



# Nuclear response to two-neutron transfer via the ( $^{18}\text{O}$ , $^{16}\text{O}$ ) reaction

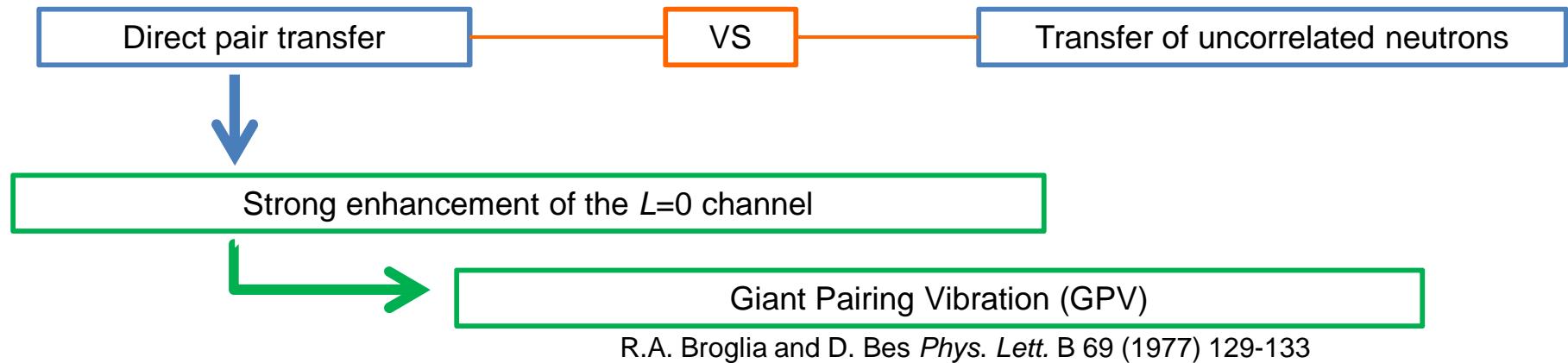
Diana Carbone  
University of Catania and LNS – INFN (Italy)

# DREB2012

*Direct Reactions with Exotic Beams*  
*Pisa, Italy, 26 - 29 March 2012*

# Two neutron transfer reactions

- Can test the nn-pairing interaction
- Possible direct transfer of one correlated pair



## Pairing vibrations observed experimentally

R. Middleton et al., *Nucl. Phys.* 51 (1964) 77  
J.H. Bjerregaard et al., *PLB* 24 (1967) 568

## Theoretical framework: particle-particle excitations

A. Bohr and B. Mottelson, *Nuclear Structure, Vol. II* (Benjamin, New York, 1975).  
D. Bes and R.A. Broglia, *Nucl. Phys.* 80 (1965) 289

Collective p-h excitations



Giant Resonances

Collective p-p or h-h excitations



Giant Pairing Vibrations (GPV)

# GPV: an old story

## Several theoretical studies:

### Predicted properties of the GPV (heavy nuclei)

- Excitation Energy  $\sim 72 A^{-1/3}$  ( $\sim 15 - 20$  MeV)
- FWHM  $\sim 7.8 A^{-1/3}$
- Collective nature
- $L = 0$  angular momentum transfer

### ✓ on Heavy nuclei (Pb and Sn isotopes)

R.A. Broglia and D. Bes *PLB* 69 (1977) 129-133

L.Fortunato et al, *EPJ. A14*, 37-42(2002)

### ✓ with weakly bound exotic nuclei (( ${}^6\text{He}$ , ${}^4\text{He}$ ) transfer reactions)

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

L.Fortunato, *Phys. of Atomic Nuclei*, Vol.66, N8, 1445 (2003)

### ✓ on light nuclei (Oxygen isotopes)

Excitation Energy  $\sim 20$  MeV

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

B.Avez et al., *PRC* 78, 044318 (2008)

## Many experimental attempts:

### ✓ (p,t) and (t,p) reactions

J. R. Shepard, et al., *NPA* 322(1979)92

G. M. Crawley et al, *PRC* 22 (1980) 316

M. Matoba et al, *PRC* 27(1983) 2598

G. M. Crawley ,et al., *PRL* 39 (1977) 1451

G. M. Crawley ,et al., *PRC* 23 (1981) 589

NEVER EXPERIMENTALLY OBSERVED

# The role of the reaction mechanism

- GPV requires  $L = 0$  transfer
- In transfer reactions typically large amount of linear and angular momentum is transferred

# The role of the incident energy

**Near the Coulomb barrier** the angular momentum transfer is minimized

Drawback:

1. The angular distributions are peaked at the **grazing angle** and are not sensitive to the structure of the populated states
2. **Q-value matching rules** typically suppress the cross section at high excitation energy where the GPV is expected

**At high incident energy** the mechanism is characterized by a large amount of angular momentum transfer and by deep inelastic collisions

At energies between **3 and 10 times the Coulomb barrier** the angular distributions are sensitive to the final populated states

*N. Anyas-Weiss et al., Phys. Rep. 12 (1974) 201-272*

*S. Kahana and A. J. Baltz, Advances in Nuclear Physics Vol. 9*

# The role of the involved nuclei

- Brink's matching conditions

D.M. Brink, Phys. Lett. B 40 (1972) 37-40

$$\Delta k = k_0 - \lambda_1 / R_1 - \lambda_2 / R_2 \approx 0$$

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

$$l_1 + \lambda_1 = even$$

$$l_2 + \lambda_2 = even$$

$$k_0 = mv / \hbar$$

$$Q_{eff} = Q - (Z_1^f Z_2^f - Z_1^i Z_2^i)$$

- The survival of a **preformed pair** in a transfer process is favored when the initial and final orbitals are the same

# $(^{18}\text{O}, ^{16}\text{O})$ reactions

On light nuclei

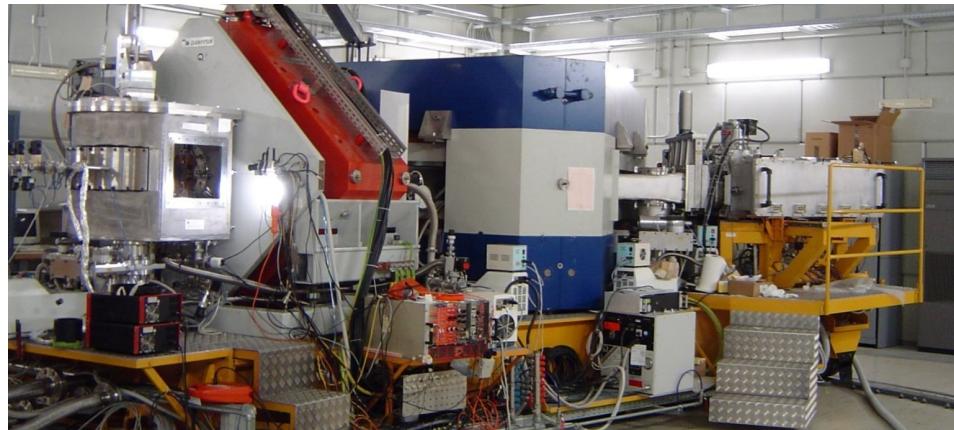
Good candidates for  $L = 0$  transitions

- ✓ Brink's matching conditions (D.M. Brink, Phys. Lett. B 40 (1972) 37-40)
- ✓ Preformed neutron pair in  $^{18}\text{O}$
- ✓ Energy range of ~ 3.5 times the Coulomb barrier

# Experimental Setup

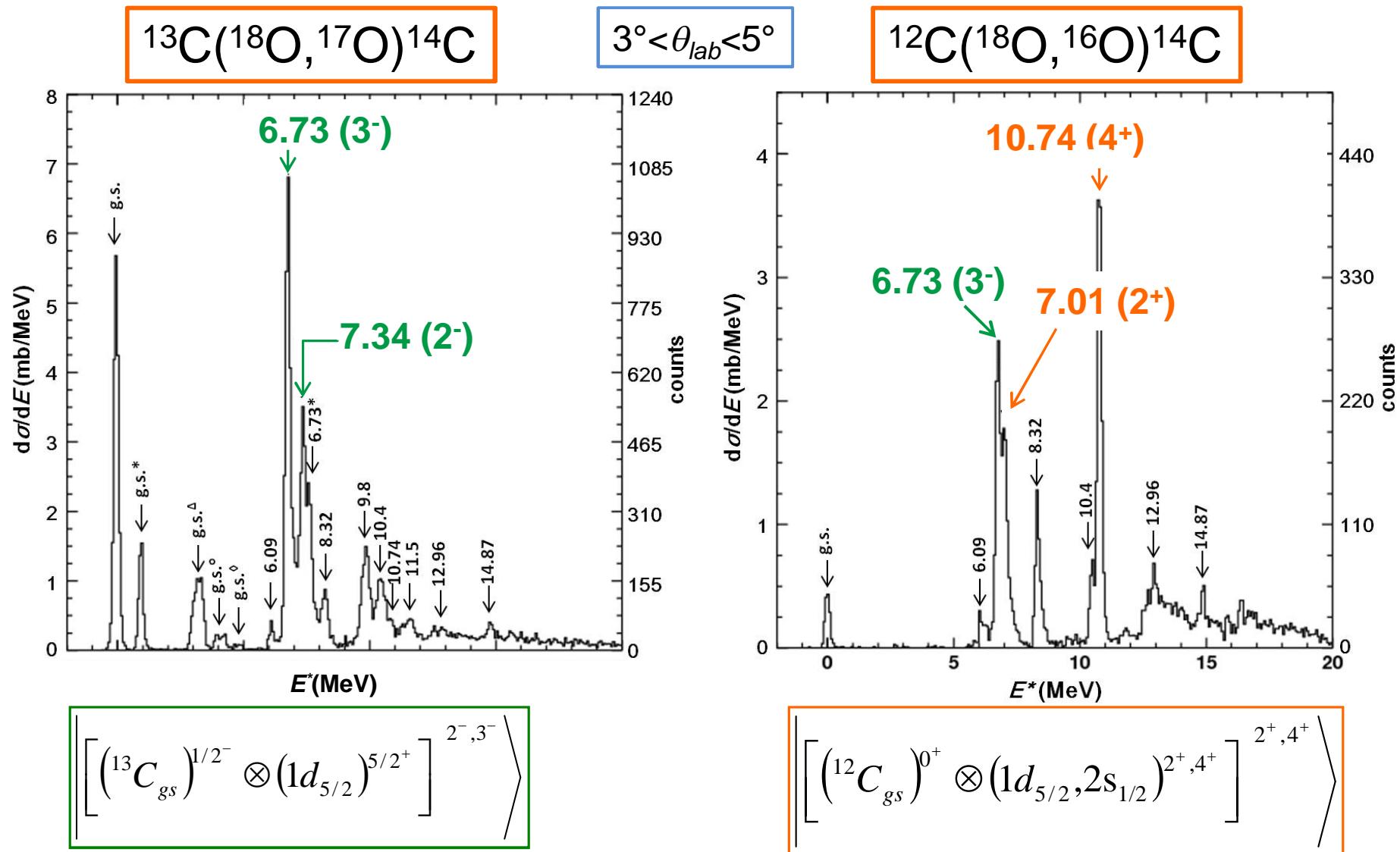
## LNS - INFN (Catania)

- $^{18}\text{O}^{7+}$  beam from Tandem accelerator at 84 MeV
- Light nuclei:  $^9\text{Be}$ ,  $^{11}\text{B}$ ,  $^{12}\text{C}$ ,  $^{13}\text{C}$
- Heavy nuclei:  $^{58}\text{Ni}$ ,  $^{64}\text{Ni}$ ,  $^{120}\text{Sn}$ ,  $^{208}\text{Pb}$
- Ejectiles detected by the MAGNEX spectrometer
- Angular setting  $\theta_{opt} = 6^\circ, 12^\circ, 18^\circ, 24^\circ \longrightarrow 4^\circ < \theta_{lab} < 30^\circ$
- Magnetic setting for ( $^{18}\text{O}, ^{16}\text{O}$ ) channel

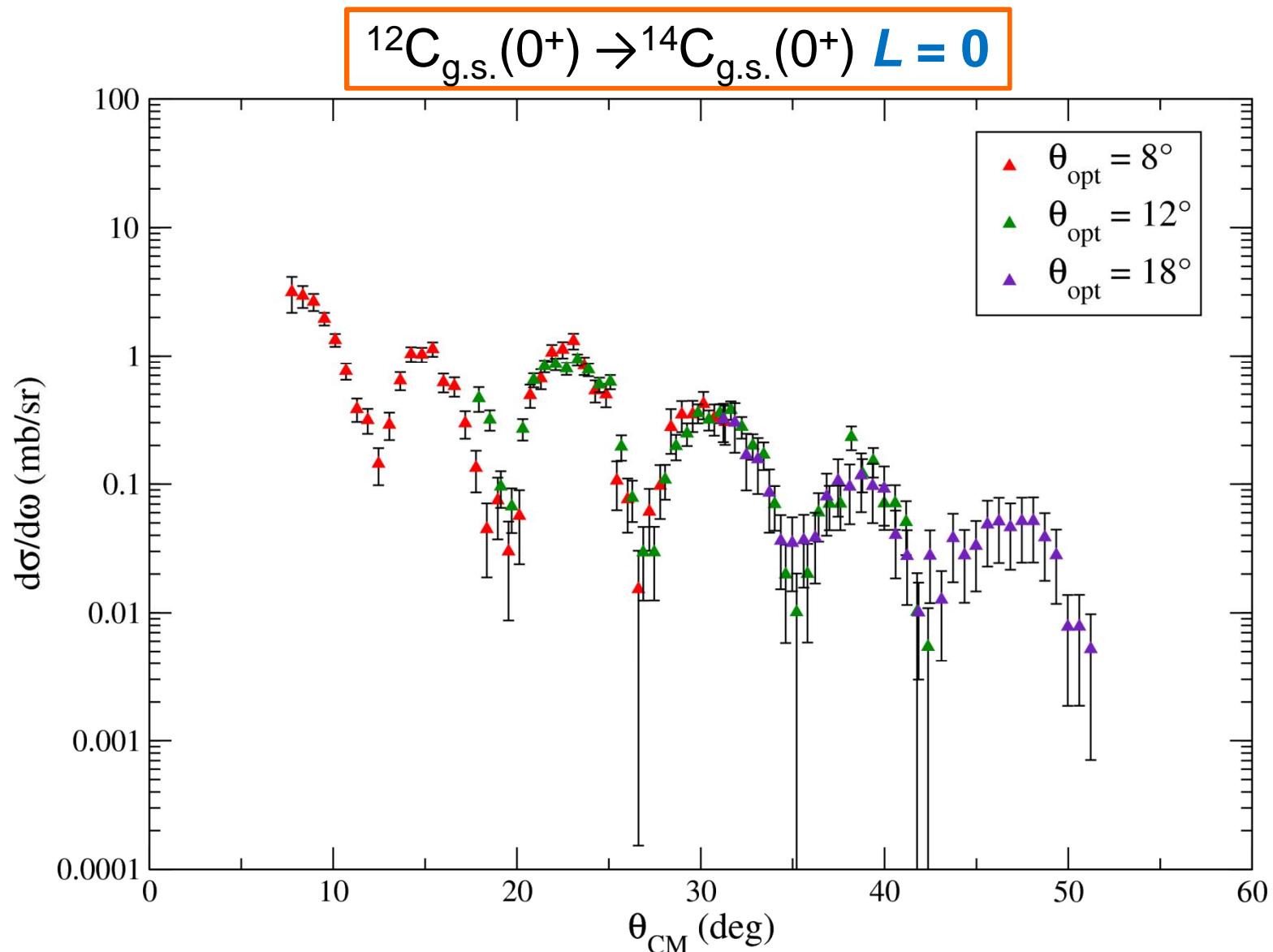


# **Experimental results**

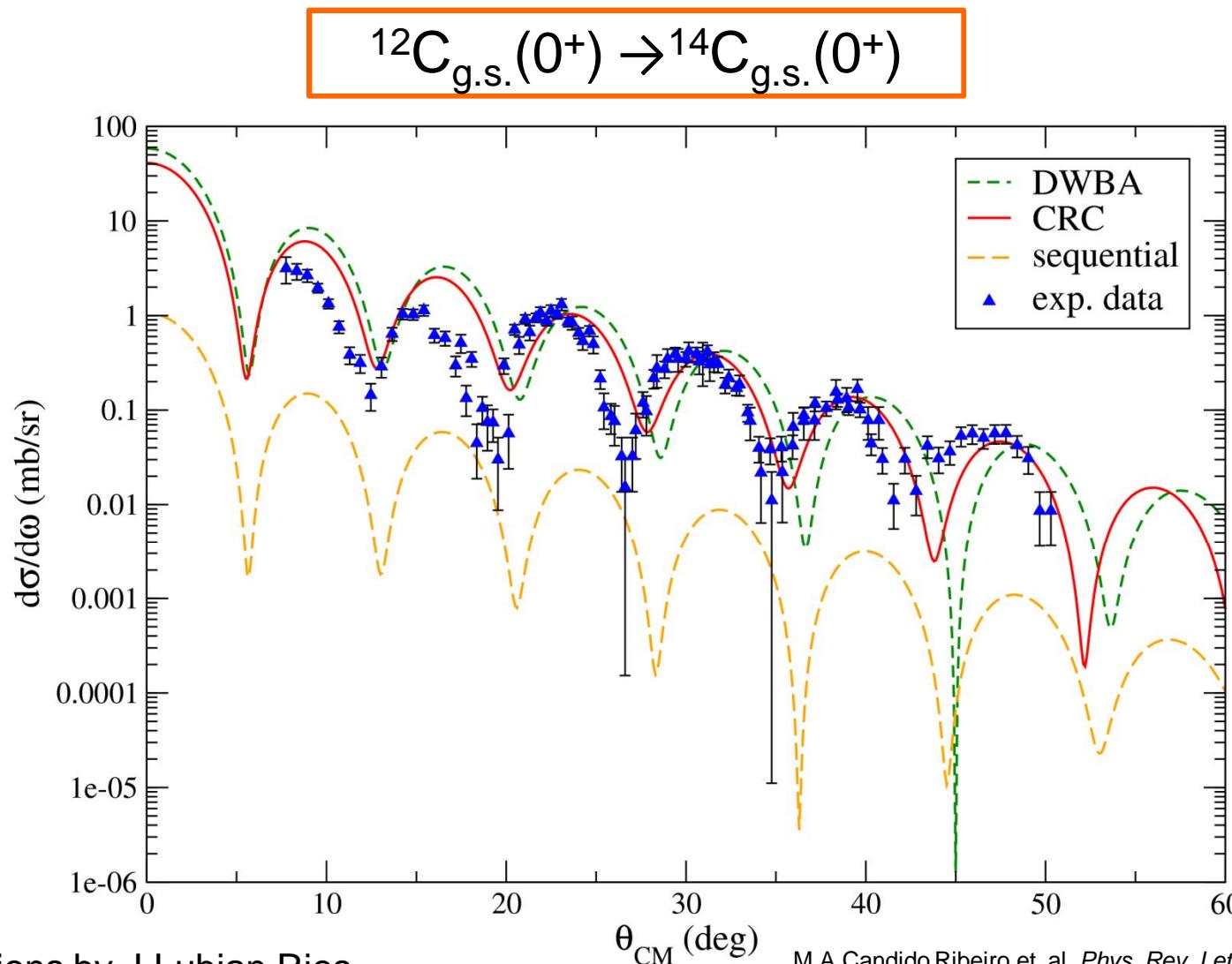
# Selectivity of the $(^{18}\text{O}, ^{16}\text{O})$



# $^{14}\text{C}_{\text{g.s.}}$ angular distribution



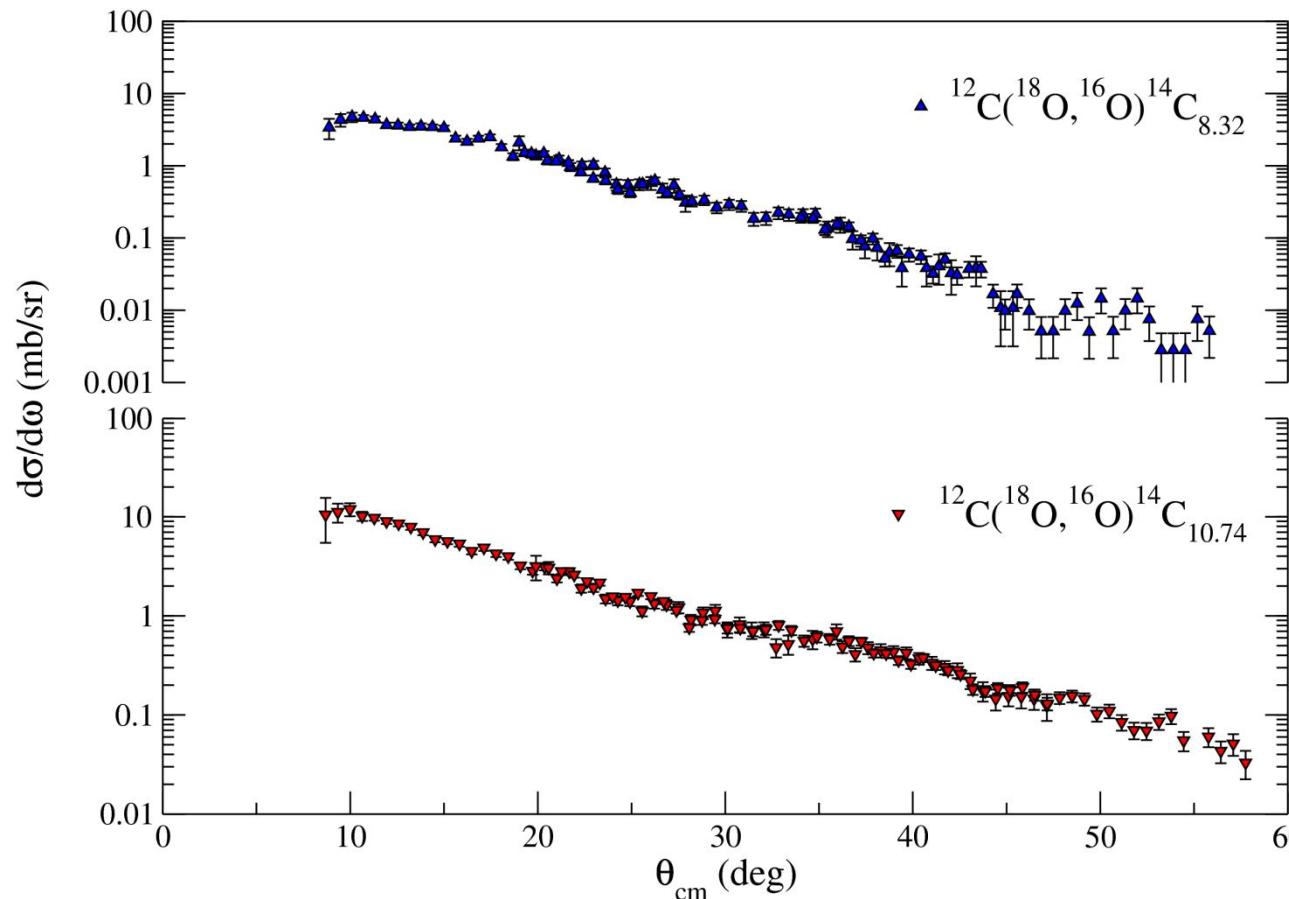
# DWBA & CRC calculations



Calculations by J.Lubian Rios  
UFF - Niteroi

M.A.Candido Ribeiro,et. al. *Phys. Rev. Lett.* **78** (1997)3270  
L.C..Chamon, D.Pereira, et. al. *Phys. Rev. Lett.* **79** (1997)5218  
L.C.Chamon, et. al. *Phys. Rev. C* **66** (2002) 014610

# $^{14}\text{C}$ angular distributions



$L = 2$

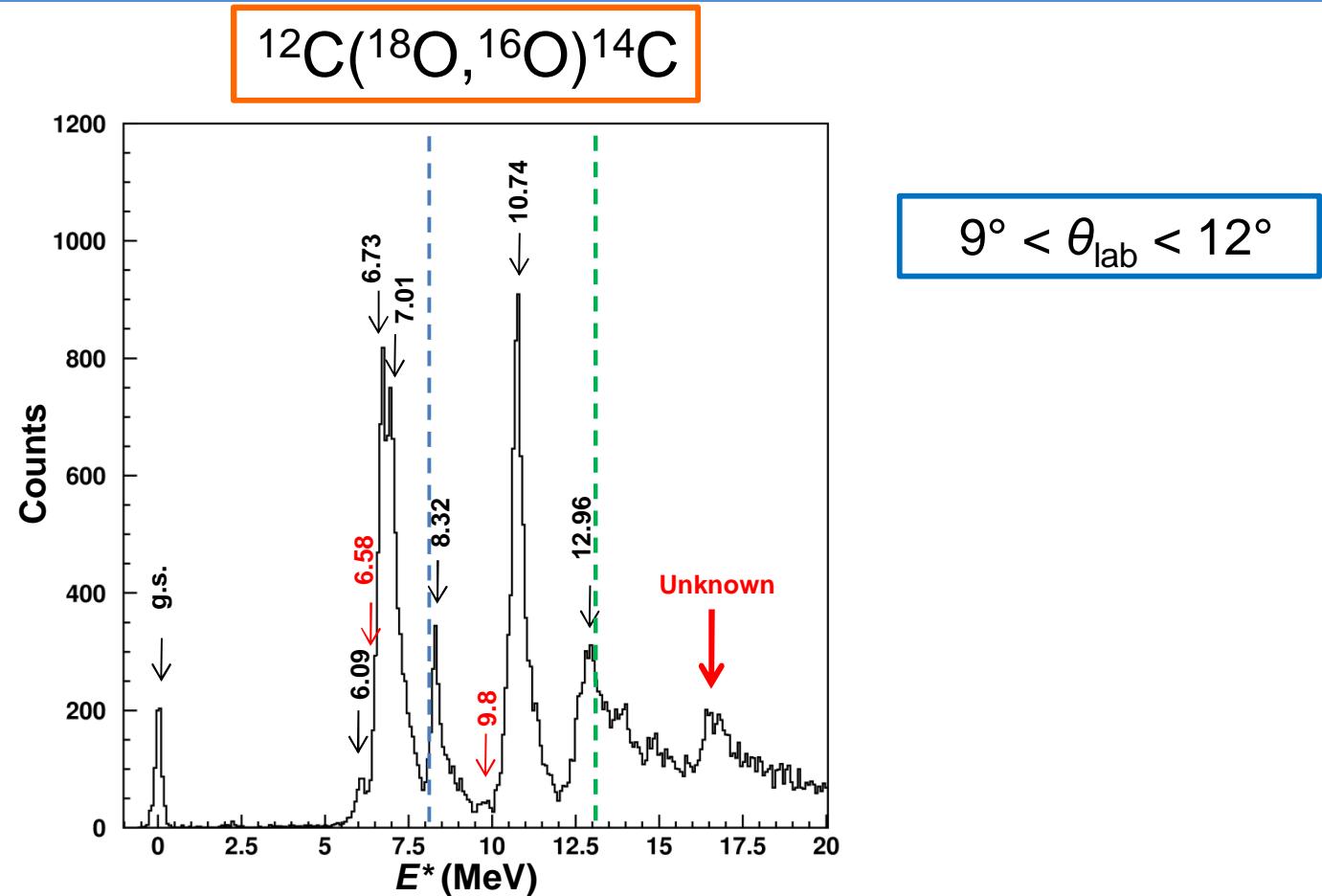
$L = 4$

Equal population of the  $M$ -states

S. Kahana and A. J. Baltz, Advances in Nuclear Physics Vol. 9

# **Q-value spectra**

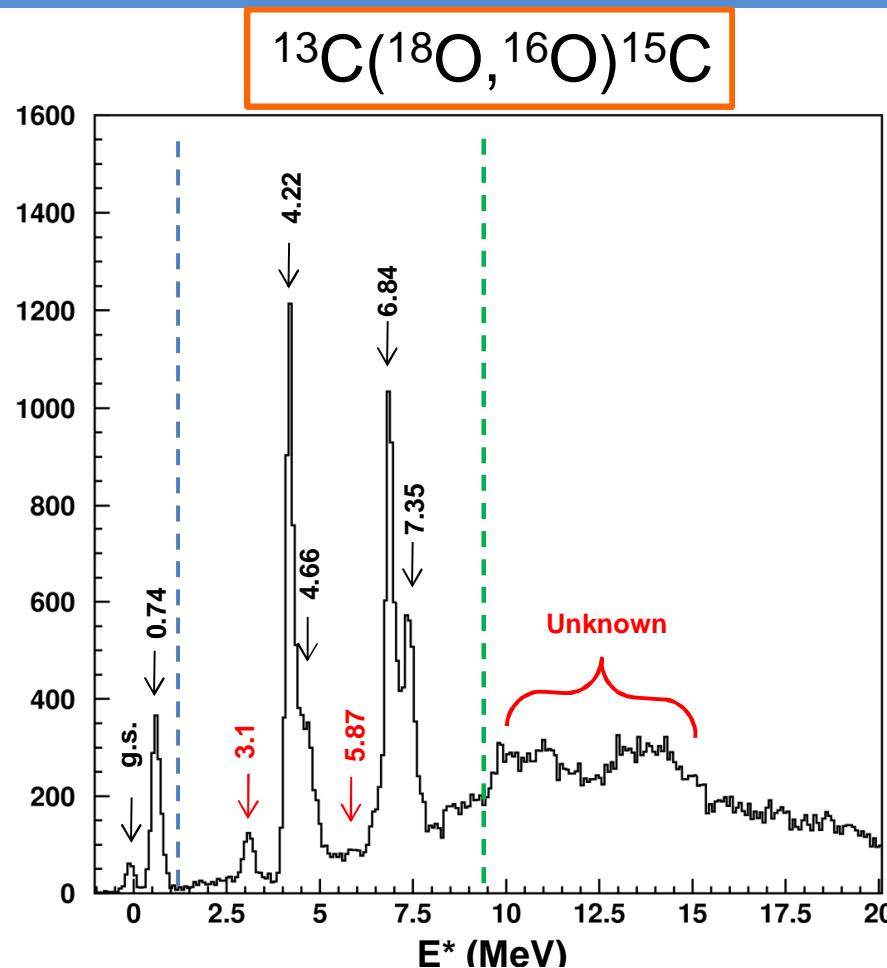
# $^{14}\text{C}$ spectrum



$^{12}\text{C}_{\text{g.s.}}(0^+) \rightarrow ^{14}\text{C}_{\text{g.s.}}(0^+)$	$L = 0$	$^{12}\text{C}_{\text{g.s.}}(0^+) \rightarrow ^{14}\text{C}_{7.01}(2^+)$	$L = 2$	$\cdots \cdots \quad S_n = 8.17 \text{ MeV}$
$^{12}\text{C}_{\text{g.s.}}(0^+) \rightarrow ^{14}\text{C}_{6.09}(1^-)$	$L = 1$	$^{12}\text{C}_{\text{g.s.}}(0^+) \rightarrow ^{14}\text{C}_{8.32}(2^+)$	$L = 2$	$\cdots \cdots \quad S_{2n} = 13.12 \text{ MeV}$
$^{12}\text{C}_{\text{g.s.}}(0^+) \rightarrow ^{14}\text{C}_{6.58}(0^+)$	$L = 0$	$^{12}\text{C}_{\text{g.s.}}(0^+) \rightarrow ^{14}\text{C}_{9.8}(0^+)$	$L = 0$	
$^{12}\text{C}_{\text{g.s.}}(0^+) \rightarrow ^{14}\text{C}_{6.73}(3^-)$	$L = 3$	$^{12}\text{C}_{\text{g.s.}}(0^+) \rightarrow ^{14}\text{C}_{10.74}(4^+)$	$L = 4$	

S.Mordechai, et al., Nucl. Phys. A301 (1978) 463  
W. Von Oertzen, et al., Eur.Phys.J. A21 (2004) 193

# $^{15}\text{C}$ spectrum



$9^\circ < \theta_{\text{lab}} < 12^\circ$

$^{13}\text{C}_{\text{g.s.}}(1/2^-) \rightarrow ^{15}\text{C}_{\text{g.s.}}(1/2^+)$	$L = 1$	$^{13}\text{C}_{\text{g.s.}}(1/2^-) \rightarrow ^{15}\text{C}_{4.66}(3/2^-)$	$L = 2$
$^{13}\text{C}_{\text{g.s.}}(1/2^-) \rightarrow ^{15}\text{C}_{0.74}(5/2^+)$	$L = 3$	$^{13}\text{C}_{\text{g.s.}}(1/2^-) \rightarrow ^{15}\text{C}_{5.87}(1/2^-)$	$L = 0$
$^{13}\text{C}_{\text{g.s.}}(1/2^-) \rightarrow ^{15}\text{C}_{3.103}(1/2^-)$	$L = 0$	$^{13}\text{C}_{\text{g.s.}}(1/2^-) \rightarrow ^{15}\text{C}_{6.84}(7/2^-, 9/2^-)$	$L = 4$
$^{13}\text{C}_{\text{g.s.}}(1/2^-) \rightarrow ^{15}\text{C}_{4.22}(5/2^-)$	$L = 2$	$^{13}\text{C}_{\text{g.s.}}(1/2^-) \rightarrow ^{15}\text{C}_{7.35}(7/2^-, 9/2^-)$	$L = 4$

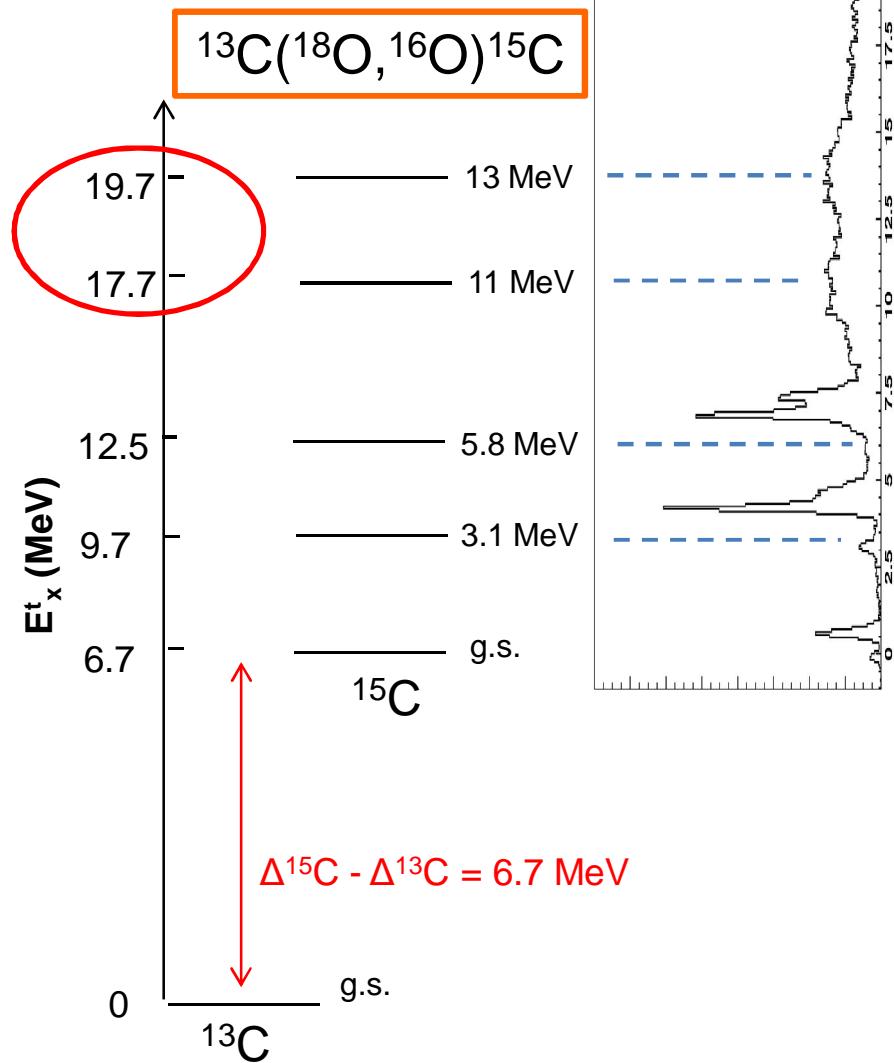
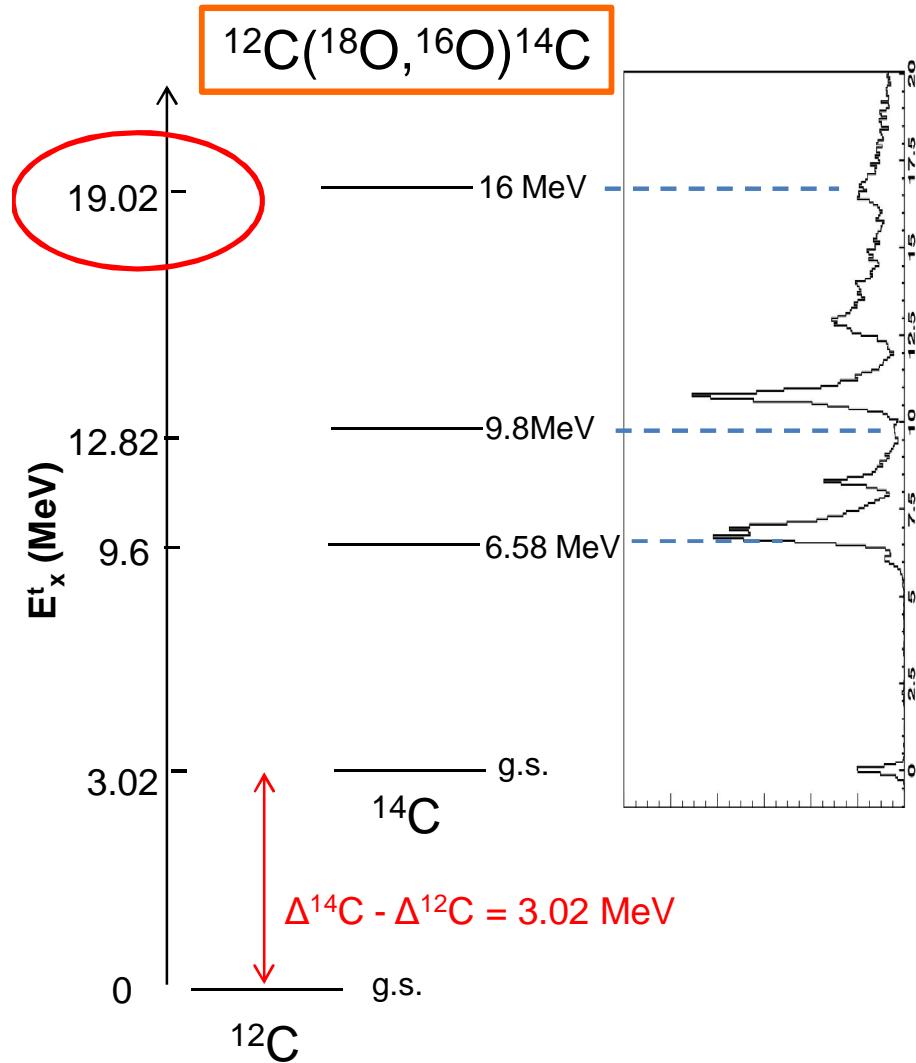
$\cdots \cdots S_n = 1.2 \text{ MeV}$

$\cdots \cdots S_{2n} = 9.4 \text{ MeV}$

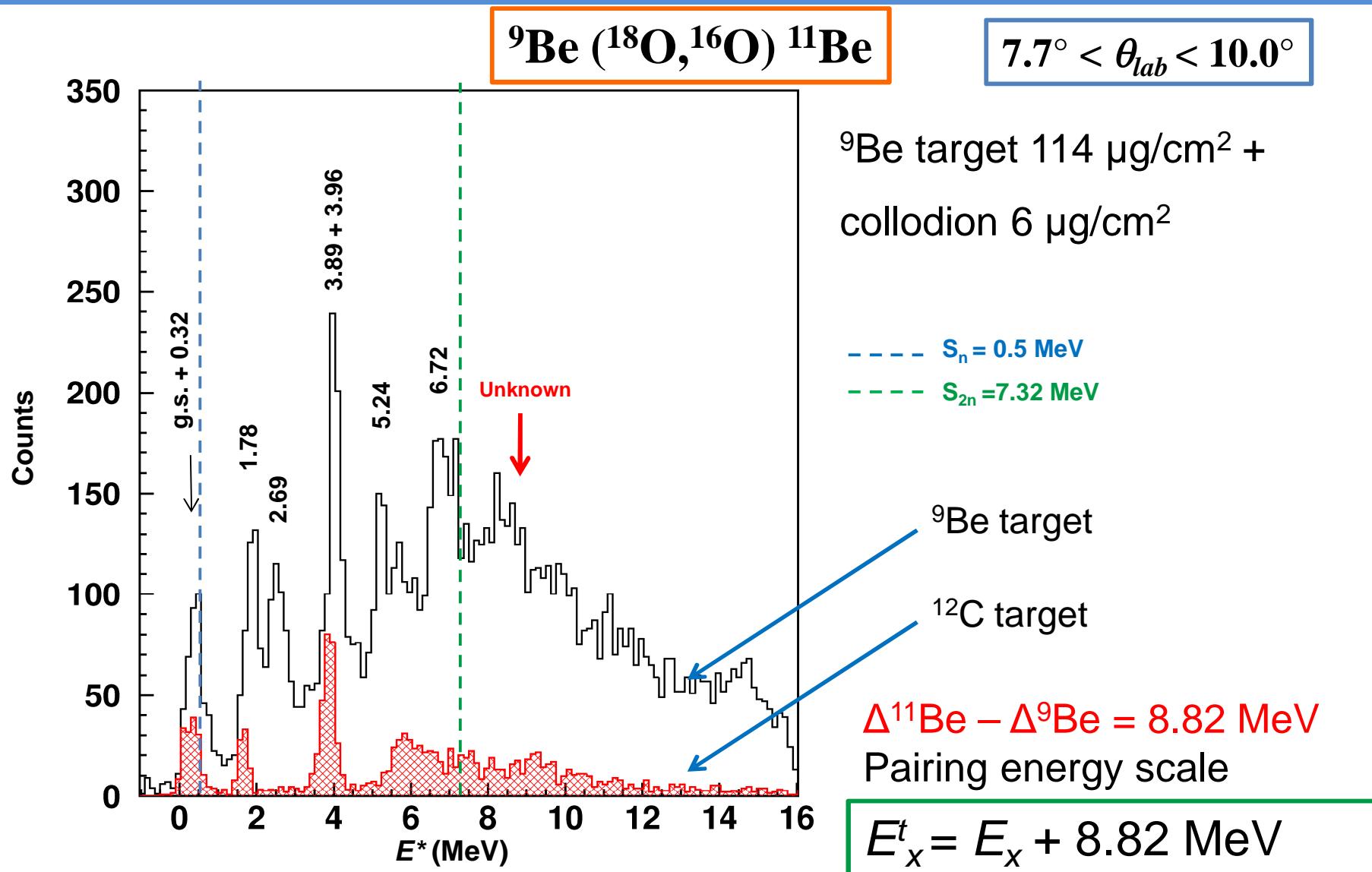
S.Truong and H.T.Fortune, Phys.Rev.C28,977(1983)

# Pairing energy scale

$$E_x^t = E_x - M_r + M_t$$



# Preliminary $^{11}\text{Be}$ spectrum



# Preliminary $^{13}\text{B}$ spectrum

$^{11}\text{B}$  target  $33 \mu\text{g}/\text{cm}^2$  +

Formvar  $4 \mu\text{g}/\text{cm}^2$

$^{12}\text{C}$  target  $50 \mu\text{g}/\text{cm}^2$

Contribution due to carbon  
and oxygen impurities  
subtracted

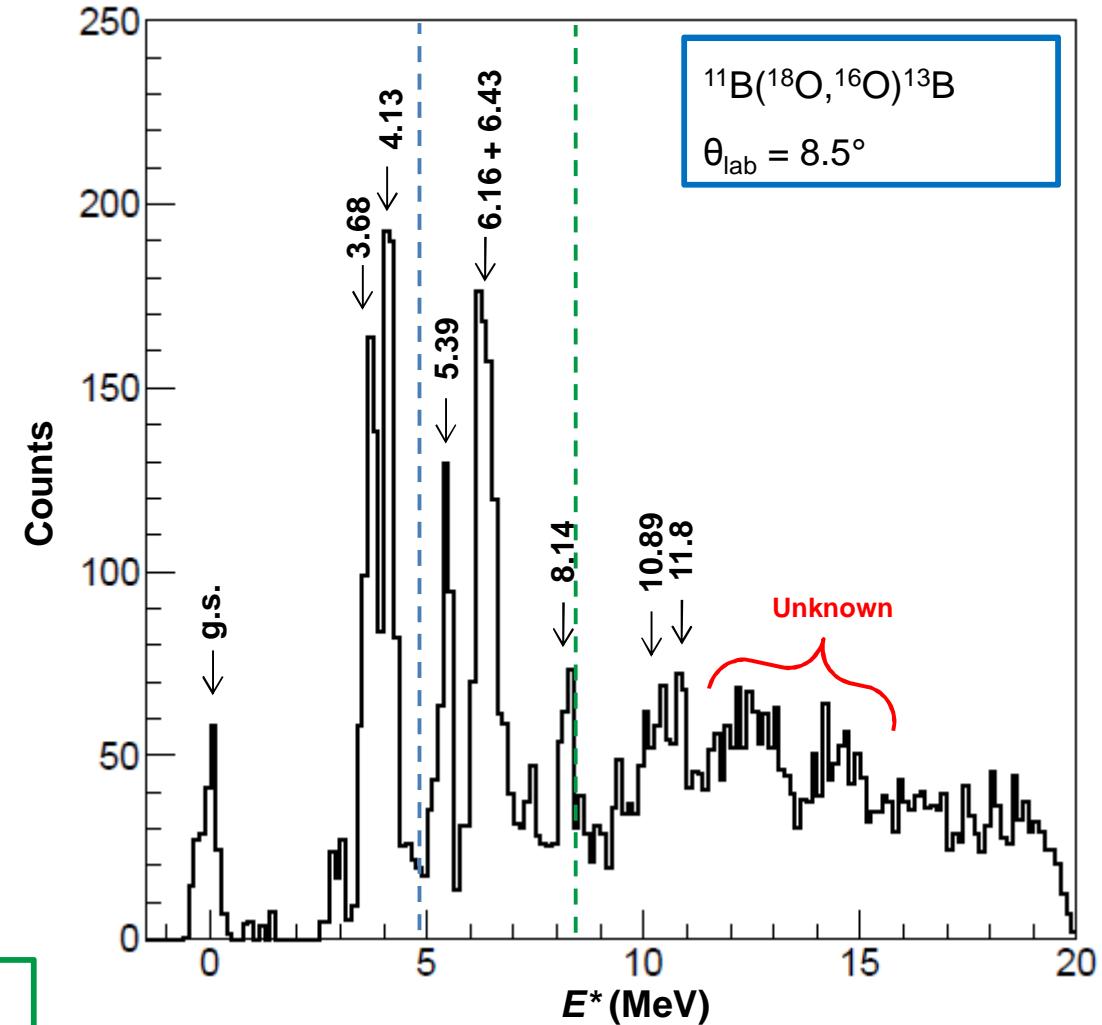
—  $S_n = 4.88 \text{ MeV}$

—  $S_{2n} = 8.25 \text{ MeV}$

$$\Delta^{13}\text{B} - \Delta^{11}\text{B} = 7.89 \text{ MeV}$$

Pairing energy scale

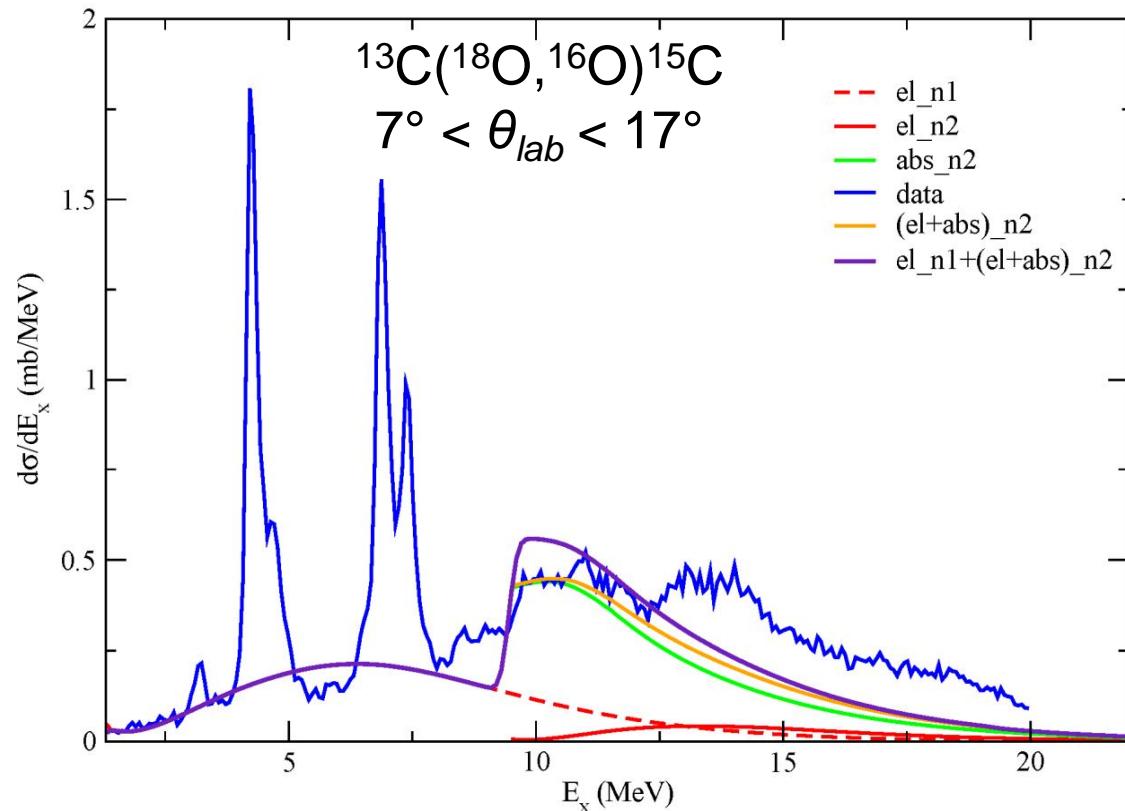
$$E_x^t = E_x + 7.89 \text{ MeV}$$



# Break-up Calculations

A.Bonaccorso, C.Rea  
(INFN-Sez. di Pisa)

Above  $S_{2n}$   
the absorption term  
dominates compared to  
the elastic BU



**Sequential transfer to the continuum of uncorrelated neutrons  
(two independent break-up processes)**

- 1)  $S_n < E_x < S_{2n}$ :  $^{18}\text{O} + ^{13}\text{C} \rightarrow ^{16}\text{O} + ^{14}\text{C} + n$
- 2)  $E_x > S_{2n}$ :  $^{18}\text{O} + ^{13}\text{C} \rightarrow ^{16}\text{O} + ^{13}\text{C} + n + n$

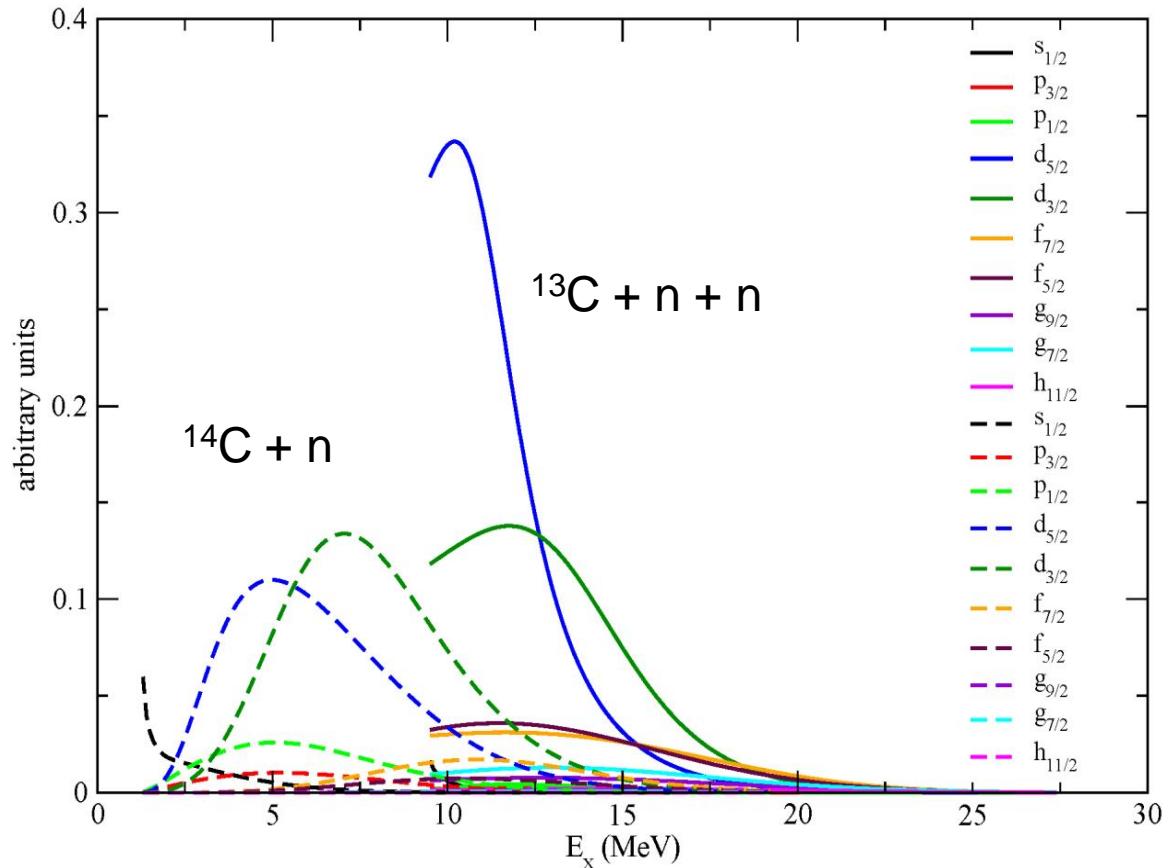
$$\begin{aligned}S_n &= 1.2 \text{ MeV} \\S_{2n} &= 9.4 \text{ MeV}\end{aligned}$$

F.Cappuzzello, et al., Submitted to PLB

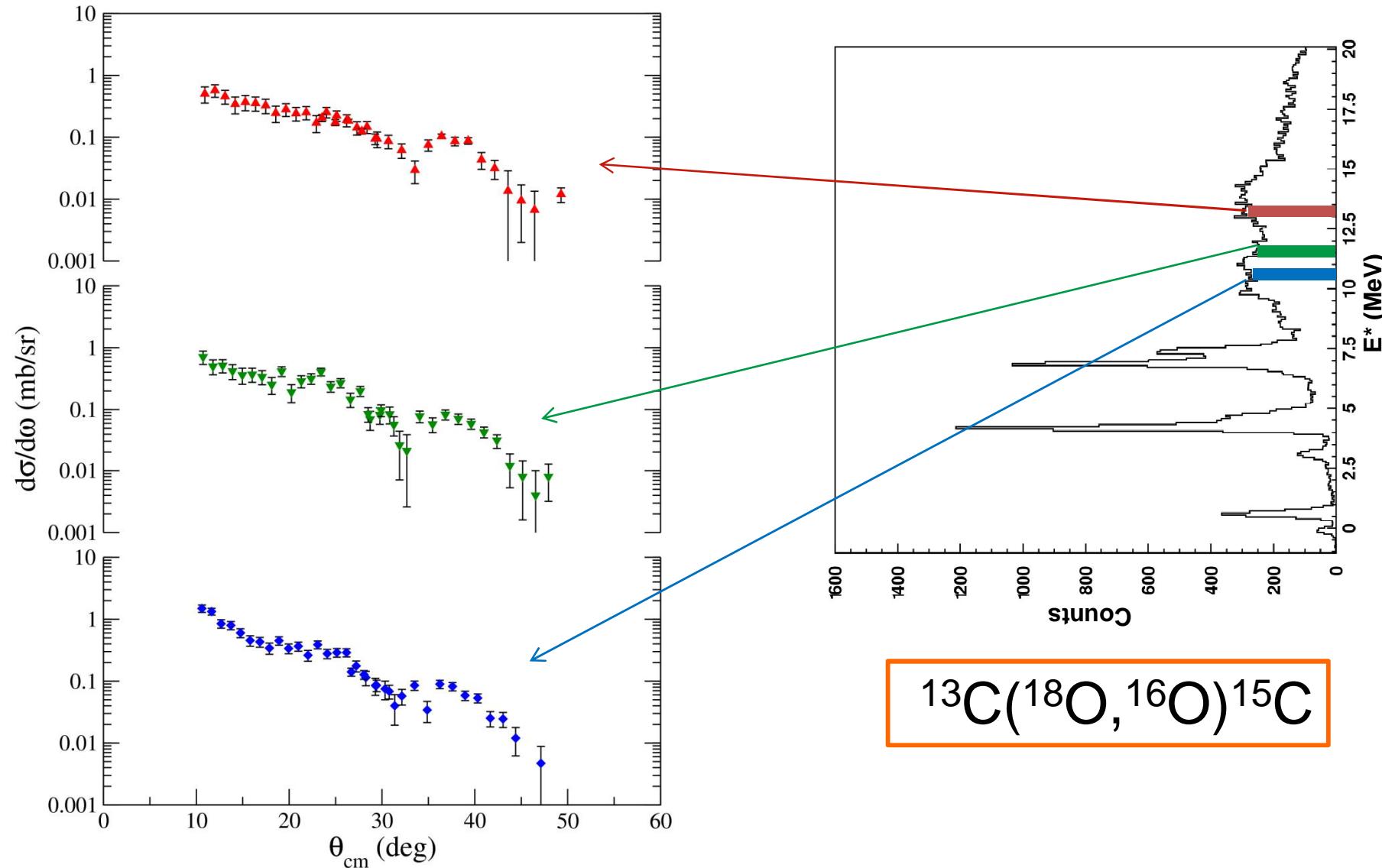
# BU calculations – partial wave decomposition

Single particle  
angular momentum  
of each individual  
strength distribution.

A.Bonaccorso, C.Rea  
(INFN-Sez. di Pisa)



# Preliminary $^{15}\text{C}$ angular distributions



# Conclusions and Outlooks

- ✓ A broad resonance observed in  $^{14}\text{C}$  and  $^{15}\text{C}$  spectrum populated via  $(^{18}\text{O}, ^{16}\text{O})$  at 84 MeV                          Compatible with *GPV*?
- ✓ Indications of the dominance of the one-step transfer channel
- ✓ Clear signatures of neutron-neutron correlations
- ✓ Analysis of the angular distributions in progress
- ✓ Break-Up calculations are on the way to study the continuum background
- ✓ CRC and CDCC calculation on the way
- ✓ Neutron detector array (*EDEN*) coupled to MAGNEX
- ✓ Data reduction in progress for:
  - other targets ( $^9\text{Be}$ ,  $^{11}\text{B}$ ,  $^{28}\text{Si}$ ,  $^{58}\text{Ni}$ ,  $^{64}\text{Ni}$ ,  $^{120}\text{Sn}$ ,  $^{208}\text{Pb}$ )
  - other angular settings  $6^\circ$ ,  $12^\circ$ ,  $18^\circ$ ,  $24^\circ$

# Working group

F.Cappuzzello<sup>1,2</sup>, D.Carbone<sup>1,2</sup>, M.Cavallaro<sup>2</sup>, M.Bondì<sup>1,2</sup>, A.Cunsolo<sup>1,2</sup>,  
C.Agodi<sup>2</sup>, M.De Napoli<sup>3</sup>, A.Foti<sup>1,3</sup>, D.Nicolosi<sup>1,2</sup>, G.Taranto <sup>1,2</sup>, S.Tropea<sup>1,2</sup>

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

A.Bonaccorso

*Istituto Nazionale di Fisica Nucleare – Sezione di Pisa*

A.Vitturi, L.Fortunato, S.Lenzi, C.Rea

Università degli Studi di Padova

F.Azaiez, M.Assie, S.Franchoo, M.Niikura, J.A.Scrapaci

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

R.Linares, J.Lubian, V.Nunes Garcia, B.Paes

Universidade Federal Fluminense, Niteroi, Brazil