First experimental indication of the Giant Pairing Vibration in the ^{14}C and ^{15}C nuclei

Diana Carbone

Outline

Searching for the Giant Pairing Vibration with two-neutron transfer reactions between heavy nuclei

- Summary of the GPV features and history

- Experimental results and analysis about $^{12}C(^{18}O,^{16}O)^{14}C$ and $^{13}C(^{18}O,^{16}O)^{15}C$ reactions @ 84 MeV
- GPV signatures: energy, width, cross section, angular distributions

- Preliminary results about the new experiment: $(^{18}O,^{16}O)$ reactions @ 270 MeV with MAGNEX

What is the Giant Pairing Vibration?

Predicted for the first time in 1977 by Broglia and Bes starting from the **quantum symmetry between particles and holes**

R.A. Broglia and D. Bes PLB 69 (1977) 129

- Collective excitation of a pair across major shell
- Analogous to **Giant Resonances** (GDR, GQR)

Giant Resonances	⟷	Collective p-h excitations
Giant Pairing Vibrations (*GPV*)	⟷	Collective p-p or h-h excitations

- L = 0 two-nucleon transfer reactions should populate it

GPV: an old story

Theoretical studies:

- First theoretical predictions limited to **heavy nuclei** (Sn and Pb isotopes)

R.A. Broglia and D. Bes PLB 69 (1977) 129-133
L.Fortunato et al. EPJ A14, 37-42(2002)

- Use of weakly bound projectiles (as the (^{6}He,^{4}He) reactions)

W.von Oertzen and A.Vitturi,Rep.Prog.Phys.64 (2001) 1247
L.Fortunato, Phys.of Atomic Nuclei,Vol.66 (2003) 1445

- Recent predictions on light nuclei (oxygen isotopes) by cQRPA calculations

E.Khan et al. PRC 69 (2004) 014314
B.Avez et al. PRC 78 (2008) 044318

GPV predicted features

- Excitation Energy ~ 20 MeV with respect to the unperturbed nucleus
- FWHM ~ 1-2 MeV (typical of giant modes)
- Cross section comparable to that of the g.s. pairing vibration
- L = 0 angular momentum transfer

Experimental attempts:

- **Unsuccessful** attempts using (p,t) or (t,p) reactions on Sn or Pb

J. R. Shepard et al. NPA 322(1979)92
G. M. Crawley et al. PRC 22 (1980) 316
G. M. Crawley et al. PRC 23 (1981) 589
M. Matoba et al. PRC 27(1983) 2598
B. Mouginot et al. PRC 83 (2011) 037302

NEVER EXPERIMENTALLY OBSERVED

Difficulties in observing the GPV

- **GPV** population requires ***L* = 0** transfer
- In transfer reactions typically **large amount of angular momentum is transferred**
- **Brink's matching conditions**

$$\Rightarrow \quad \Delta L = (\lambda_2 - \lambda_1) + \tfrac{1}{2}k_0(R_1 - R_2) + Q_{eff}\, R/\hbar v \approx 0$$

D.M. Brink PLB 40 (1972) 37

- In heavy nuclei **the level density** is very high already at low energy, thus making the identification of such modes very hard

(^{18}O,^{16}O) reactions on light nuclei: good candidates to populate the GPV

- Low *L* transfer favoured by Brink's matching conditions
- Compromise between the level density and the collectivity
- Preformed neutron pair in ^{18}O
- Very low polarizability of ^{16}O core

Experimental setup @ INFN-LNS

- $^{18}O^{7+}$ beam at 84 MeV incident energy delivered by Tandem accelerator
- ^{12}C, ^{13}C thin targets
- Ejectiles detected by the MAGNEX large acceptance spectrometer
- Angular settings $\theta_{opt} = 6°, 12°, 18°$ ⇨ $3° < \theta_{lab} < 24.3°$

MAGNEX spectrometer

Optical characteristics	Actual values
Maximum magnetic rigidity (Tm)	1.8
Solid angle (msr)	50
Momentum acceptance	-14%, +10%
Momentum dispersion	3.68
First order momentum resolution	5400

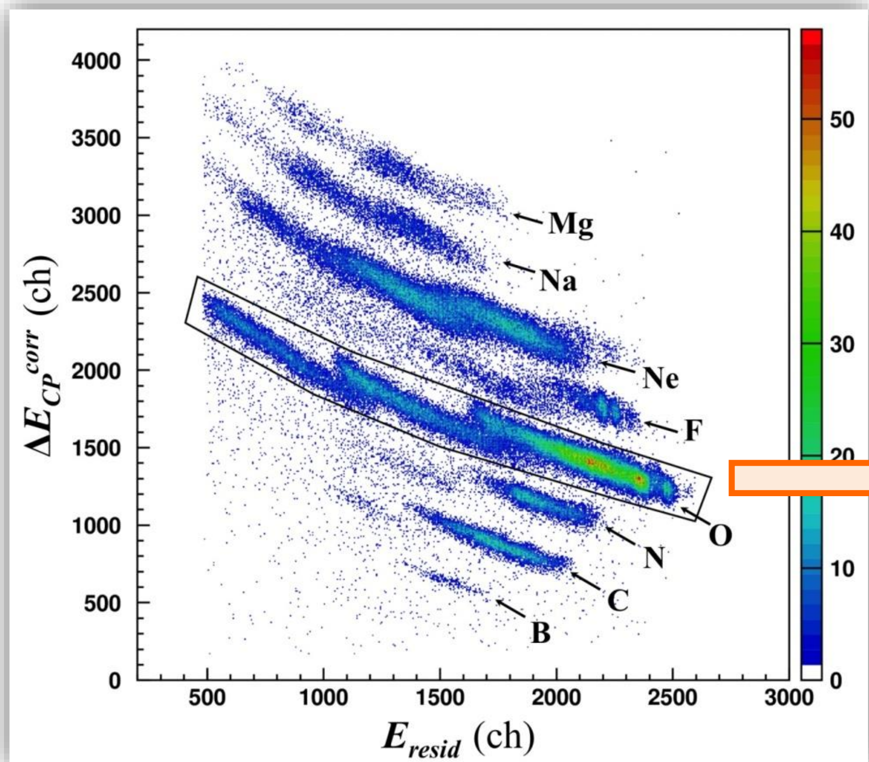
Good compensation of the aberrations:
Trajectory reconstruction

Measured resolutions:
- Energy $\Delta E/E \sim 1/1000$
- Angle $\Delta\theta \sim 0.3°$
- Mass $\Delta m/m \sim 1/160$

F. Cappuzzello et al. Nova Publisher Inc (2011) 1

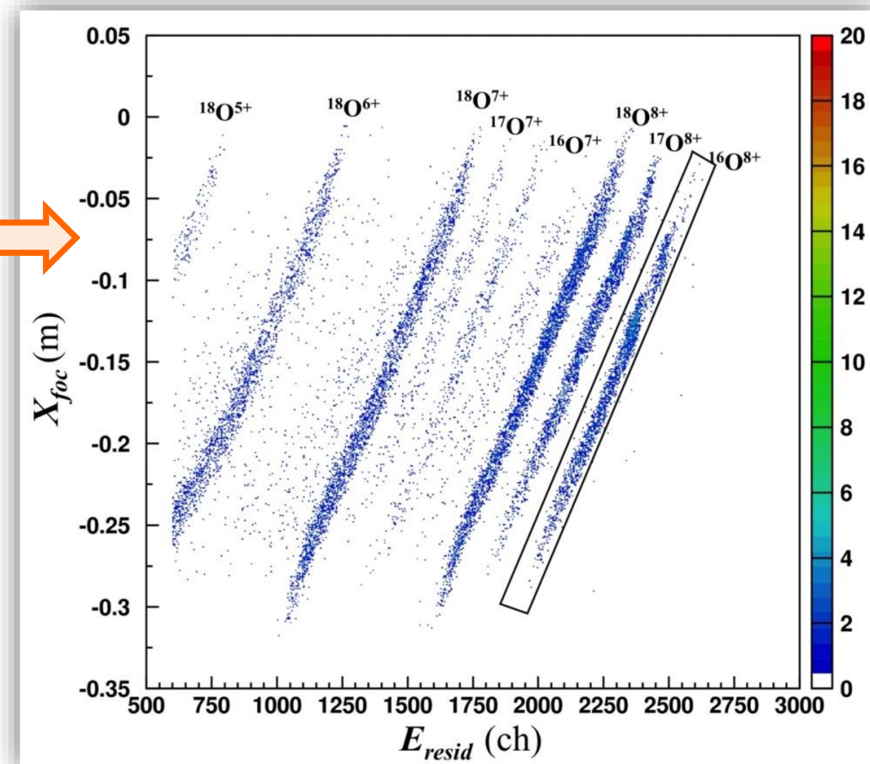
Particle identification

Z identification



A identification

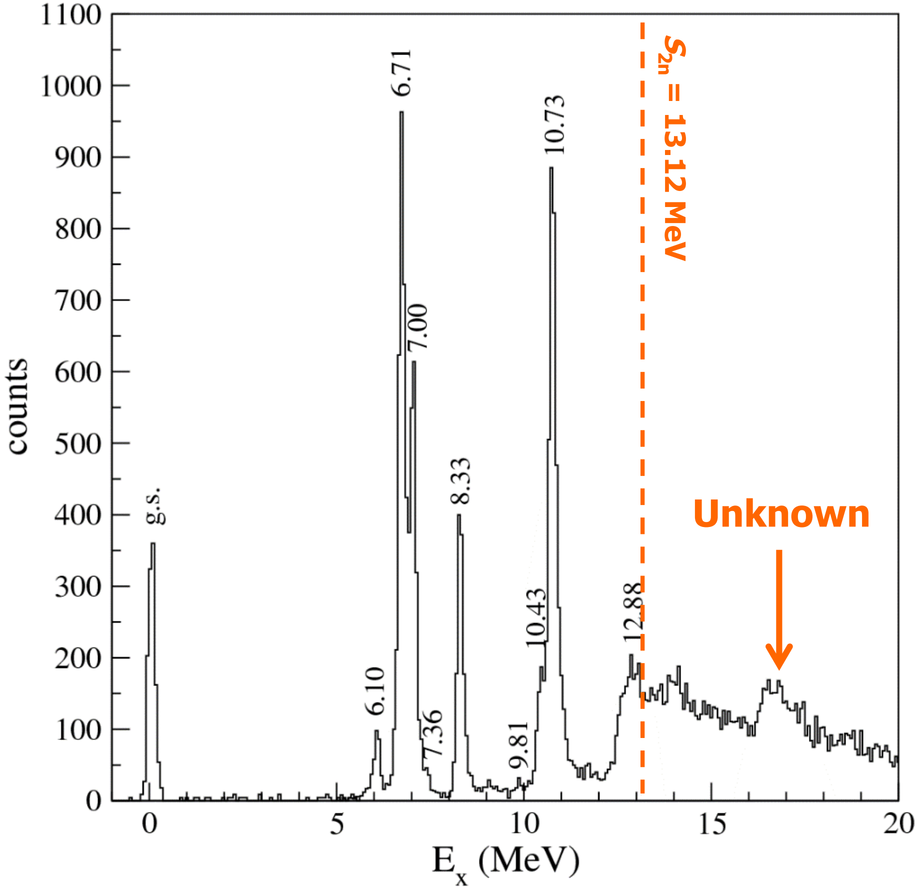
$$B\rho = \frac{p}{q} \quad \rightarrow \quad X_{foc}^2 \propto \frac{m}{q^2} E_{resid}$$



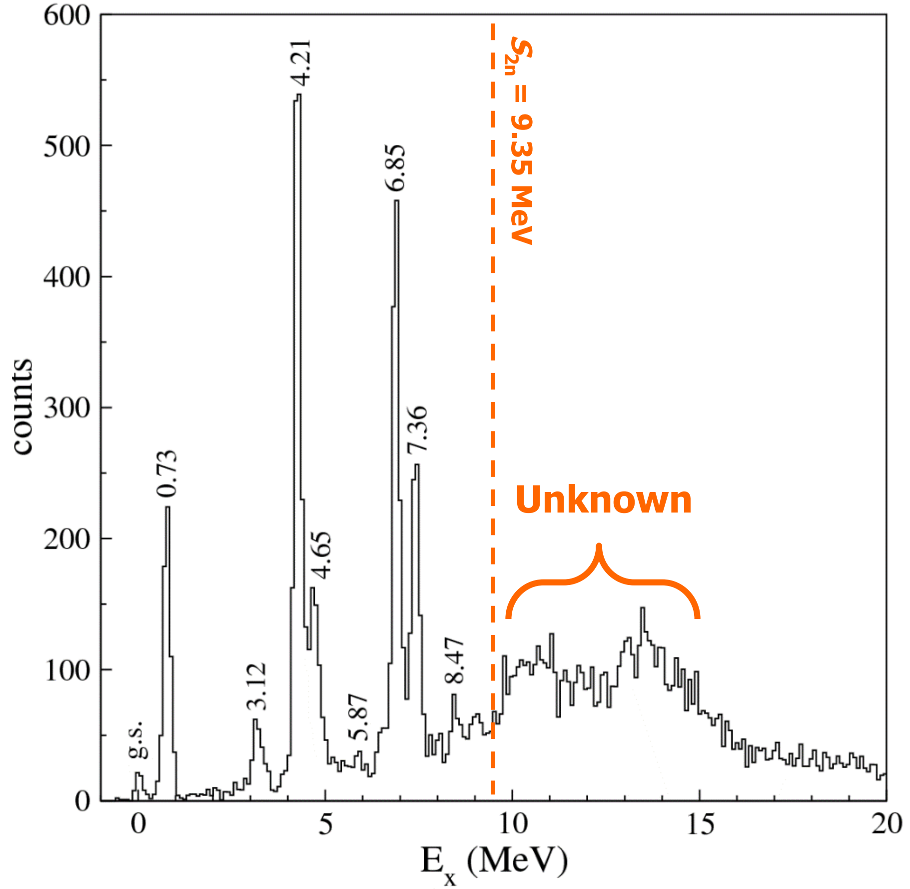
F. Cappuzzello et al., NIMA 621 (2010) 419

Energy spectra

$^{12}C(^{18}O,^{16}O)^{14}C$



$^{13}C(^{18}O,^{16}O)^{15}C$

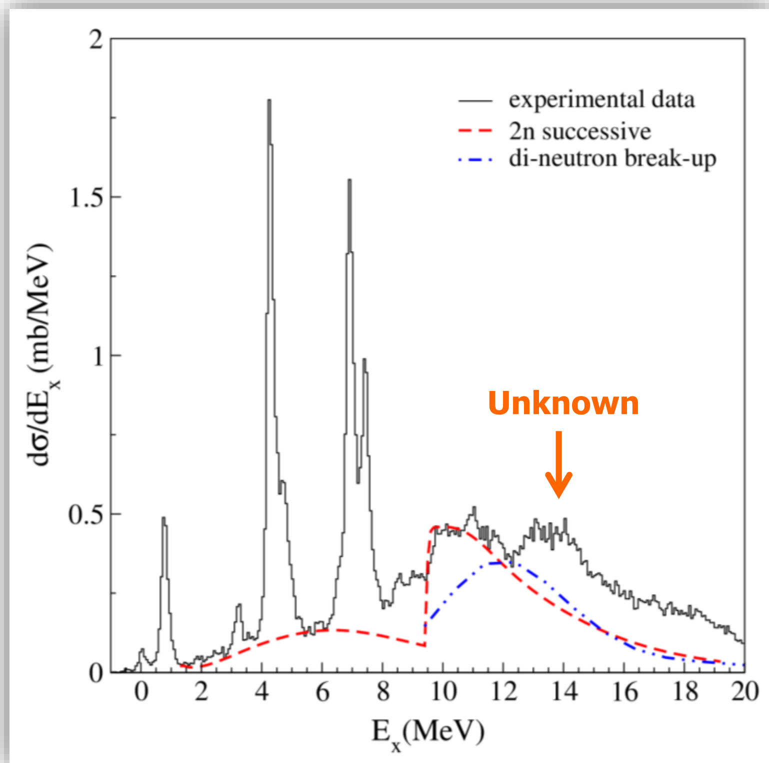


$9° < \theta_{lab} < 10°$

Energy resolution ~ 200 keV

Projectile break-up contribution

$^{13}C(^{18}O,^{16}O)^{15}C$ @ 7° < θ_{lab}<17°



Two independent semi-classical models

1) Removal of two independent neutrons from the projectile
   - Transfer to the continuum of the target+n+n
   - Two-step mechanism
   - No n-n correlations
   - Optical model S-matrix for the n-target interaction

F. Cappuzzello et al., PLB 711 (2012) 347

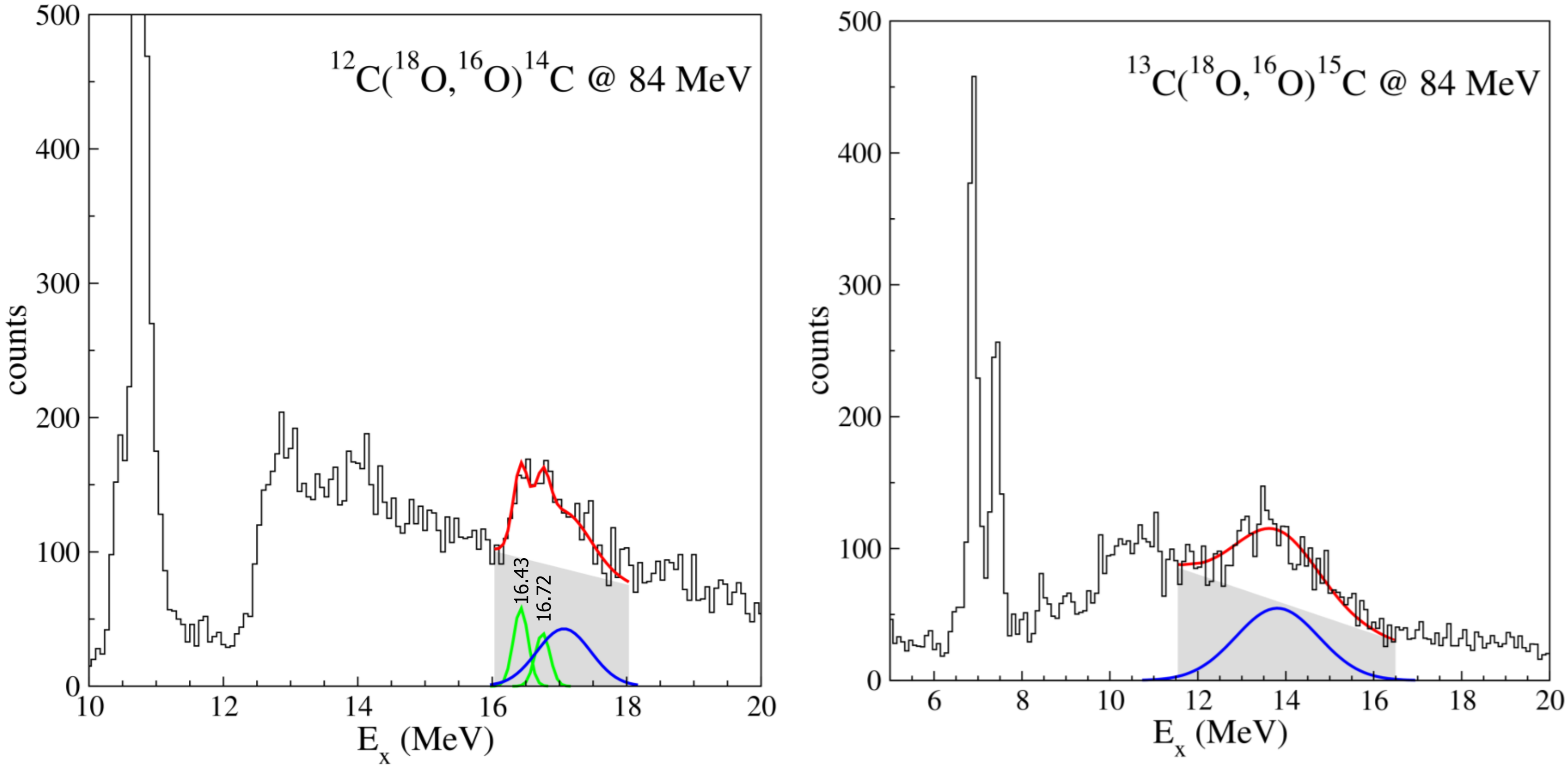
2) Towing of a di-neutron system
   - Extreme hypothesis of the removal of a di-neutron from projectile
   - TDSE approach

J.A. Scarpaci et al., PLB 428 (1998) 241

The ^{15}C bump at 13.7 ± 0.1 MeV is not reproduced

Similar results for ^{14}C case

Energy and width of the bumps

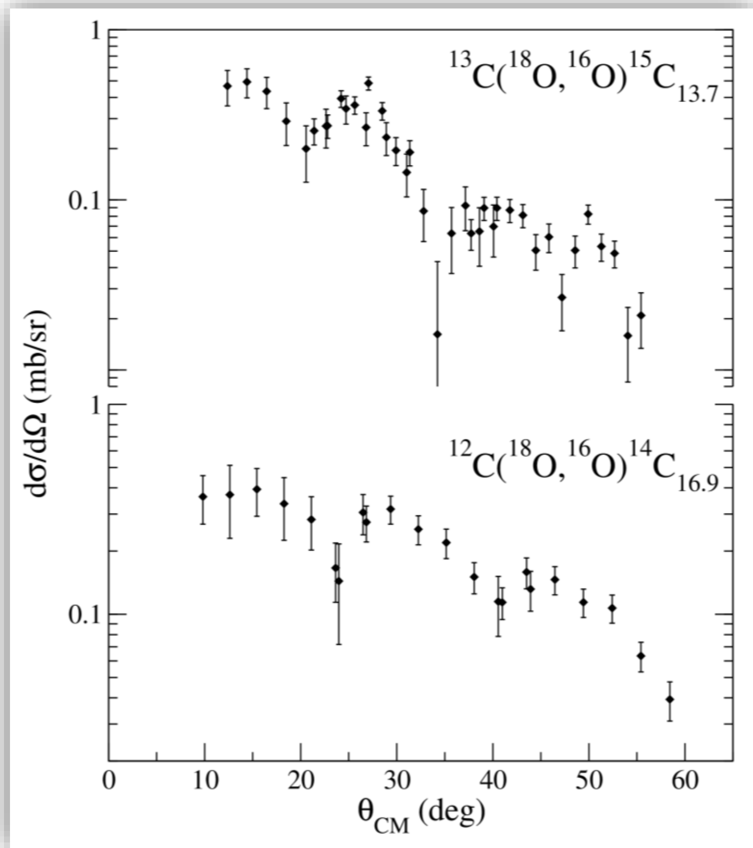


Gaussian model superimposed on a linear background

^{14}C E_x = 16.9 ± 0.1 MeV FWHM = 1.2 ± 0.3 MeV

^{15}C E_x = 13.7 ± 0.1 MeV FWHM = 1.9 ± 0.3 MeV

Bump angular distributions



Clear oscillating pattern in the bump angular distributions

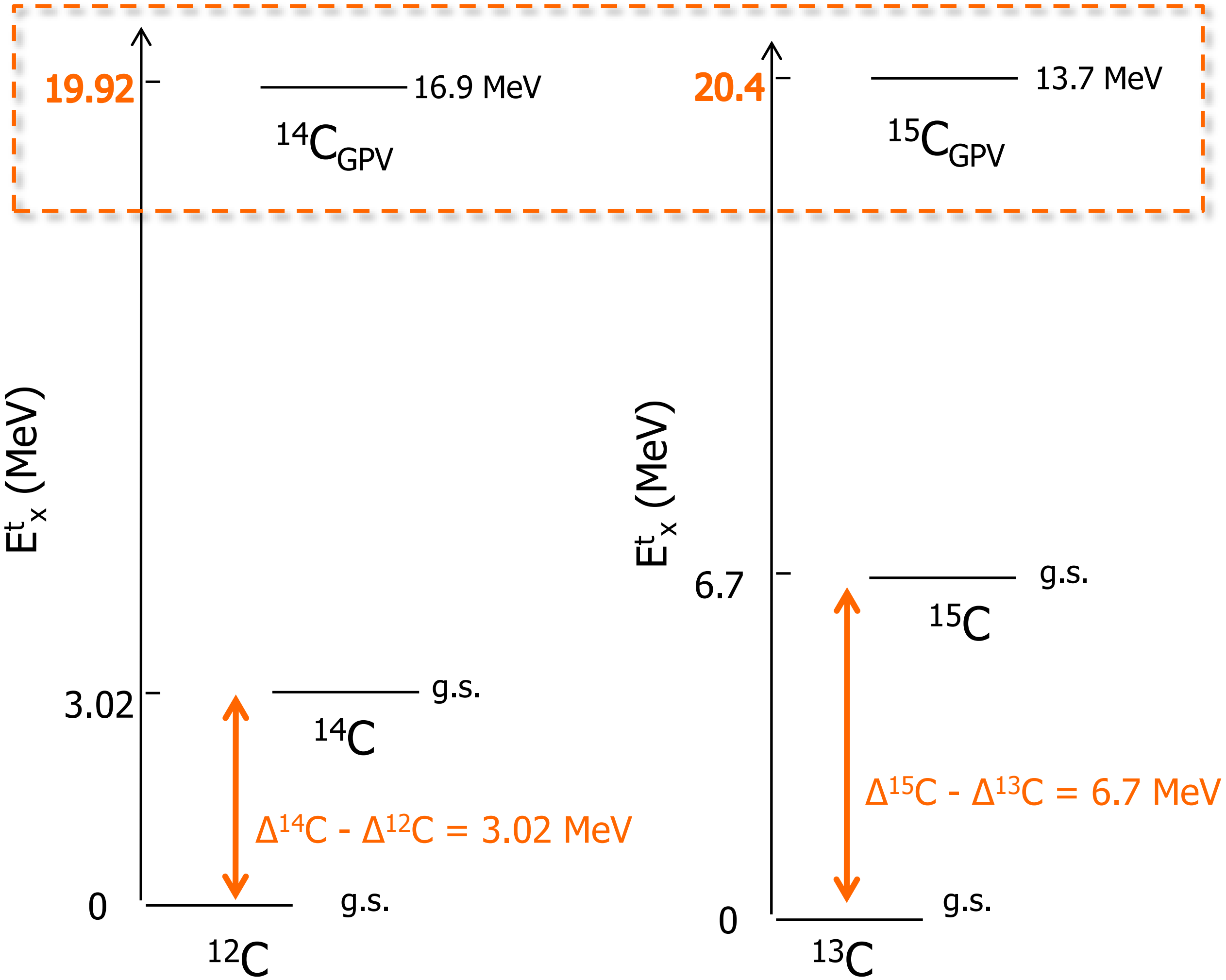
Resonant states characterized by a well-defined angular momentum

GPV properties

- Excitation Energy ~ 20 MeV with respect to the unperturbed nucleus
- FWHM ~ 1-2 MeV (typical of giant modes)
- Cross section comparable to that of the g.s. pairing vibration
- $L = 0$ angular momentum transfer

Excitation energy

The excitation energy of the two resonances compared to the target ground state is the same (~ 20 MeV)



Pairing energy scale

$$E^t_x = E_x + M_r - M_t$$

Consistent with cQRPA predictions

E.Khan et al. PRC 69 (2004) 014314

Width and cross section

Measured widths

^{14}C E_x = 16.9 ± 0.1 MeV **FWHM = 1.2 ± 0.3 MeV**

^{15}C E_x = 13.7 ± 0.1 MeV **FWHM = 1.9 ± 0.3 MeV**

Consistent with the discussions about the GPV

W. von Oertzen and A. Vitturi, Rep. Prog. Phys. 64 (2001) 1247

Cross section

The GPV cross section is predicted to be similar to the L = 0 transition to the g.s.

R.A. Broglia and D. Bes PLB 69 (1977) 129

^{14}C case

$$\left.\begin{array}{l}\sigma(^{14}C_{g.s.}) = 0.92 \pm 0.10 \text{ mb} \\ \sigma(^{14}C_{GPV}) = 0.66 \pm 0.07 \text{ mb}\end{array}\right\}$$ Consistent with theoretical predictions

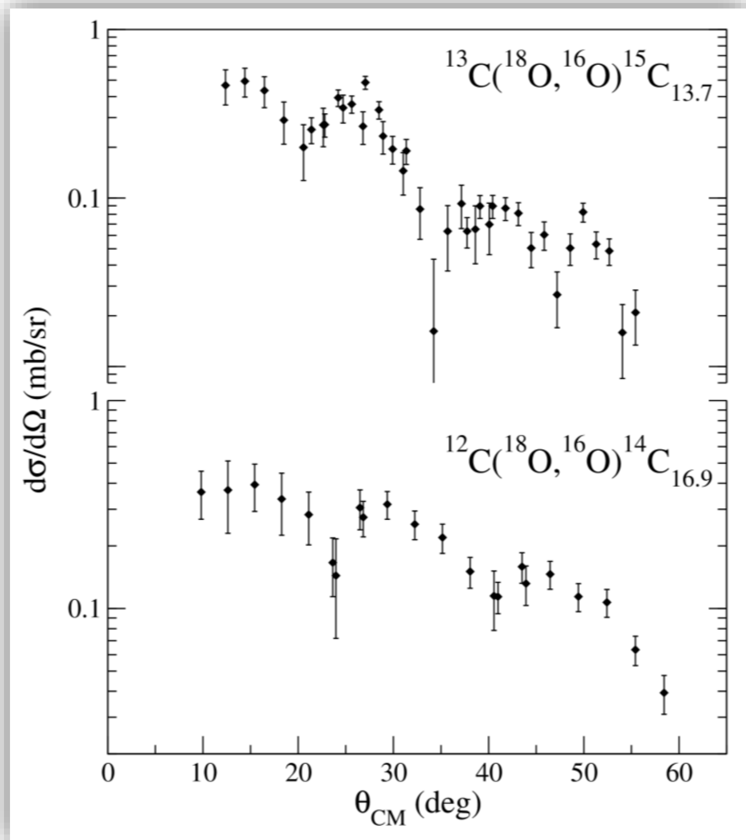
^{15}C case ⇨

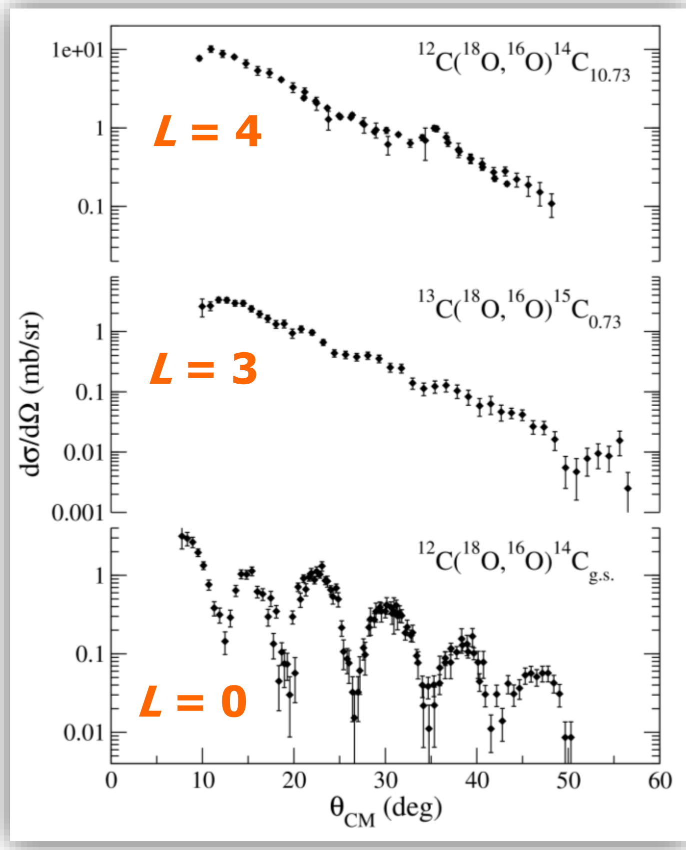
$$\left(\frac{d\sigma(\theta)}{d\Omega}\right)_{tr} = \left(\frac{d\sigma(\theta)}{d\Omega}\right)_{sc} P_{tr}(\theta) F(Q,L)$$

W. von Oertzen and A. Vitturi, Rep. Prog. Phys. 64 (2001) 1247

$$\frac{strength\ (^{15}C_{GPV})}{strength\ (^{14}C_{g.s.})} = 3.5 \pm 0.8$$

Multipolarity: angular distributions





First *L* = 0 indication

Equal population of the *M*-states in heavy-ion reactions near the Coulomb barrier

- L ≠ 0 transitions: featureless shape
- *L* = 0 transitions: oscillations clearly appear

Multipolarity: calculations for $^{14}C_{GPV}$

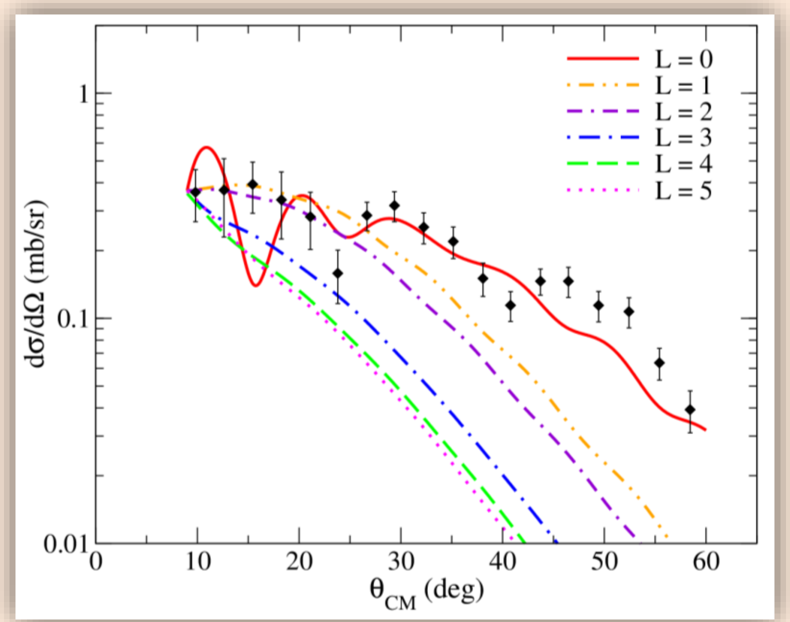
Common ingredients: a. Sao-Paulo parameter free double folding potential
b. Extreme cluster model approximation for the two neutrons

1. Discretized continuum scheme calculations

A.M. Moro and F.M. Nunes, Nucl. Phys. A 767 (2006) 138

- Three body assumption ⇨ finer details not accurate
- Global features: *L* = 0 cross section absolute value is found consistent with the experimental **without any scaling factor**

2. CRC calculations



- Same approach used to describe transitions to bound and resonant states in ^{14}C
M. Cavallaro et al., PRC 88 (2013) 054601
- Calculations for various *L* components
- Artificial energy value of 12 MeV (below S_{2n})
- No spectroscopic amplitudes available
⇨ Renormalization at θ_{CM} = 9°
- Shape of the *L* = 0 calculation consistent with the experimental angular distribution

Both approaches suggest *L* = 0 transfer for the ^{14}C resonance at 16.9 MeV

^{14}C E_x = 16.9 MeV FWHM = 1.2 MeV

^{15}C E_x = 13.7 MeV FWHM = 1.9 MeV

- ✓ Right energy
- ✓ Right width
- ✓ Right cross section
- ✓ L = 0 transfer

GPV population

Particle-hole symmetry confirmation

nature COMMUNICATIONS

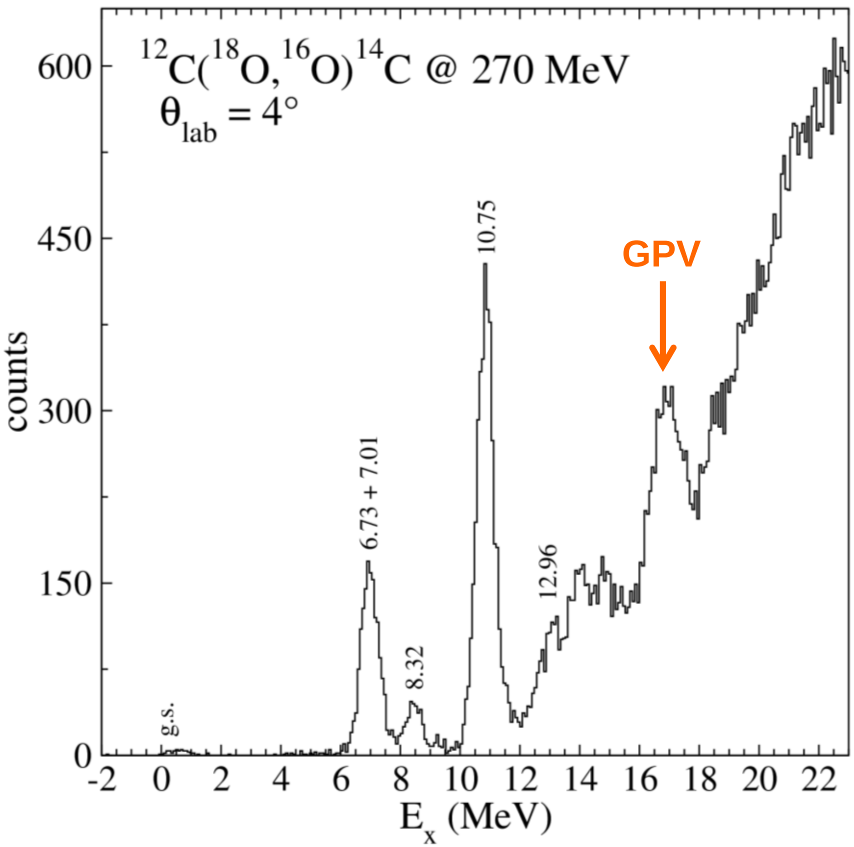
ARTICLE

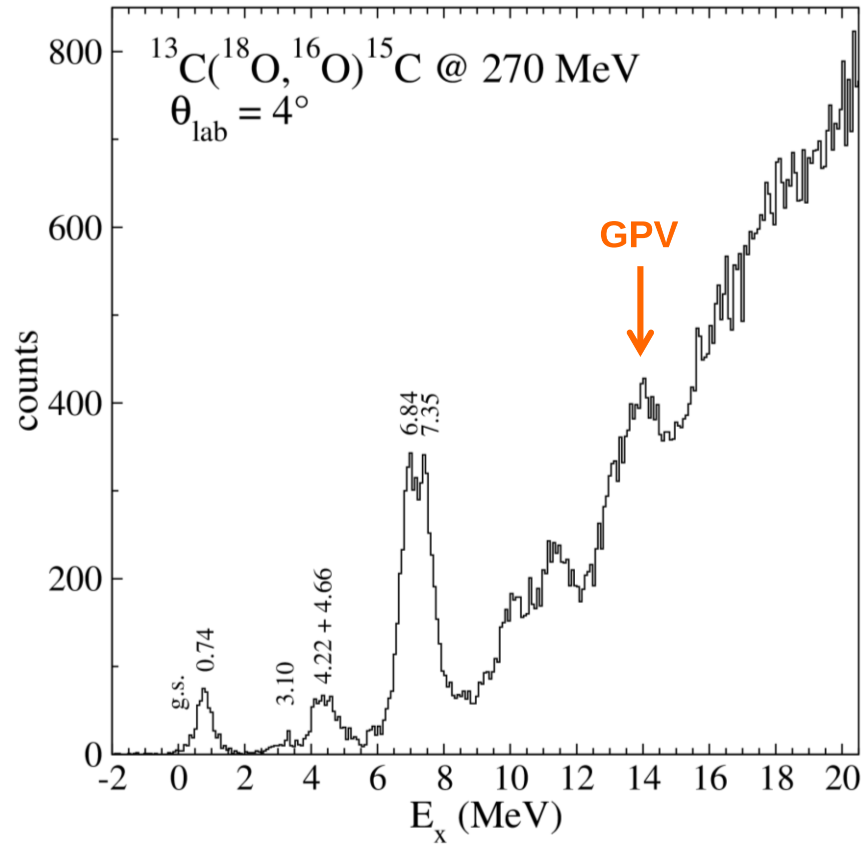
Received 28 Dec 2014 | Accepted 24 Feb 2015 | Published 27 Mar 2015 DOI: 10.1038/ncomms7743 OPEN

Signatures of the Giant Pairing Vibration in the ^{14}C and ^{15}C atomic nuclei

F. Cappuzzello[1,2], D. Carbone[2], M. Cavallaro[2], M. Bondì[1,2], C. Agodi[2], F. Azaiez[3], A. Bonaccorso[4], A. Cunsolo[2], L. Fortunato[5,6], A. Foti[1,7], S. Franchoo[3], E. Khan[3], R. Linares[8], J. Lubian[8], J.A. Scarpaci[9] & A. Vitturi[5,6]

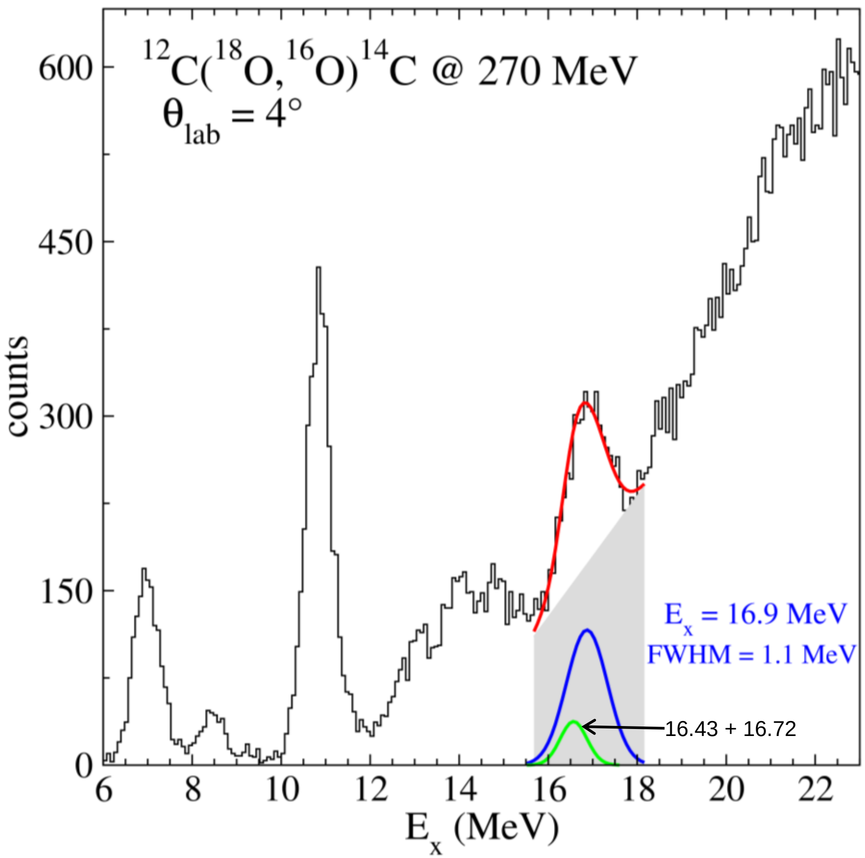
New experiment @ 270 MeV

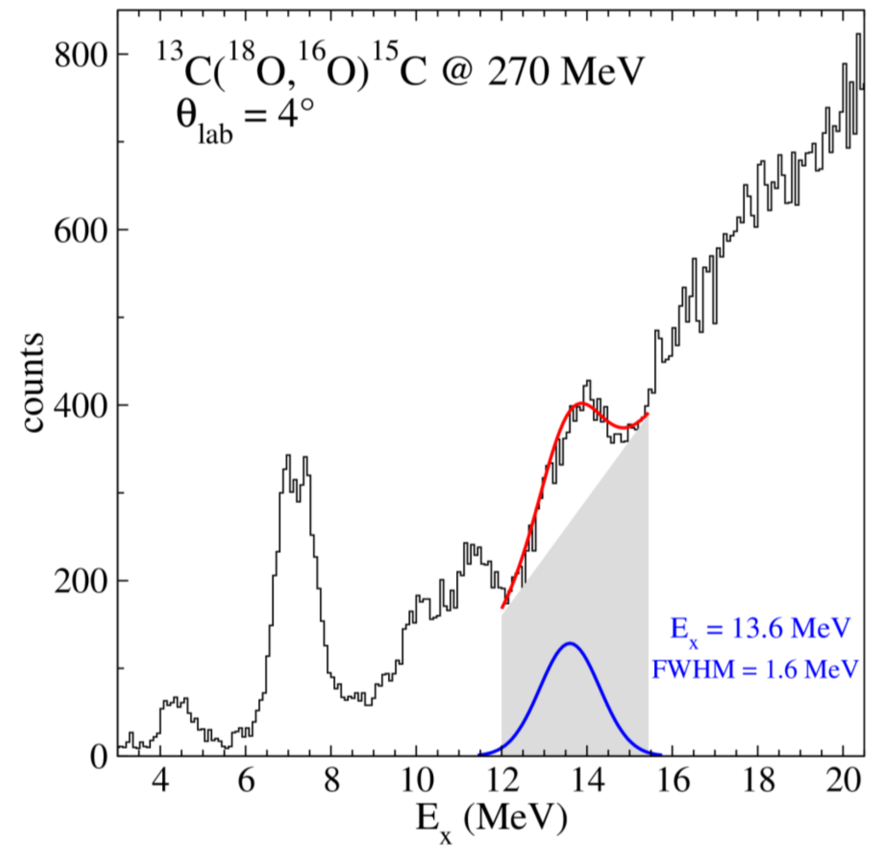




Energy resolution ~ 600 keV

New experiment @ 270 MeV





@ 84 MeV incident energy

$^{14}C_{GPV}$ $E_x = 16.9 \pm 0.1$ MeV
FWHM = 1.2 ± 0.3 MeV

$^{15}C_{GPV}$ $E_x = 13.7 \pm 0.1$ MeV
FWHM = 1.9 ± 0.3 MeV

Conclusions and Outlooks

- $^{12}C(^{18}O,^{16}O)^{14}C$ and $^{13}C(^{18}O,^{16}O)^{15}C$ at 84 MeV
- Known bound and resonant states of the residual nuclei
- Unknown bumps in the continuum
- Angular distributions in wide range $6° < \theta_{CM} < 60°$

Evidence of the GPV population

- Particle-hole symmetry confirmation

New experiment:

- $^{12}C(^{18}O,^{16}O)^{14}C$ and $^{13}C(^{18}O,^{16}O)^{15}C$ at 270 MeV
- Population of the same resonances:
  - ✓ same energy
  - ✓ same width

Outlooks:

- Bumps angular distributions
- Other targets

Working group

C.Agodi, M.Bondì, D.Carbone, M.Cavallaro, F.Cappuzzello, A.Cunsolo, A.Foti

Dipartimento di Fisica e Astronomia, Università degli Studi di Catania, Italy
Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud, Italy
Istituto Nazionale di Fisica Nucleare – Sezione Catania, Italy

A.Bonaccorso

Istituto Nazionale di Fisica Nucleare – Sezione di Pisa

A.Vitturi, L.Fortunato

Università degli Studi di Padova

F. Azaiez, S.Franchoo, E. Khan, J.A.Scarpaci

CNRS - IN2P3 – Institut de Physique Nucléaire d'Orsay, France

R.Linares, J.Lubian

Universidade Federal Fluminense, Niteroi, Brazil