The G-NUMEN gamma spectrometer project - present status and demonstrator test

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for the NUMEN collaboration

Outline

- NUMEN and its motivation
- NUMEN experiments
- Motivation for G-NUMEN
- G-NUMEN characteristics
- Demonstrator experiment
- Final remarks

The NUMEN project

An international collaboration led by LNS/INFN, Catania [Cappuzzello et al., Progr. in Part. and Nucl. Phys. 128, 2023, 103999]

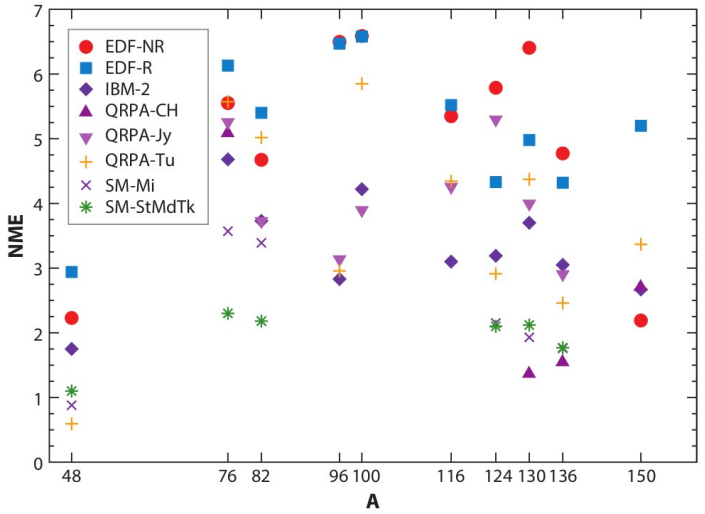
- Objective: Measurement of nuclear Double Charge Exchange (DCE) reactions to obtain experimental constraints on the nuclear matrix elements (NME) related to neutrinoless double beta decay

- Motivation:

  - Neutrino oscillations show that neutrinos are not massless implying physiscs beyond the Standard Model
  - Neutrinoless Double-Beta Decay (NLDBD) searches are the main approach to determine the nature of neutrinos – if Majorana or Dirac particles.
  - In the light-neutrino exchange model (among others), the NLDBD half life is related to the effective neutrino mass:

$$t_{1/2}^{0\nu} = \left(G^{0\nu}(Z, Q_{\beta\beta}) |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2 \right)^{-1}$$

- The phase space factor $G^{0\nu}$ is known, but the NME $M^{0\nu}$ is strongly model dependent



Dolinski, Poon, Rodejohann, Annu. Rev. Nucl. Part. Sci. 2019. 69:219

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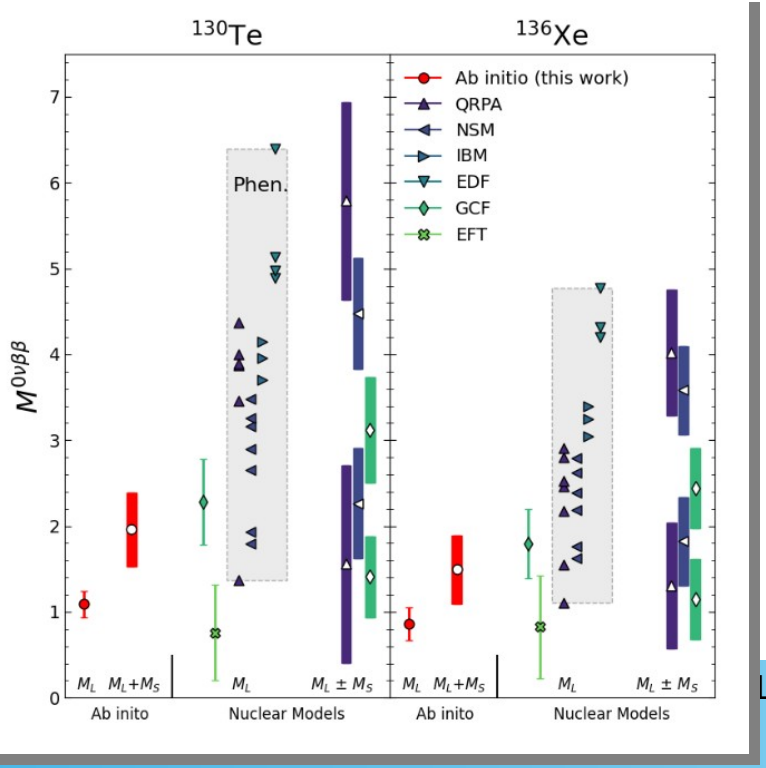


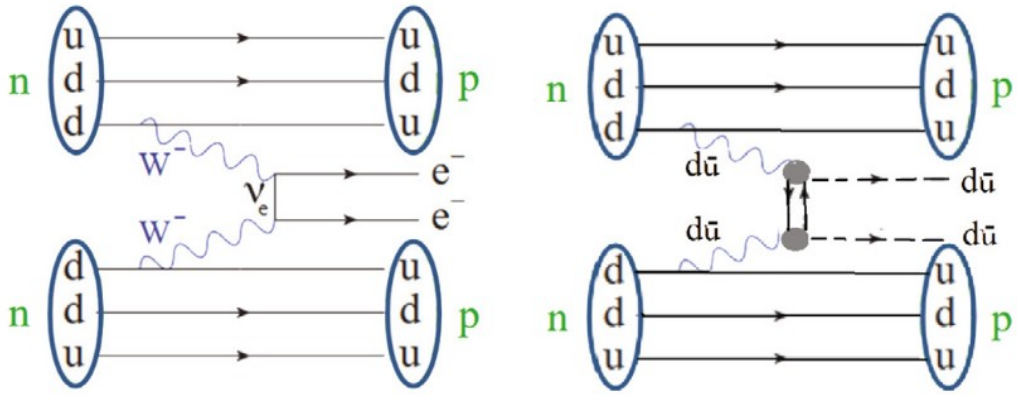
Ab initio – A. Belley, ...J.D. Holt, arXiv:2307.15156v1

The NUMEN project

Motivation:

- The matrix elements (NME) of DBD and DCE are presumably closely related:

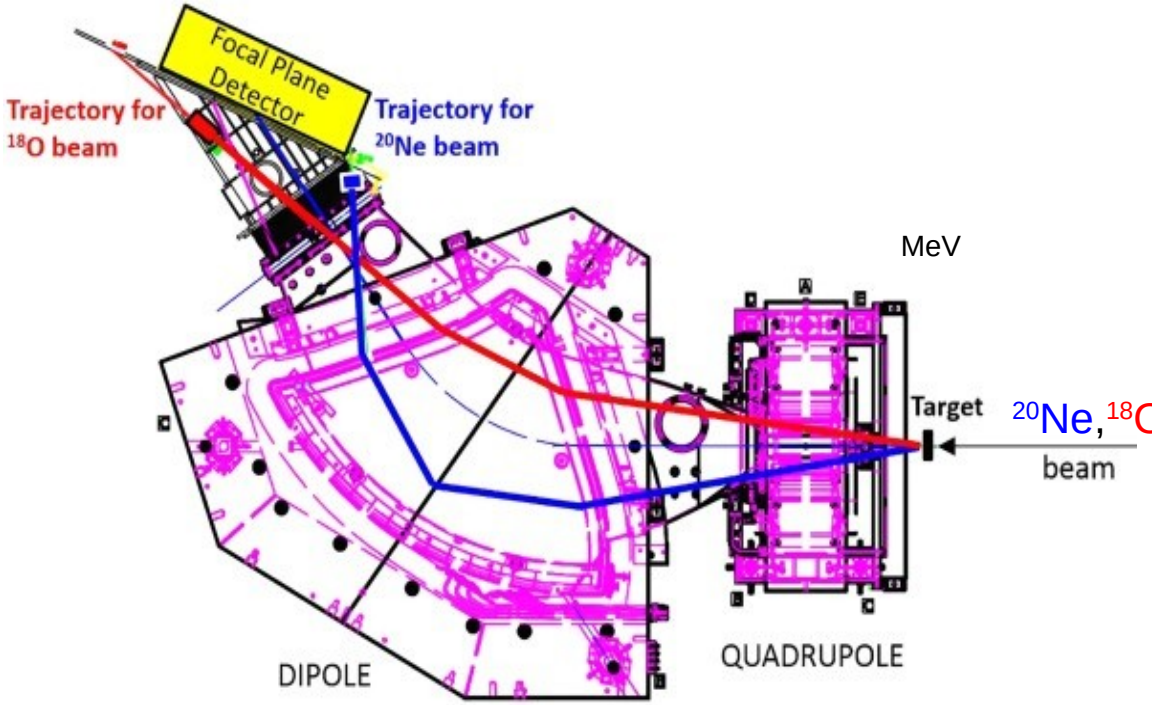
$$M^{0\nu} = \langle \psi_f | O^{0\nu} | \psi_i \rangle \quad M^{DCE} = \langle \psi_f | O^{DCE} | \psi_i \rangle$$

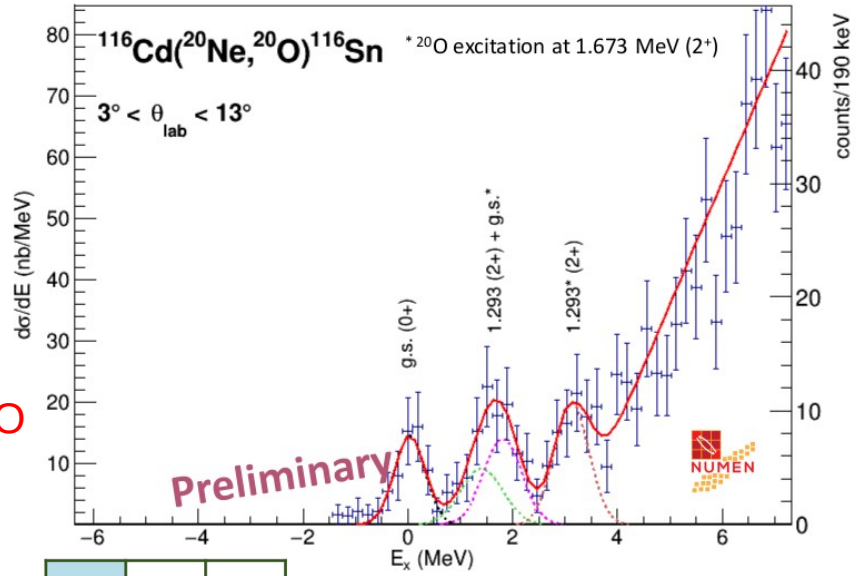


- Similar features
  - Same parent/daughter nuclear states
  - Similar in medium effects
  - Short range interaction, Fermi, GT
  - Large virtual momentum
  - Non-locality (2 vertices)
  - ...

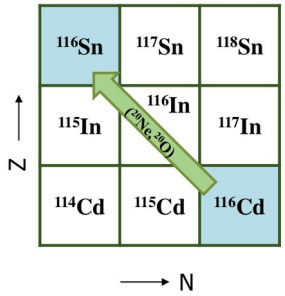
Lenske et al., Progress in Particle and Nuclear Physics 109 (2019) 103716

The NUMEN DCE experiments





D. Carbone, V International conference on Nuclear Structure & Dynamics, May 2024

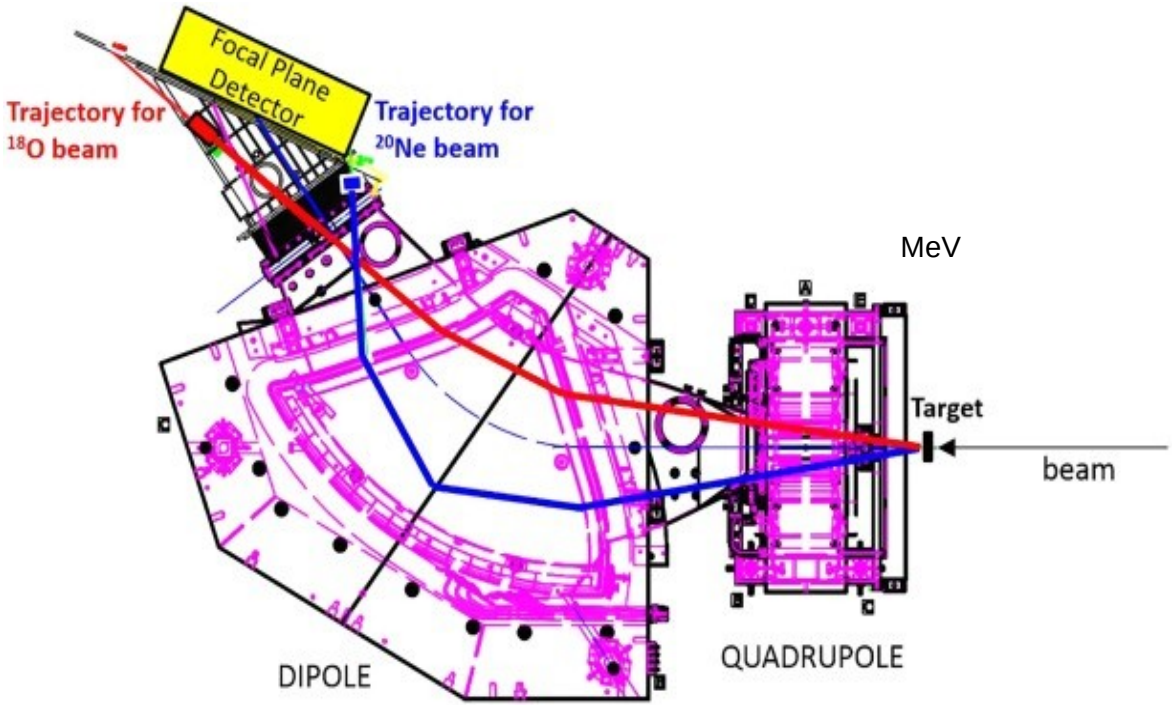


Other cases:

^{20}Ne + ^{130}Te, ^{76}Ge, ...

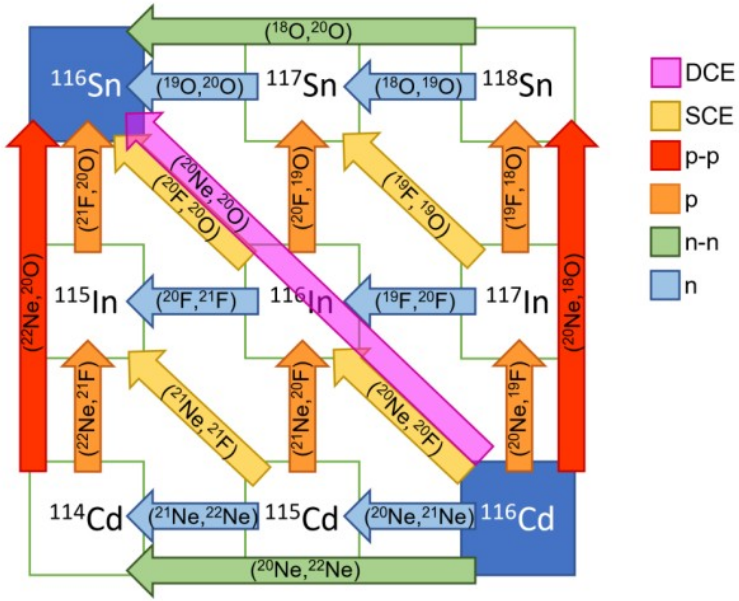
^{18}O + ^{116}Sn, ^{76}Se, ^{40}Ca, ^{48}Ti, ...

The NUMEN DCE experiments



MAGNEX

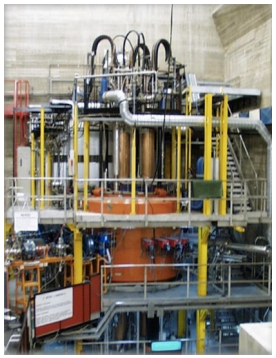
Nuclear reaction network
Multi-channel approach

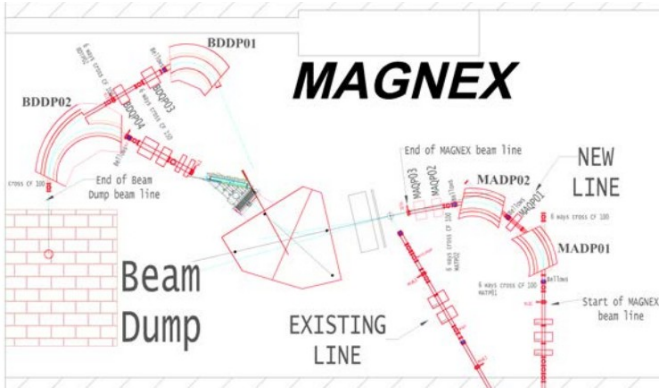


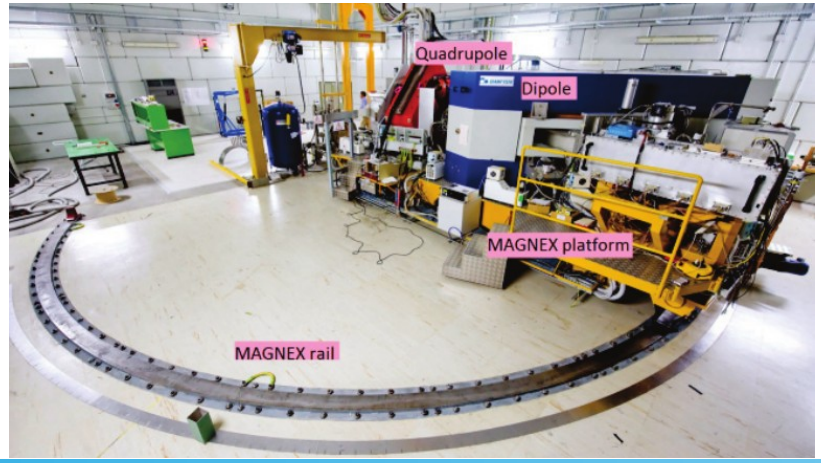
J. Ferreira et al., PRC 105 (2022) 014630

Facility upgrades

- New extraction channel of the CS cyclotron beam → increase in beam intensities to >10^{13} p/s!
- Beam lines/beam dump
- New gas tracker
- New PID wall
- Targets/target cooling
- Acquisition system and data storage
- ...
- → Gamma Spectrometer

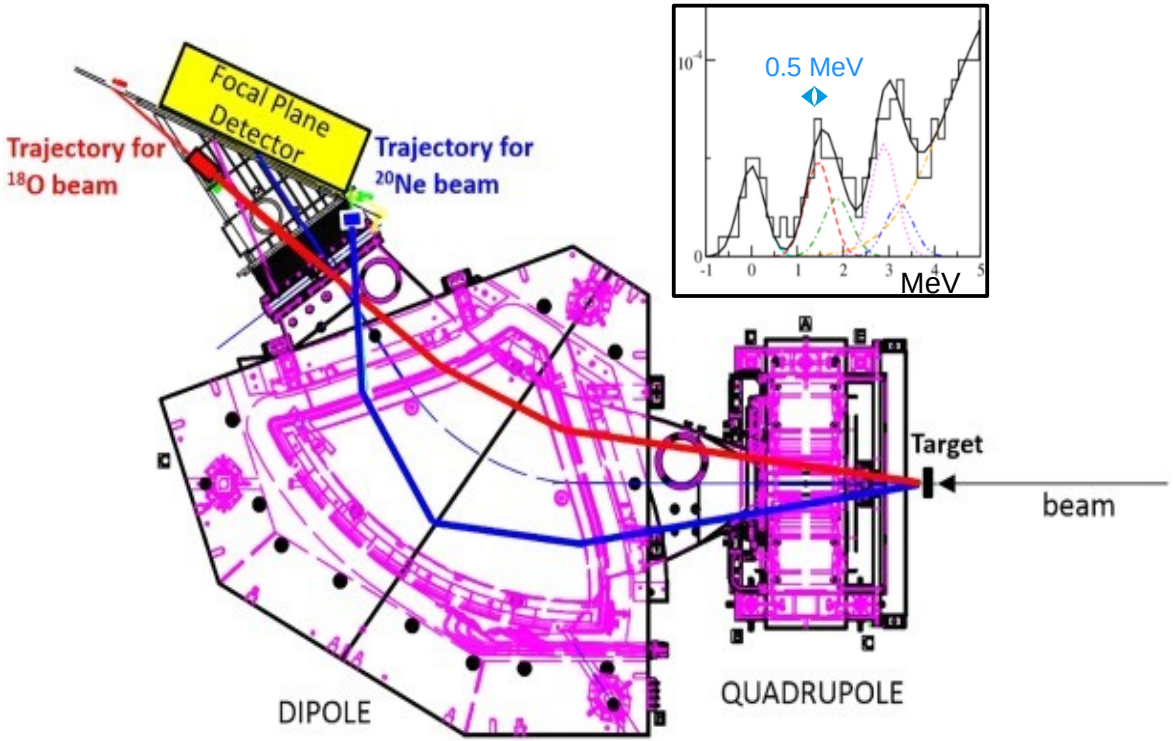






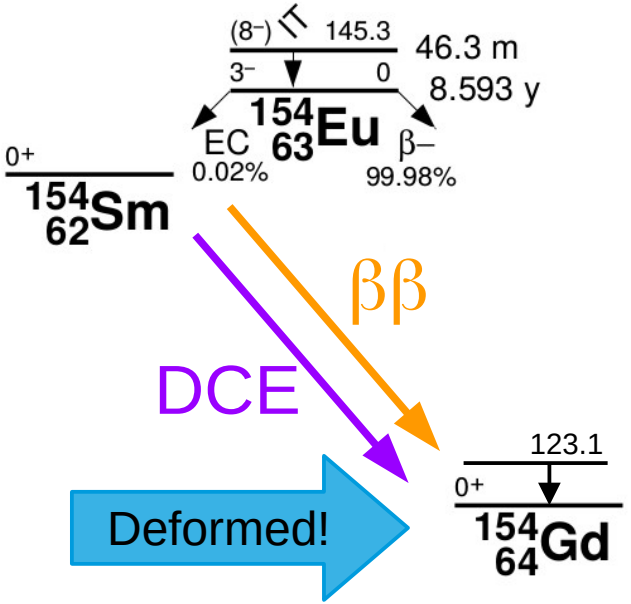
[TDR] "The NUMEN technical design report", F. Cappuzzello et al., International Journal of Modern Physics A 36, 30 (2021)

G-NUMEN motivation



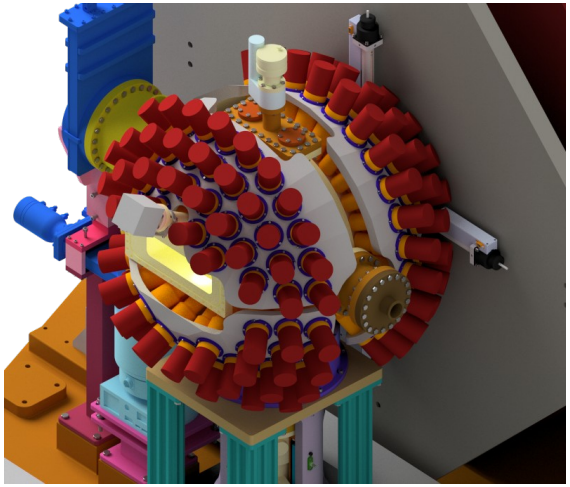
MAGNEX

Ex.: ^{20}Ne+^{154}Sm → ^{20}O+^{154}Gd



Deformed nuclei and higher beam energy experiments → Require high energy resolution → get info from gamma rays!

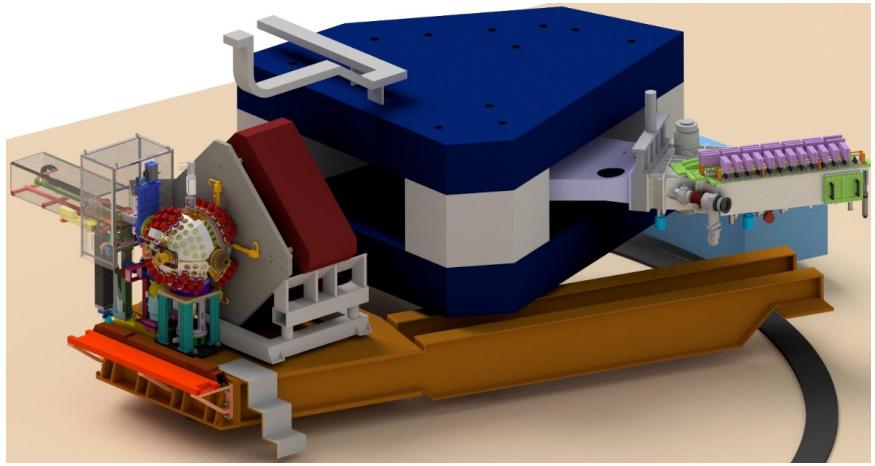
The G-NUMEN gamma spectrometer



Tolerant to high n flux

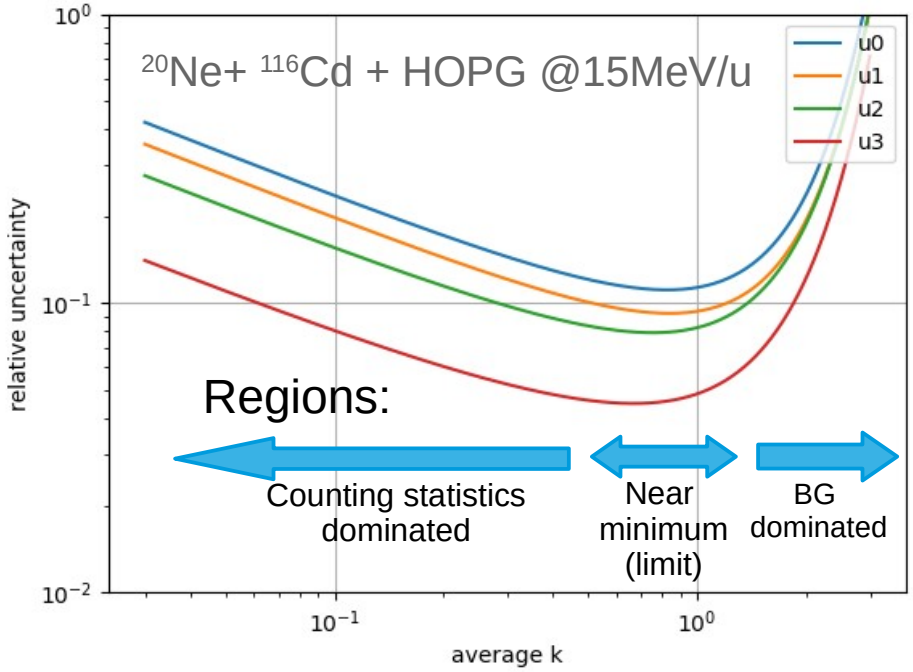
G-NUMEN

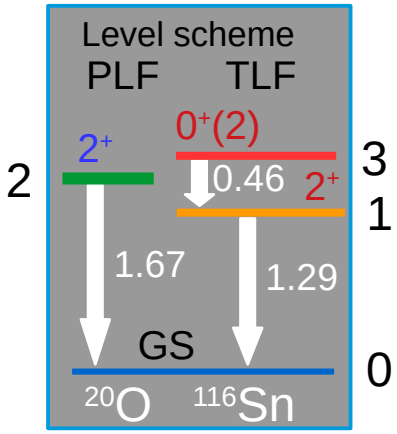
- 105 $LaBr_3$(Ce) detectors @24 cm from target
- 4% photopeak efficiency @1.3 MeV
- Measurements in coincidence with PLF (@FPD of **MAGNEX** spectrometer)
- Good energy resolution to separate gs from E* in DCE measurements
- Observational limit ~1 nb [1]



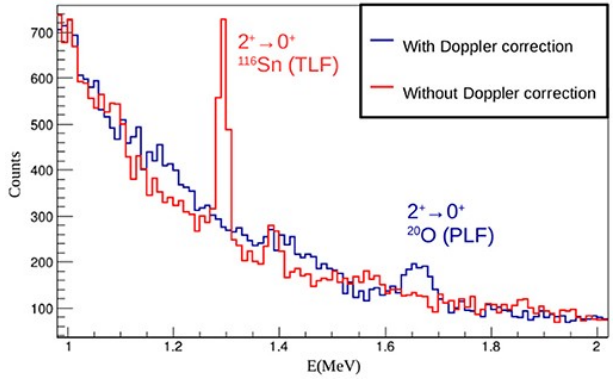
Observational limit

Relative uncertainty as a function of beam intensity in terms the of average k (number of reactions/bunch) for a cross section of **1 nb**/state (in a 1 month G-NUMEN experiment) [see TDR].



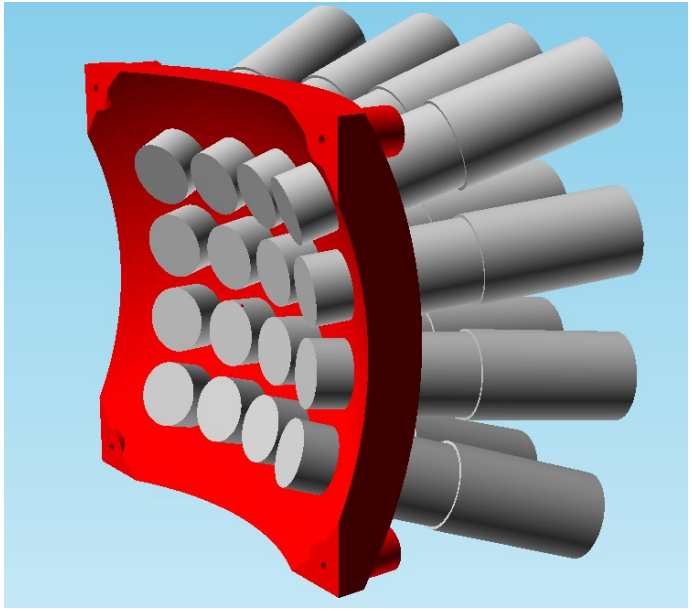


Geant4 simulation

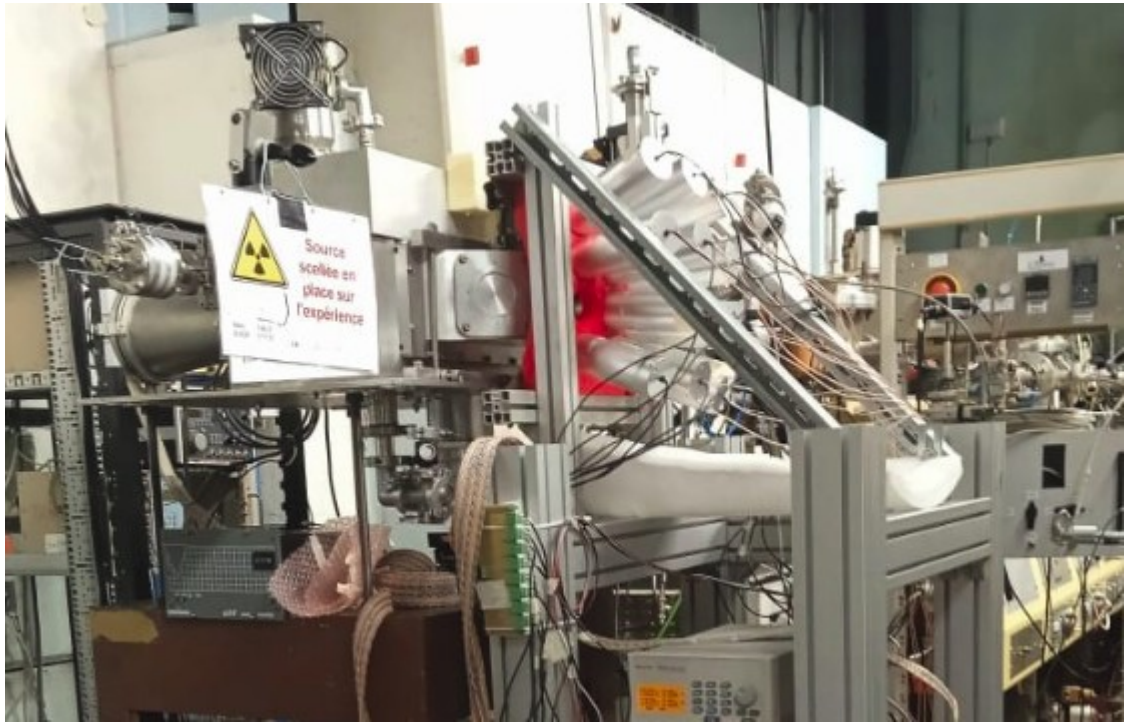


Demonstrator array

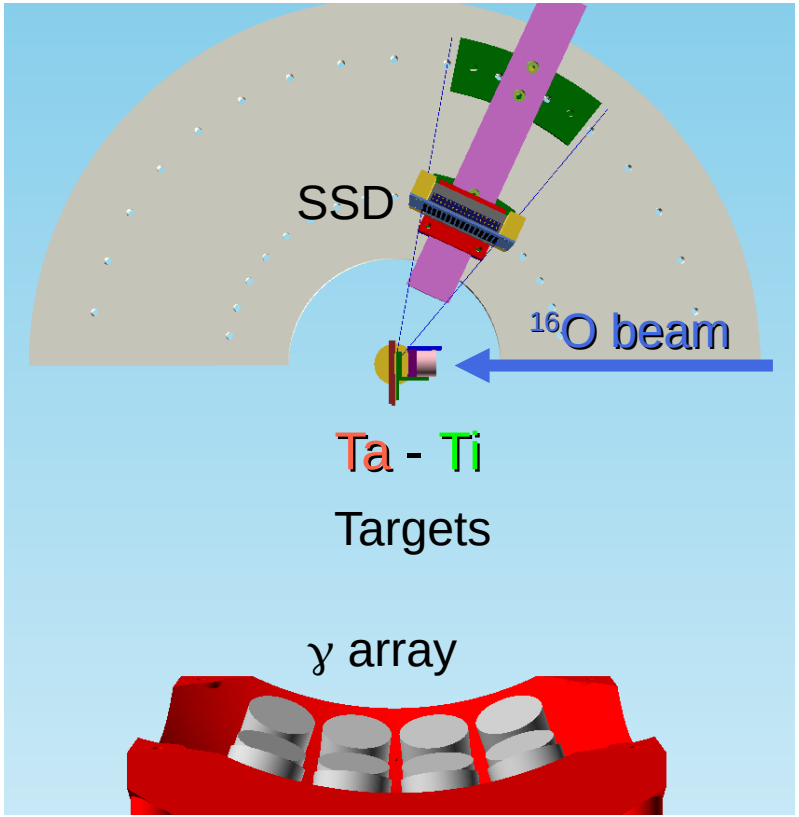
15 G-NUMEN $LaBr_3(Ce)$ scintillator detectors

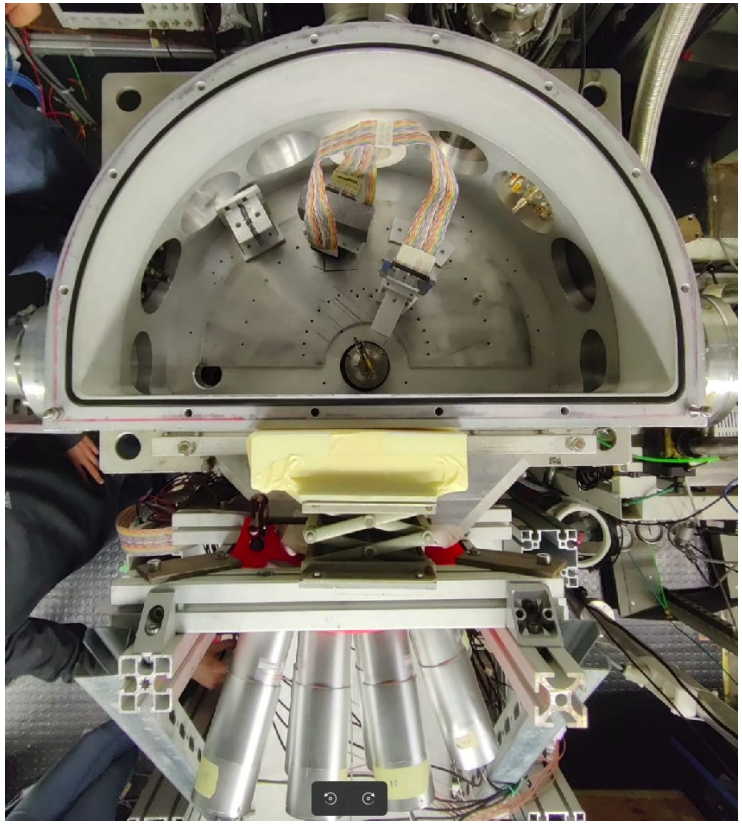


Mounted at ALTO Tandem beam line
by the Demi-Camembert chamber



Setup @ Demi-Camembert chamber

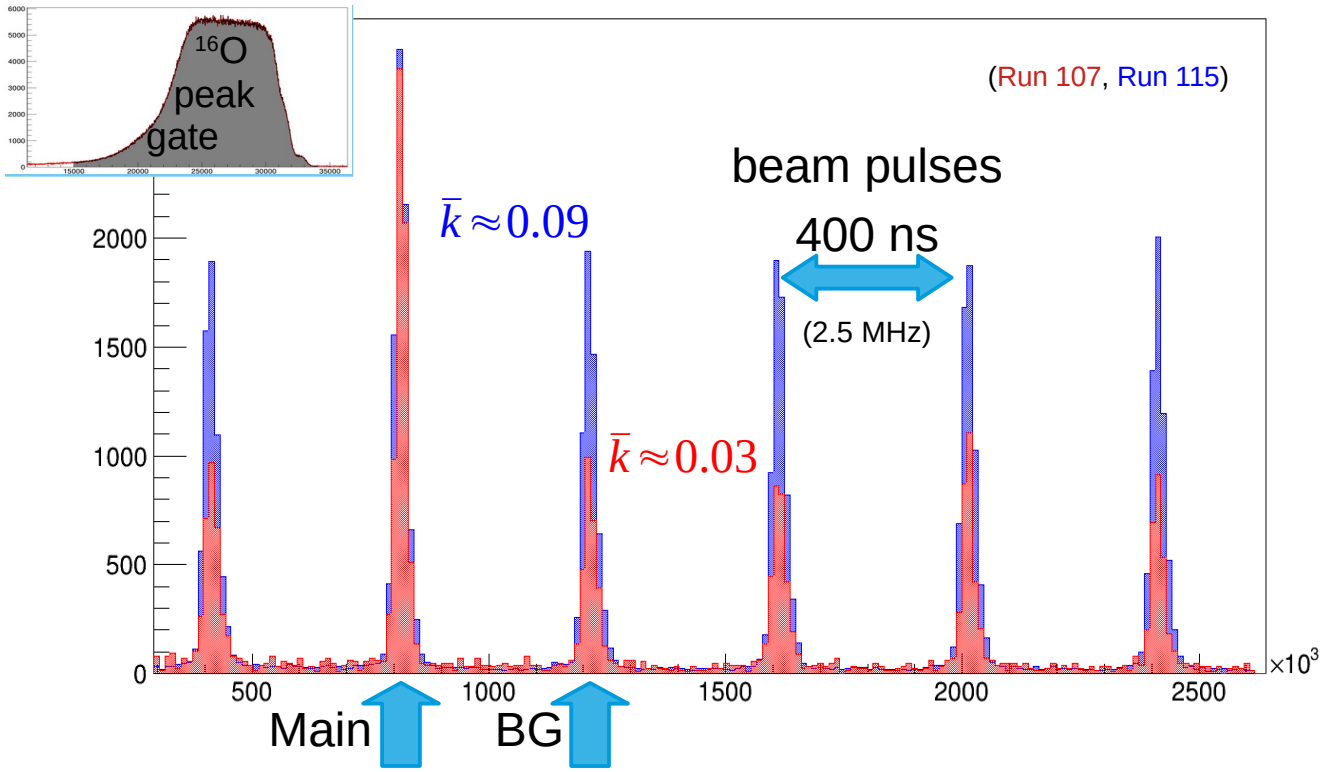




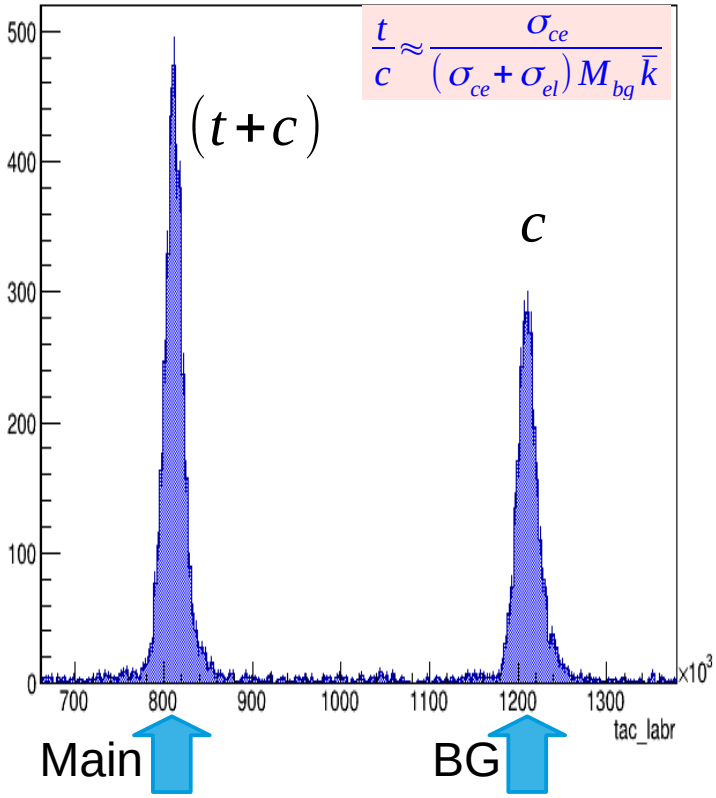
^{181}Ta/Ti(^{16}O,^{16}O) @ 83.5 MeV

Gamma time spectra

$\bar{k}$: average number of reactions per beam bunch



true and chance coincidences



t/c rate estimates

- *t*rue vs *c*hance coincidence rates

$$t = R_{SSD}\,\varepsilon_\gamma\,M_{Coul}\,\frac{\sigma_{Coul}}{(\sigma_{El}+\sigma_{Coul})}$$

$$c = R_{SSD}(1-\varepsilon_\gamma)\,M_{bg}\,\varepsilon_\gamma\,R_R/f_{cycl}$$

$$R_R/f_{cycl} = \bar{k}$$

Demonstrator

$$t \approx \frac{1}{2}\,R_{SSD}\,\varepsilon_\gamma\,M_{Coul}$$

$$c \approx R_{SSD}\,M_{bg}\,\varepsilon_\gamma\,\bar{k}$$

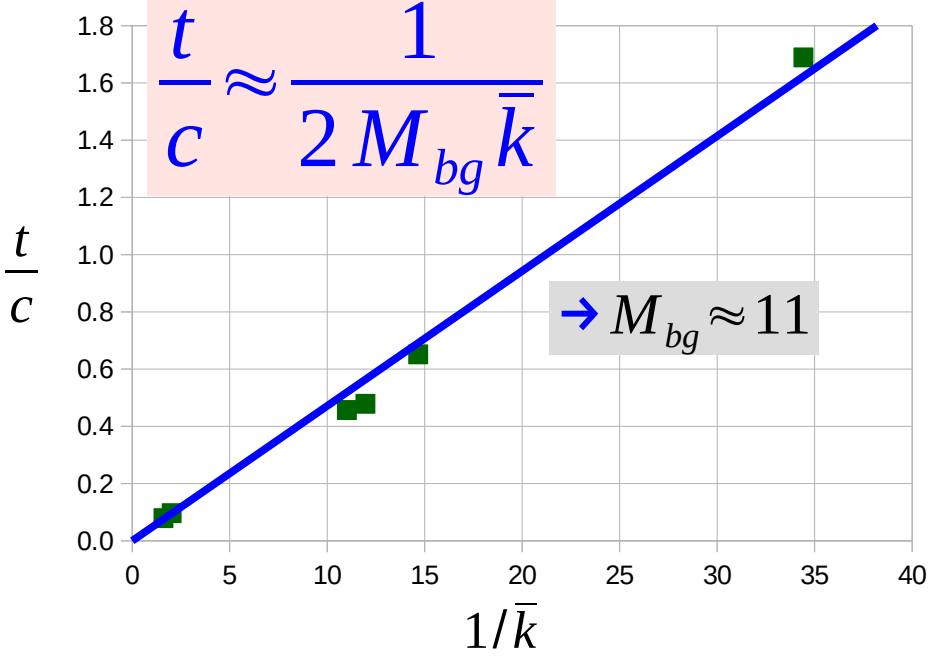
$$(\varepsilon_\gamma < \varepsilon_{geo} \approx 0.02 \ll 1)$$

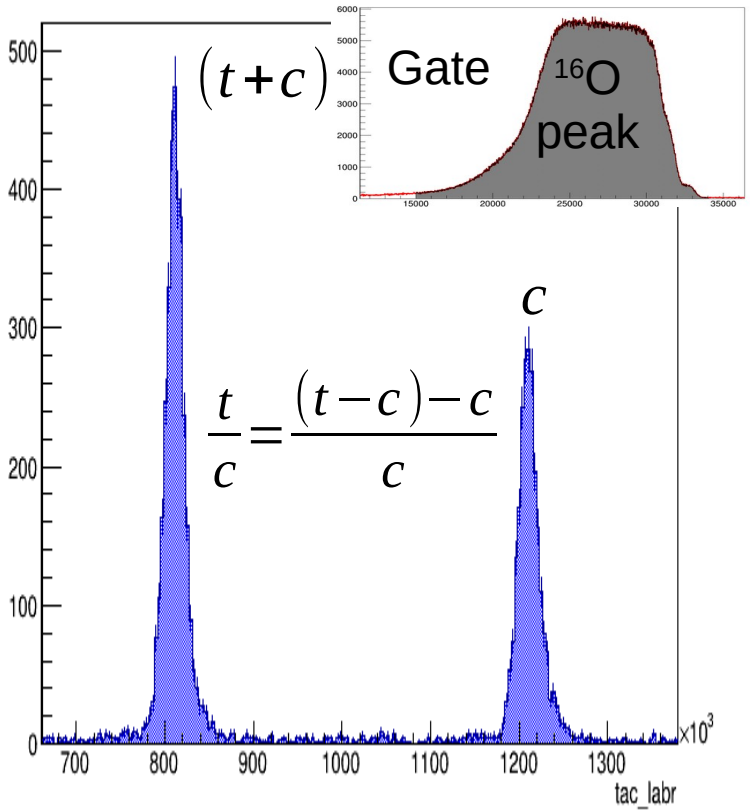
$$\bar{k} = N_{bunch}\,\sigma_{fus}(\mathrm{Ti})\,n_{Ti}$$

$$\frac{t}{c} = \frac{\sigma_{Coul}}{(\sigma_{coul}+\sigma_{El})(1-\varepsilon_\gamma)\,M_{bg}\,\bar{k}} \approx \frac{1}{2\,M_{bg}\,\bar{k}}$$

Gamma/SSD time spectra model

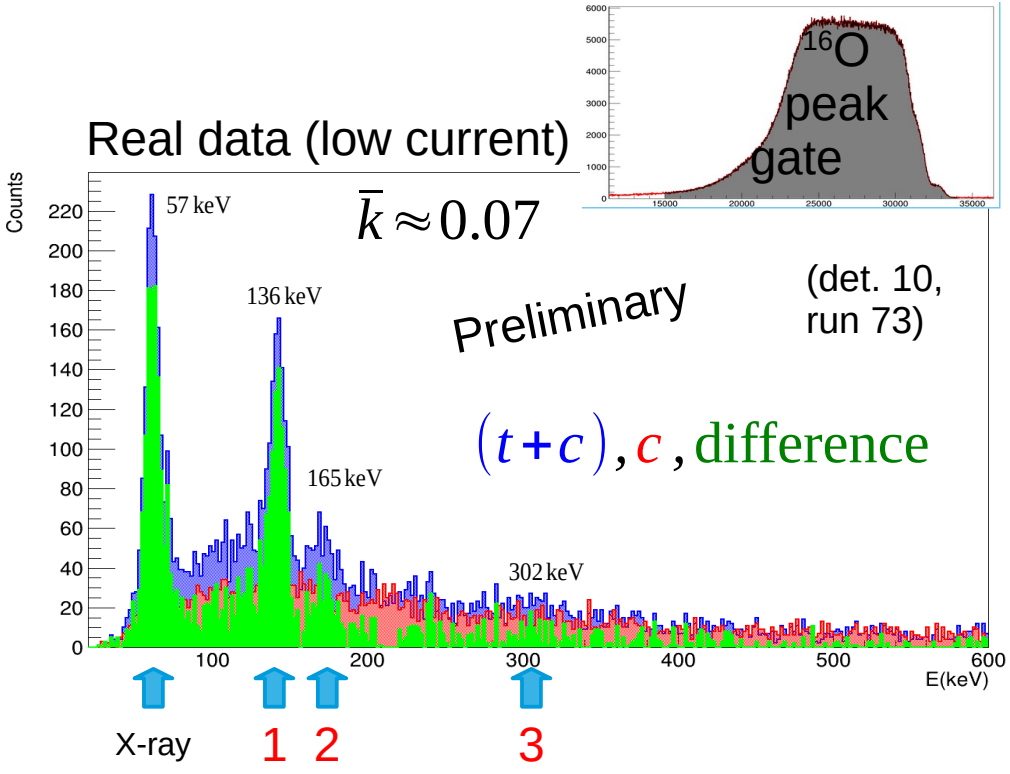
$$\frac{t}{c} \approx \frac{1}{2 M_{bg} \bar{k}}$$



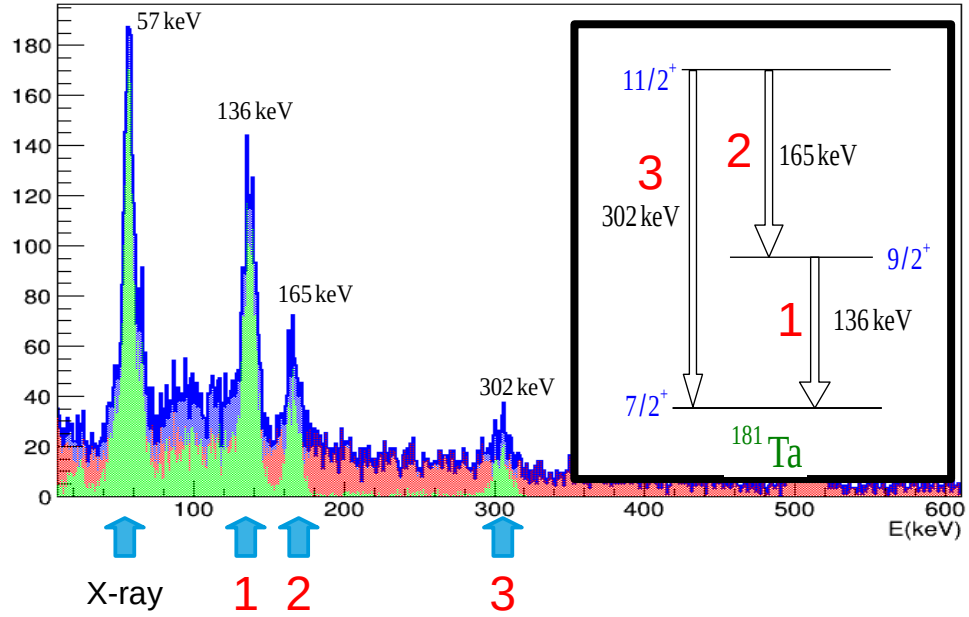


Data vs simulation comparison

Real data (low current)

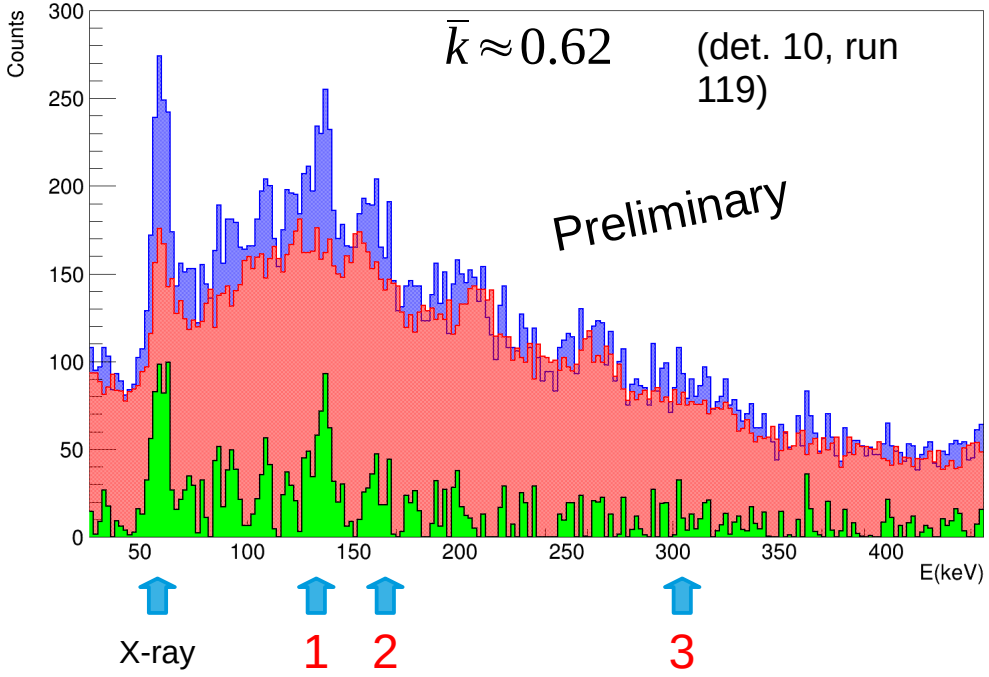


Simulation (addapted)

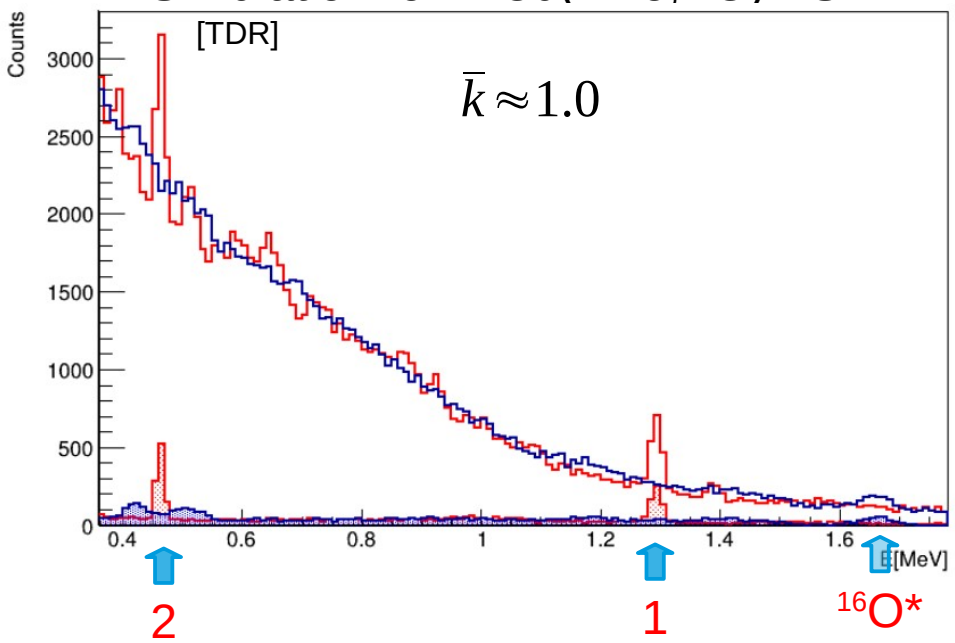


Highest beam current result

Demonstrator data



Simulation for $^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$



$M_{BG}(1-\varepsilon_\gamma)\bar{k} \approx 6.8$ (near O.L.) $M_{BG}(1-\varepsilon_\gamma)\bar{k} \approx 6.7$

Final remarks

- Demonstrator experiment → preliminary agreement with expectations → corroboration of the spectrometer performance
- Simulations of actual setup to be done for a precise validation by the experiment
- New PMT base project under development to withstand measurements at high count rates (~300 kHz)
- n-Irradiation test of $LaBr_3(Ce)$ to be completed (→ 10^{12} n/cm²)

- Students and post-docs welcome!

The NUMEN collaboration

(NUclear Matrix Elements for Neutrinoless double beta decay)

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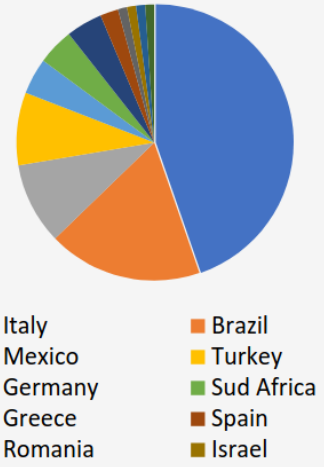
94 Researchers
32 Institutions
12 Countries

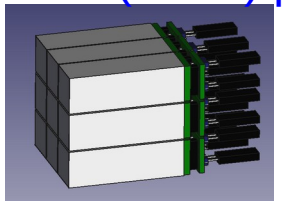


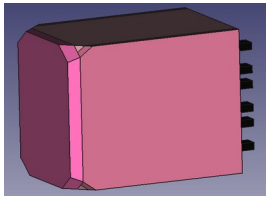
Parallel activities at IFUSP

- The “Nossa Caixa” spectrometer

- LYSO(Ce) 12.4 mm² X 40 mm scintillator crystals with SiPM readout (pixels)

- 12 X (3 X 3) pixel detectors





- Crystal faces at 54 mm from target
- 10% photopeak efficiency at 1.3MeV
- Radiation tolerant and insensitive to magnetic fields (for stable or RIB)
- Fast timing (2-3 ns)
- Operates in air and in vacuum

… & plastic scintillators under development for detection of charged particles

Thanks !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FAPESP
NUMEN
IJCLab
Irène Joliot-Curie
Laboratoire de Physique
des 2 Infinis