THE HENRYK NIEWODNICZAŃSKI
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# Experimental studies of the strength function below binding energy

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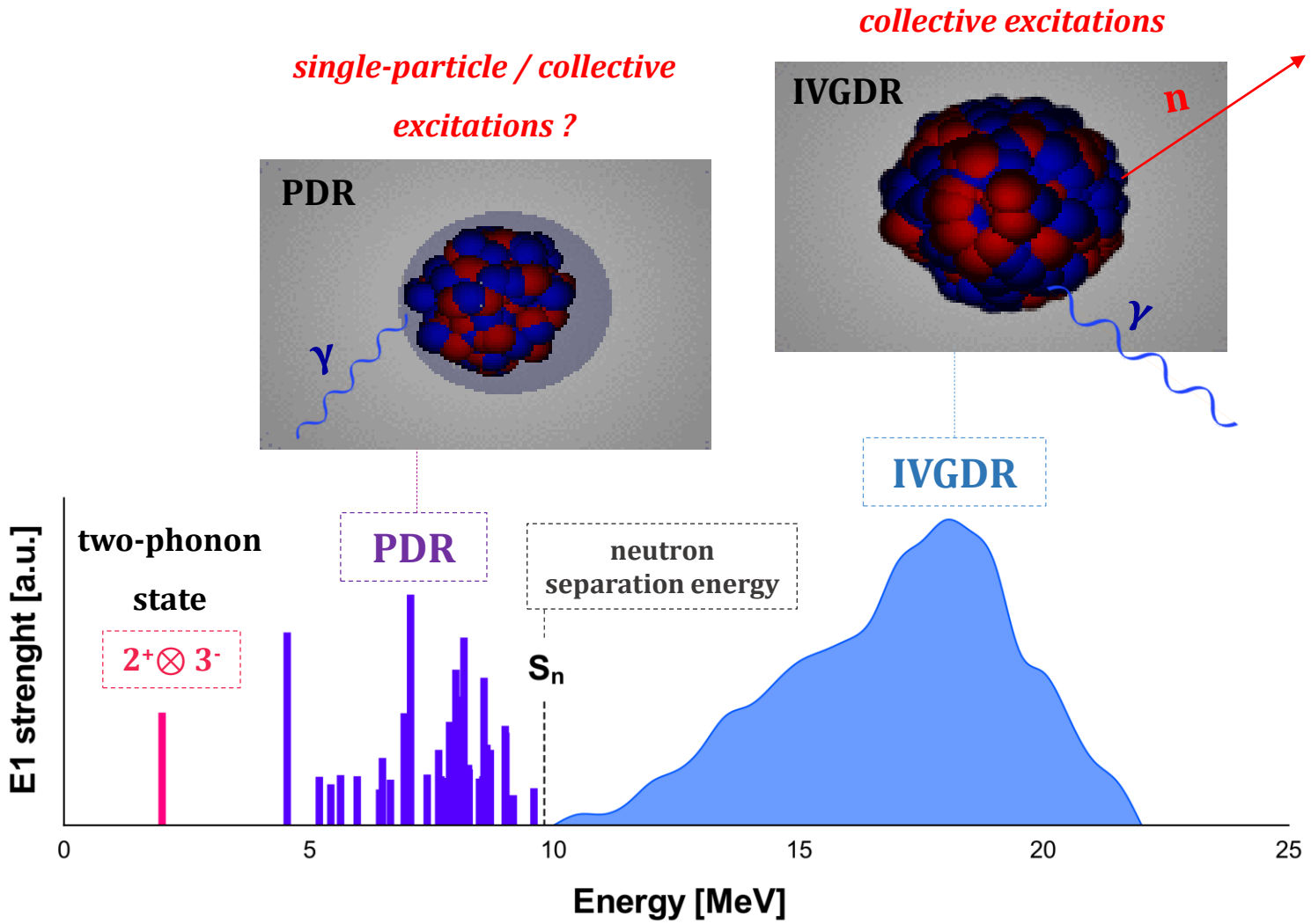
***Electric Dipole (E1) Response*** (e.g. spherical $^{140}$Ce nucleus)



## Nuclear Resonance Fluorescence (NRF) (γ,γ')

- *photons* are *highly selective to dipole-excited states*
- the excitation mechanism is well known and includes *exclusively the electromagnetic force*
- interacts with whole nucleus

**Intrinsic properties** like spin, parity or transition strengths can be extracted from the measured quantities in a *model independent way.*

## How can we study PDR in Poland with particle accelerators ?

### Inelastic scattering of protons (p,p')

- RCNP (Osaka) ← Kraków group involved
- iThemba LABS (Cape Town)
- CCB (Kraków)

### Inelastic scattering of alpha particles (α,α')

- RCNP (Osaka) ← Kraków group involved
- KVI (Groningen)

### Inelastic scattering of heavy ions ($^{17}O, ^{17}O'$)

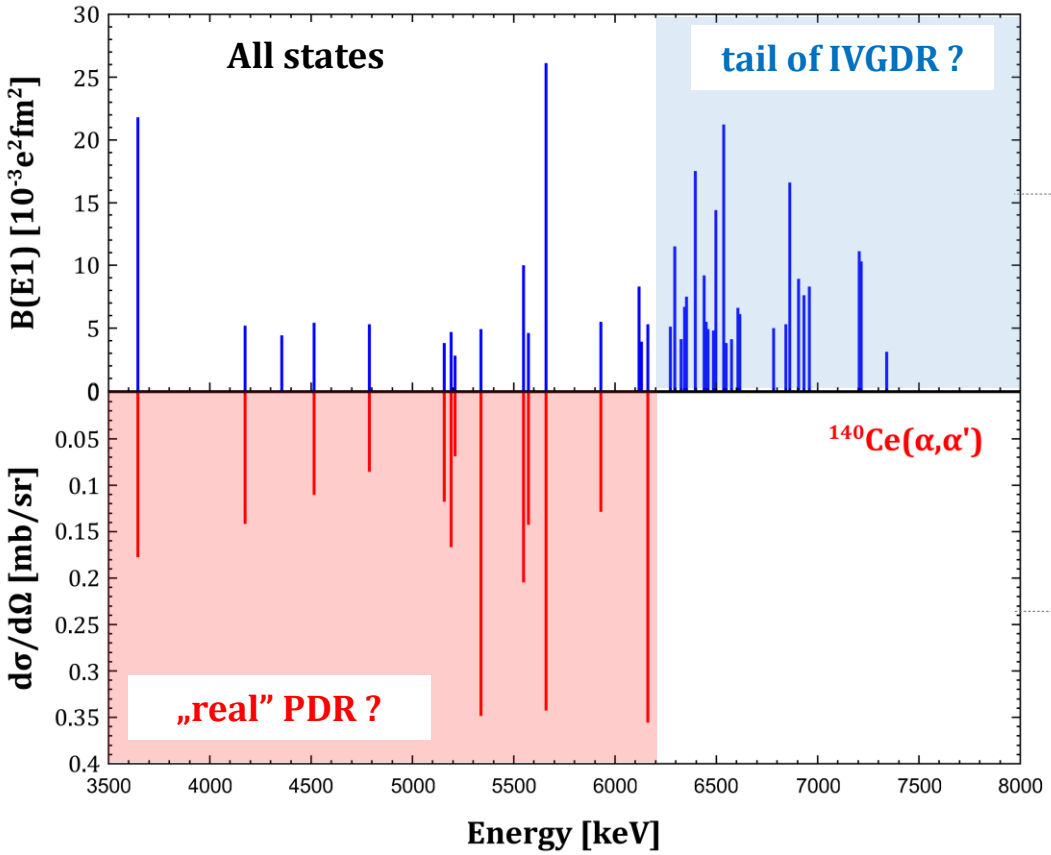
- LNL (Legnaro) ← Kraków group involved

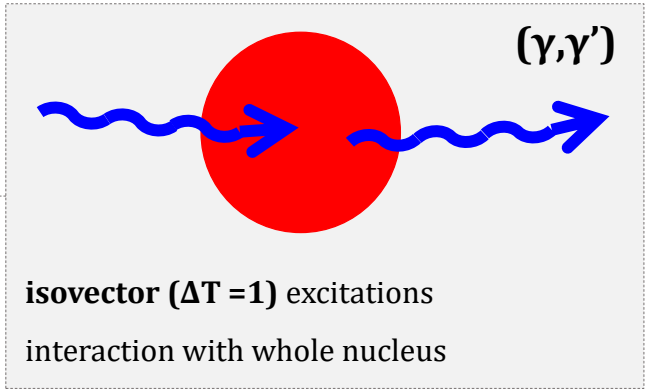
### Neutron-transfer reactions (d,p)

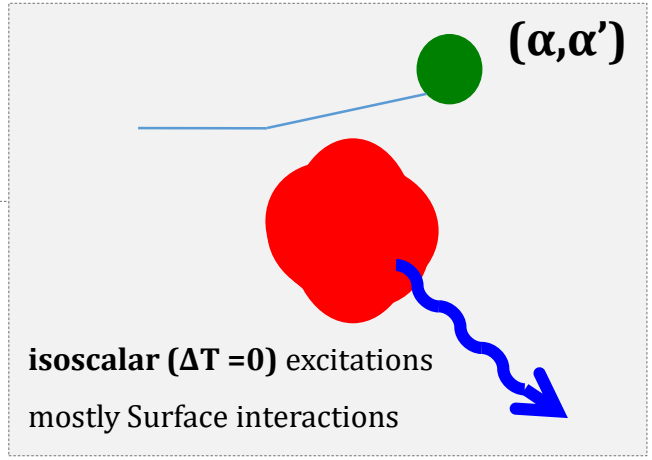
- IKP (Cologne)

## **Pygmy states** *isospin character*

D. Savran *et al.*, PRL 97 (2006) 172502



## How can we study PDR in Poland with particle accelerators ?

**Inelastic scattering of protons (p,p')**

- at small forward angles → excitation mechanism similar to photons
- for higher angles both coulomb and nuclear parts play role

**Inelastic scattering of alpha particles (α,α')**

- isoscalar probe
- surface interactions

**Inelastic scattering of heavy ions ($^{17}O, ^{17}O'$)**

- predominantly isoscalar probe
- surface interactions

**Isospin properties**

**Neutron-transfer reactions (d,p)**

- sensitive to the neutron single-particle structure

**Collectivity**

***Gamma – particle coincidence measurements*** can be performed at **CCB (Krakow)** and **new cyclotron at HIL (Warsaw)** to study stable nuclei response near neutron threshold mainly ***Pygmy Dipole Resonance***

## Possible beams

***CCB***

- **protons**
- energy: 70-230 MeV
- Intensity: 0.1 - 600 nA

***New Cyclotron at HIL***

- from **alpha** to $^{209}$**Bi**
- energy ≤ 10 MeV/A
- intensity: 10pμA for A=50

***CCB***

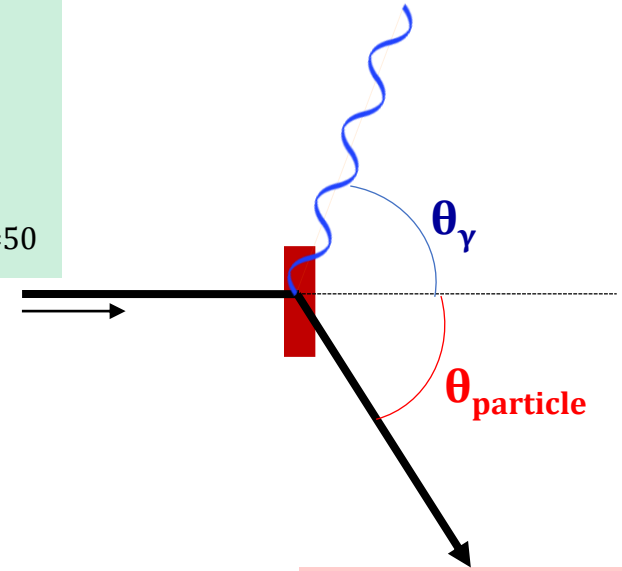
- (p,p')

***New Cyclotron at HIL***

- (α,α')
- ($^{17}$O, $^{17}$O')
- ($^{13}$C, $^{12}$C')

## Gamma detection

- EAGLE / AGATA
  → high-resolution measurements
- PARIS / Large volume $LaBr_3$:Ce
  → high-efficiency γ-γ measurments




## γ-particle coincidence matrix

selection of decay path: $E_x = E_{level} + E_\gamma$
→ ground-state decay: $E_x = E_\gamma$

## Particle detection

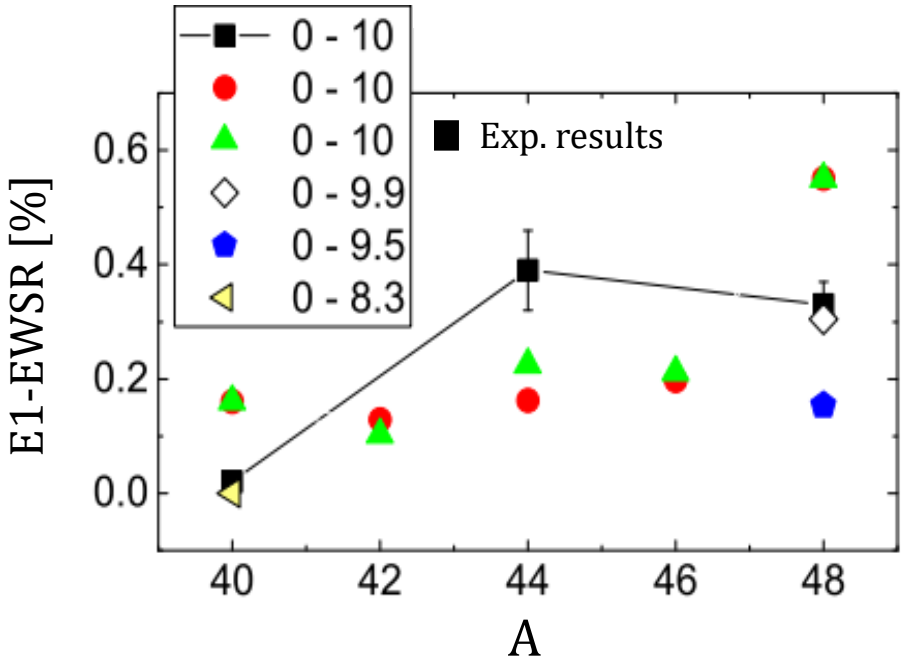
- KRATTA
- Segmented ΔE-E silicon telescopes
- Magnetic spectrometer

## Physics cases

- Systematic studies would be needed for selected isotopic chain

**Motivation for calcium isotopes:**

- ❑ are well studied theoretically
- ❑ discrepancies observed in PDR region between theory and existing data
- ❑ no systematic study for all stable isotopes




I.A. Egorova and E Litvinova, Phys. Rev.C 94, 034322 (2016)

❑ also well-suited for **neutron transfer...**

**Proposal for HIL: ($^{13}$C, $^{12}$C$\gamma$)**

$^{13}C + {}^{40}Ca \rightarrow {}^{41}Ca + {}^{12}C + 3.42$ MeV

$^{13}C + {}^{42}Ca \rightarrow {}^{43}Ca + {}^{12}C + 2.99$ MeV

**$^{13}C + {}^{43}Ca \rightarrow {}^{44}Ca + {}^{12}C + 6.18$ MeV**

$^{13}C + {}^{44}Ca \rightarrow {}^{45}Ca + {}^{12}C + 2.47$ MeV

$^{13}C + {}^{46}Ca \rightarrow {}^{47}Ca + {}^{12}C + 2.33$ MeV

**Beam energy of >5 MeV/A should be fine**

# Beam energy for inelastic scattering

**Alpha particles:**

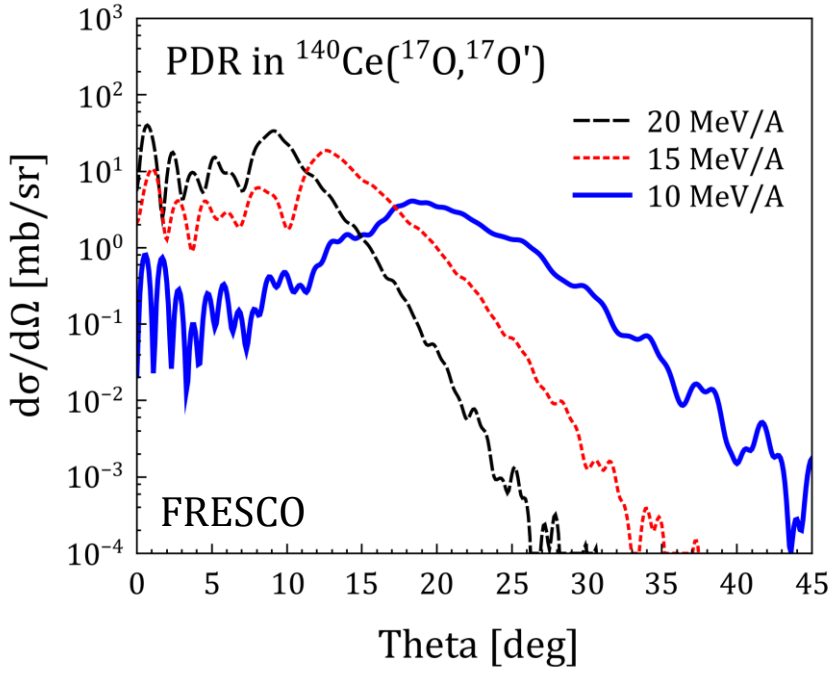
Most of (α,α'γ) experiments **at ≥30 MeV/A**

Successful measurement also for $^{208}$Pb at **12 MeV/A** P. Decowski et al, Phys. Lett. B 101 (1981) 147

**Higher energy → higher PDR cross section, but also higher contribution from other excitations**

**Heavy ions:**

- Inelastic scattering of $^{17}$O at **20 MeV/A** on $^{140}$Ce (LNL Legnaro) M. Krzysiek et al., Phys. Rev. C 93, 044330 (2016)
- DWBA calculations for PDR (total strength) excitation :




**Lower energy → lower PDR cross section**

but:

- **lower unwanted contribution from IVGDR**
- **shape of distribution could be better probed with high angular coverage**

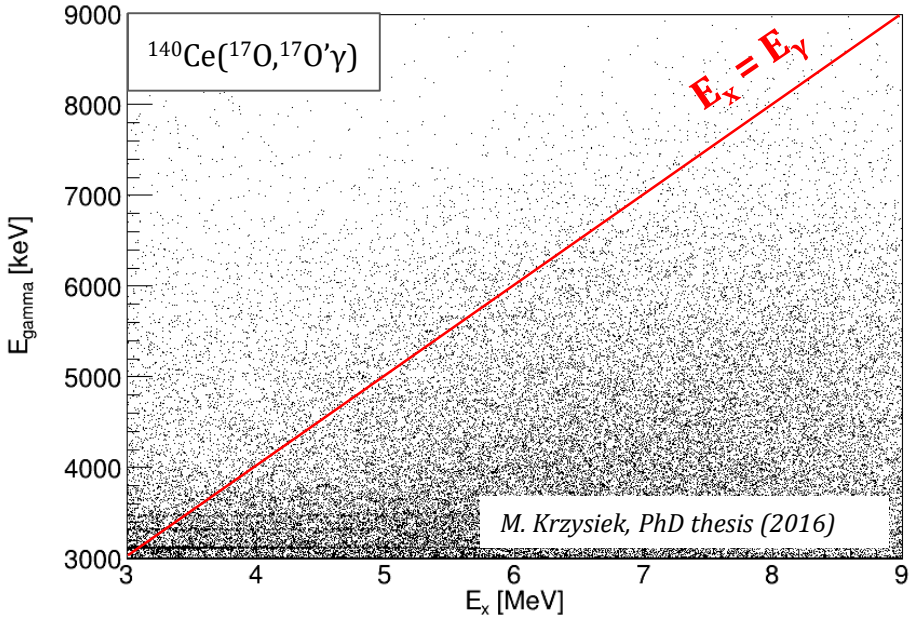
**Particle Detection** ➡ additional to existing KRATTA array

**ΔE-E silicon detectors**

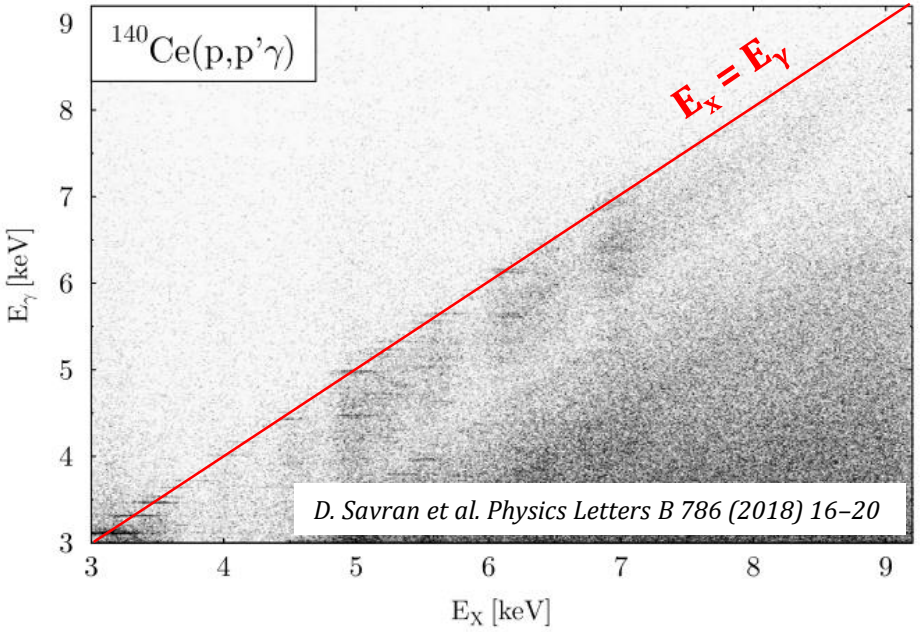
- ➡ portable solution
- ➡ relatively low price
- ➡ worse energy resolution
- ➡ radiation damage
- ➡ possible wide angular coverage

**Magnetic spectrometer** e.g. BBS at KVI

- ➡ stationary solution
- ➡ expensive
- ➡ better energy resolution
- ➡ 0°-scattering option
- ➡ rather limited opening angle




Good for non 0°-scattering, low-energy and light particles




Excellent for 0°-scattering, high-resolution measurements

## **Gamma Detection** ➡ additional to existing EAGLE array

### **AGATA array:** currently 32 HPGe at GANIL

**Pulse-Shape Analysis (PSA)**

Allows to identify the point of γ-ray interaction in the crystal

**Tracking**

Allows to reconstruct the time sequence of interactions and *estimate the γ-ray energy*

Excellent for high-efficiency high-resolution gamma spectroscopy

### **PARIS array:** currently 36 phoswiches

- Phoswich: NaI + $LaBr_3$ or $CeBr_3$
- Clusters of 9 phoswiches → position sensitivity
- Possible 4π coverage
- Good timing properties
- Efficient for high-energy gamma rays

Excellent for high-efficiency γ-γ coincidence measurement with high-resolution HPGe

S. Akkoyun et al., Nucl. Instr. and Meth. in Phys. A 668 (2012) 26–58

A. Maj et al. Acta Physica Polonica B 40 (2009) 3

**We propose a campaign of systematic studies in both facilities (CCB and HIL)**

As a first case, a good candidates are ***stable Ca isotopes***

## Isospin properties of PDR

- **(p,p'γ)** @ 70-230 MeV at ***CCB Kraków***
- **(α,α'γ)**
- **($^{17}$O,$^{17}$O'γ)**

} @ highest energy available at ***new cyclotron of HIL Warsaw***

## Single-particle structure of PDR

- **Neutron-transfer reactions** e.g. $^{43}$Ca($^{13}$C,$^{12}$Cγ)$^{44}$Ca @ > 5 MeV/A at ***new cyclotron of HIL Warsaw***
  → comparison with the other measurements (p,p'γ) (α,α'γ) ($^{17}$O,$^{17}$O'γ)

## PDR decay branching to excited states

- Very precise measurement of γ-particle coincidence matrix (preferably with magnetic spectrometer)
- High-resolution HPGe array (EAGLE or AGATA) + high-efficient PARIS array (γ-γ coincidences)

**10 MeV/A** energy should be enough for proposed studies, however **15-20 MeV/A** would be preferable

⇩

**Post-acceleration system** would be a solution

# Thank you for your attention