Transfer reactions and neutron decay studies by the MAGNEX-EDEN facility

Manuela Cavallaro

INFN-Laboratori Nazionali del Sud
Catania (Italy)

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French–Italian–Polish Collaborations on

Nuclear Structure and Reactions

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Collaboration

C. Agodi, F. Cappuzzello, D. Carbone, M. Cavallaro, 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. Gargano
Istituto Nazionale di Fisica Nucleare – Sezione di Napoli, Italy

L. Fortunato, S.M. Lenzi, A. Vitturi

Istituto Nazionale di Fisica Nucleare – Sezione di Padova, Italy
Dipartimento di Fisica, Università di Padova, Italy

A. Bonaccorso
Istituto Nazionale di Fisica Nucleare – Sezione di Pisa, Italy

M. Assié, F. Azaiez, S. Franchoo, E. Khan, M. Niikura, J.A. Scarpaci
IN2P3 – Institut de Physique Nucléaire d'Orsay, France
IN2P3 – CSNSM, Orsay, France

R. Linares, J. Lubian, V.N. Garcia
IFUFF, Niteroi, Brasil
IFUSP, San Paulo, Brasil

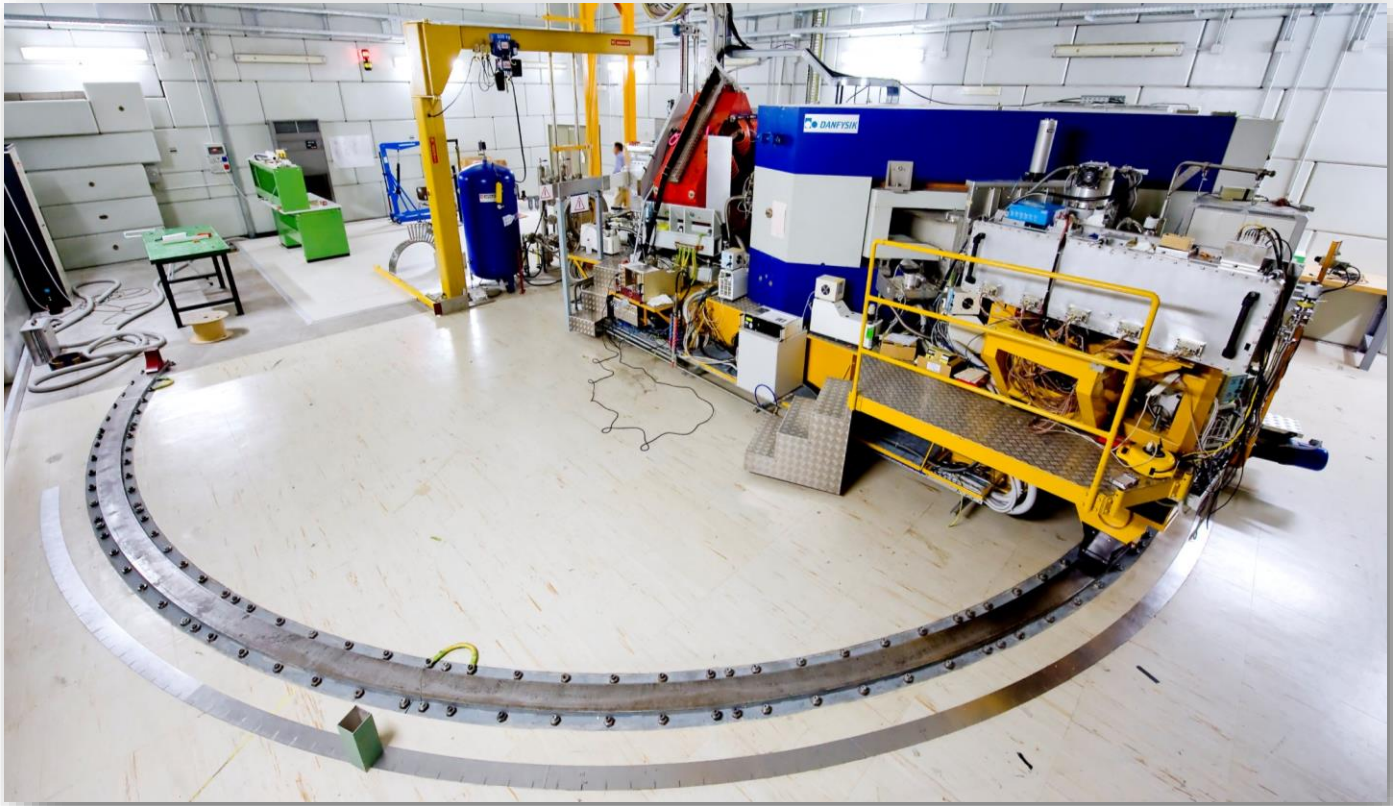
The experiments

- $^{18}O^{7+}$ beam from Tandem at 84 MeV and from CS at 270MeV
- ^{9}Be, ^{11}B, $^{12,13}C$, ^{16}O, ^{28}Si, ^{64}Ni targets 50-100 μg/cm²
- Ejectiles detected by the **MAGNEX** spectrometer
- Angular setting $\theta_{opt} = 8°, 12°, 18° \longrightarrow \boxed{3° < \theta_{lab} < 24°}$

Large acceptance:
Energy -28%, +20%
Angle 50 msr

MAGNEX

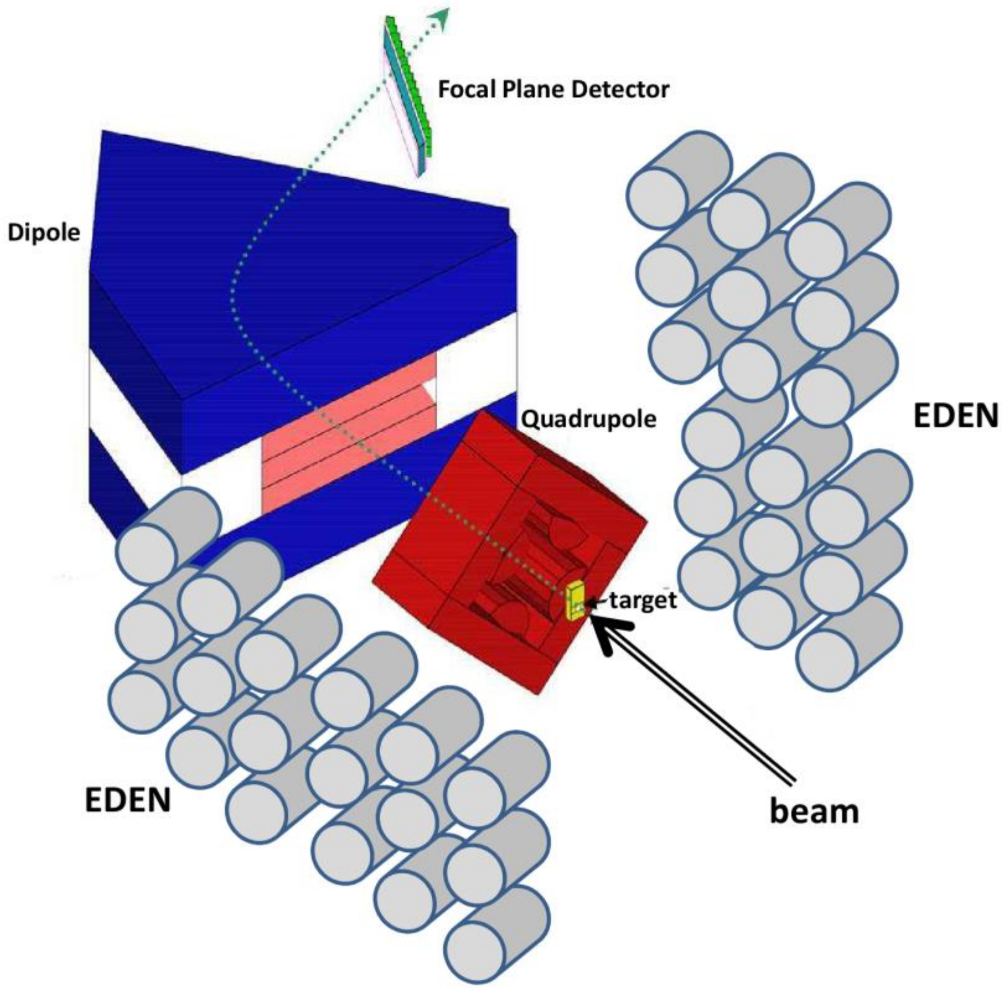
Measured resolution:
Energy $\Delta E/E \sim 1/1000$
Angle $\Delta\theta \sim 0.3°$
Mass $\Delta m/m \sim 1/160$



- *F. Cappuzzello et al., "MAGNEX: an innovative large acceptance spectrometer for nuclear reaction studies" in: Magnets: Types, Uses and Safety, Nova Publisher Inc., New York, 2011, pp 1-63*
- *F. Cappuzzello et al., Eur. Phys. Journ. A, accepted (2016)*

The EDEN neutron detector array

IPN-Orsay



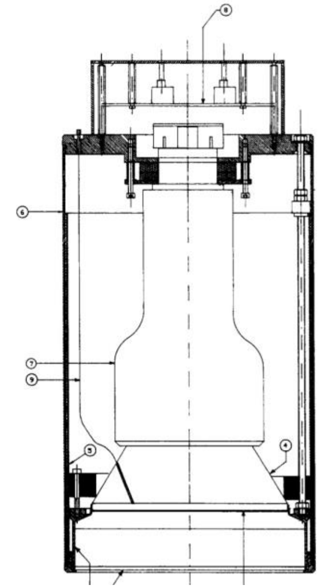
MAGNEX + EDEN coupling

MAGNEX to measure high resolution energy spectra for charged reaction products

EDEN to study the decaying neutrons emitted by the observed resonances with good efficiency and energy resolution

The EDEN neutron detector array

H. Laurent et al., NIM A 326, 417 (1993)
M. Cavallaro et al., NIM A 700, 65 (2013)



❖ 40 liquid scintillator detectors (NE213)

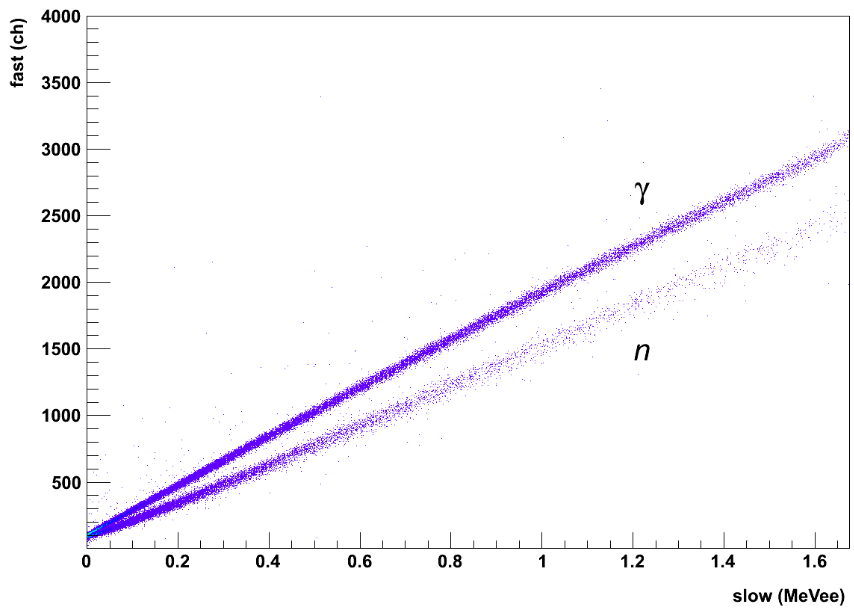
❖The cells are cylindrical, 5 cm thick with 20 cm diameter

❖ Possibility of n - γ discrimination by pulse shape analysis

❖ Energy measurement by TOF with time resolution of 1 ns

❖ Typical energy resolution at a 1.7 m distance from the target: 60 keV for 850 keV neutrons and 500 keV for 6 MeV neutrons

❖ Intrinsic efficiency ~ 50% for 1 MeV and 30% for 6 MeV neutrons

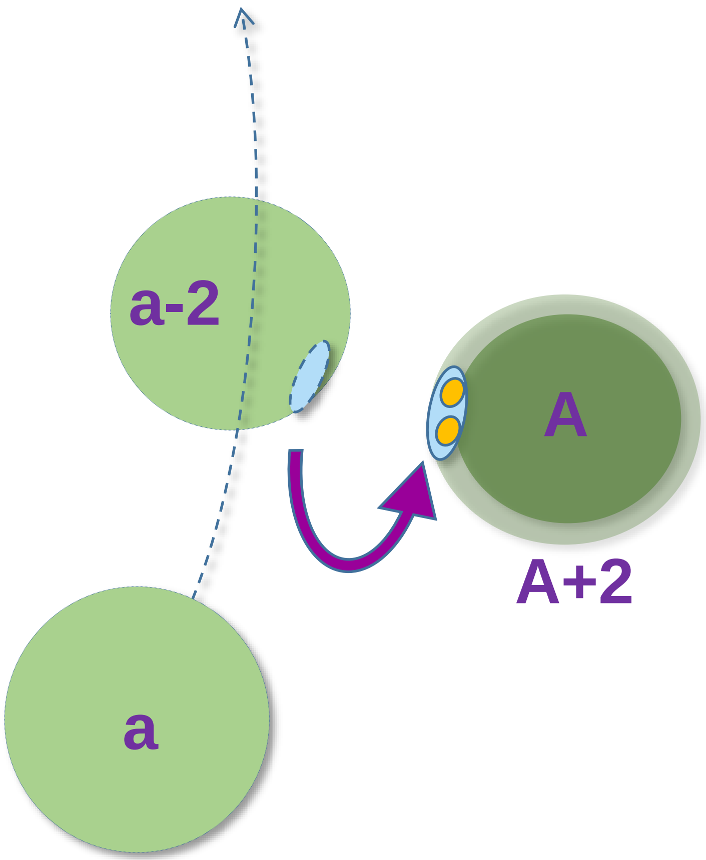


The (^{18}O,^{16}O) probe for spectroscopic studies

Direct transfer reactions

- Select specific degrees of freedom in the complex many-body nuclear system

- Exploration of the nuclear structure
  - 1n transfer and single-particle configurations
  - α transfer and clustering
  - 2n transfer probabilities and pairing correlations in nuclei



$$a + A \rightarrow a\text{-}2 + A\text{+}2$$

Heavy ions

The extraction of structure information from 2n transfer cross-sections is not straightforward

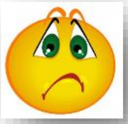
Experiments

- ❖ PID
- ❖ Forward angles
- ❖ High resolution

Cross section description

- ❖ Coupling with inelastic excitations (CC corrections)
- ❖ Sequential transfer
- ❖ Recoil effects
- ❖ Finite range f.f.
- ❖ Only the product of projectile and target S.F. is accessible

Arbitrary scaling factors
"unhappiness" **(>>1)**
to reproduce the exp. angular distributions



$(^{18}O,^{16}O)$ 2n transfer reactions

Why?

The **$(^{18}O,^{16}O)$** reactions are good candidates to show the role of **pairing interaction** thanks to

- The presence of a **correlated pair** of neutrons in the $^{18}O_{g.s.}$ w.f.
- The very low polarizability of the **^{16}O core**

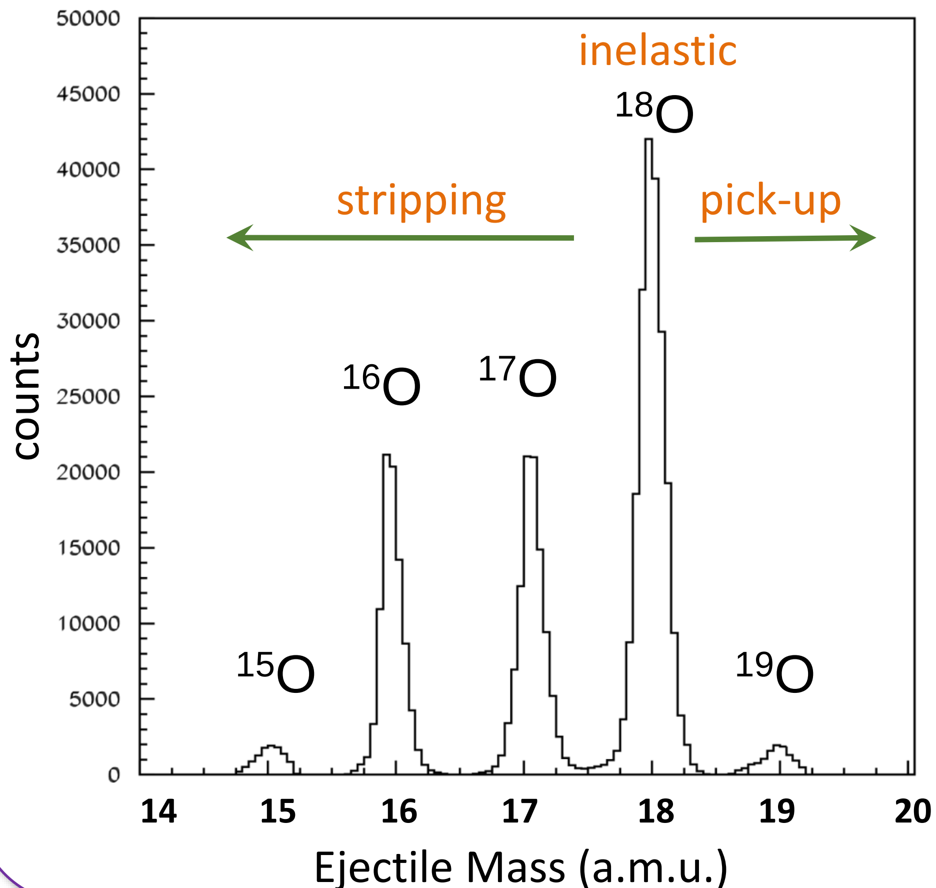
Different targets ^{9}Be, ^{11}B, $^{12,13}C$, ^{16}O, ^{28}Si, ^{64}Ni, ^{116}Sn, ^{208}Pb

Also **one-neutron** transfer reaction $(^{18}O,^{17}O)$

1. Transfer yields

$^{18}O+^{13}C$

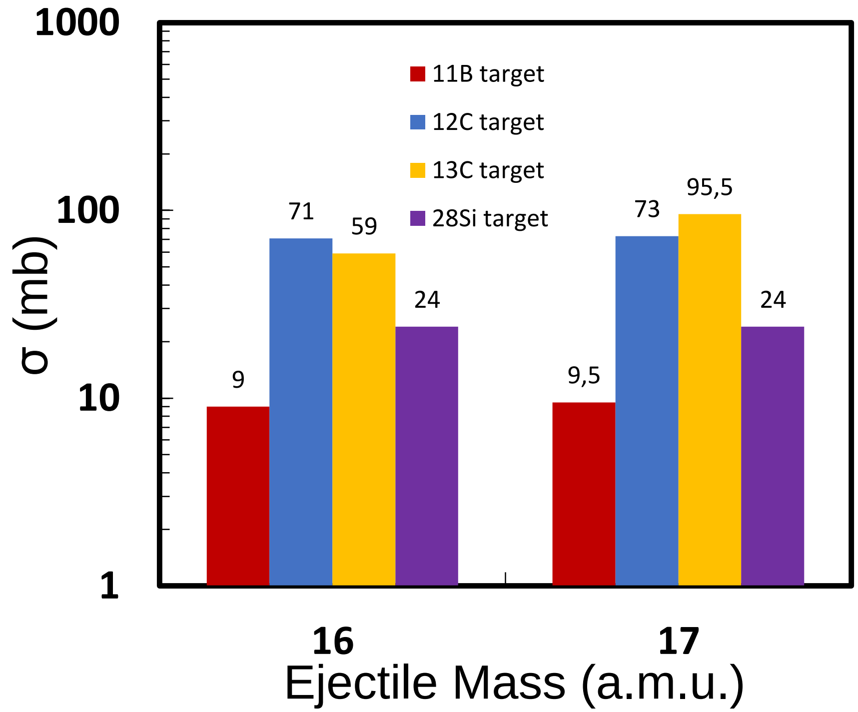
$7° < \theta_{lab} < 13°$

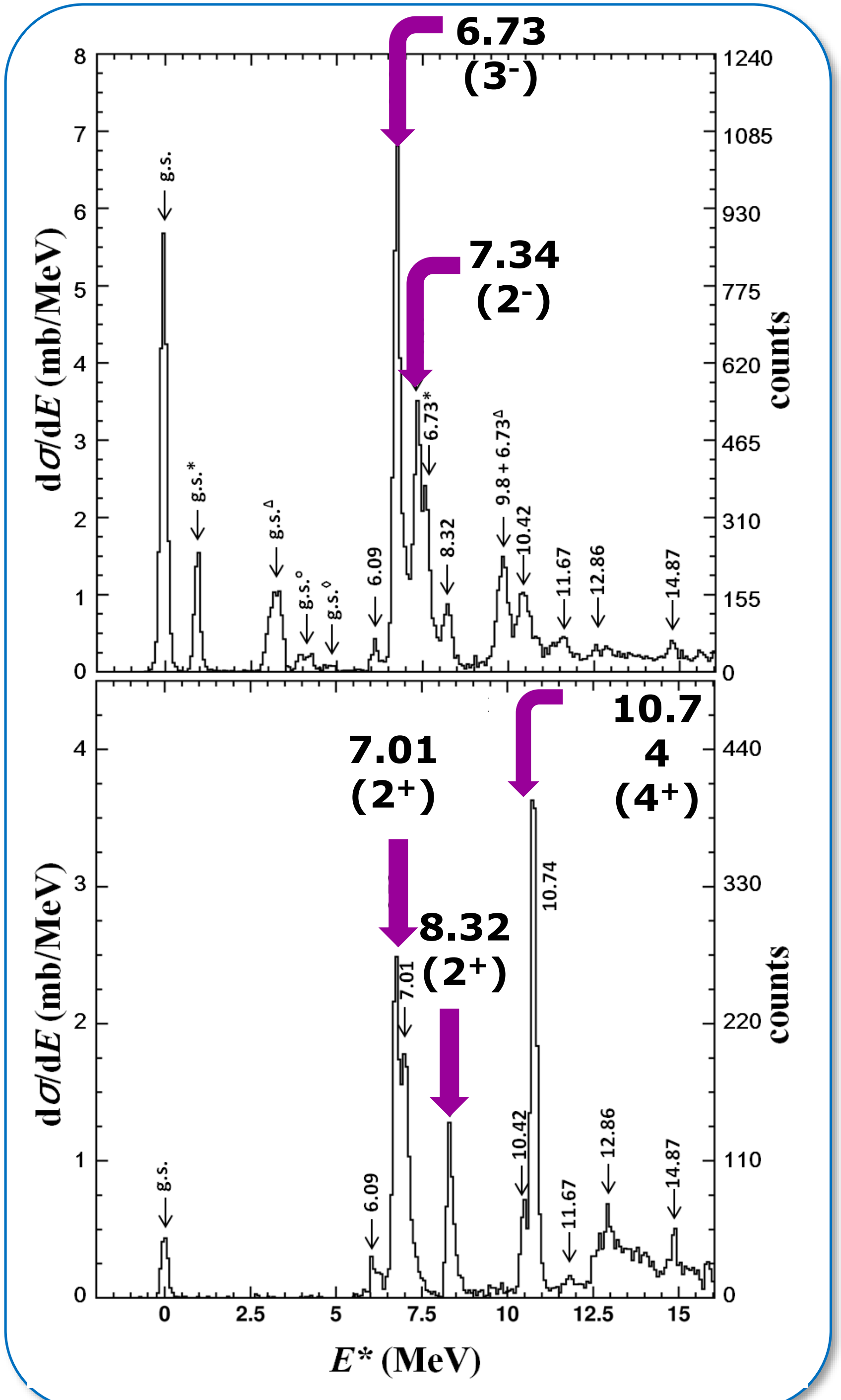


Enhancement of the two-neutron transfer channel

The 2n transfer is not a 2nd order process

TRANSFER OF A CORRELATED PAIR





2. Energy spectra:

$3° < \theta_{lab} < 5°$

${}^{13}C({}^{18}O,{}^{17}O){}^{14}C$

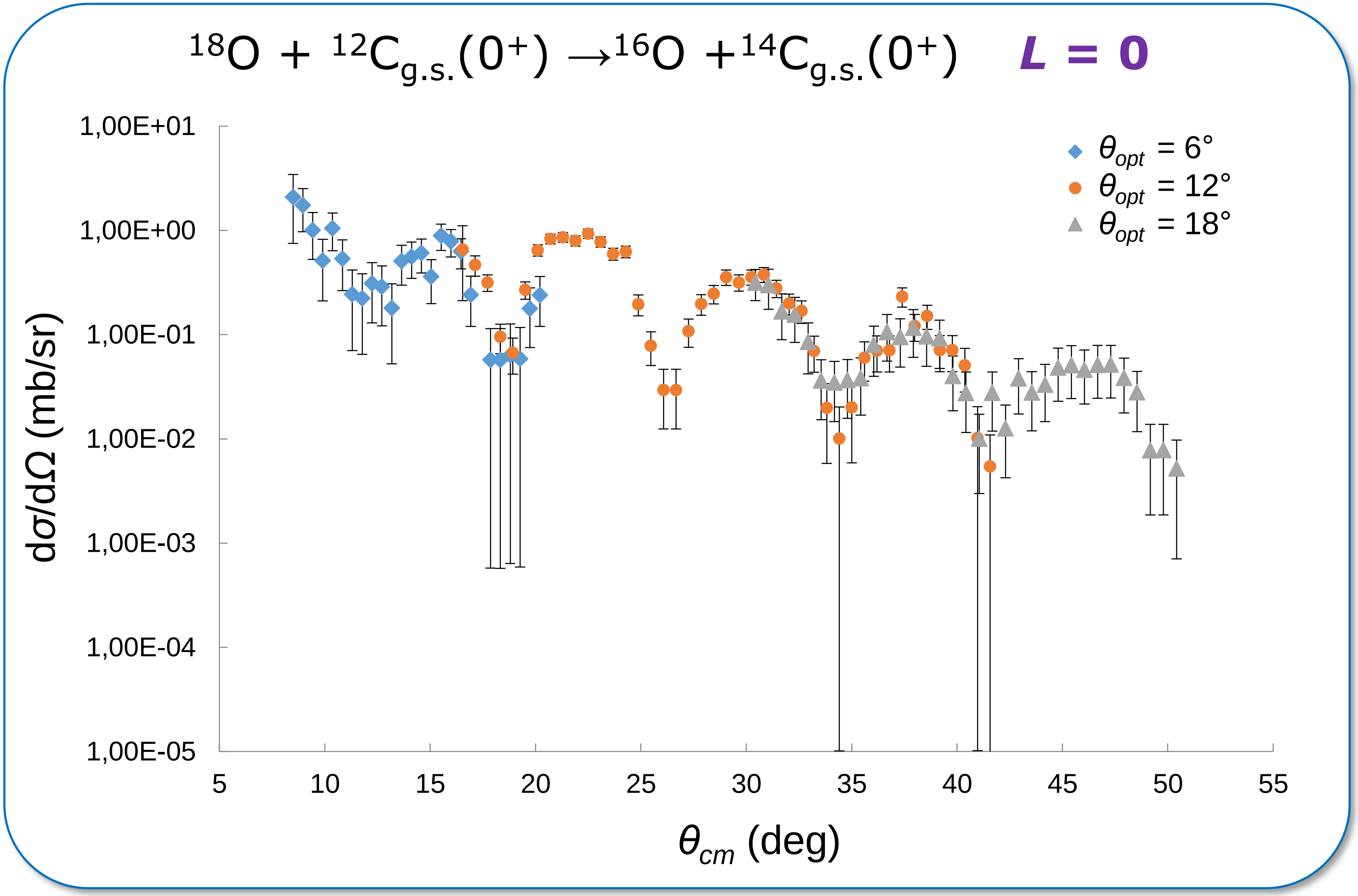
$$\left|\left[\left({}^{13}C_{gs}\right)^{1/2^-}\otimes\left(1d_{5/2}\right)^{5/2^+}\right]^{2^-,3^-}\right\rangle$$

In the (${}^{18}O$,${}^{16}O$), the **suppression of s.p. states**, which would require an uncorrelated transfer of 2n and the breaking of the initial pair in the ${}^{18}O_{g.s.}$, reveals the minor role of the **two-step dynamics**

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

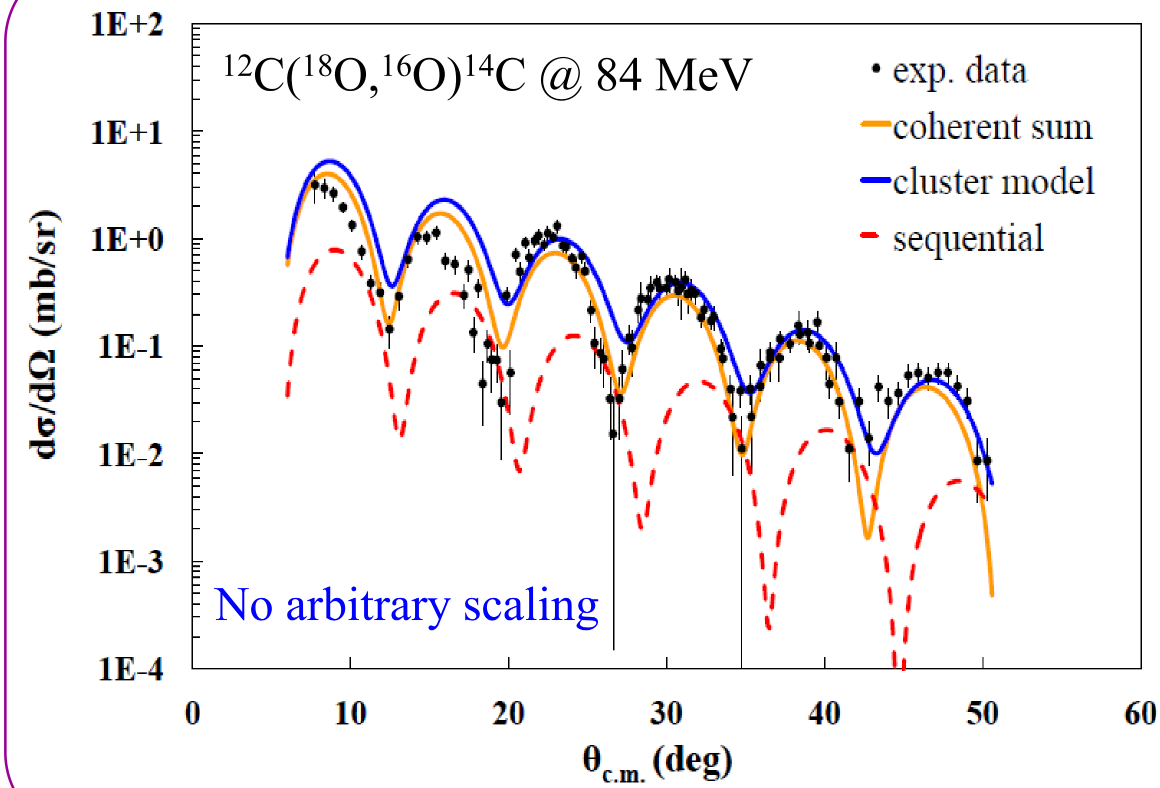
$$\left|\left[\left({}^{12}C_{gs}\right)^{0^+}\otimes\left(1d_{5/2},2s_{1/2}\right)^{2^+,4^+}\right]^{2^+,4^+}\right\rangle$$

3. Angular distributions



Exact Finite Range CRC

M. Cavallaro, et al., PRC 88 (2013) 054601



A **0.89** amplitude is obtained by scaling to the experimental data (**0.91** S.A. predicted by shell model for the $(p_{1/2})^2$ configuration).

Extreme Cluster Model

(CRC)

❖ Relative motion of the 2n system frozen and separated by the c.m.

❖ Only the term with the 2n coupled to S = 0 participates to the transfer

Sequential transfer

(DWBA)

Introducing the $^{17}O + ^{13}C$ intermediate partition

Coherent sum

Presence of two-neutron pairing correlations in the ^{14}C ground state

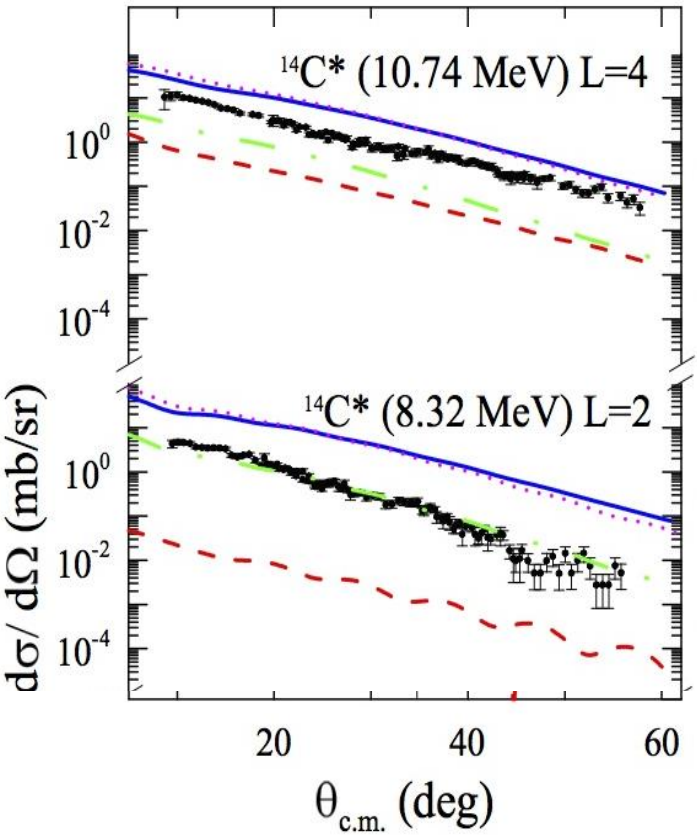
Some of the other targets studied

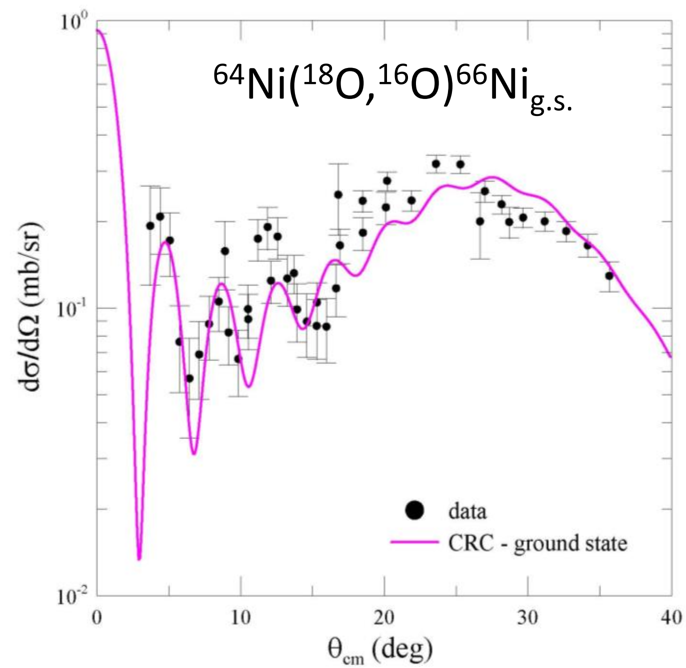
$^{12}C(^{18}O,^{16}O)^{14}C$ @ 84 MeV

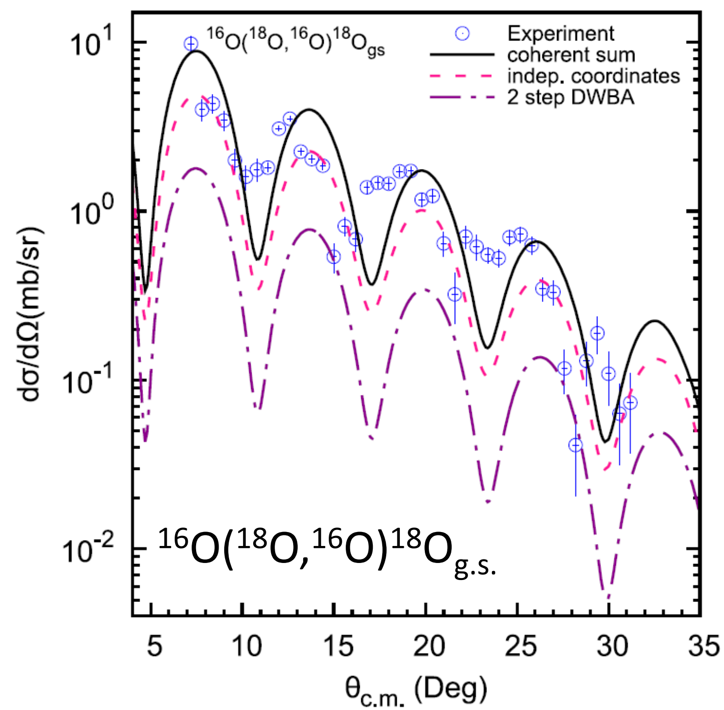
Cluster model

Sequential transfer

Independent coordinates







Structure studies

nature COMMUNICATIONS

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ARTICLE

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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]

The pairing force

Large experimental activity on 2n-transfer and pairing → Still basic unresolved questions

Giant Pairing Vibrations (*GPV*)

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

- Collective excitation of a pair of particles (or holes) across major shells
- Analogy with **Giant Resonances** (GDR, GQR) Collective p-h excitations

What are the hypotheses?

- Particle-hole symmetry (basic symmetry for systems of interacting fermions)
- Mean field description of the system ground state (true for nuclei)

We expect they exist!

Why never observed

- **GPV** requires ***L* = 0** transfer
- In transfer reactions typically **large amount of angular momentum is transferred**, especially at high excitation energy

Incident energy →

1. Near the Coulomb barrier, weak sensitivity to angular momentum transfer
2. At high incident energy, Q-value matching

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

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

Projectile/target →

1. **Brink's matching conditions**

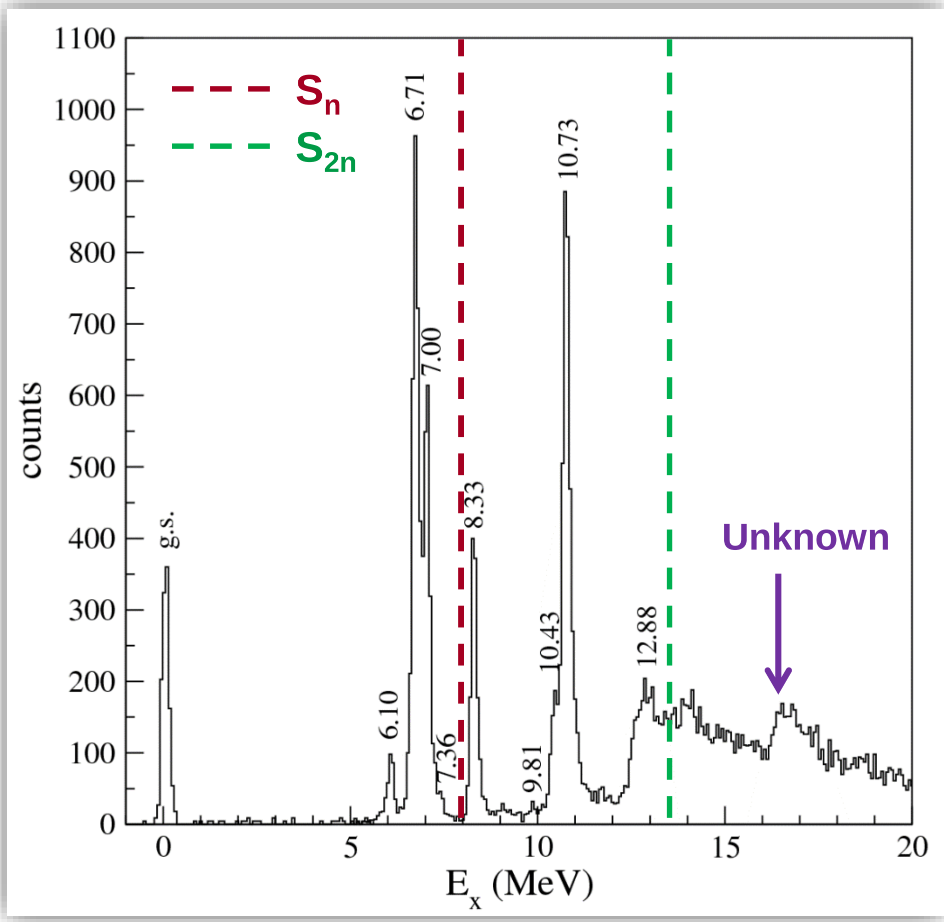
$$\Delta L = (\lambda_2 - \lambda_1) + \tfrac{1}{2} k_0 (R_1 - R_2) + Q_{eff}\, R/\hbar v \approx 0$$

D.M. Brink, PLB 40 (1972) 37

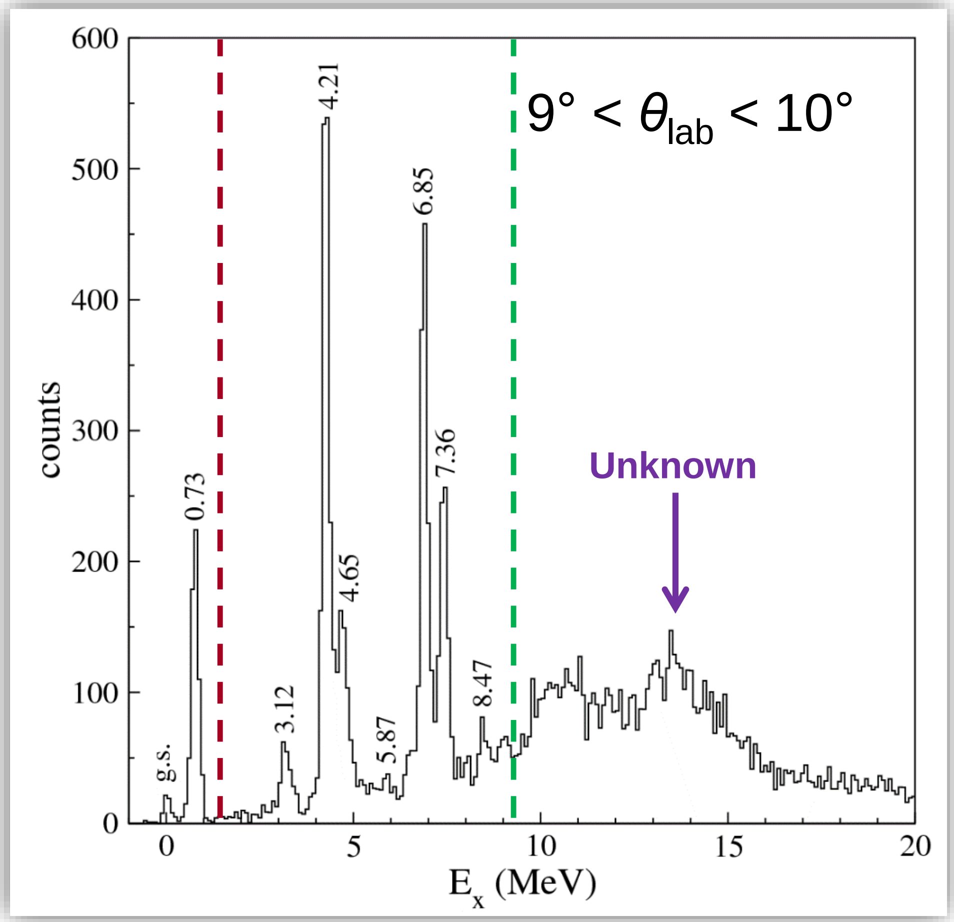
2. Survival of a **preformed pair** in a transfer process favored if the initial and final orbitals are the same

Our measurement

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

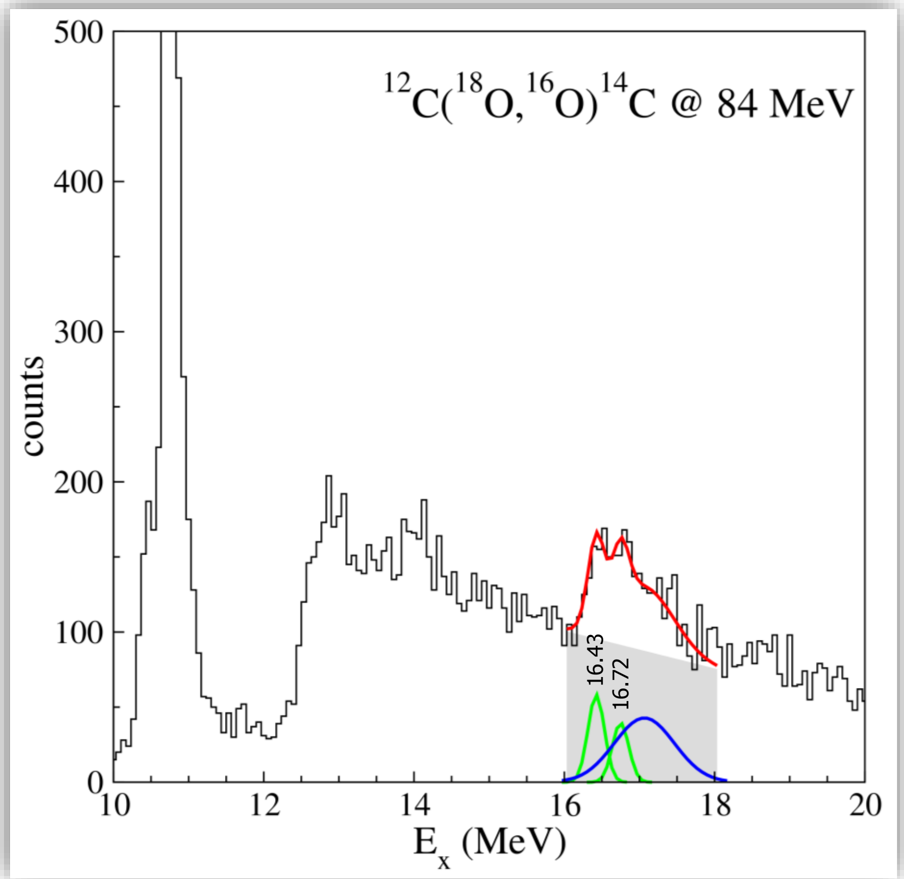


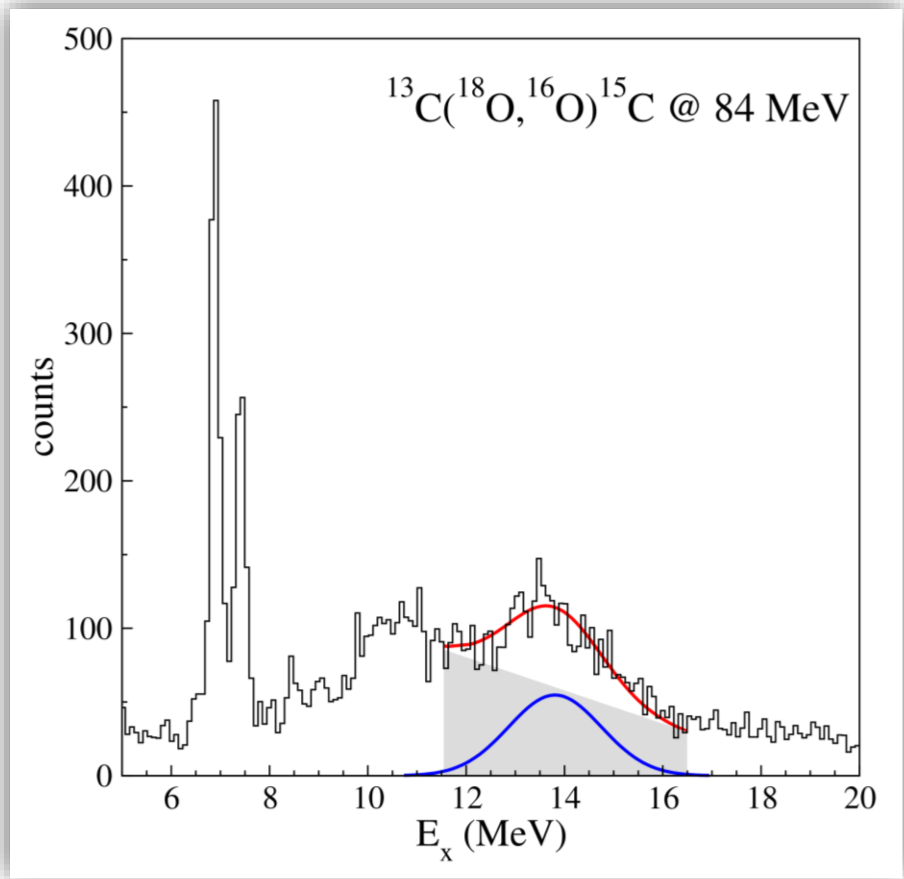
$^{13}C(^{18}O,^{16}O)^{15}C$



- Strong population of states with large 2n⊗core overlap
- Almost complete suppression of the 0^+_2 , 0^+_3 states

Energy and width of the bumps





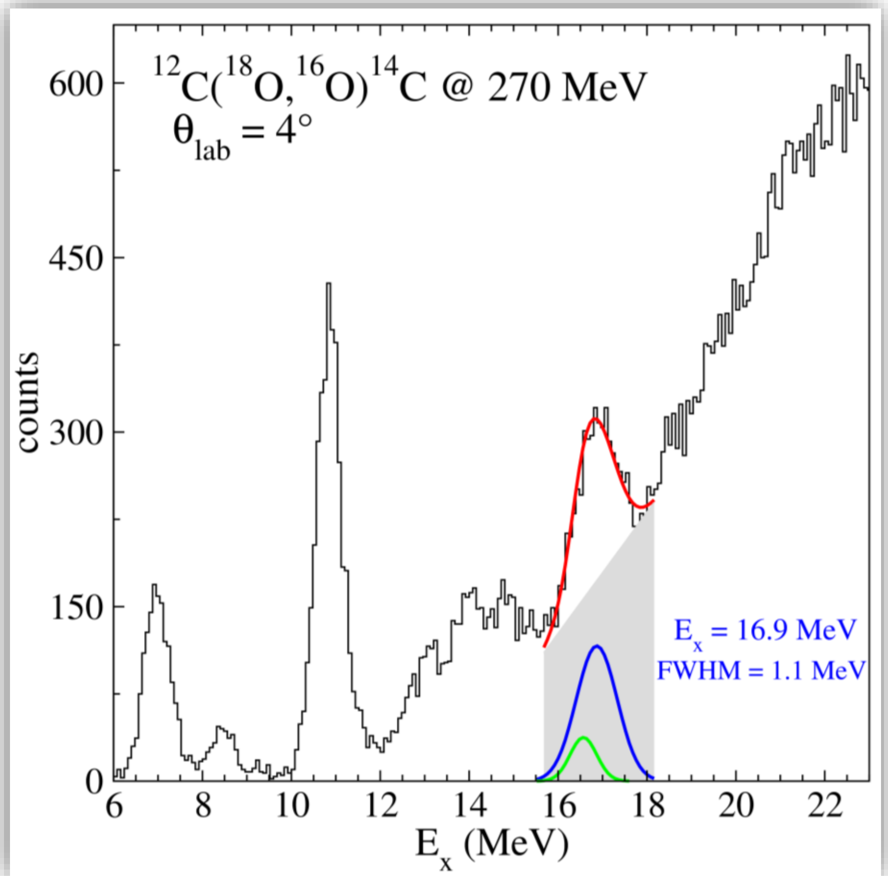
Gaussian + linear background

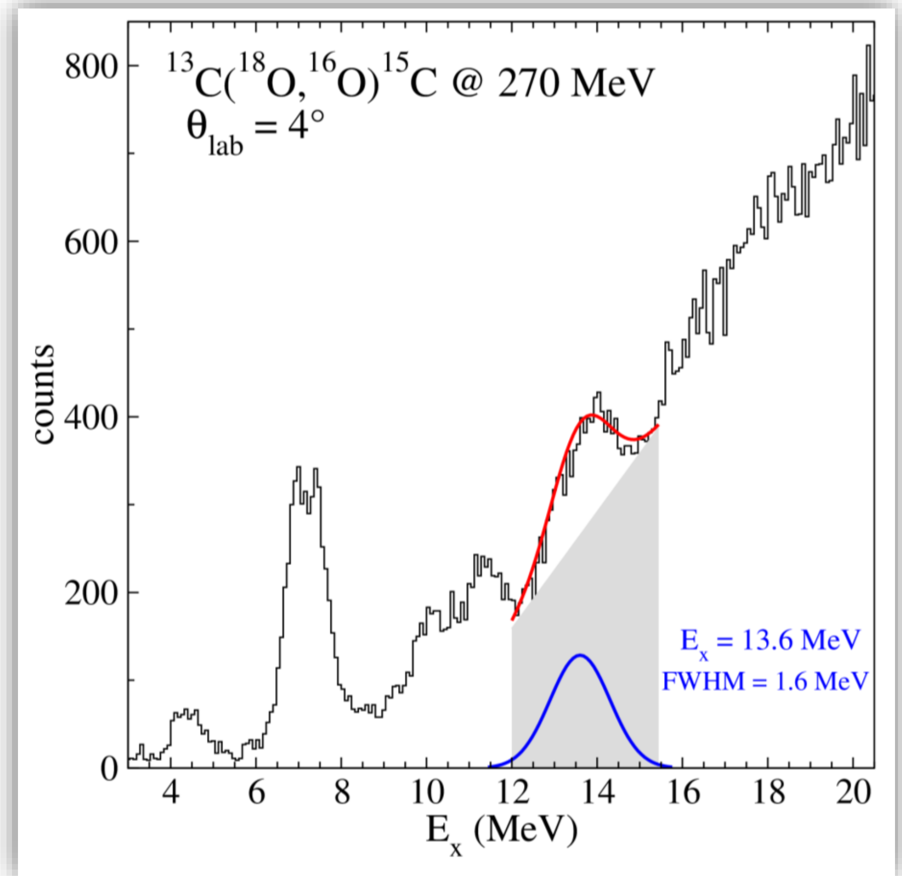
^{14}C **E_x = 16.9 ± 0.1 MeV** **FWHM = 1.2 ± 0.3 MeV**

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

Experiment @ 270 MeV

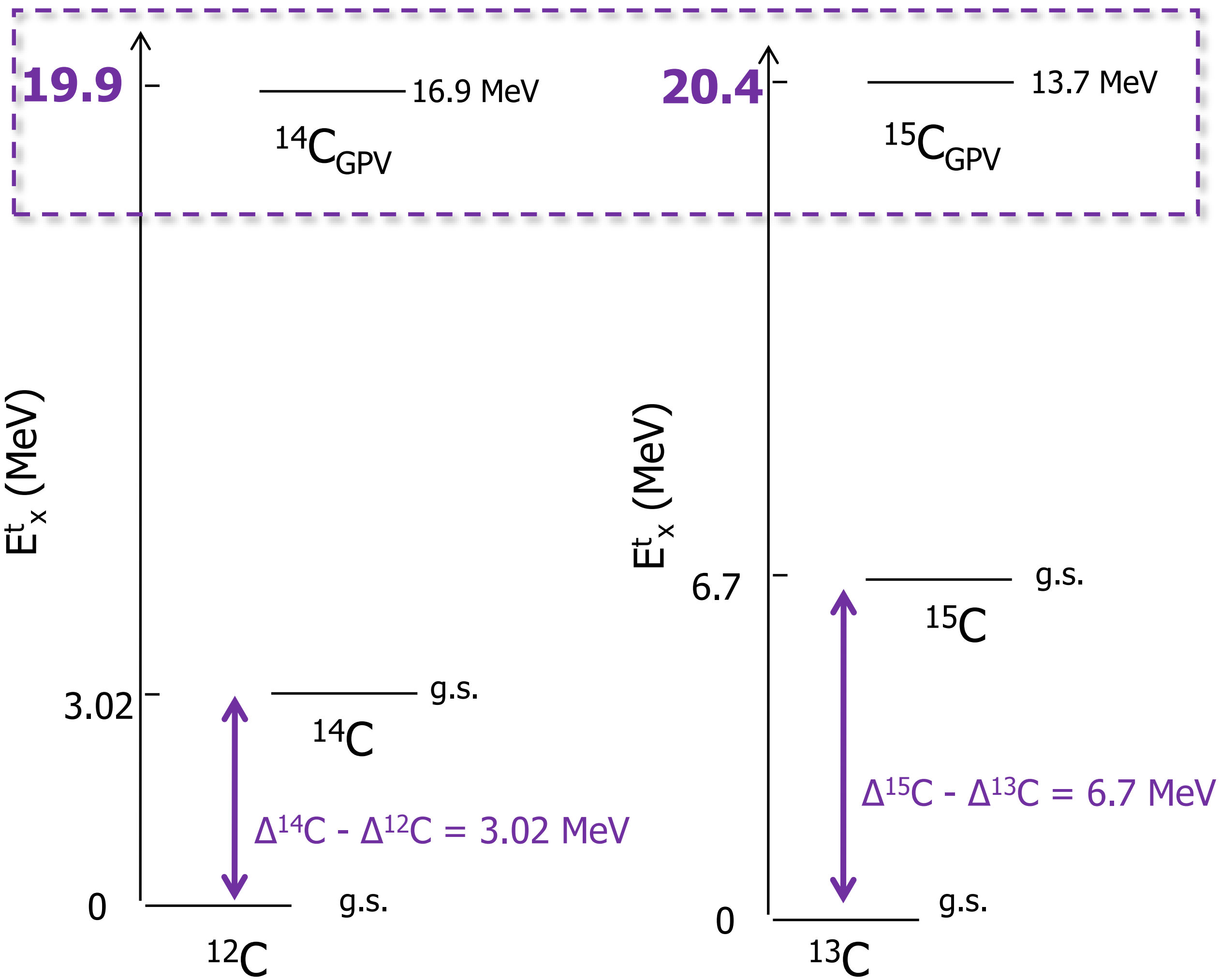
Using the Superconducting Cyclotron at LNS





Excitation energy

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



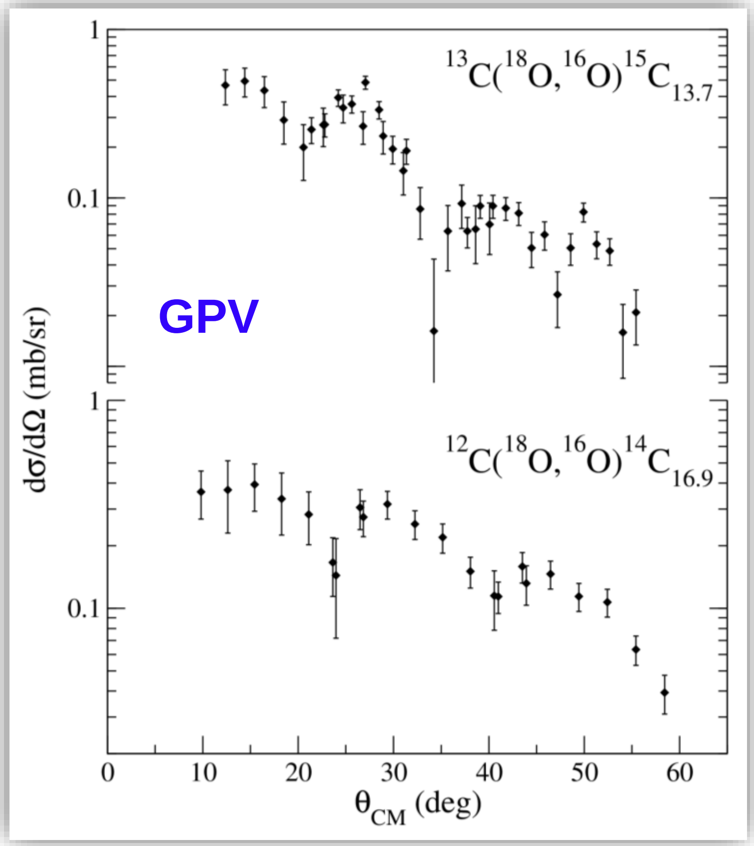
Pairing energy scale

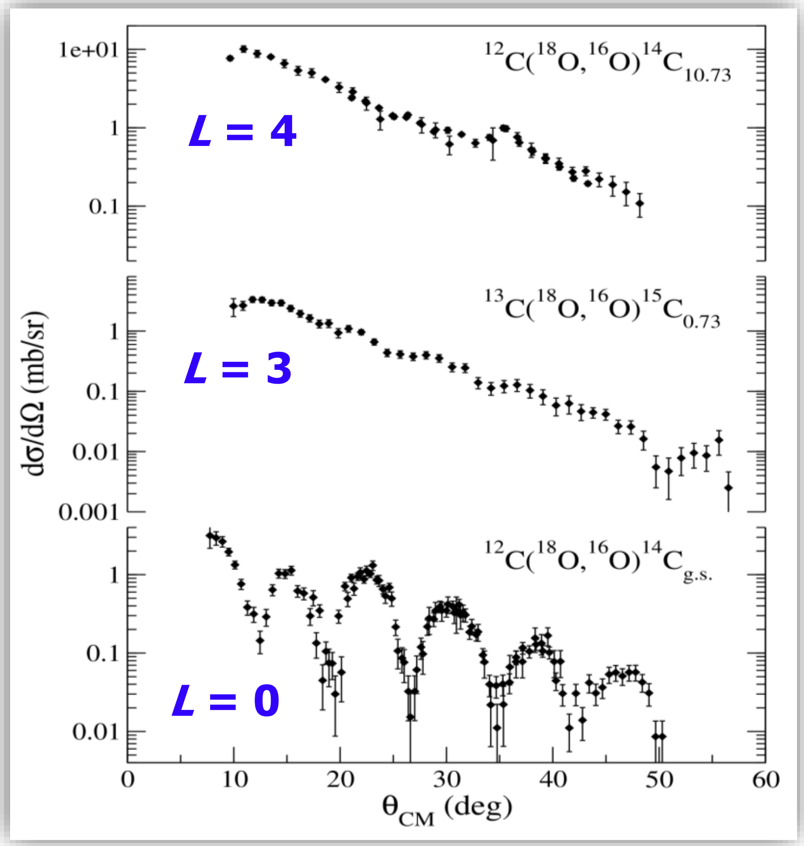
$$E^t_x = E_x + M_r - M_t$$

Consistent with cQRPA predictions

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

Multipolarity: angular distributions





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

- L ≠ 0 transitions: featureless shape
- *L* = 0 transitions: oscillating shape

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

Model independent indication of *L* = 0

Collectivity

The GPV strength is predicted to be similar to that of the *L* = 0 transition to the ground state in Pb and Sn even-even isotopes

Transfer probability (semi-classical description of the relative motion)

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

$$\eta = \frac{Z_1 Z_2 e^2 p}{2E\hbar} = 3.5$$

$F(Q, L)$ Quantal corrections

$\left(\frac{d\sigma(\theta)}{d\Omega}\right)_{sc}$ Elastic scattering $\Longrightarrow$ $P_{tr}(\theta)$ Transfer probability

$$\boxed{\frac{P_{tr}({}^{14}C_{GPV})}{P_{tr}({}^{14}C_{g.s.})} = 3.2 \pm 1.7}$$

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

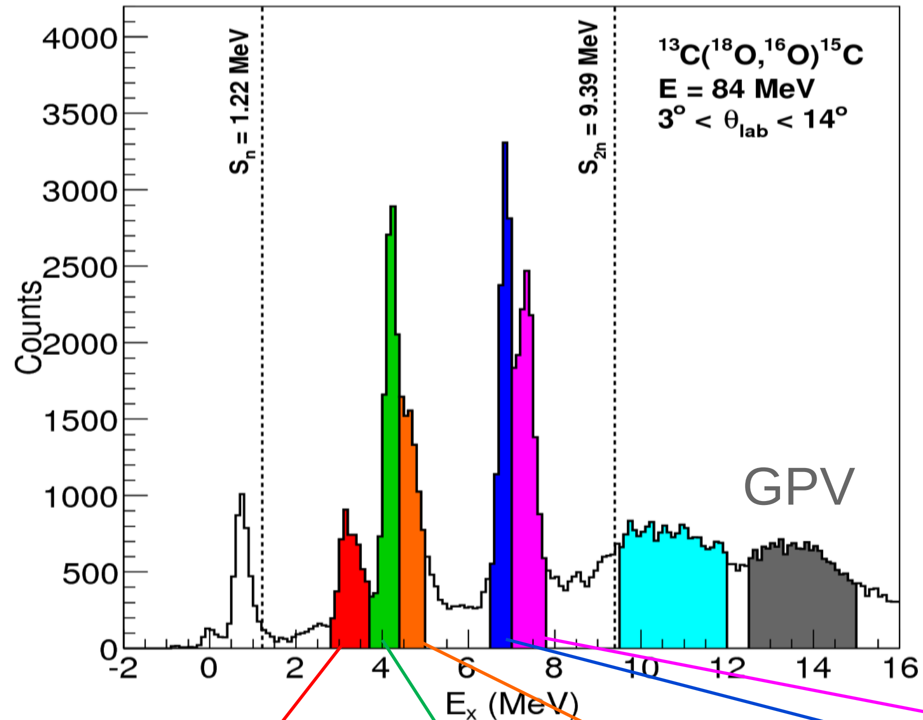
W. von Oertzen and A. Vitturi, Rep. Prog. Phys. 64 (2001) 1247
R.A. Broglia and A. Winther, Heavy Ion Reactions, (Addison-Wesley, 1991)

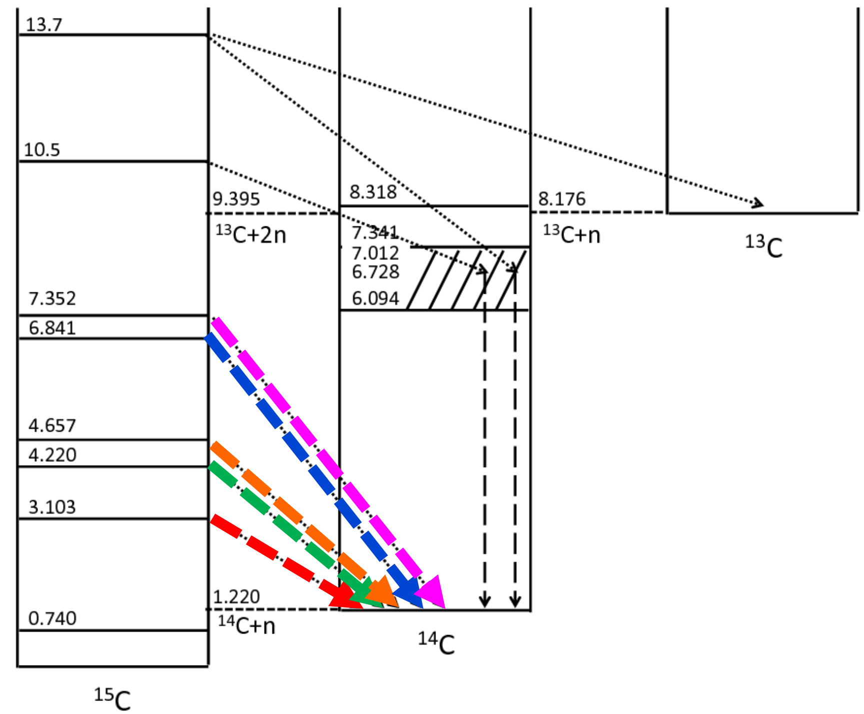
Neutron decay

Neutron decay

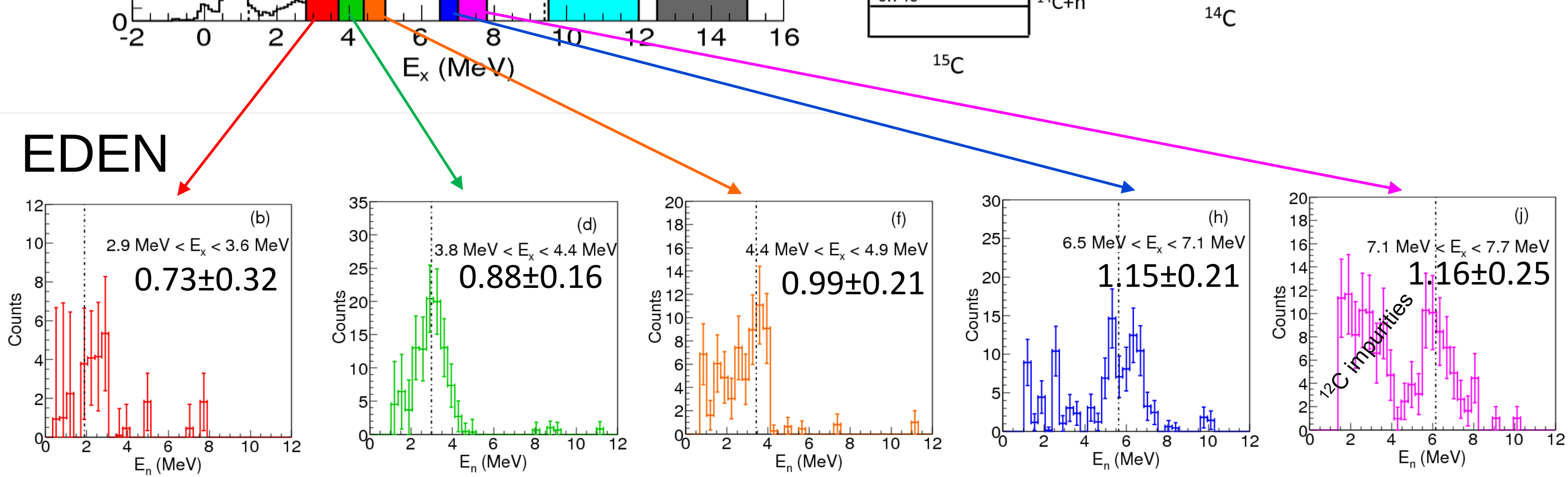
M. Cavallaro, et al., Phys. Rev. C, accepted

MAGNEX





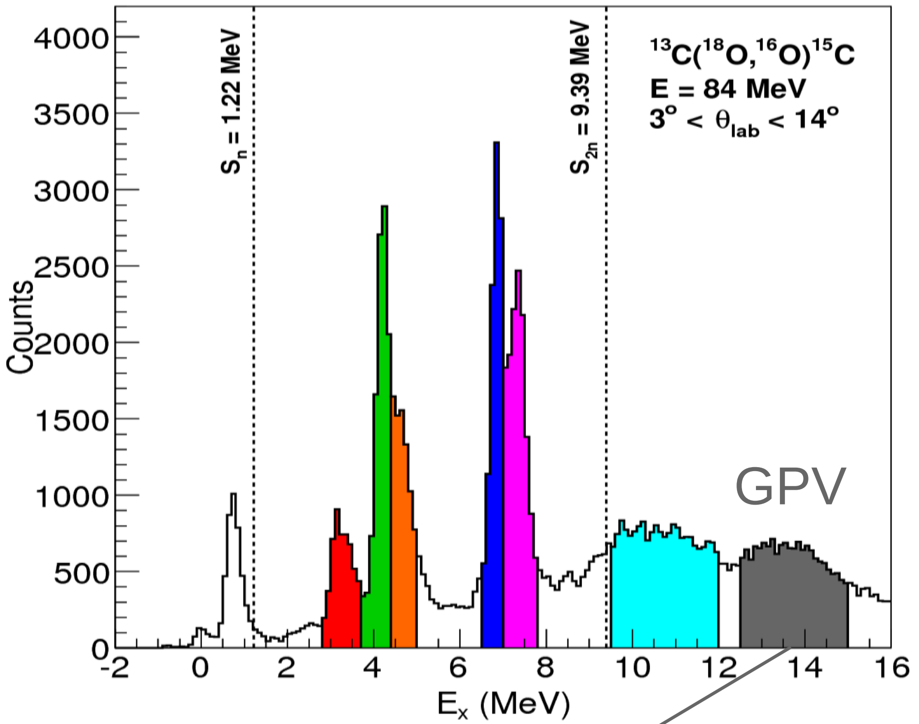
EDEN

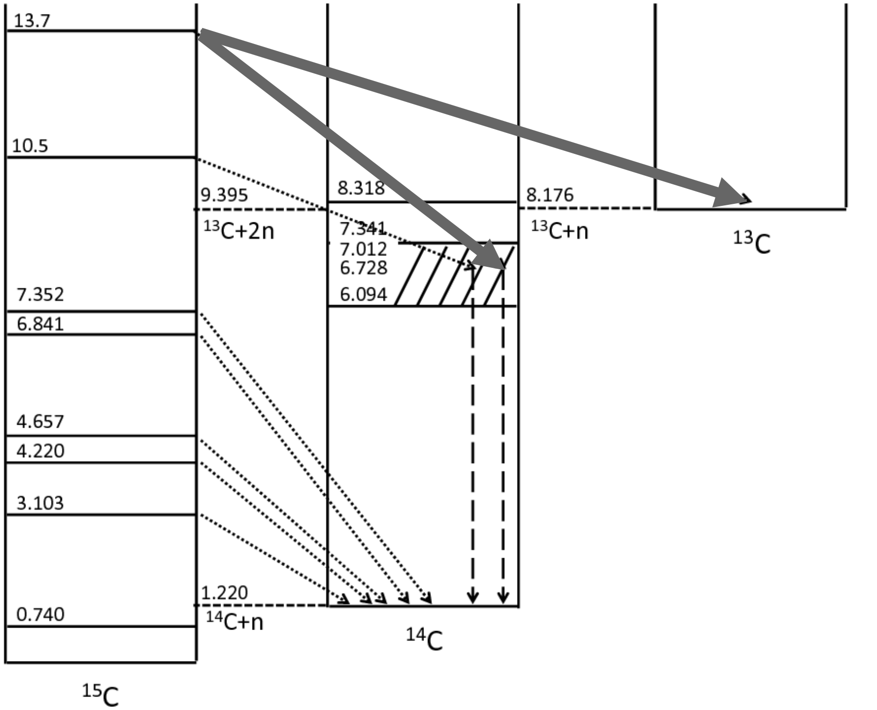


Neutron decay

M. Cavallaro, et al., Phys. Rev. C, accepted

MAGNEX





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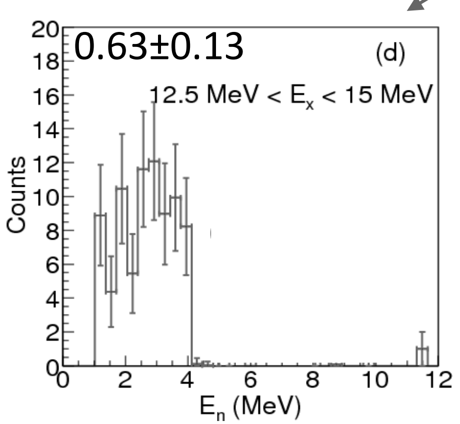

Not enough statistics for neutron-neutron coincidence

The GPV mainly decays emitting **two neutrons sharing the available energy**, while the single neutron emission is ruled out

Conclusions

- The **(^{18}O,^{16}O)** reaction is a **powerful tool** to explore the effects of the pairing force

- The **reaction mechanism** is under control
  - Transfer yields
  - Energy spectra
  - Angular distribution

- The observed bumps in ^{14}C and ^{15}C populated by (^{18}O,^{16}O) have all the features of the **GPV**

- **Neutron decay** by EDEN confirms the decay mode by **2n emission**, but more statistics is needed to look at 2n coincidence measurements