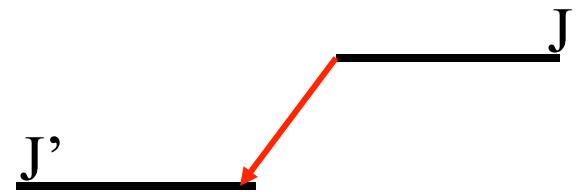
# Isospin mixing estimate in $^{64}\text{Ge}$

Amount of isospin mixing:  $\alpha^2 = \frac{1}{2} \langle N = Z | T_- T_+ | N = Z \rangle$

Isospin mixing between  $T=0$  and  $T=1$  states of equal  $J$

$$|i, J\rangle = \beta_i |J, T=0\rangle + \alpha_i |J, T=1\rangle$$

$$|f, J'\rangle = \beta_f |J', T=0\rangle + \alpha_f |J', T=1\rangle$$



For  $\alpha \ll 1$   $\beta \sim 1$  and considering

$$^{66}\text{Ge} = {^{64}\text{Ge}} + 2n_{0+} \text{ (pair)}$$

$$B(E1, J \rightarrow J', {^{64}\text{Ge}}) = \frac{8}{3} \alpha^2 B(E1, J \rightarrow J', {^{66}\text{Ge}})$$

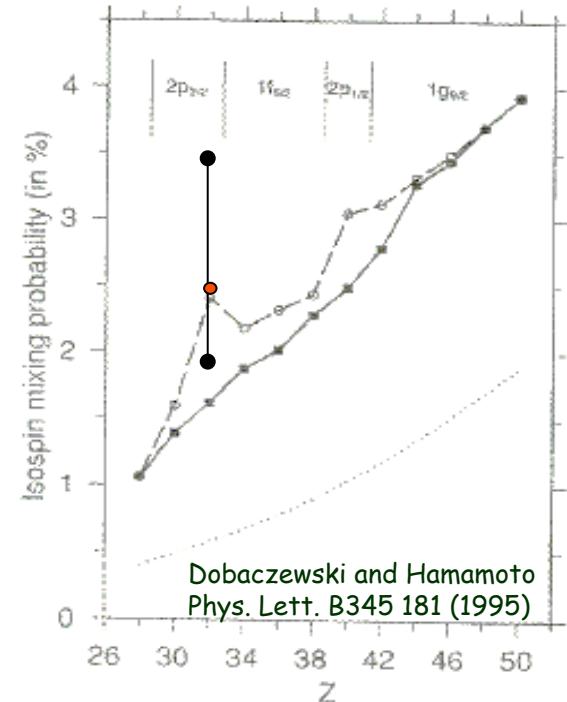
With the experimental values

$$\alpha^2 = 2.5\% {}^{+1.0\%}_{-0.7\%}$$

E. Farnea et al. Phys. Lett. B (2002)

G. Colò et al., Phys. Rev. C 52 (1995) R1175

$$\alpha^2 = 1.3\%$$





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Available online at [www.sciencedirect.com](http://www.sciencedirect.com)



PHYSICS LETTERS B

Physics Letters B 551 (2003) 56–62

[www.elsevier.com/locate/npe](http://www.elsevier.com/locate/npe)

2002

## Isospin mixing in the $N = Z$ nucleus $^{64}\text{Ge}$

E. Farnea<sup>a,b,\*1</sup>, G. de Angelis<sup>a</sup>, A. Gadea<sup>a,b</sup>, P.G. Bizzeti<sup>c</sup>, A. Dewald<sup>d</sup>, J. Eberth<sup>d</sup>,  
A. Algora<sup>b,2</sup>, M. Axiotis<sup>a</sup>, D. Bazzacco<sup>e</sup>, A.M. Bizzeti-Sona<sup>c</sup>, F. Brandolini<sup>e</sup>,  
G. Colò<sup>f</sup>, W. Gelletly<sup>g</sup>, M.A. Kaci<sup>b</sup>, N. Kintz<sup>h</sup>, T. Klug<sup>d</sup>, Th. Kröll<sup>a</sup>, S.M. Lenzi<sup>e</sup>,  
S. Lunardi<sup>e</sup>, N. Mărginean<sup>a</sup>, T. Martínez<sup>a</sup>, R. Menegazzo<sup>e</sup>, D.R. Napoli<sup>a</sup>, J. Nyberg<sup>i</sup>,  
P. Pavan<sup>e</sup>, Zs. Podolyák<sup>g</sup>, C.M. Petrache<sup>j</sup>, B. Quintana<sup>e</sup>, B. Rubio<sup>b</sup>, P. Spolaore<sup>a</sup>,  
Th. Steinhardt<sup>d</sup>, J.L. Taín<sup>b</sup>, O. Thelen<sup>d</sup>, C.A. Ur<sup>e</sup>, R. Venturelli<sup>e</sup>, M. Weiszflog<sup>i</sup>



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Nuclear Instruments and Methods in Physics Research A 400 (1997) 87–95

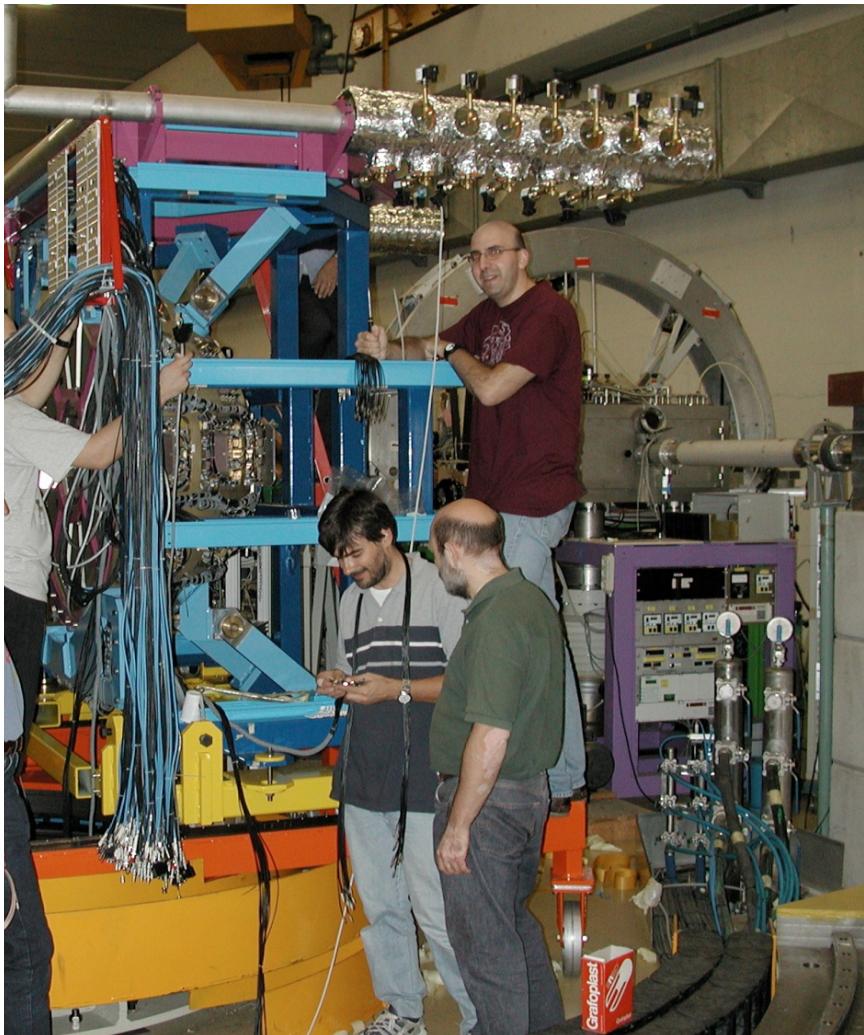
NUCLEAR  
INSTRUMENTS  
& METHODS  
IN PHYSICS  
RESEARCH  
Section A

1997

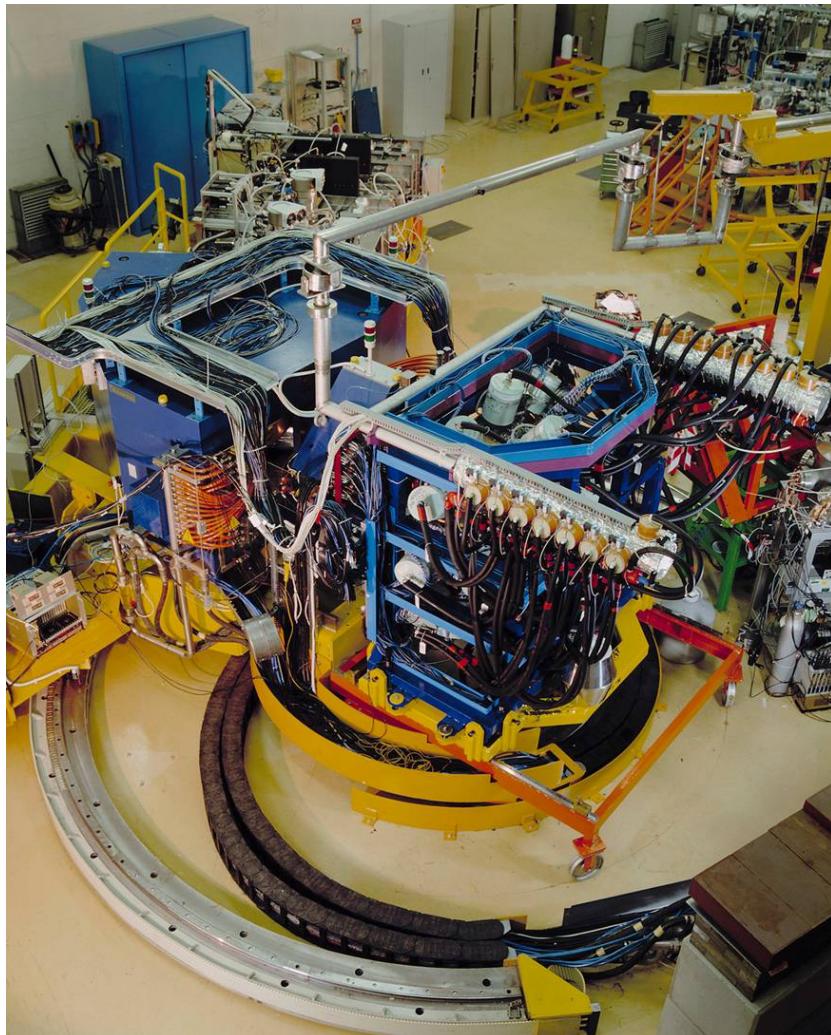
## A $4\pi$ light-charged particle Si detector as a trigger device for in-beam $\gamma$ -ray spectroscopy

E. Farnea<sup>a,\*</sup>, G. de Angelis<sup>a</sup>, M. De Poli<sup>a</sup>, D. De Acuña<sup>a</sup>, A. Gadea<sup>a,1</sup>, D.R. Napoli<sup>a</sup>,  
P. Spolaore<sup>a</sup>, A. Buscemi<sup>b</sup>, R. Zanon<sup>b</sup>, R. Isocrate<sup>b</sup>, D. Bazzacco<sup>b</sup>, C. Rossi Alvarez<sup>b</sup>,  
P. Pavan<sup>b</sup>, A.M. Bizzeti-Sona<sup>c</sup>, P.G. Bizzeti<sup>c</sup>

# CLARA+PRISMA



Resp. Electronics 2004-2006  
Project Manager 2006-2008



Efficiency ~ 3 % Peak/Total ~ 45 %  
FWHM < 10 keV (at v/c = 10 %)

# The CLARA-PRISMA collaboration

- France  
IPHC (IReS) Strasbourg  
GANIL Caen
- U.K.  
University of Manchester  
Daresbury Laboratory  
University of Surrey  
University of Paisley
- Germany  
HMI Berlin  
GSI Darmstadt
- Poland  
IFJ-PAN Kraków
- Croatia
- Ruder Boskovic Institute, Zagreb
- Italy  
INFN LNL-Legnaro  
INFN and University Padova  
INFN and University Milano  
INFN and University Genova  
INFN and University Torino  
INFN and University Napoli  
INFN and University Firenze  
INFN and University Camerino
- Spain  
University of Salamanca
- Romania  
Horia Hulubei NIPNE Bucharest

**Project managers: Andres Gadea, Enrico Farnea**

## Summary of the Physics campaign

24 experiments (2004-2008)

16 papers (so far)

40+ talks at Conferences/Workshops

6+ diploma/PhD theses (in Italy)

# AGATA

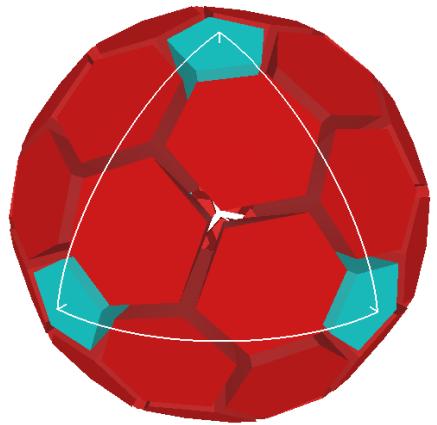
- Mars (in charge of, at LNL in 1996-1997)
- Conceptual Design
- Monte Carlo Simulations
- Key experiments
- Ancillary detectors
- Local project Manager at LNL
- Member AMB (Infrastructure)

# Comparison of the proposed configurations for the AGATA array

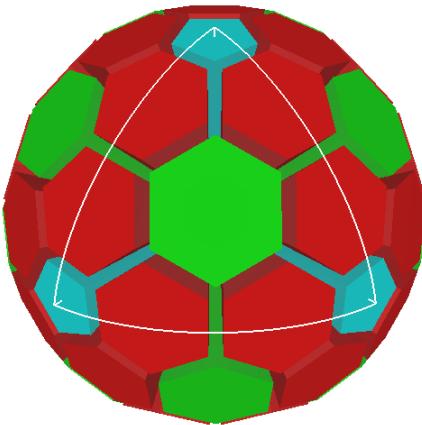
**E.Farnea**

INFN Sezione di Padova

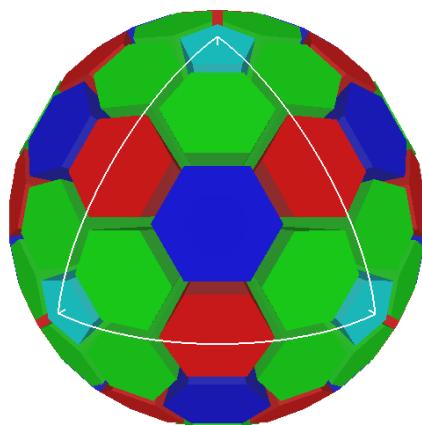
# Geodesic Tiling of Sphere using 60–240 hexagons and 12 pentagons



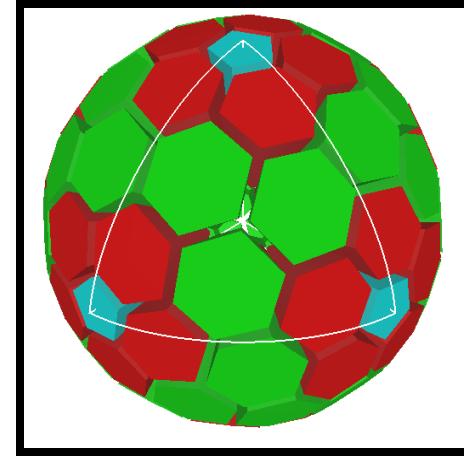
60



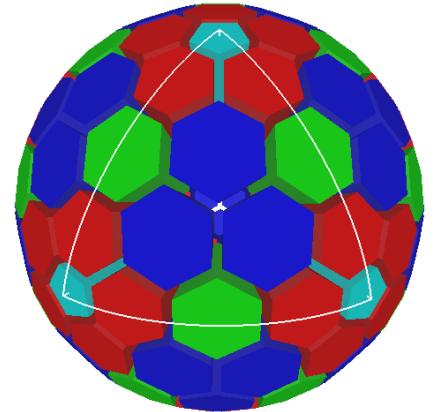
80



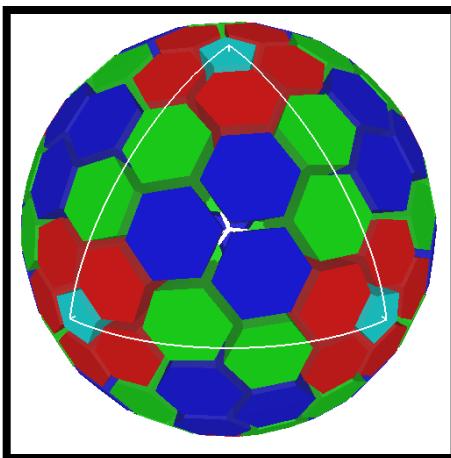
110



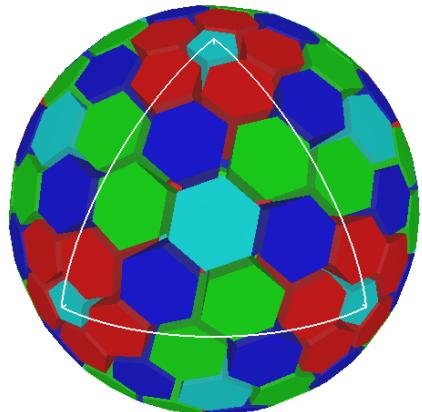
120



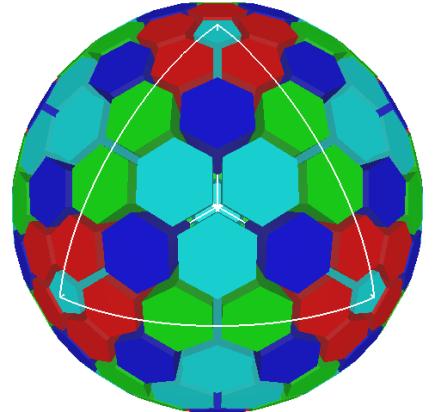
150



180



200



240

Agata

Event  
generation  
+  
detector  
response

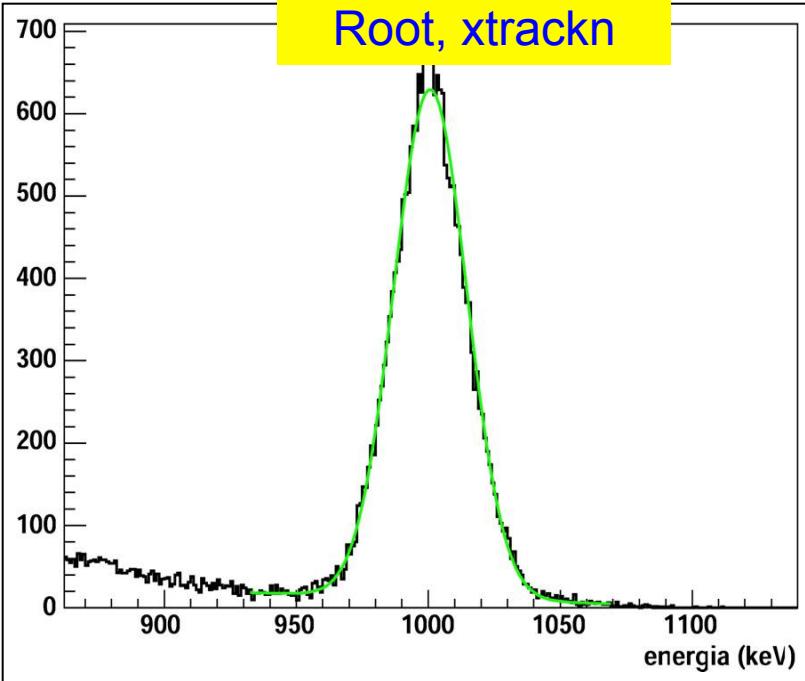
List-mode file:

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-101 0.05005 -0.00000 -0.00056 1.00000
-102 0.466 -1.660 0.000
-1 993.359 -0.48689 -0.86533 -0.11889 36
131 150.495 -12.660 -26.164 -3.122 40
132 155.894 -10.057 -25.571 -1.729 34
132 1.402 -10.088 -25.595 -1.801 34
```

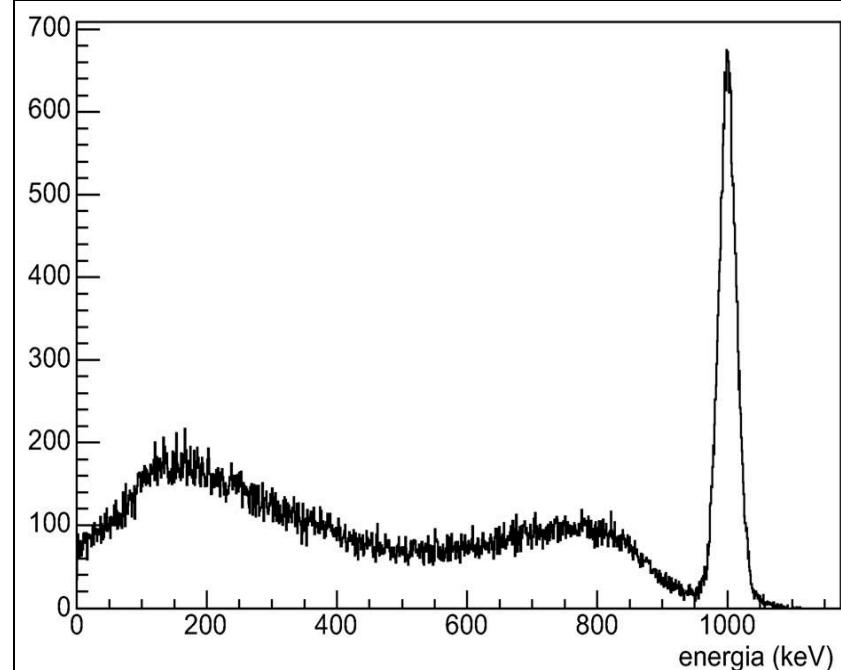
No experimental  
uncertainty!

mgt

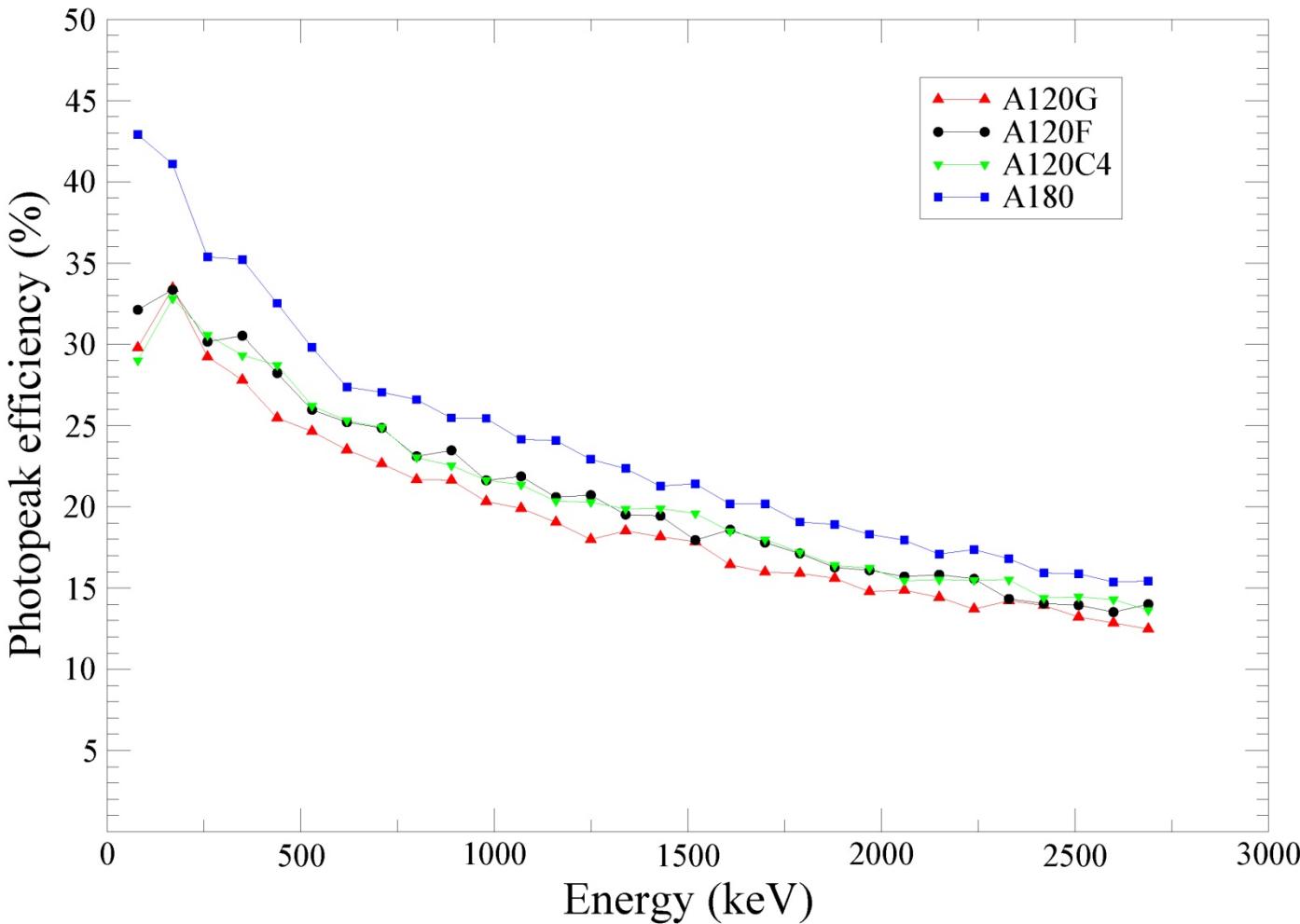
Analysis of the spectra



Packing/smearing  
+  
 $\gamma$ -ray tracking



# Photopeak efficiency



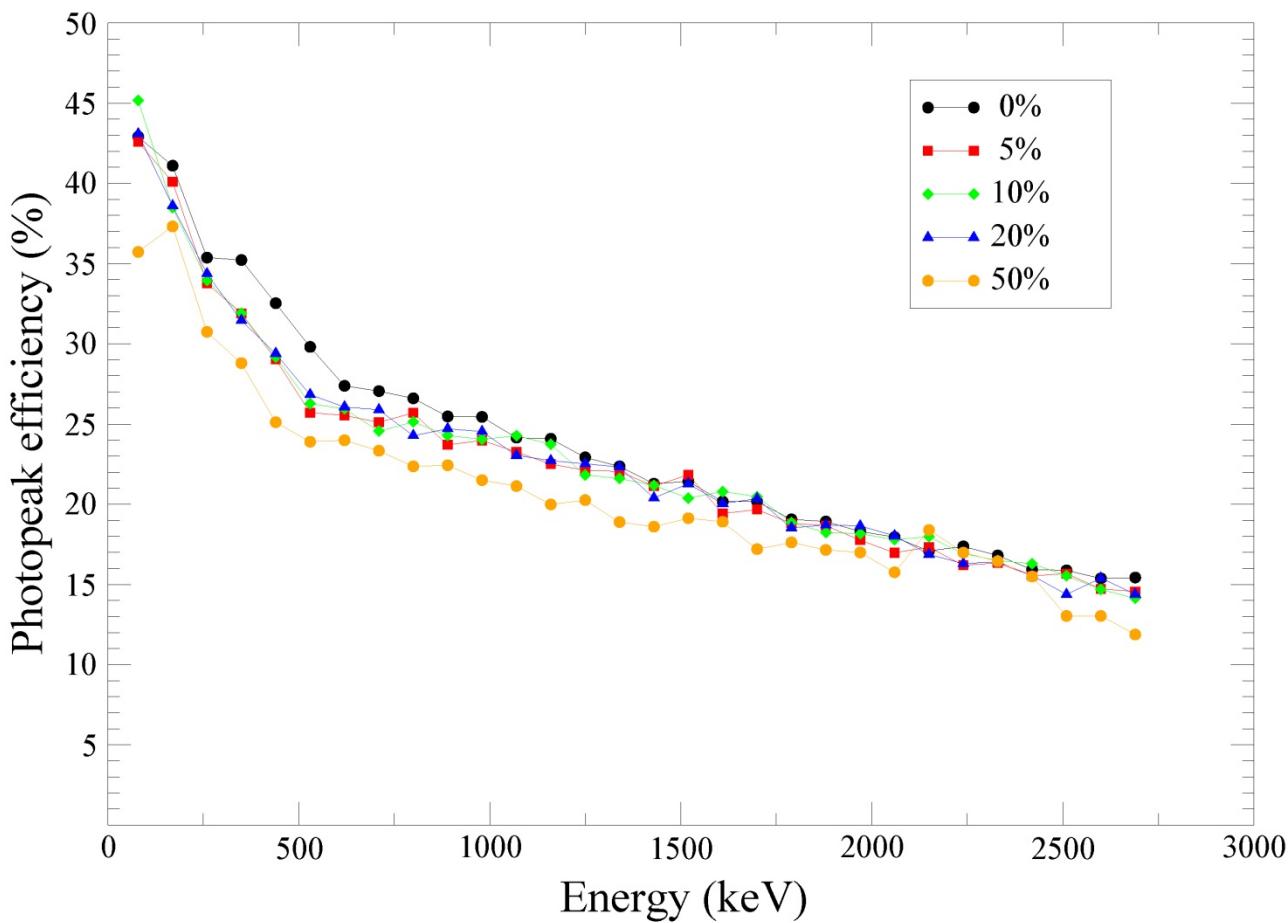
30 photon  
rotational  
cascade

$$E_{\gamma} = E_0 + n \Delta E_{\gamma}$$

Recoil velocity  
 $\beta = 0$

# Effect of the recoil velocity - 1

## Photopeak efficiency



30 photon rotational cascade

$$E_\gamma = E_0 + n\Delta E_\gamma$$

A180 configuration  
(no scattering chamber)

Recoil direction:  
**z axis**

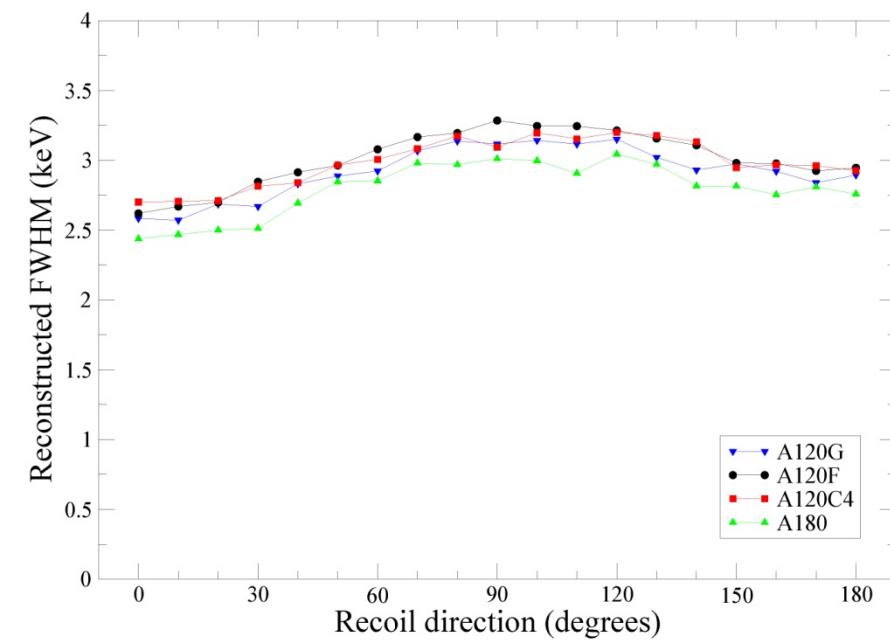
$\beta$ : **constant**  
(event by event)

Recoil velocity  
perfectly known  
when reconstructing

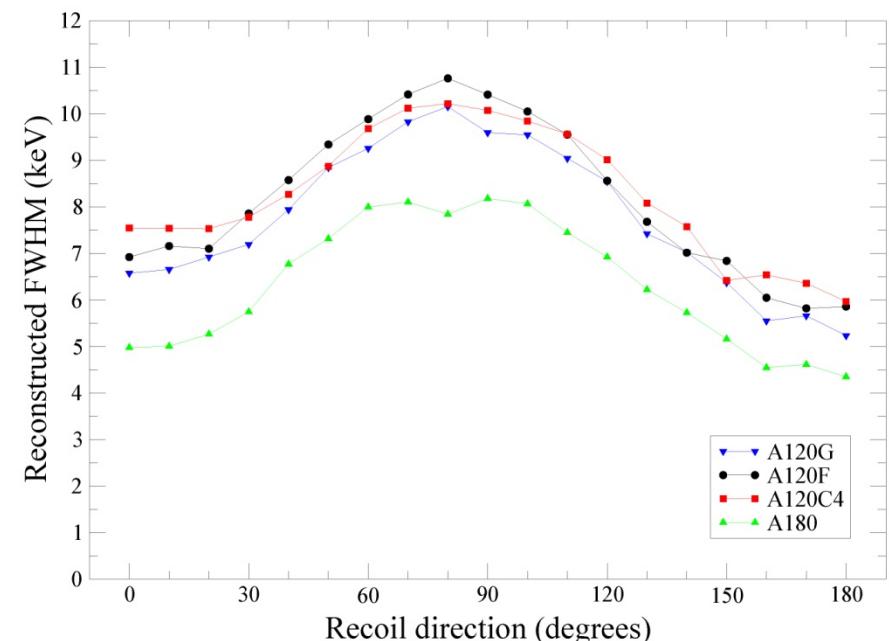
# Effect of the recoil velocity - 2

1 MeV single photons, recoil velocity perfectly known when reconstructing.  
Passivated areas, cryostats and capsules are considered.

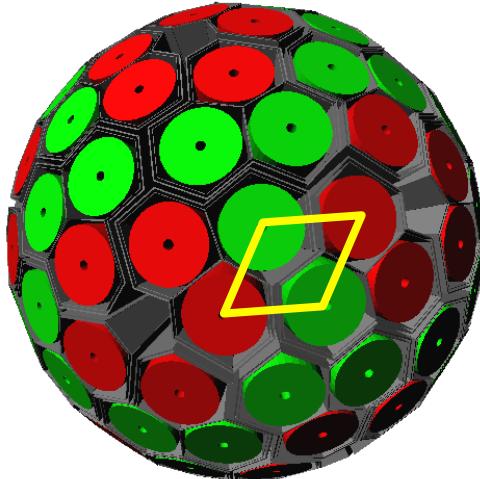
**Reconstructed FWHM –  
 $\beta=10\%$**



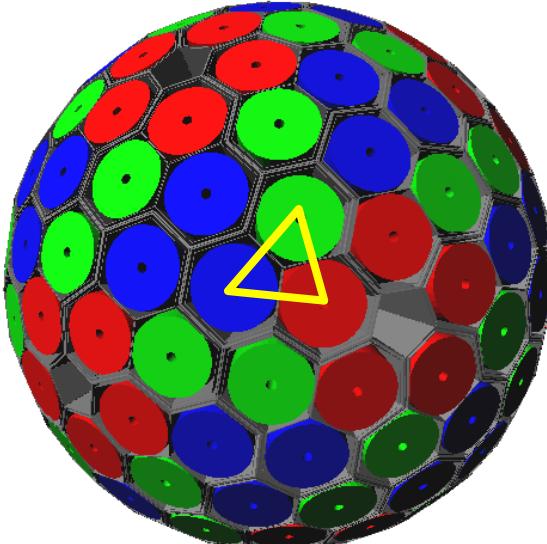
**Reconstructed FWHM –  
 $\beta=50\%$**



# Two Suitable Geodesic Configurations



120 crystals → GRETA



180 crystals → AGATA

Configuration	“small”	“big”
# of hexagonal crystals	120	180
# of crystal shapes	2	3
# of clusters	30	60
Covered solid angle (%)	78.0	78.4
Germanium weight (kg)	230	370
Centre to crystal-face (cm)	18.5	23.5
Signal channels	4440	6660
Efficiency at $M_\gamma = 1$ (%)	36.4	38.8
Efficiency at $M_\gamma = 30$ (%)	22.1	25.1
P/T at $M_\gamma = 1$ (%)	51.8	53.2
P/T at $M_\gamma = 30$ (%)	43.4	46.1

Monte Carlo and Simulations by Enrico Farnea

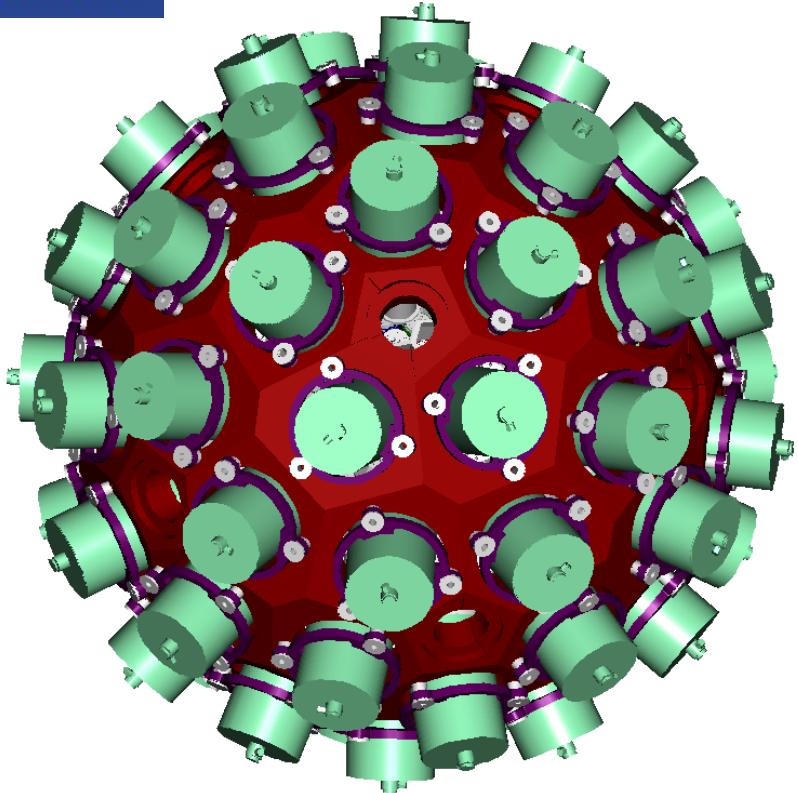
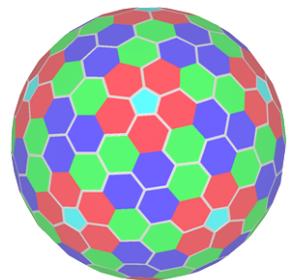
# ASC+AMB meeting: decision to go for 180 crystals





# AGATA

(Advanced **G**amma **T**racking **A**rray)



6660 high-resolution digital electronics channels

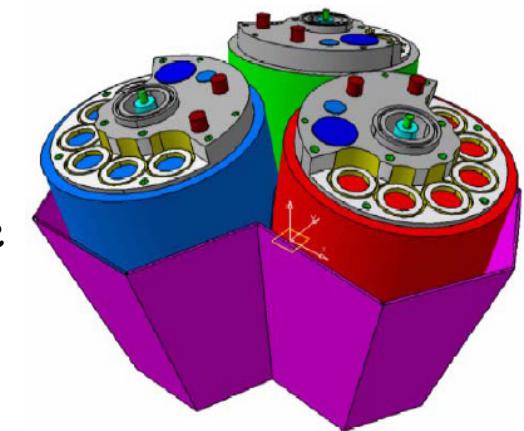
High throughput DAQ

Pulse Shape Analysis → position sensitive operation mode

$\gamma$ -ray tracking algorithms to achieve maximum efficiency

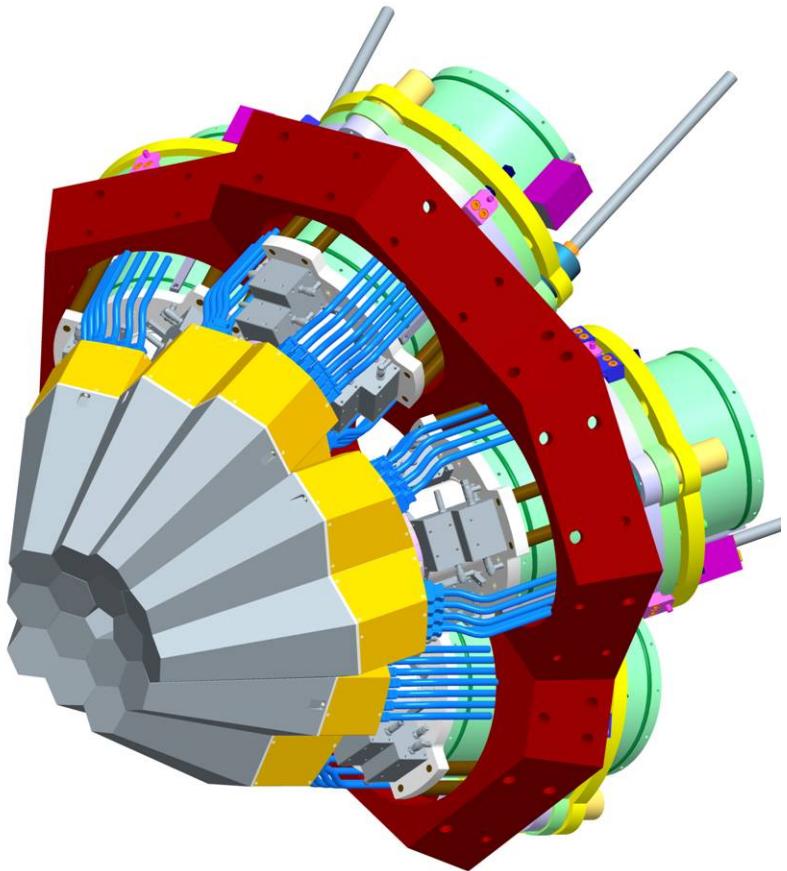
Coupling to ancillary detectors for added selectivity

180 hexagonal crystals	3 shapes all equal
60 triple-clusters	23.5 cm
Inner radius (Ge)	362 kg
Amount of germanium	82 %
Solid angle coverage	6480 segments
36-fold segmentation	$\sim$ 50 kHz
Singles rate	
Efficiency:	43% ( $M_\gamma=1$ )    28% ( $M_\gamma=30$ )
Peak/Total:	58% ( $M_\gamma=1$ )    49% ( $M_\gamma=30$ )



# The AGATA Demonstrator

## Objective of the final R&D phase 2003-2008



1 symmetric triple-cluster  
**5 asymmetric triple-clusters**  
15 36-fold segmented crystals  
540 segments  
555 high resolution digital-channels

Eff. 3 - 8 % @  $M_{\gamma} = 1$

Eff. 2 - 4 % @  $M_{\gamma} = 30$

**Operate in real time ACQ,  
Pulse Shape Analysis and  $\gamma$ -ray Tracking**

**Hosting sites:**

**LNL** → 2008 - 2011

**GSI** → 2012 - 2014

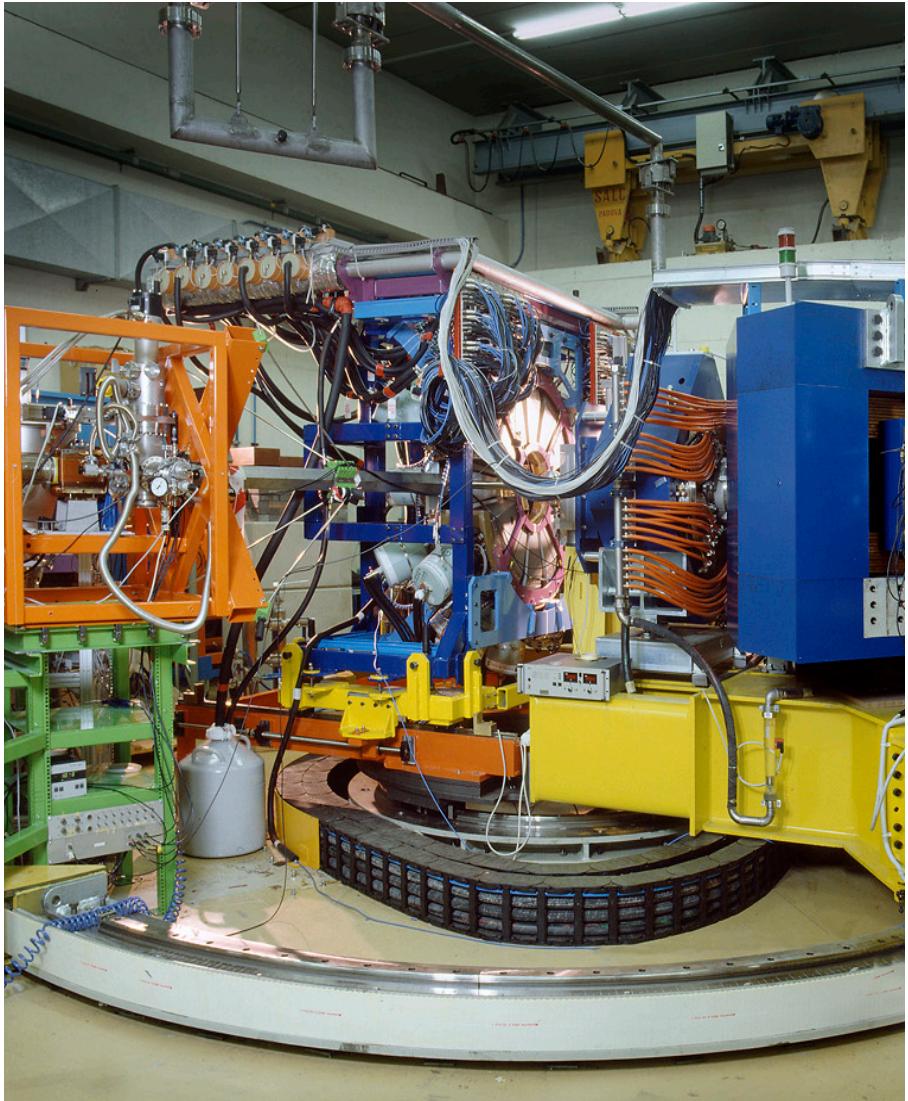
**GANIL** → 2014 - 2016



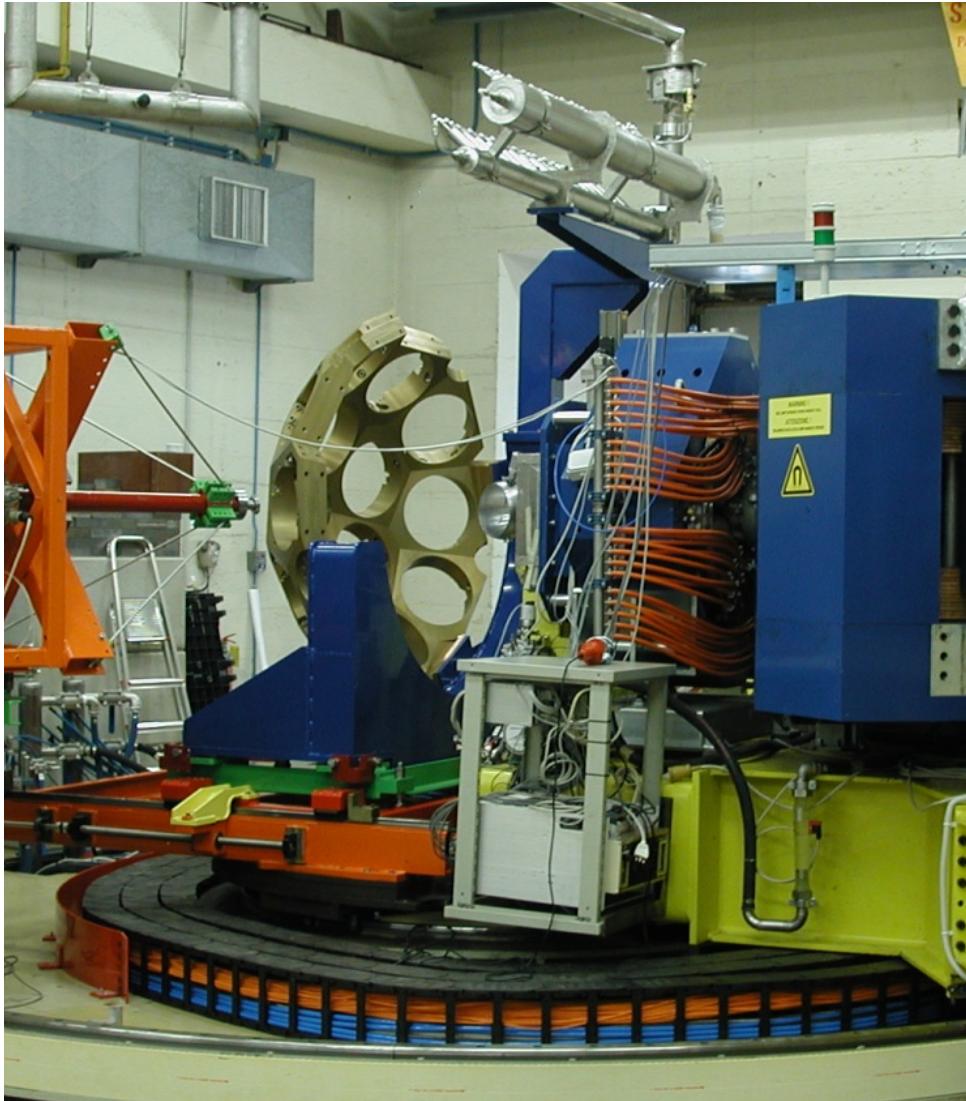
09.06.2006 18:14

Fourth AGATA Week, 6-9<sup>th</sup> June 2006, Liverpool

# From Clara to the AGATA Demonstrator



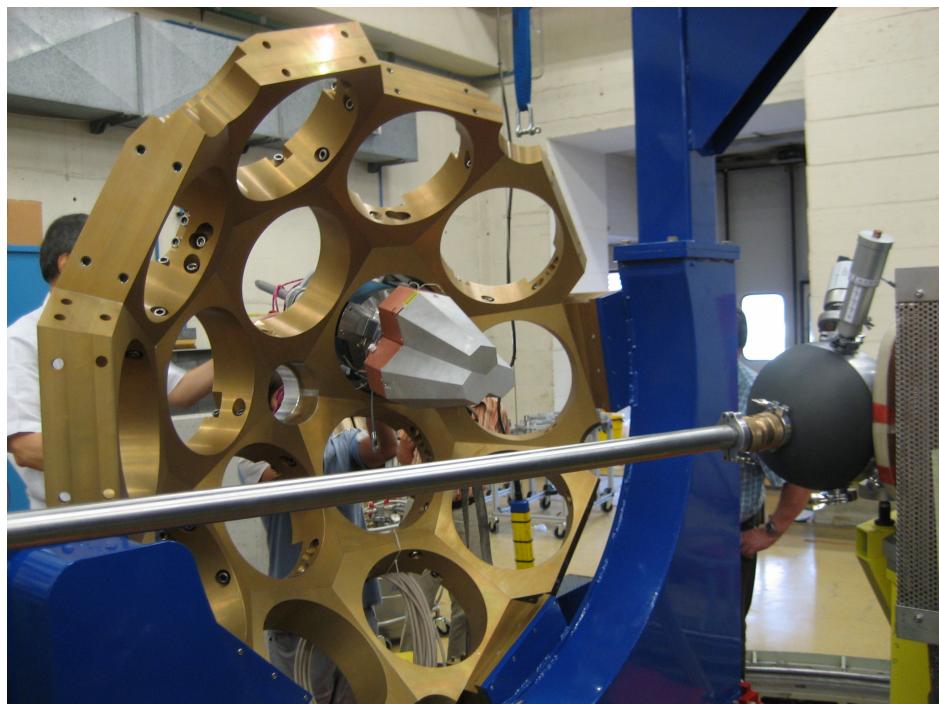
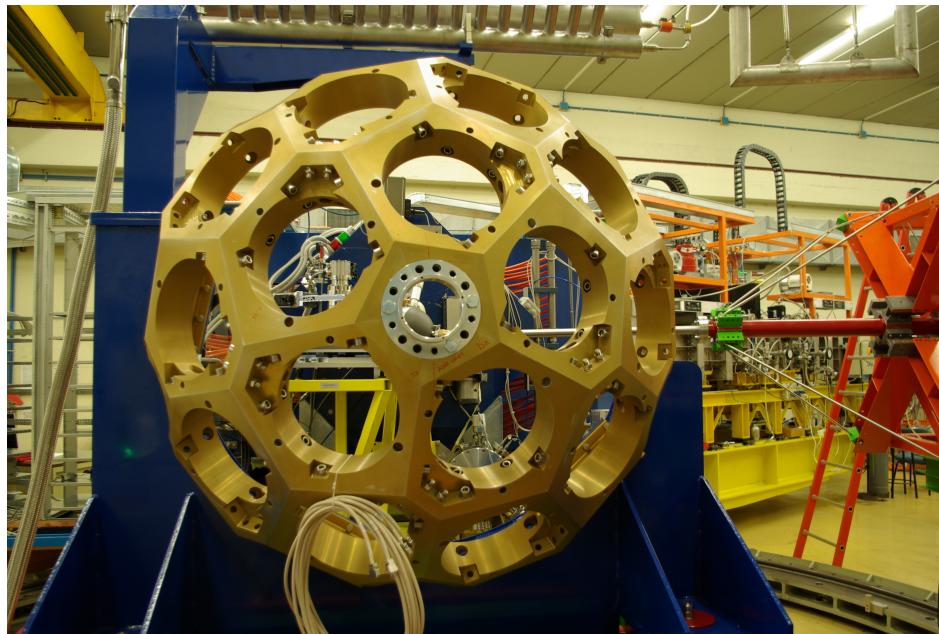
End March 2008



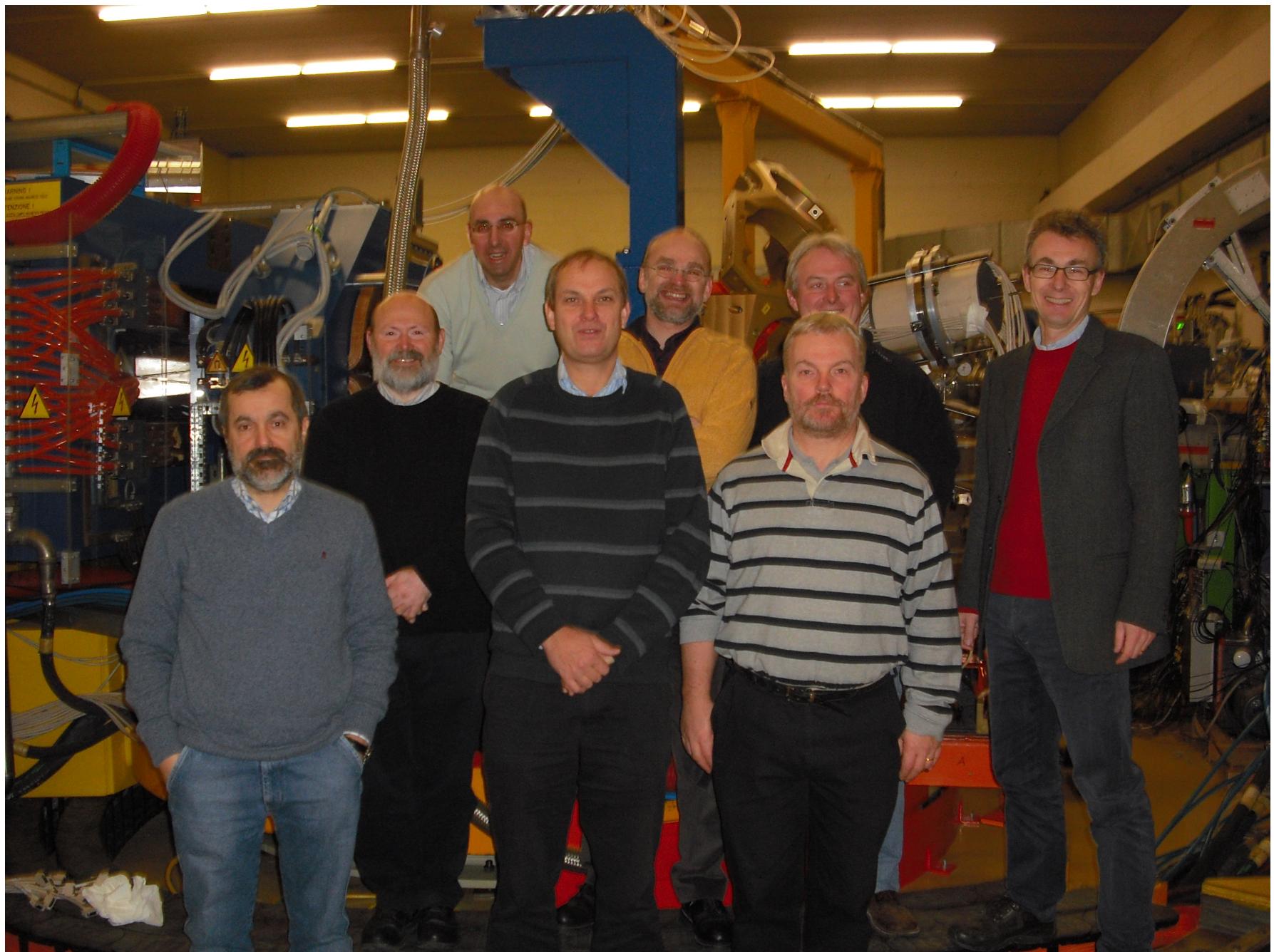
End July 2008

# Assembling the AGATA frame

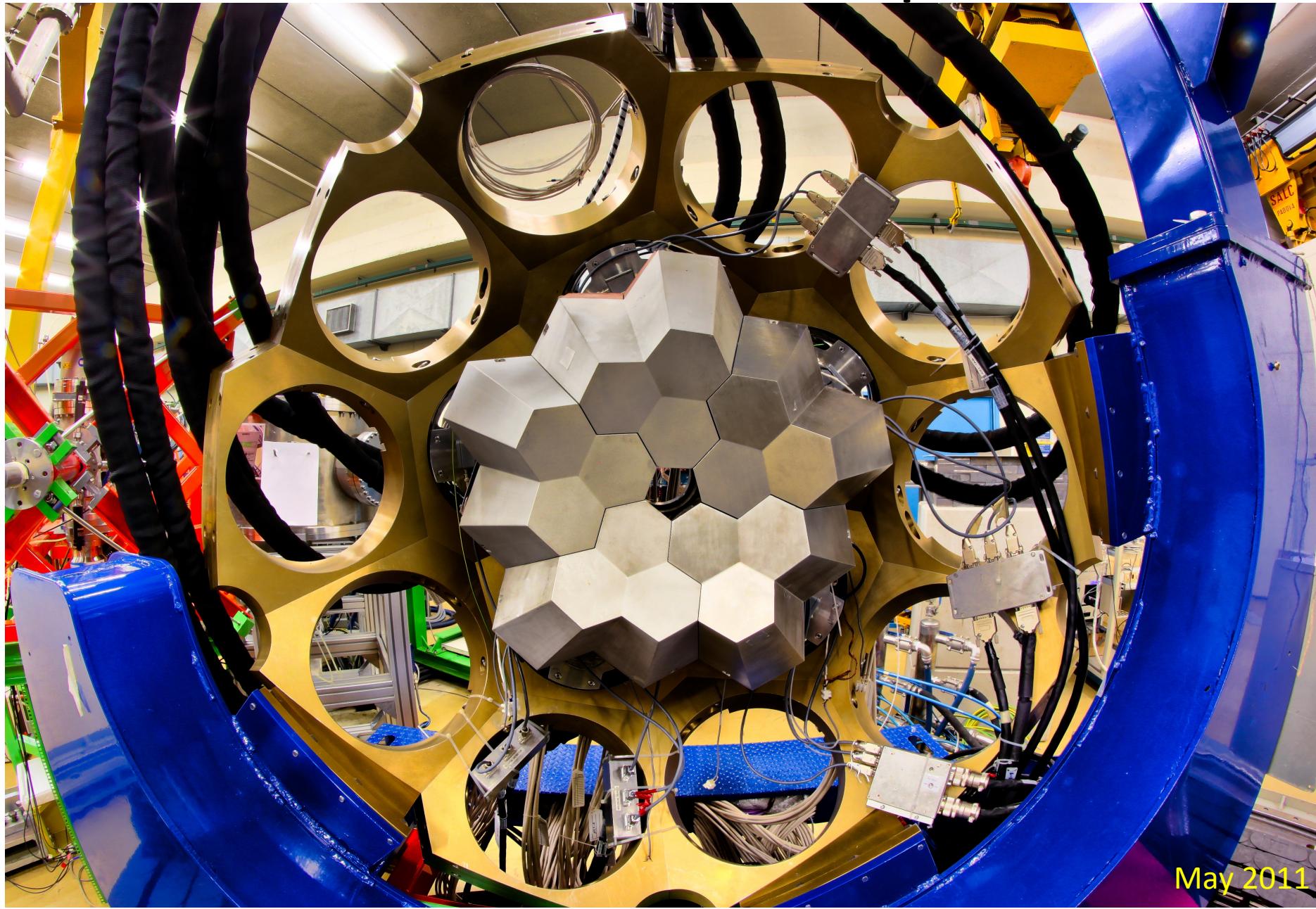






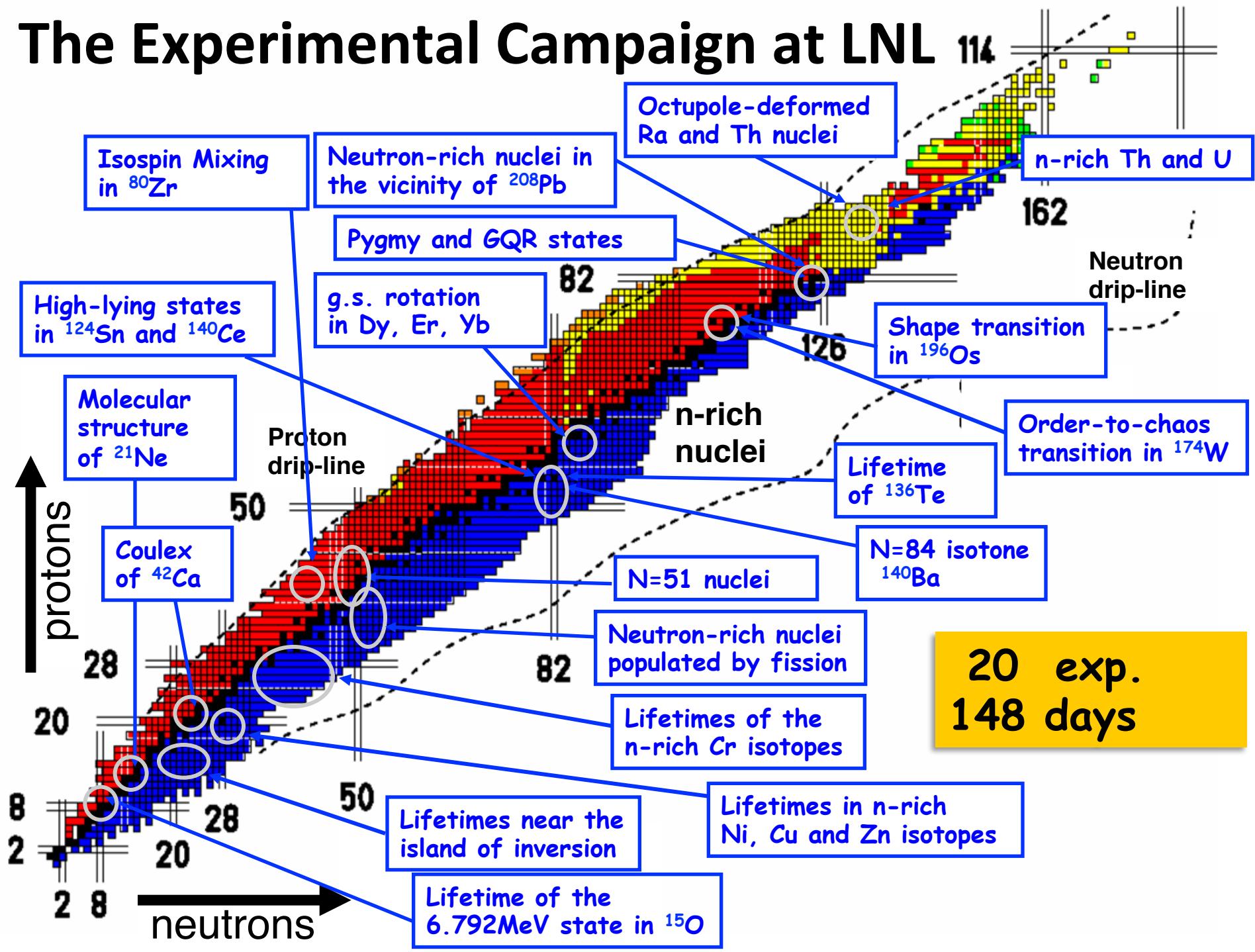


# Demonstrator complete



May 2011

# The Experimental Campaign at LNL



# The AGATA project: a $\gamma$ -array for structure and reaction mechanism studies

## FUSION06 – S.Servolo – March 19-23, 2006



# Inauguration of the AGATA Demonstrator

## LNL, April 6, 2010



# LNL, 2007





The GAMMA group with Enrico and Caterina , Padova, Eremitani Church, April 7, 2013