Test of the three body interactions: lifetime measurements of excited states in neutron-rich C and O isotopes

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AGATA
ADVANCED GAMMA TRACKING ARRAY

PARIS

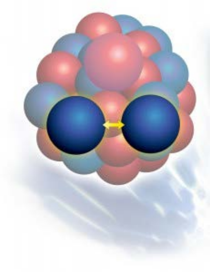
Presentation plan

- Motivation
- Experimental setup
- Data analysis
- Lifetime determination method and simulations
- Results and plans for future

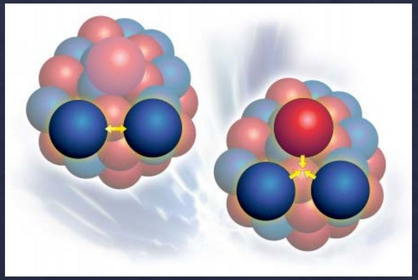
Motivation

Nuclear force is the „heart” of nuclear physics, and has been studied from ~1930.

During the past few decades a large effort has been made toward describing the nucleon-nucleon (NN) interaction in the framework of chiral Effective Field Theory (EFT). The main idea is to exploit the symmetries of QCD to obtain an effective theory for low energy nuclear systems.



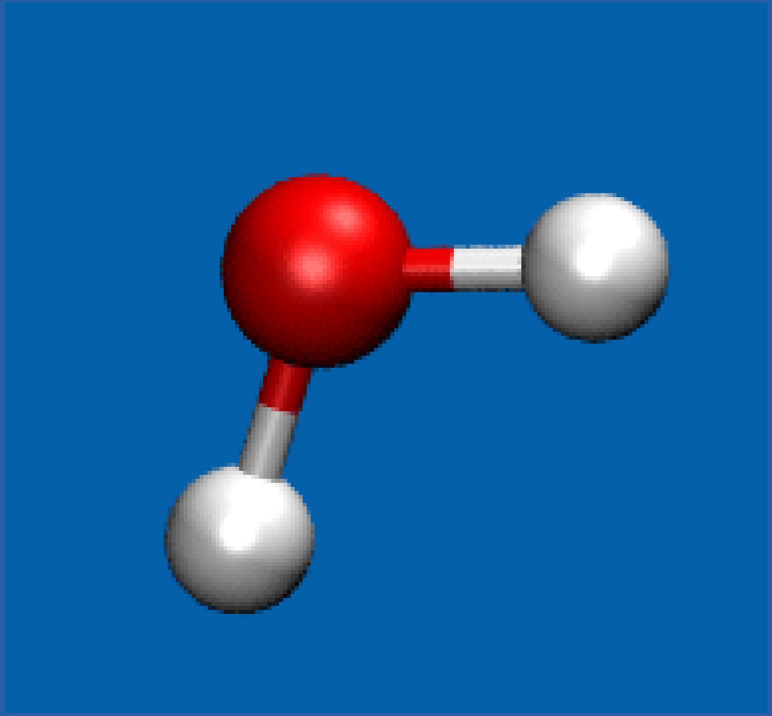
NN



NN+NNN

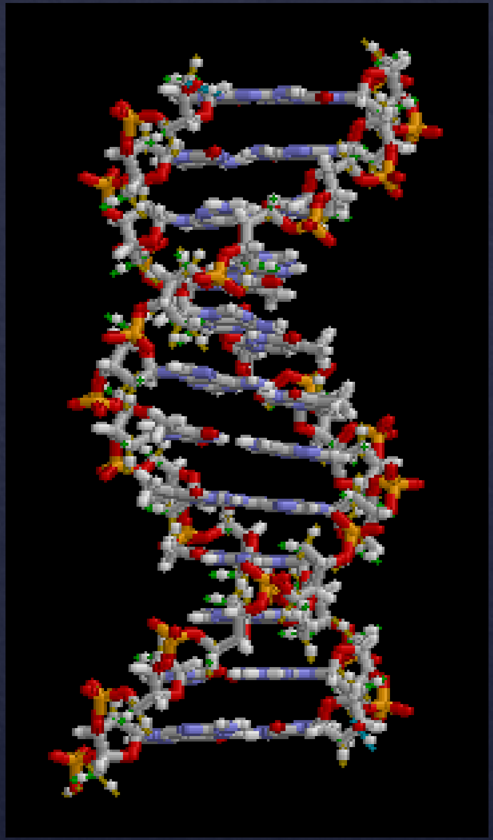
3 body interactions are common in many fields of complex systems.

water molecule
H_2O



three body interaction contribution **14.5%**

DNA molecule

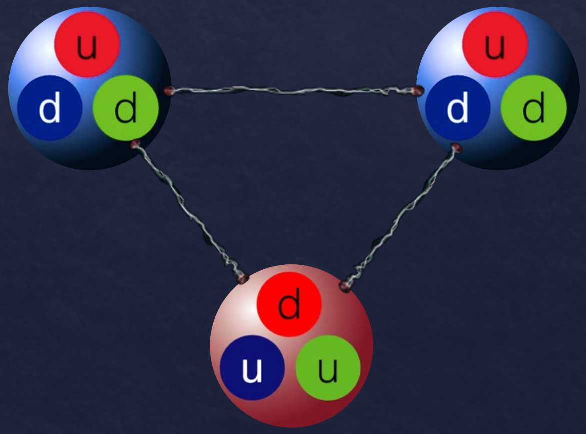


three body interaction contribution **24%**

Source: en.wikipedia

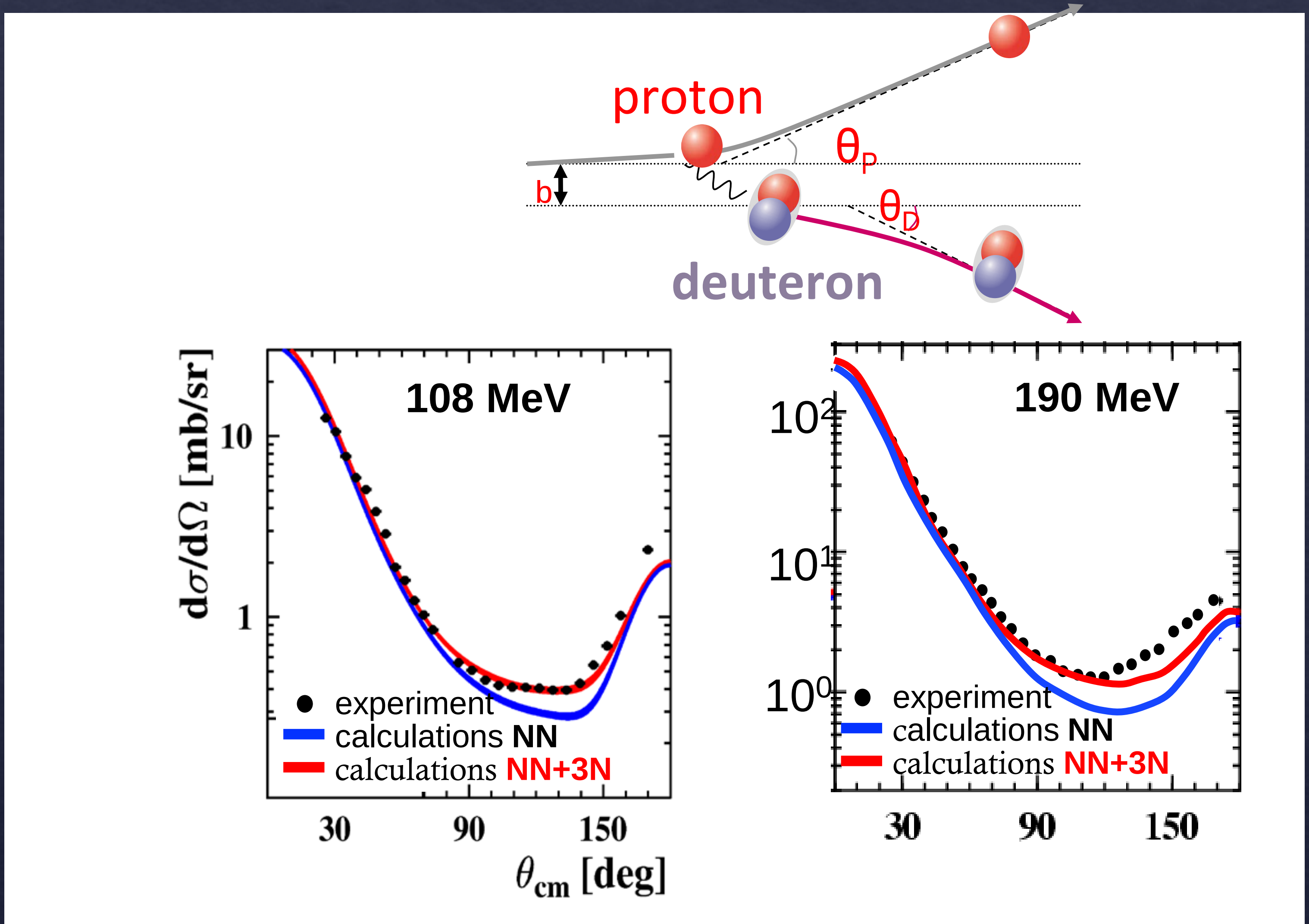
The potential of a system of three or more nucleons must be accompanied by a contribution from the irreducible three-body force that is absent in the case of an isolated pair

$$V = V_{12} + V_{23} + V_{13} + \mathbf{V_{123}}$$

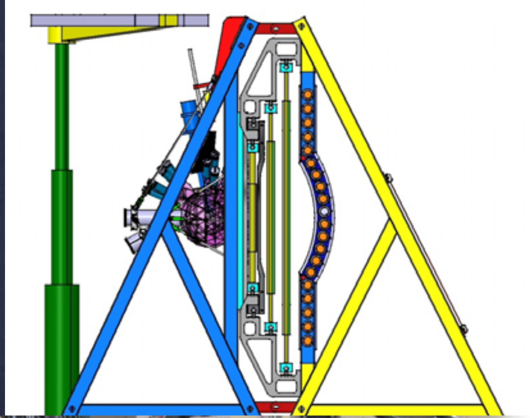


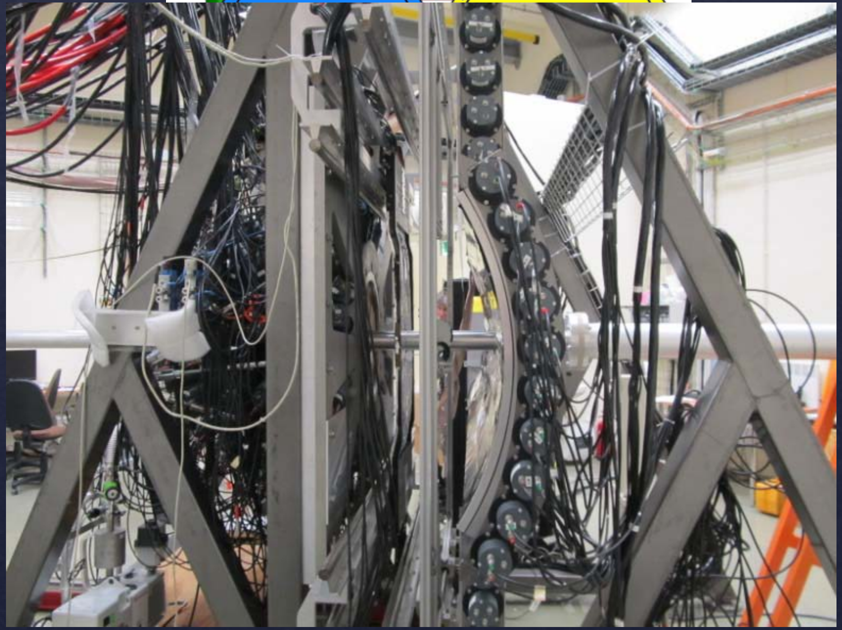
Proton-deuteron elastic scattering

Experiments at CCB IFJ PAN with
BINA setup



K. Ermisch (J. Golak, R. Skibiński, H. Witała) et al., Phys. Rev. C 68, 051001(R) (2003)



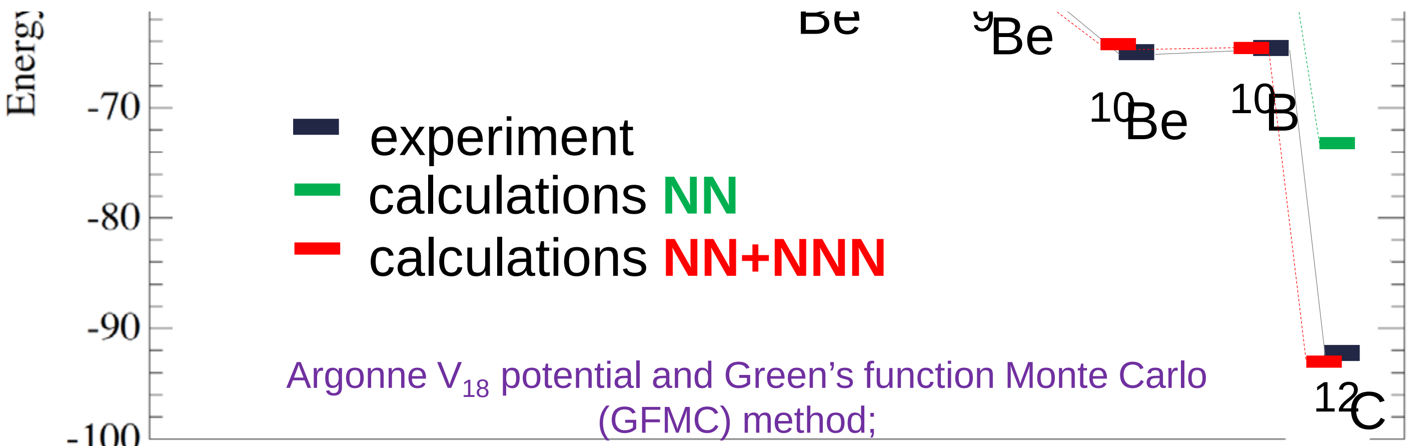


S. Kistryn, A. Kozela, E Stephan,
(UJ, IFJ PAN, UŚ)

Binding energy of selected light nuclei: values from the experiment (black) and calculations performed with: (i) two-body interactions only (**NN)** and, (ii) two-body + three-body terms (NN + NNN).

Are there observables, which are more sensitive to the three-nucleon term of the nucleon-nucleon interaction?

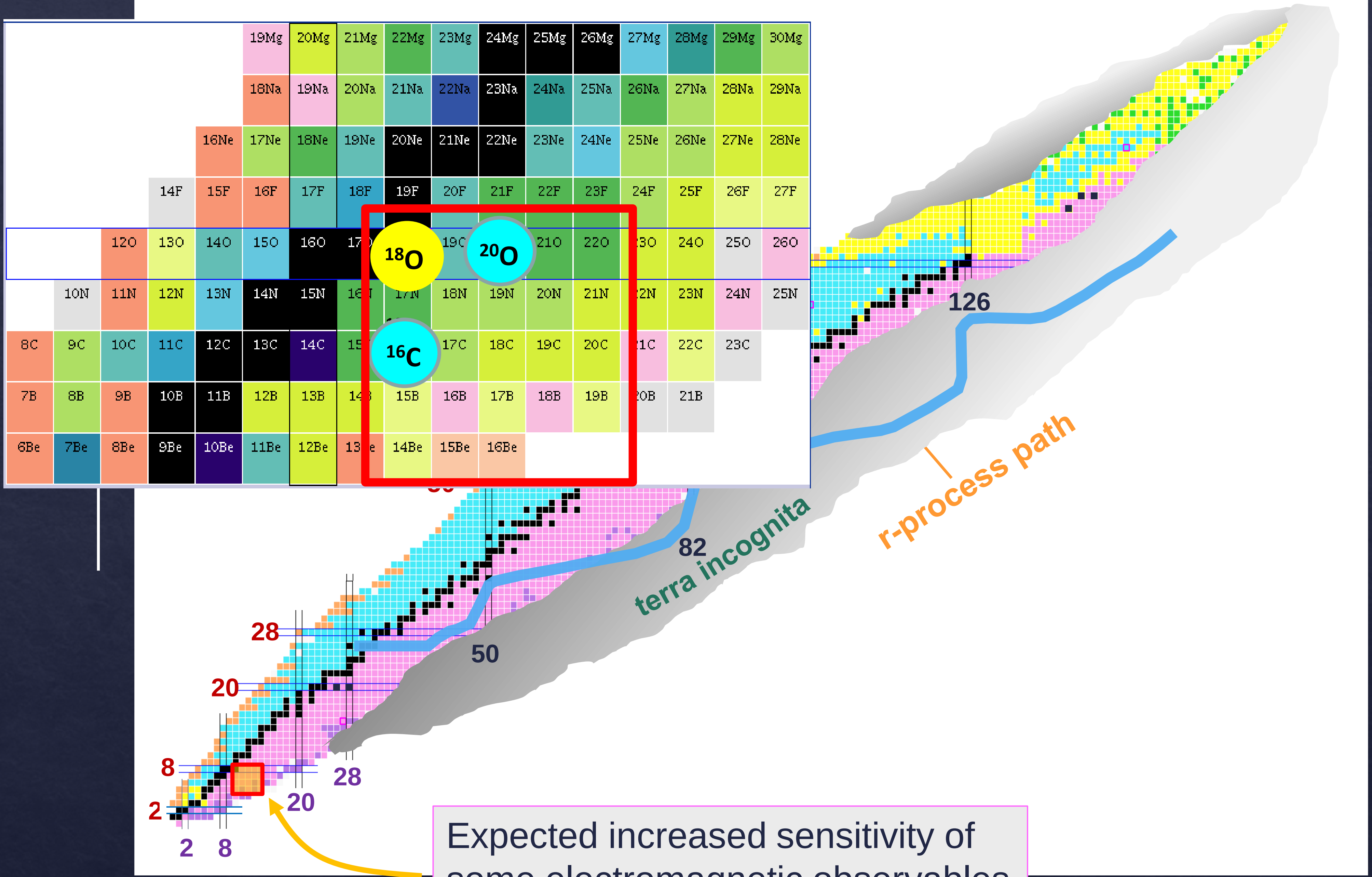
For example, electromagnetic observables?



Argonne V_{18} potential and Green's function Monte Carlo (GFMC) method;

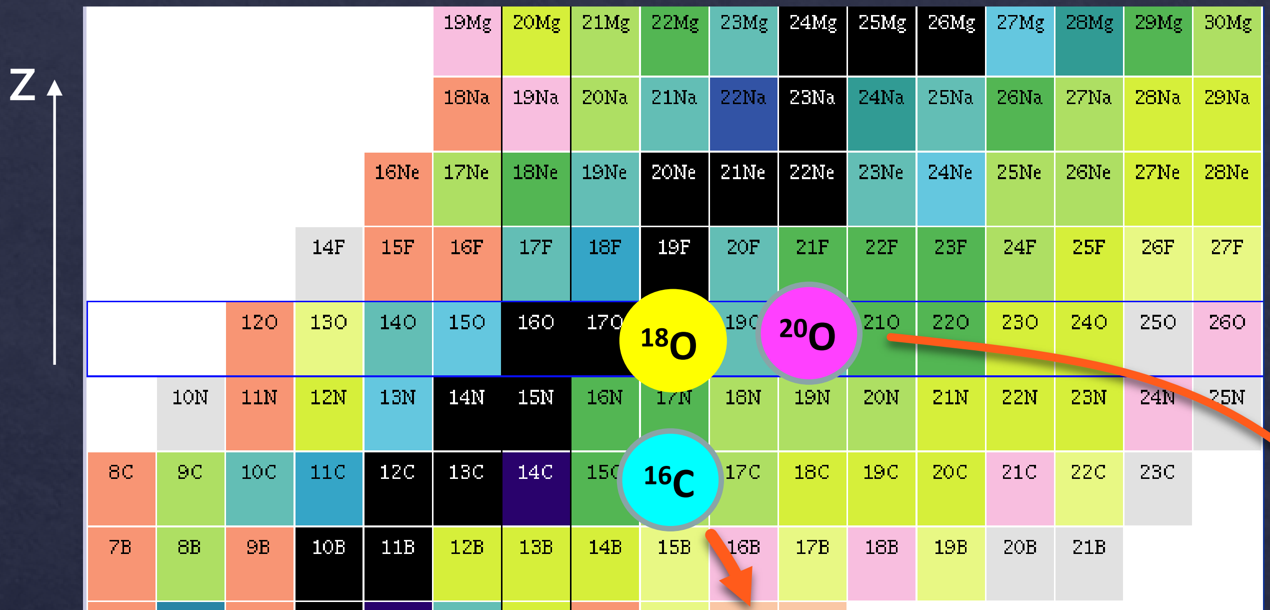
Pieper & Wiringa, Ann. Rev. Nucl. Part. Sci. 51, 53 (2001)

For binding energy and excited state energy, the effect of three-nucleon forces is of the order of 10-30%.



					19Mg	20Mg	21Mg	22Mg	23Mg	24Mg	25Mg	26Mg	27Mg	28Mg	29Mg	30Mg
					18Na	19Na	20Na	21Na	22Na	23Na	24Na	25Na	26Na	27Na	28Na	29Na
				16Ne	17Ne	18Ne	19Ne	20Ne	21Ne	22Ne	23Ne	24Ne	25Ne	26Ne	27Ne	28Ne
			14F	15F	16F	17F	18F	19F	20F	21F	22F	23F	24F	25F	26F	27F
		12O	13O	14O	15O	16O	17	^{18}O	19O	^{20}O	21O	22O	3O	24O	25O	26O
	10N	11N	12N	13N	14N	15N	16	17N	18N	19N	20N	21N	2N	23N	24N	25N
8C	9C	10C	11C	12C	13C	14C	15	^{16}C	17C	18C	19C	20C	1C	22C	23C	
7B	8B	9B	10B	11B	12B	13B	14	15B	16B	17B	18B	19B	OB	21B		
6Be	7Be	8Be	9Be	10Be	11Be	12Be	13 e	14Be	15Be	16Be						

Expected increased sensitivity of some electromagnetic observables to the details of n-n force



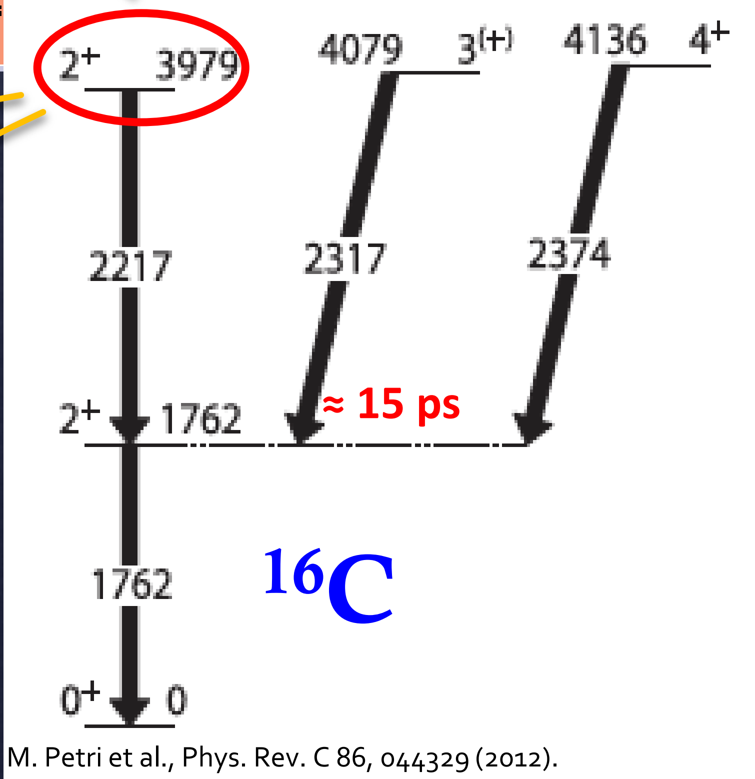
					19Mg	20Mg	21Mg	22Mg	23Mg	24Mg	25Mg	26Mg	27Mg	28Mg	29Mg	30Mg
					18Na	19Na	20Na	21Na	22Na	23Na	24Na	25Na	26Na	27Na	28Na	29Na
				16Ne	17Ne	18Ne	19Ne	20Ne	21Ne	22Ne	23Ne	24Ne	25Ne	26Ne	27Ne	28Ne
			14F	15F	16F	17F	18F	19F	20F	21F	22F	23F	24F	25F	26F	27F
		12O	13O	14O	15O	16O	17O	^{18}O	19O	^{20}O	21O	22O	23O	24O	25O	26O
	10N	11N	12N	13N	14N	15N	16N	17N	18N	19N	20N	21N	22N	23N	24N	25N
8C	9C	10C	11C	12C	13C	14C	15C	^{16}C	17C	18C	19C	20C	21C	22C	23C	
7B	8B	9B	10B	11B	12B	13B	14B	15B	16B	17B	18B	19B	20B	21B		
6Be	7Be	8Be	9Be	10Be	11Be	12Be	13B									

ab initio

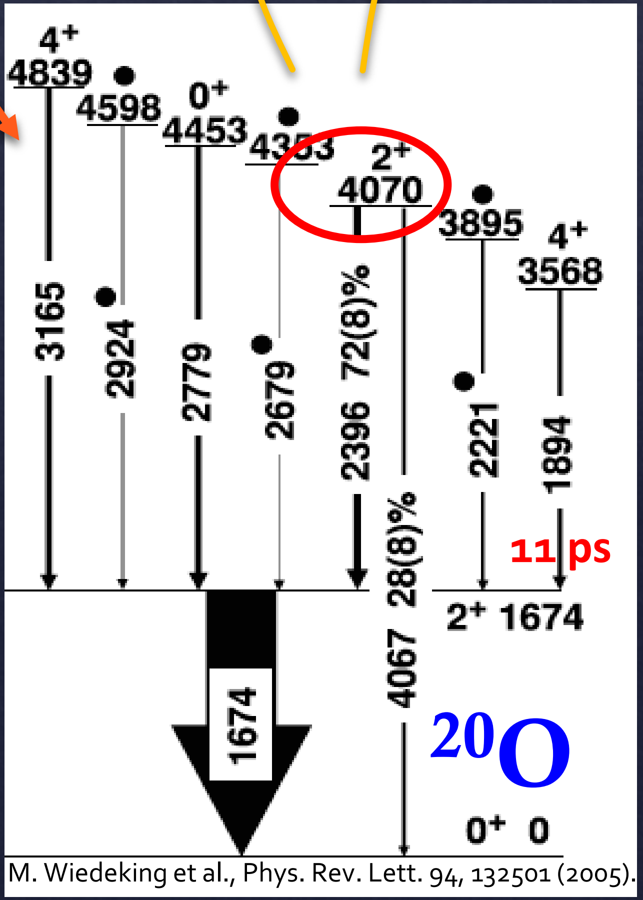
Many-Body-Pert. Theory calculations of the 2^+_2 lifetimes

J.D. Holt, et al., Eur. Phys. J. A49, 39 (2013).

NN	**NN+NNN**
320 fs	200 fs



M. Petri et al., Phys. Rev. C 86, 044329 (2012).



M. Wiedeking et al., Phys. Rev. Lett. 94, 132501 (2005).

NN	**NN+NNN**
300 fs	80 fs

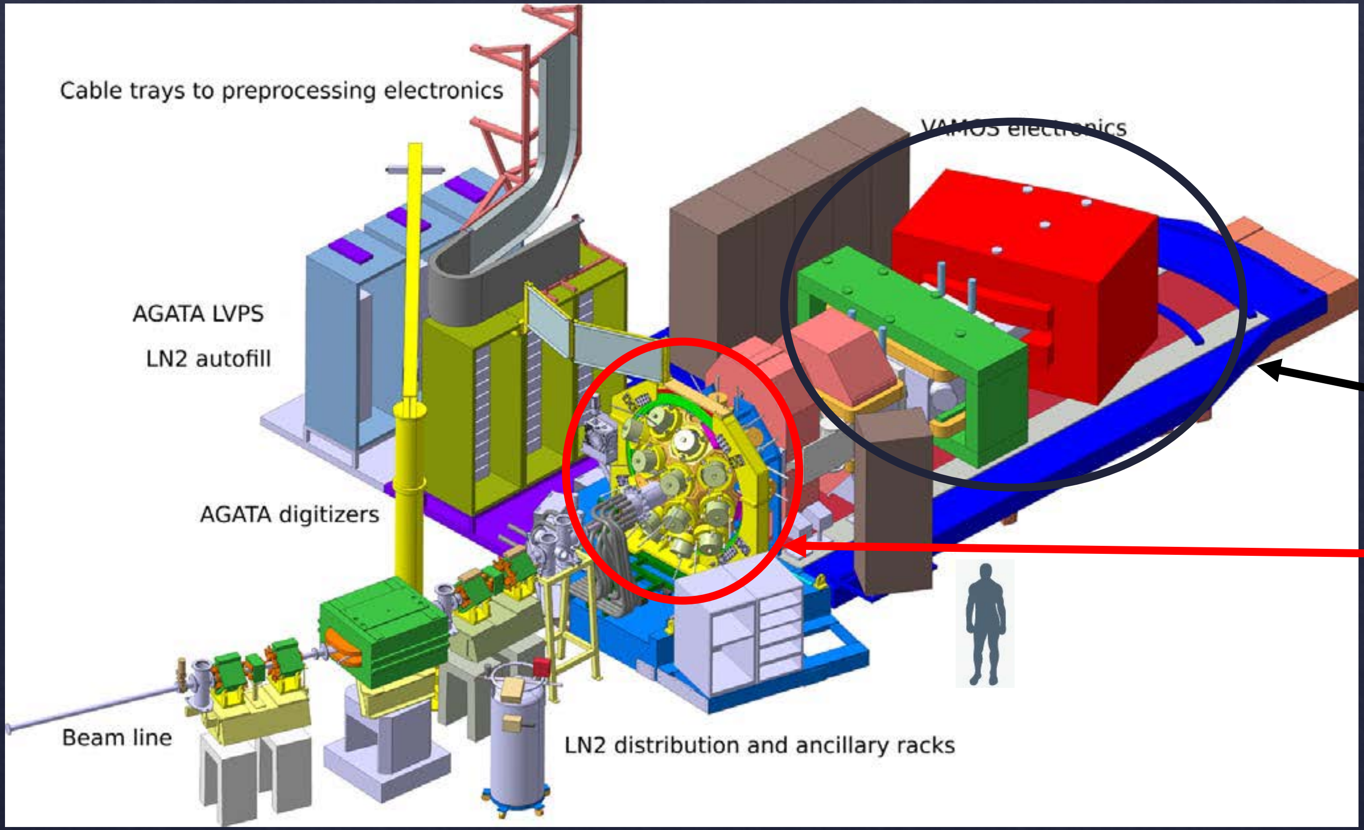
ab initio

No-Core-SHELL Model calculations

C. Forssén, et al., J. Phys. G: Nucl. Part. Phys. 40, 055105 (2013).

Experimental setup

Experiment at GANIL, Caen, France
One of the most sophisticated setups: VAMOS+AGATA+PARIS



E. Clement et al. NIMA 885, 1-12 (2017)

Beam: ^{18}O ions, 7.0 MeV/A

Target: ^{181}Ta 4 μm thick

Goal:
excited state lifetime determination

Detectors used:
AGATA+PARIS+VAMOS setup

Beam time:
10 days data taking in July 2017

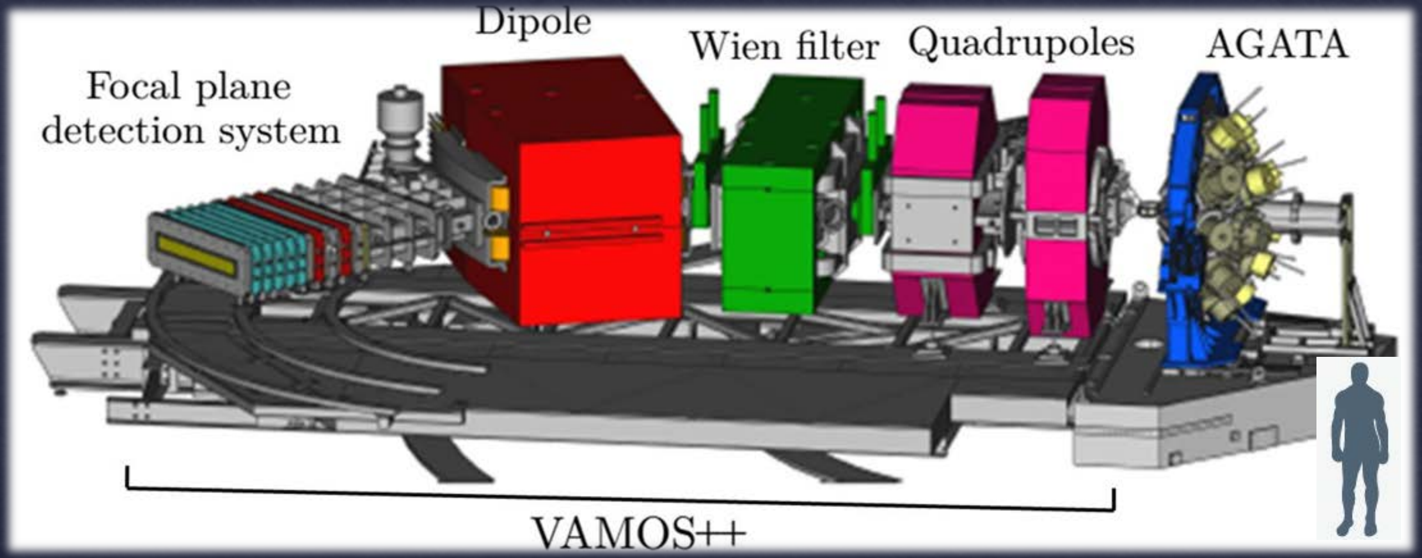
Experimental setup –VAMOS++ magnetic spectrometer

Allows to analyse and select the ions of interest resulting in the reaction.

VAMOS++ at 45 degree

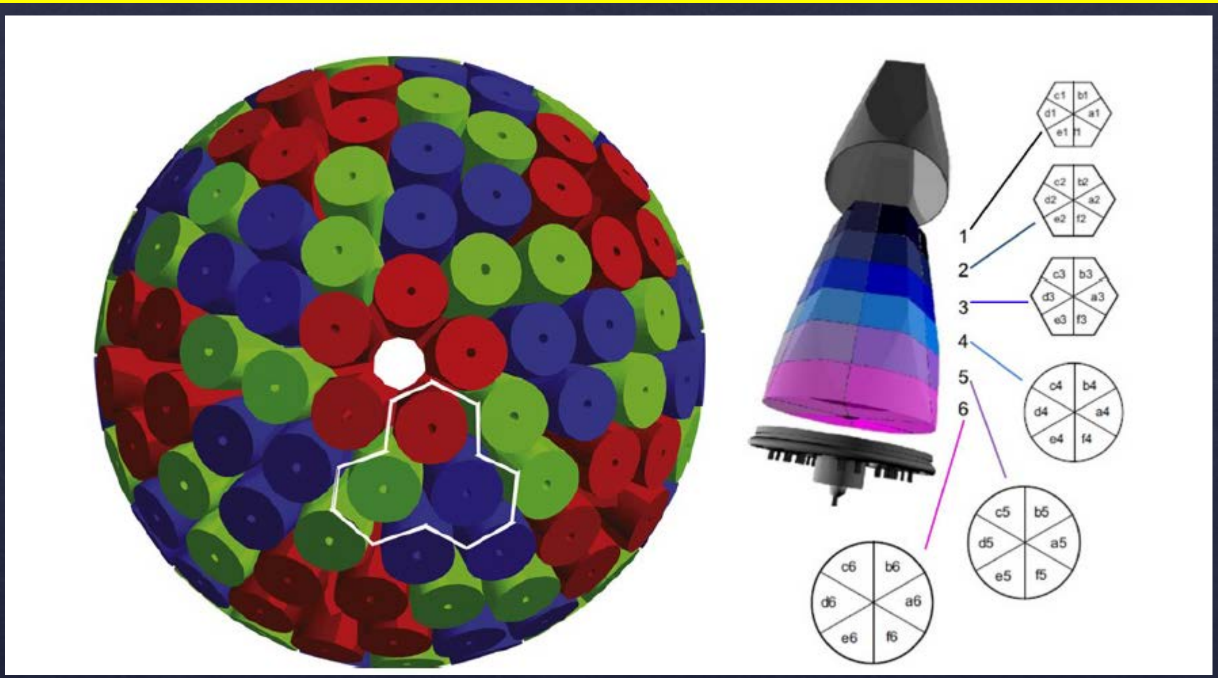
VAMOS entrance detector:
2 Drift Chambers (for ions angle)

VAMOS focal plane:
DC (for Brho reconstruction),
6 rows of Ionization Chambers (for ΔE)
Plastic (for trigger and ToF)
Angular acceptance:
+/- 6 degree in theta, +/- 15 degree in phi



Experimental setup -AGATA

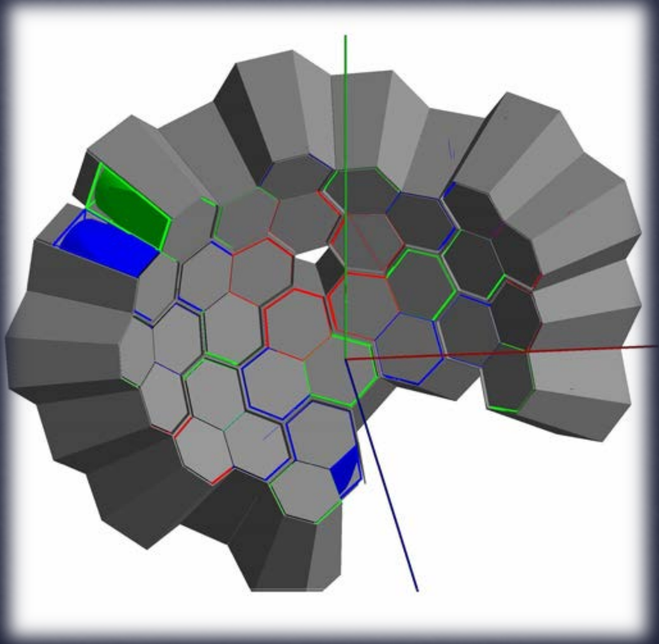
AGATA - *Advanced Gamma Tracking Array,* ***high resolution*** *gamma-ray detector*
AGATA is being built within large European collaboration.
After completion of construction AGATA will be the world-best gamma spectrometer.



AGATA White Book:
W. Korten et al, Eur. Phys. J. A (2020) 56:137

AGATA

31 crystals (backward angles)
Working d**uring our experiment at GANIL**



AGATA
36 segments per crystal (6 longitudinal rings and 6 transversal sectors)

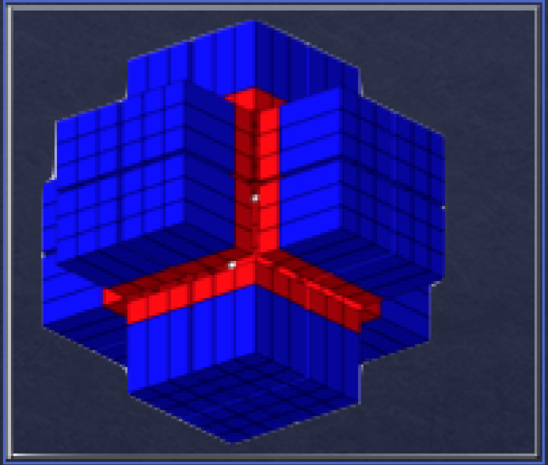
Tracking algorithms allow to reconstruct the
path of the interacting g-ray in the detection material, its energy and incoming direction.

Experimental setup - PARIS (High energy gamma-ray calorimeter)

PARIS PHOTON ARRAY FOR STUDIES WITH RADIOACTIVE ION AND STABLE BEAMS

High efficiency gamma detector, based on scintilation materials,
for medium resolution spectroscopy
and calorimetry of g-rays in large energy range.
It is characterized by very good time resolution (< 1 ns).

PARIS is made of clusters:
1 Cluster = 9 phoswiches



24 PARIS cluster view

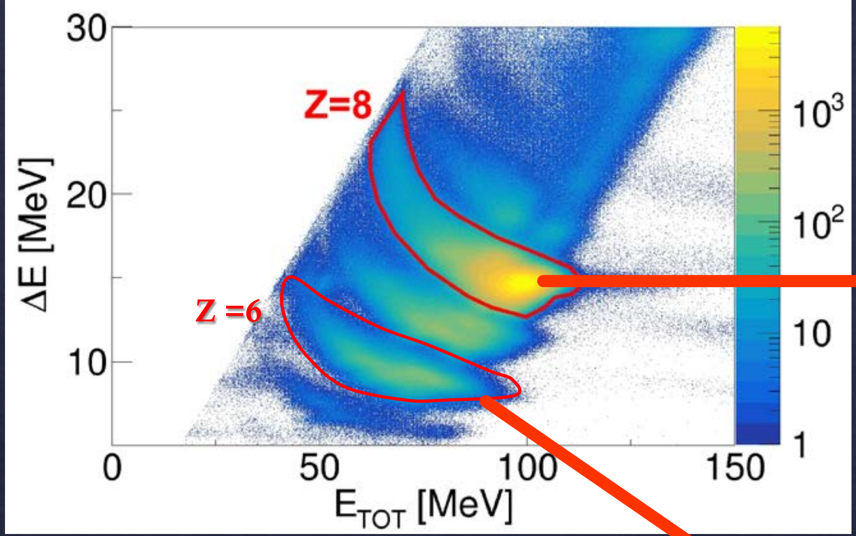
2 PARIS clusters (18 phoswiches used) used in our experiment.

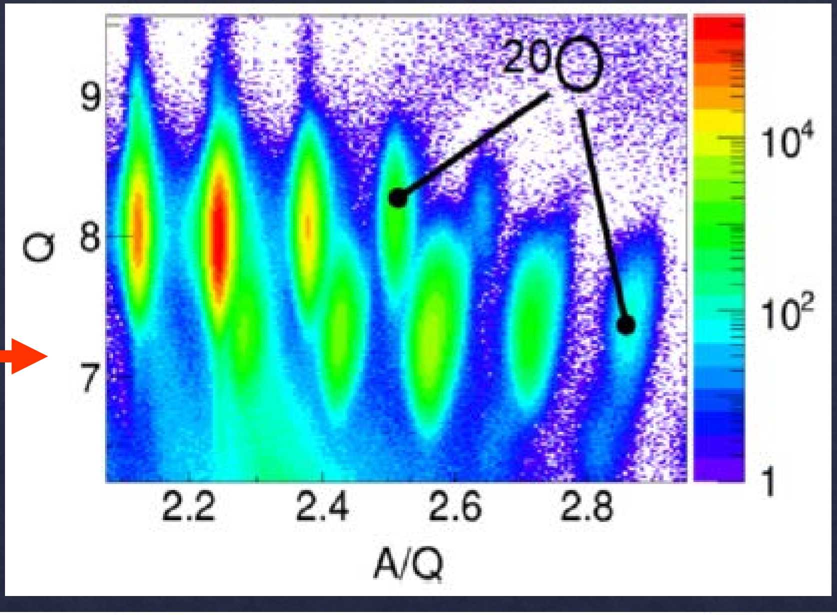
For measurement of high energy gamma-rays and for time definition.

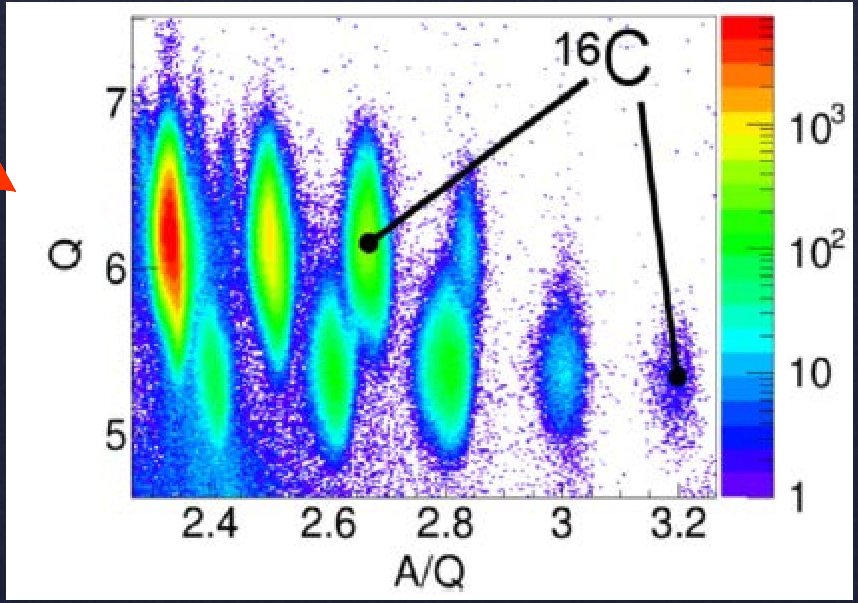
PARIS is constructed in international collaboration coordinated by IFJ PAN Krakow.
After completion of construction PARIS will be the world-best high-energy gamma calorimeter

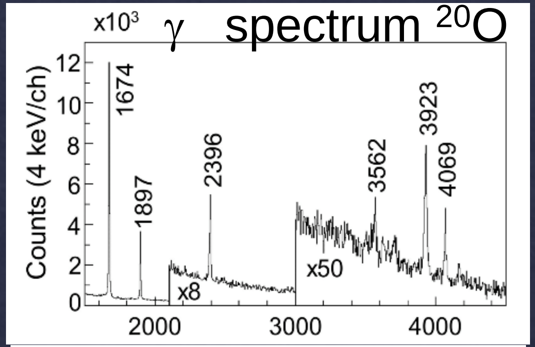
Data analysis

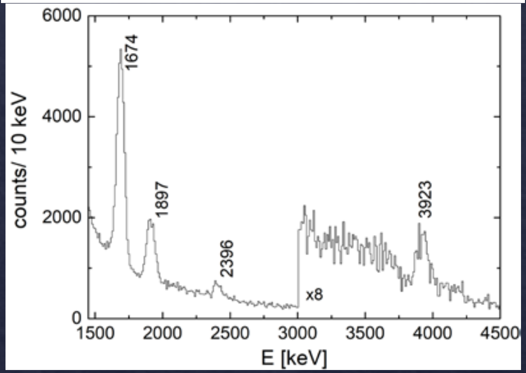
VAMOS magnetic spectrometer, ion mass selection:

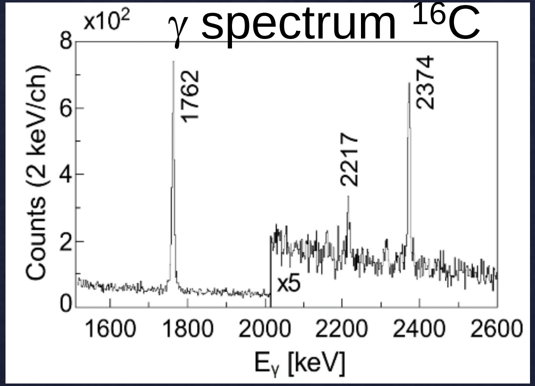












Ion mass:

$M/Q = B\rho/(3.105\gamma\beta)$

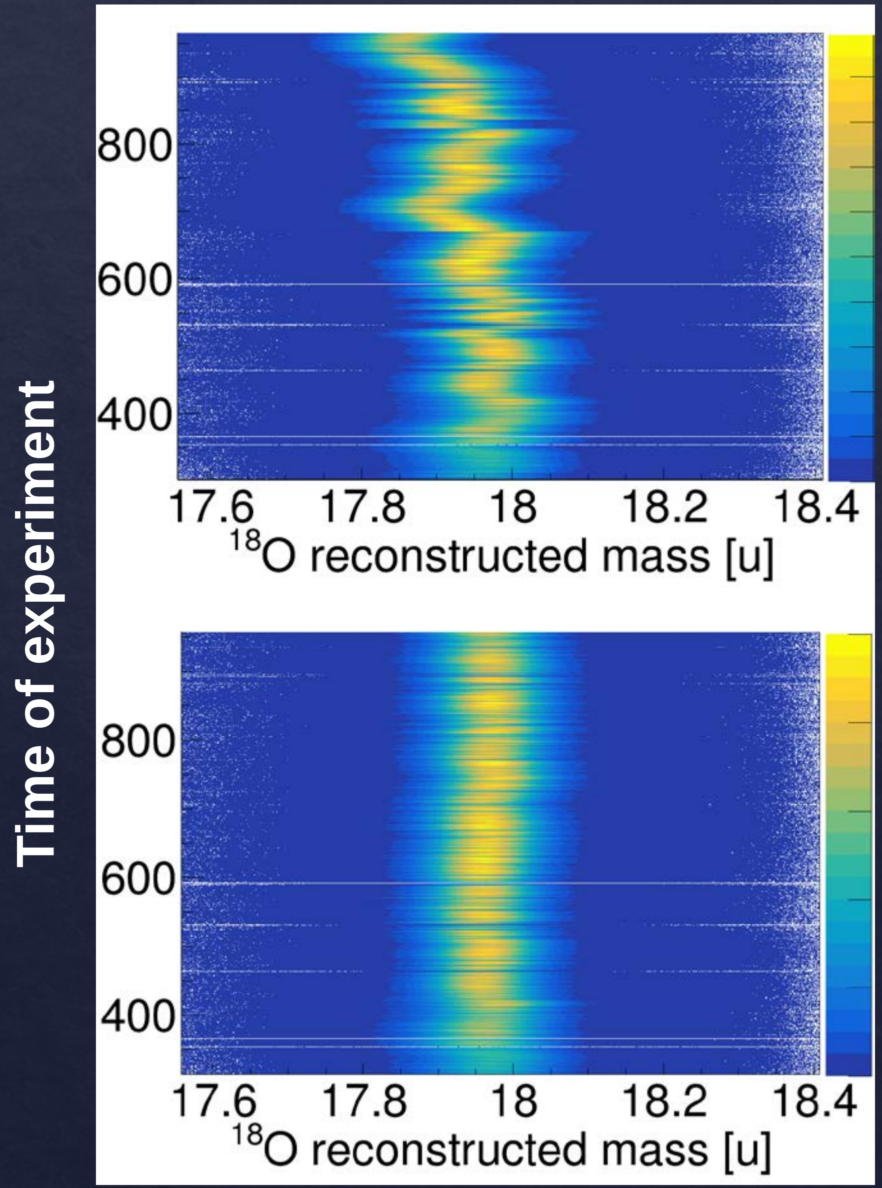
$M_0 = E/(931.5(\gamma - 1))$

$Q = M_0/(M/Q)$

$M_r = (M/Q)Q_{int}$

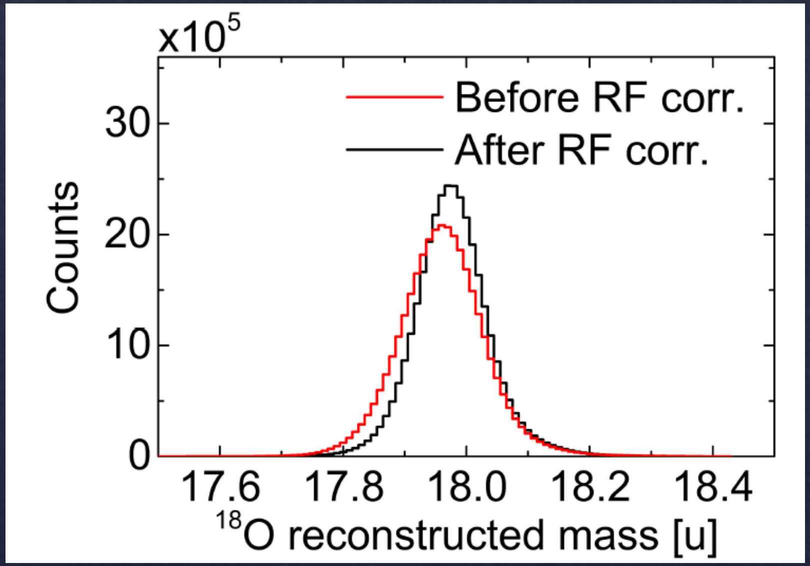
PARIS timing: large improvement in ion mass reconstruction

We measure velocity by: measuring the path in the spectrometer and the time between RF and Plastic at the end of focal plane.



^{18}O MASS reconstruction using ion Time of flight with respect to cyclotron RF

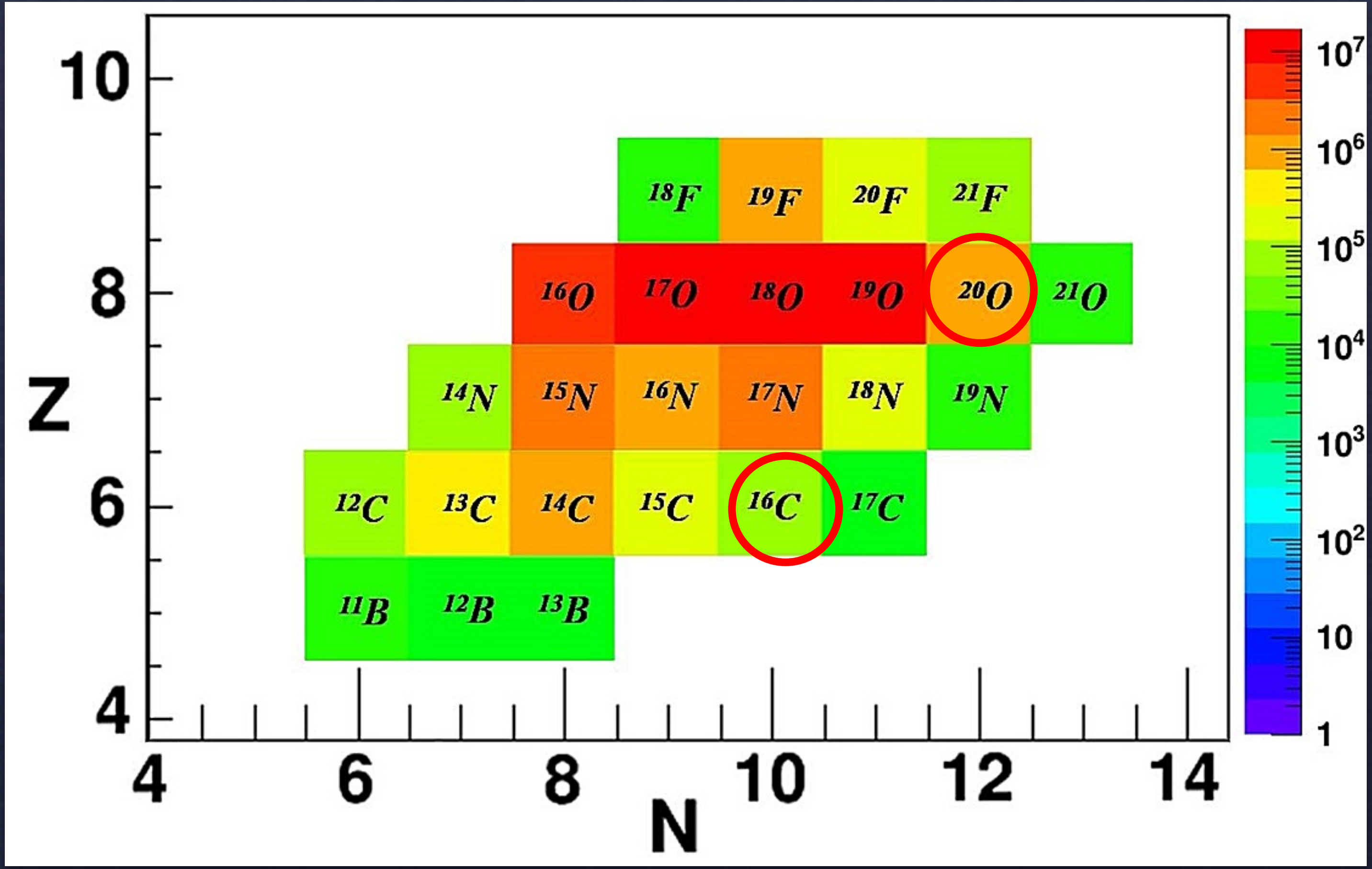
but RF signal is **NOT stable** in time



^{18}O MASS reconstruction after PARIS correction

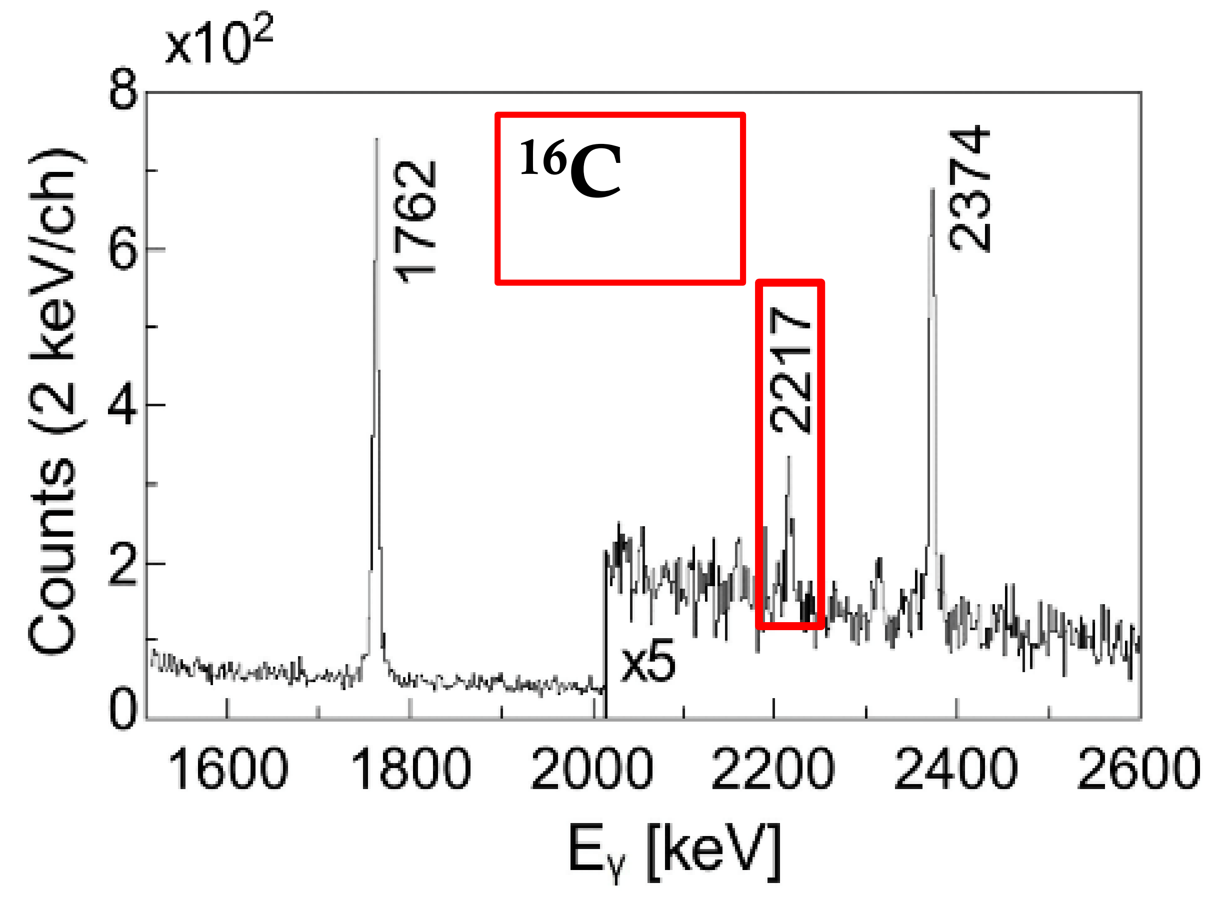
Using the excellent time response of PARIS ($LaBr_3$ part, FWHM < 1ns)
RF fluctuations are corrected

VAMOS magnetic spectrometer, ion mass selection:



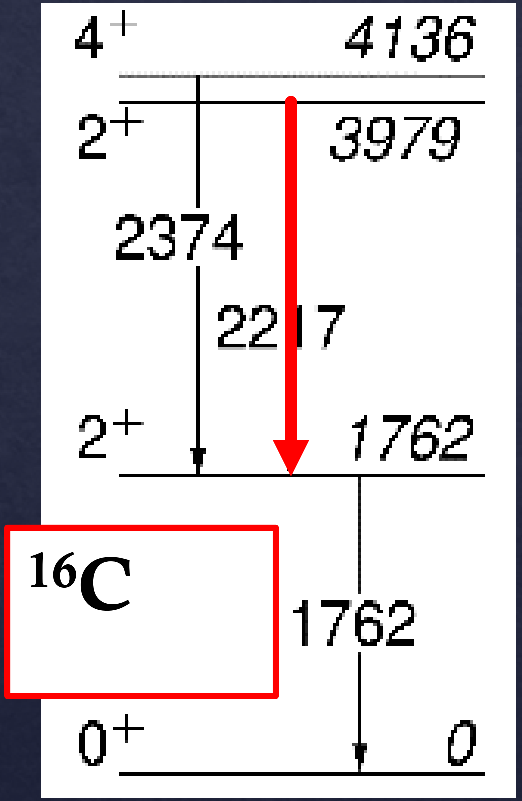
Identified isotopes from B to F.

AGATA Spectra –Tracked and Doppler Corrected



NN 300 fs

NN+NNN 80 fs

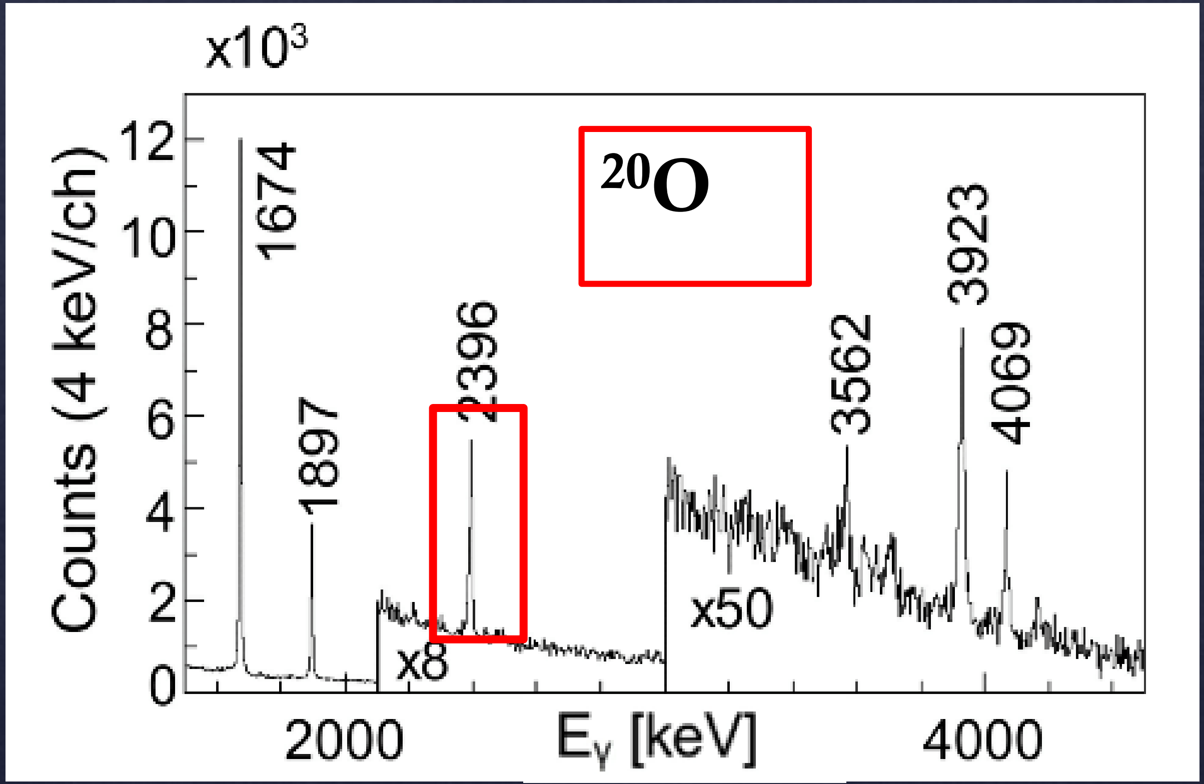


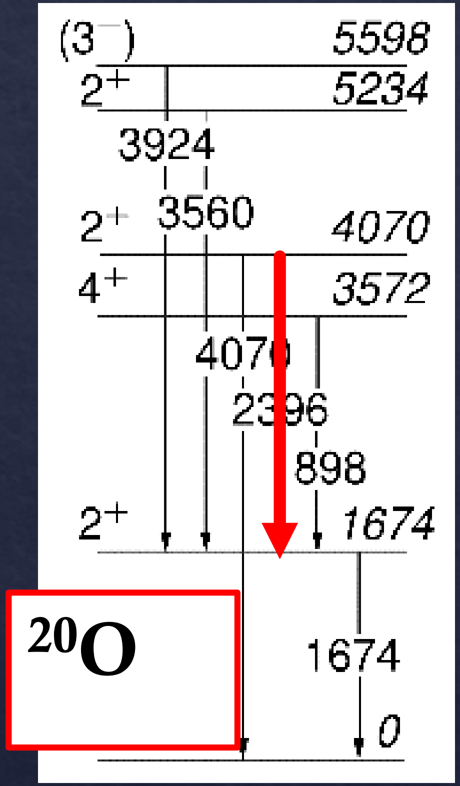
Ion gated by VAMOS spectrometer

AGATA Spectra –Tracked and Doppler Corrected

NN
320 fs

NN+NNN
200 fs





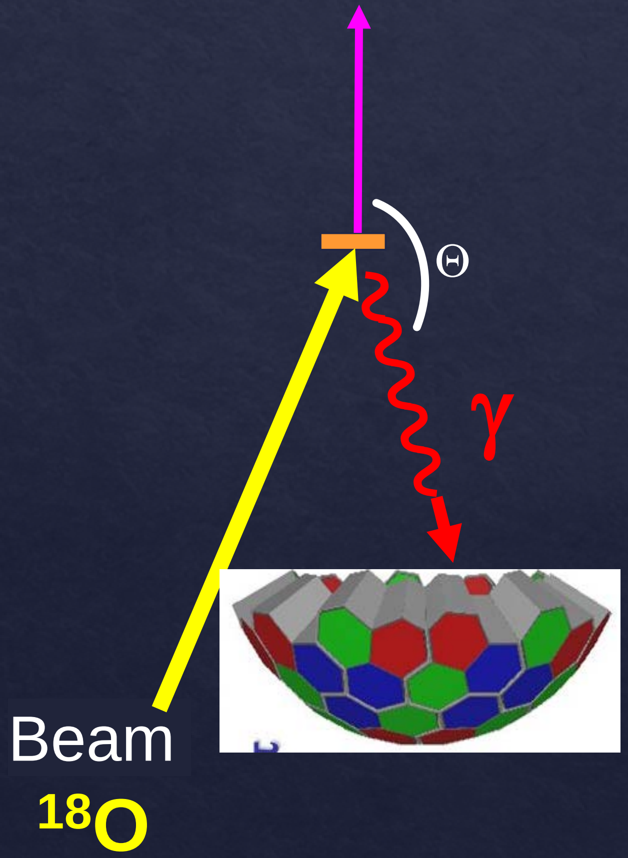
Ion gated by VAMOS spectrometer

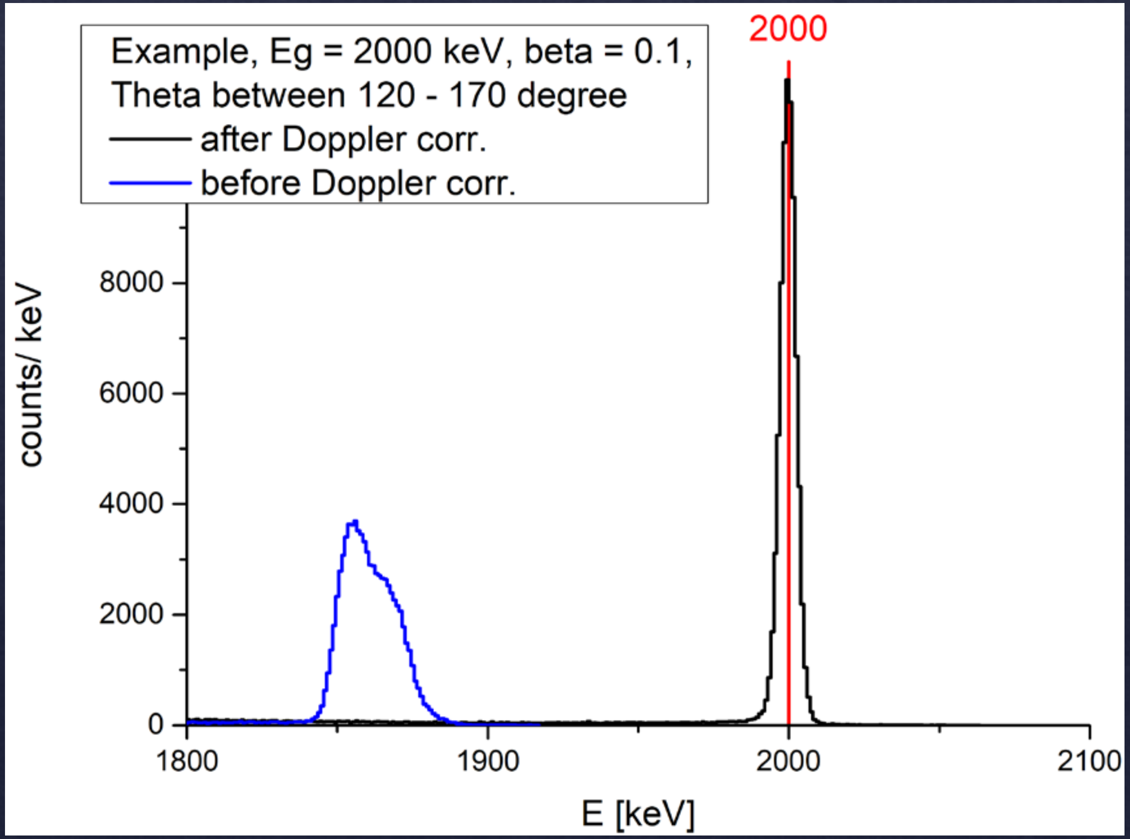
Lifetime determination method and simulations

Gamma-ray Doppler shift - example

$$E = \frac{E_0}{\gamma(1-\beta\cos\Theta)}$$

Correction with assumed ideally determined: emitter velocity (v) and angle between ion and gamma-ray (Θ).

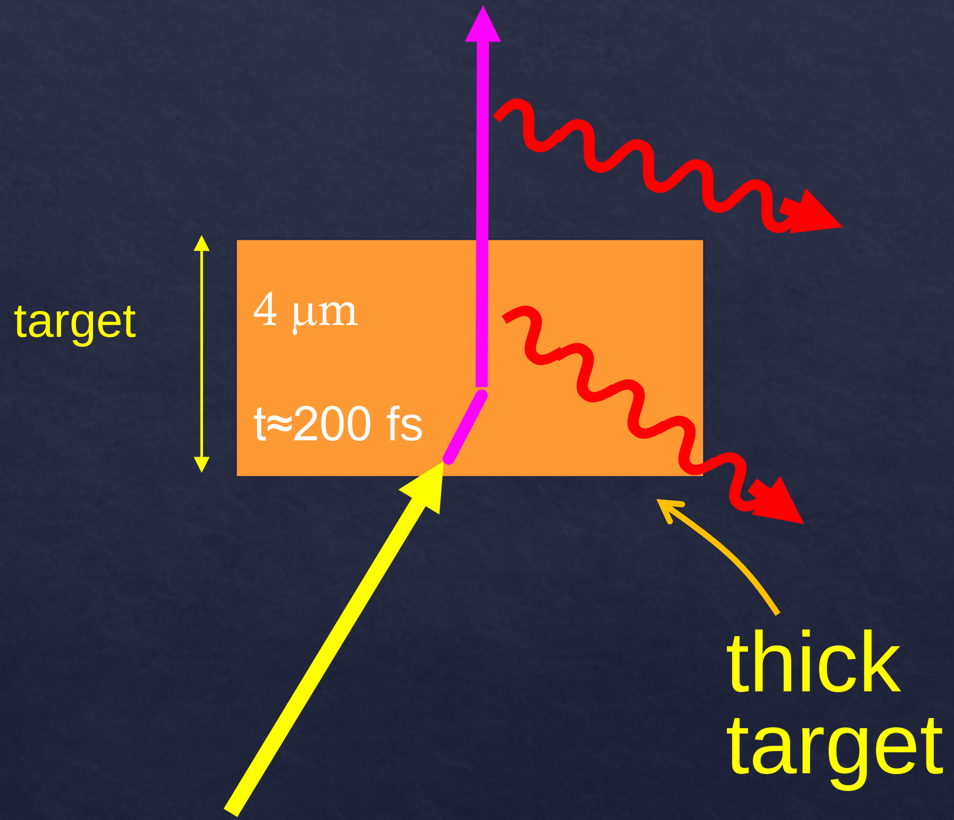




METHOD: Doppler shift dependence on the point of gamma emission

$$E = \frac{E_0}{\gamma(1 - \beta\cos\Theta)}$$

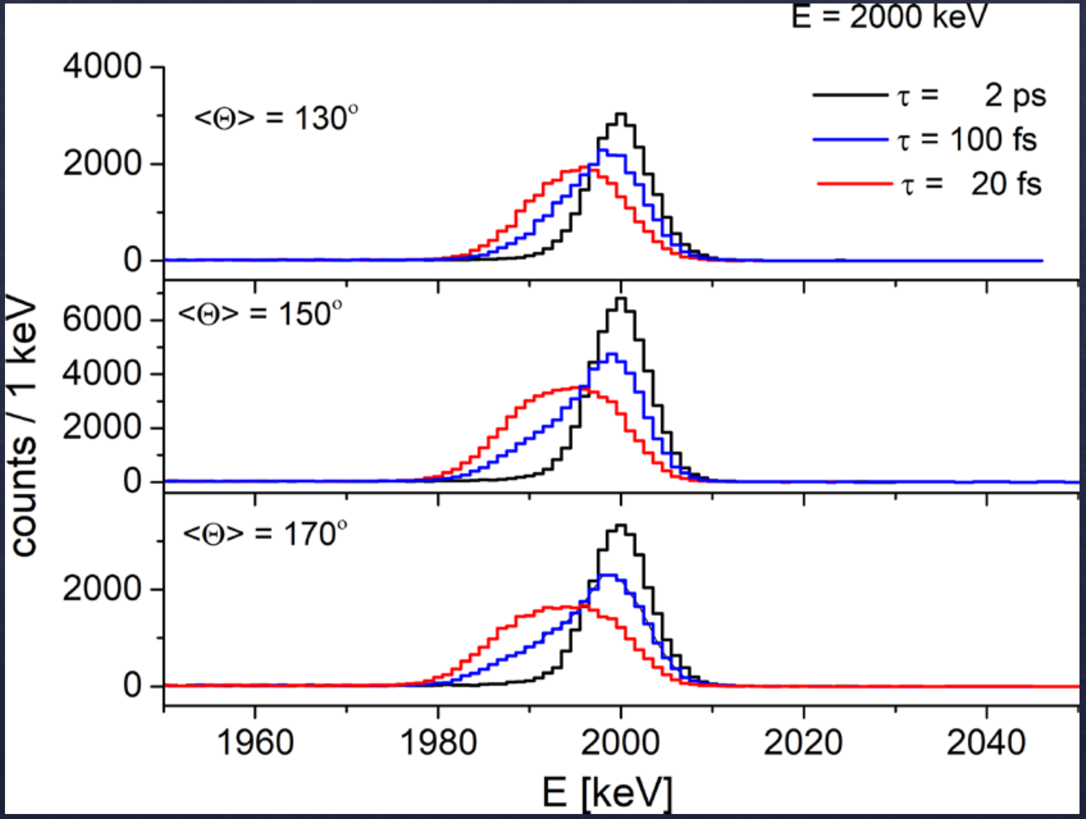
^{18}O (7 MeV/A) + ^{181}Ta target (6 mg/cm^2)



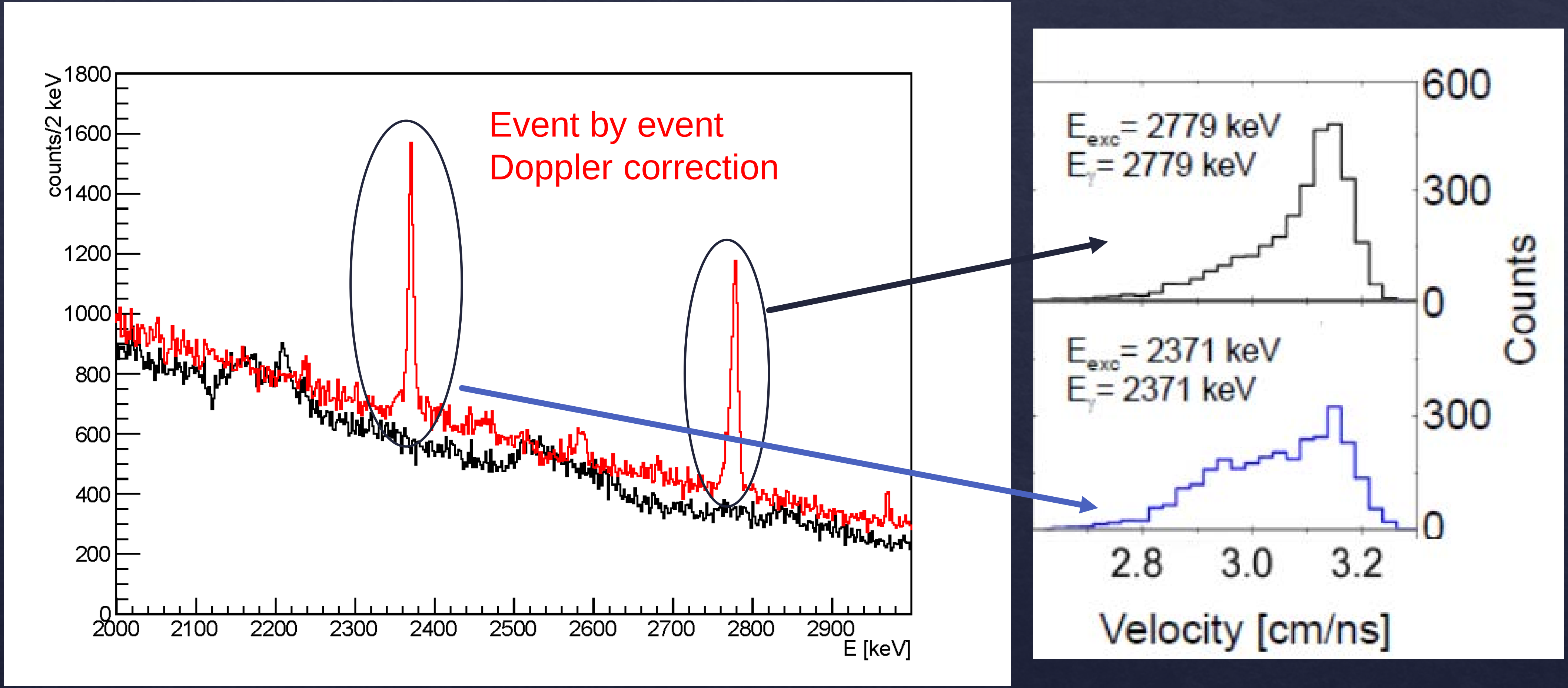
thick target

Beam

^{18}O



Velocity profile selection – example: ^{19}O



Event by event
Doppler correction

Simulations are needed to extract lifetimes from γ lineshape

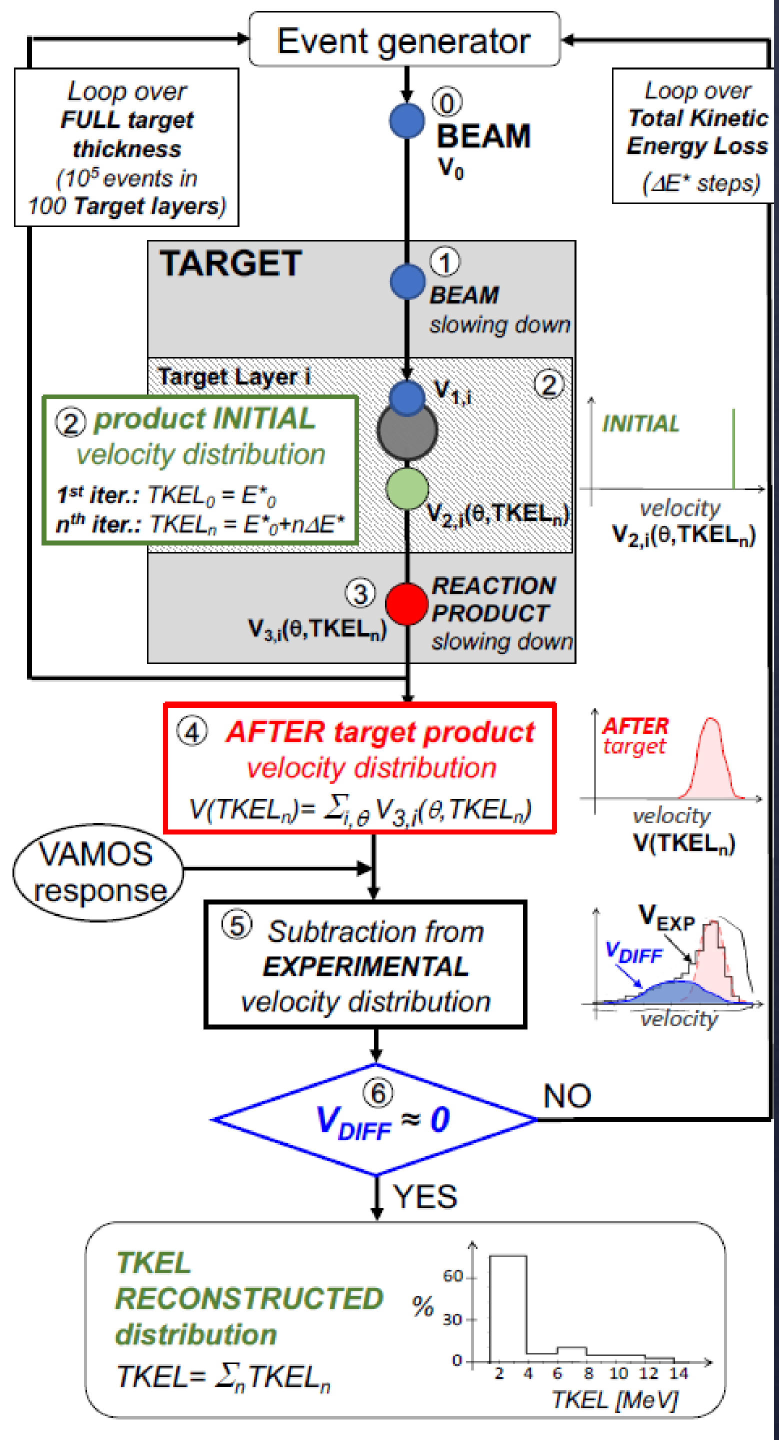
Event generator and simulations

1. Event generator (written by MC):
   The beam is passing through the target decreasing its energy – dE/dx.
   Multi nucleon transfer reactions occur inside the target – kinematics, excitation energy.
   Excited level is let to decay by gamma ray (Eg) with lifetime t to be tested.

2. Simulation with detector response – comparison to the experimental gamma-ray spectrum by 2D chi^2 used to determine optimum lifetime.

From the measured velocity, by iterative process we deconvolute initial velocity after the rection.

Initial velocity after the reaction



Event generator

Loop over ***FULL target thickness*** *(10^5 events in* ***100 Target layers****)*

Loop over ***Total Kinetic Energy Loss*** *(ΔE^* steps)*

⓪ **BEAM** V_0

TARGET

① ***BEAM*** *slowing down*

Target Layer i

② $V_{1,i}$

② ***product INITIAL*** *velocity distribution*

1st iter.: $TKEL_0 = E^*_0$

nth iter.: $TKEL_n = E^*_0 + n\Delta E^*$

$V_{2,i}(\theta, TKEL_n)$

③ ***REACTION PRODUCT*** *slowing down*

$V_{3,i}(\theta, TKEL_n)$

④ ***AFTER target product*** *velocity distribution*

$V(TKEL_n) = \Sigma_{i,\theta} V_{3,i}(\theta, TKEL_n)$

VAMOS response

⑤ *Subtraction from* ***EXPERIMENTAL*** *velocity distribution*

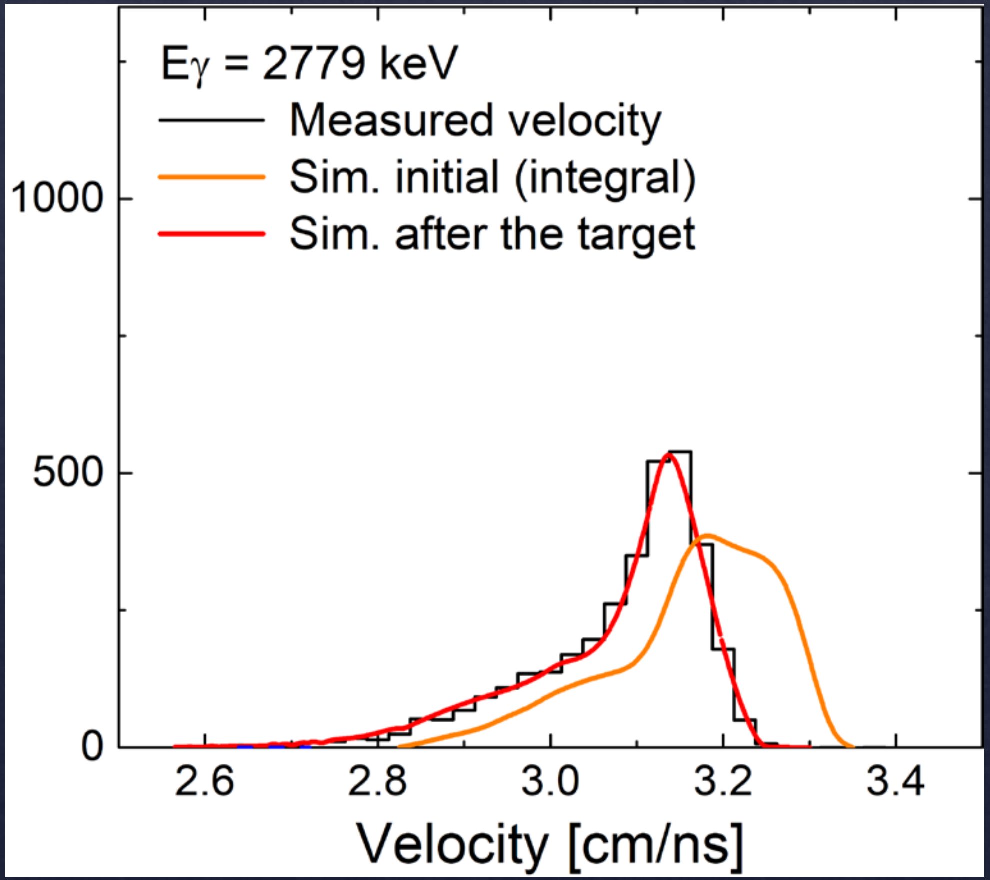
⑥ $V_{DIFF} \approx 0$

NO

YES

TKEL RECONSTRUCTED distribution

$TKEL = \Sigma_n TKEL_n$

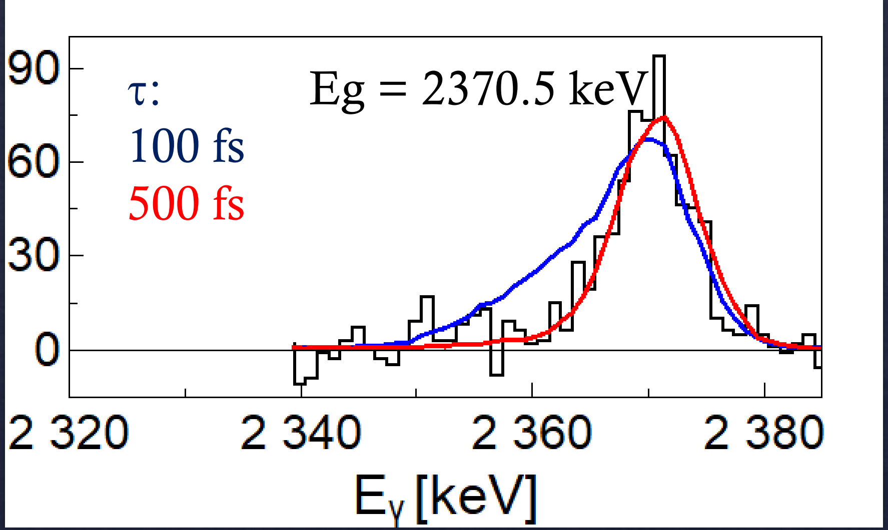


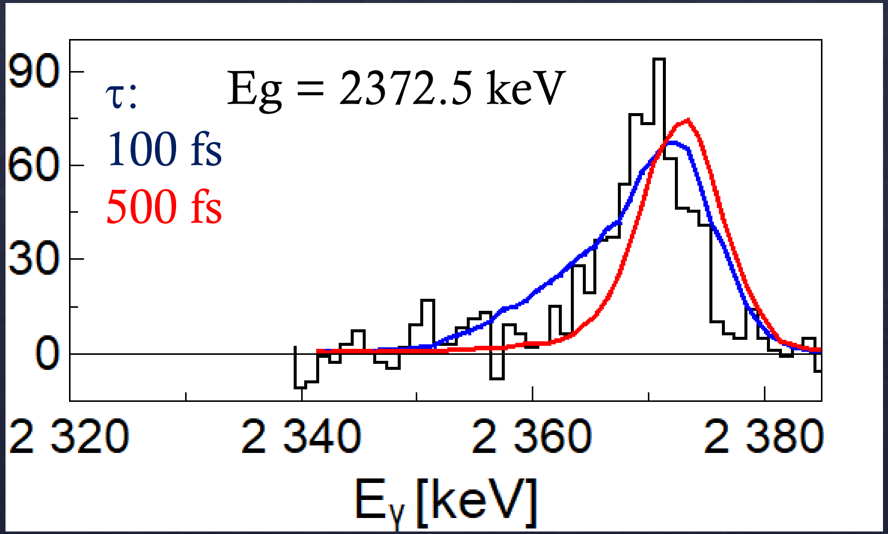
M. Ciemała et al., submitted to EPJA (description of the method) *https://arxiv.org/abs/2012.05180*

Results

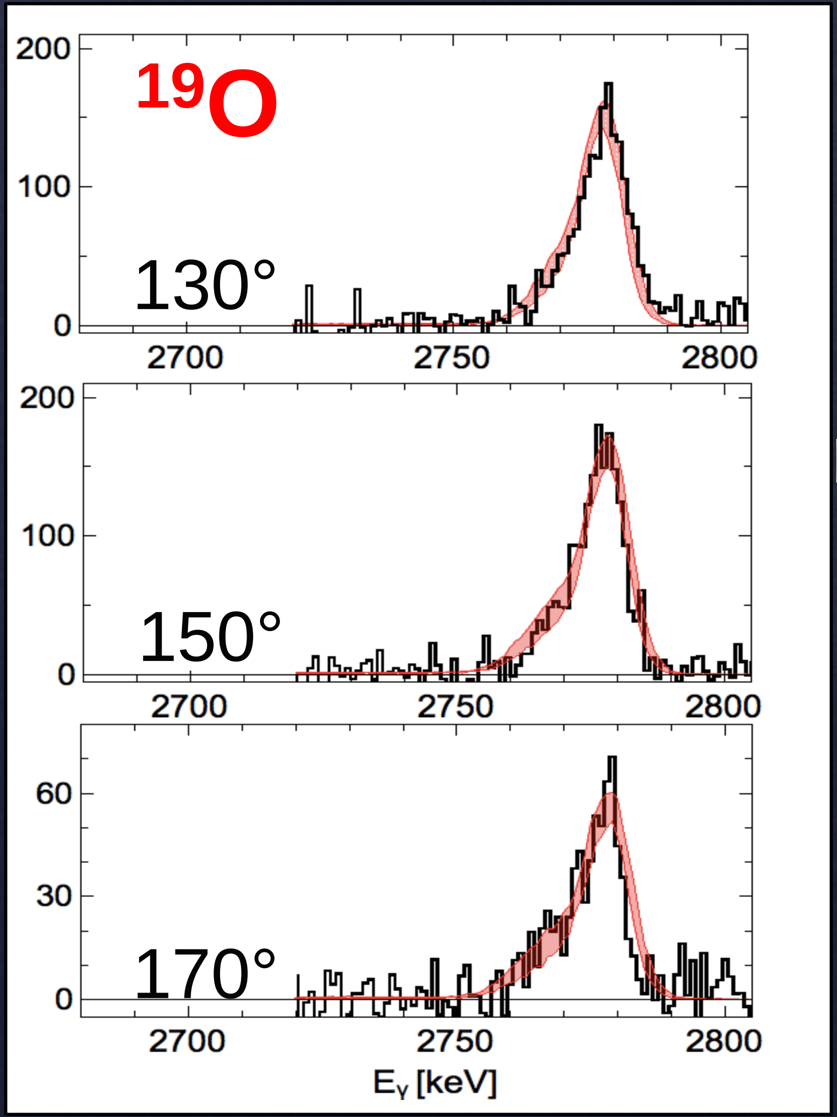
2D χ^2 minimization

Compare by use of χ^2 simulated gamma-ray spectrum to experimental one, varying in the simulation lifetime t, and gamma-ray energy $E\gamma$.

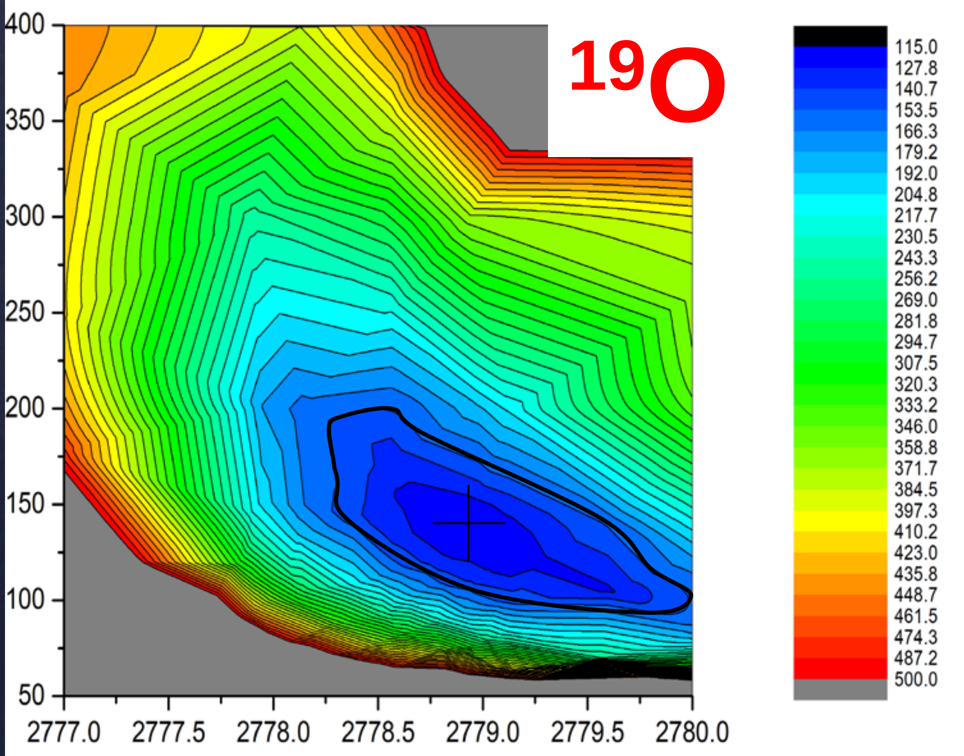


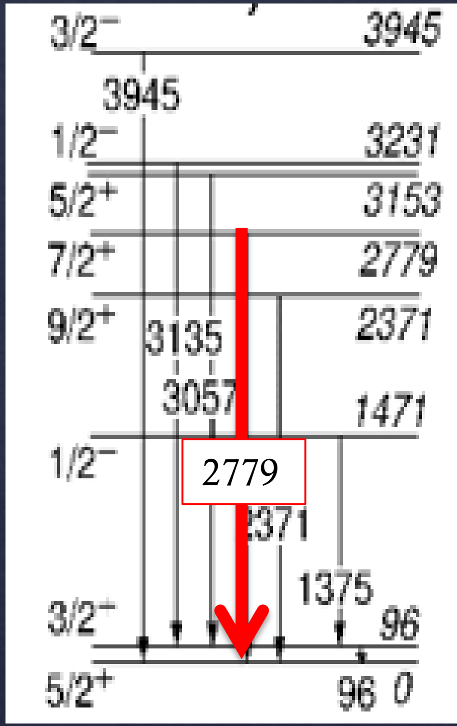


TEST of KNOWN lifetimes in the 100s femtoseconds region



^{18}O (7 MeV/A) + ^{181}Ta target (6 mg/cm^2)



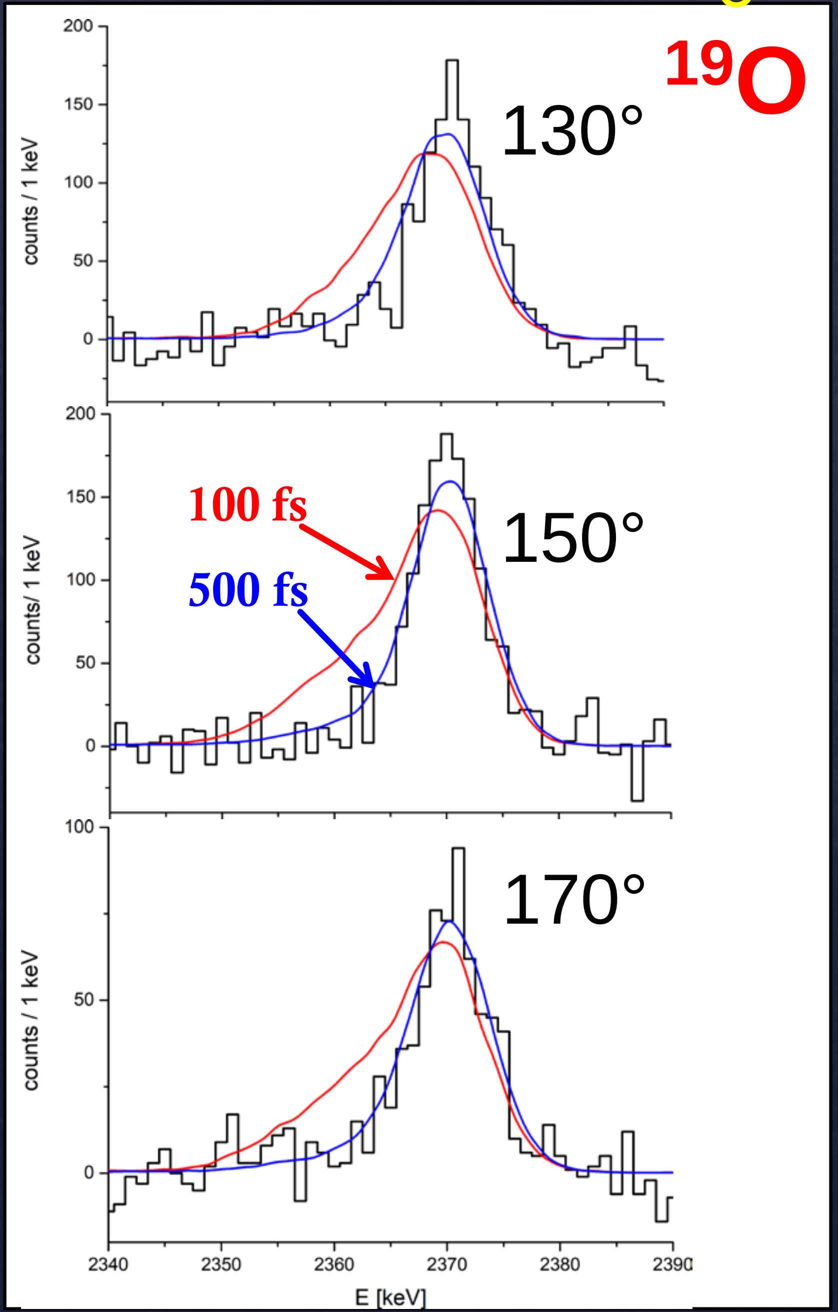


$$\tau = 140^{+50}_{-40}\ \text{fs}$$

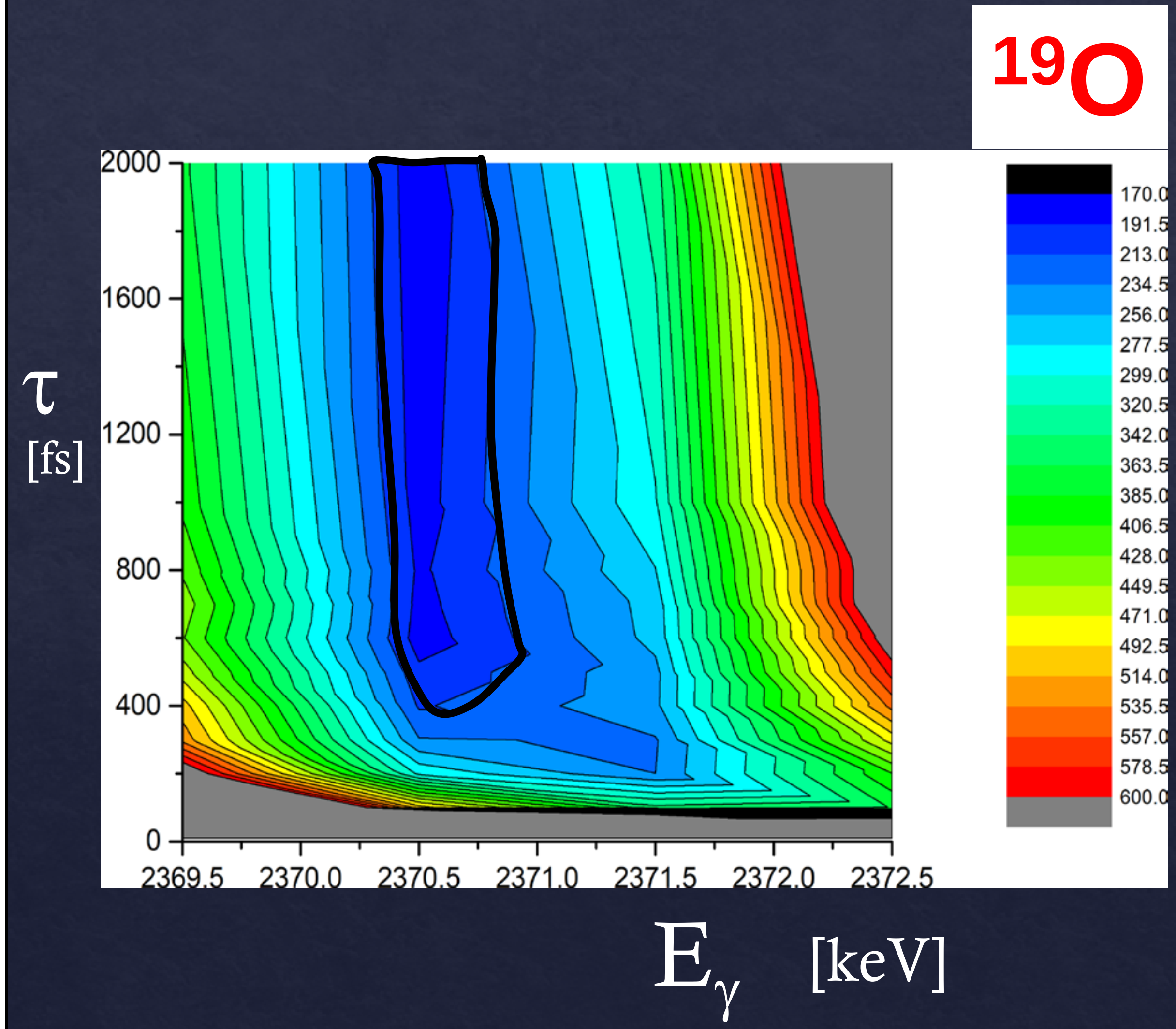
Literature Eγ = 2779(1) keV

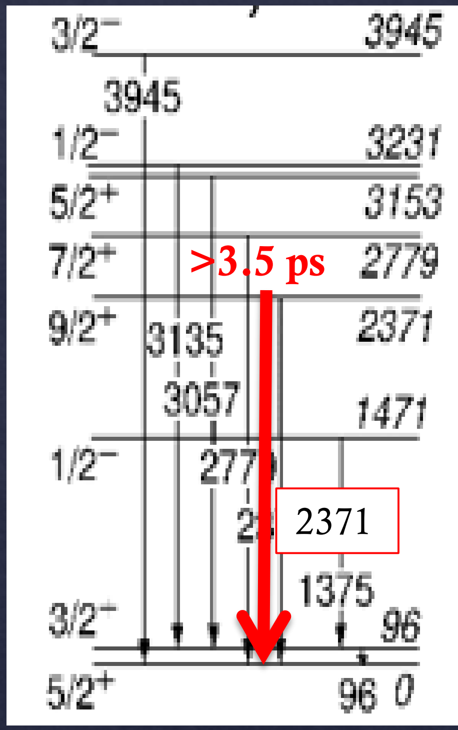
Very old
literature values (1971)
τ = 70(26) fs
τ = 117(26) fs

TEST of KNOWN long lifetime in the region



^{18}O (7 MeV/A) + ^{181}Ta target (6 mg/cm^2)

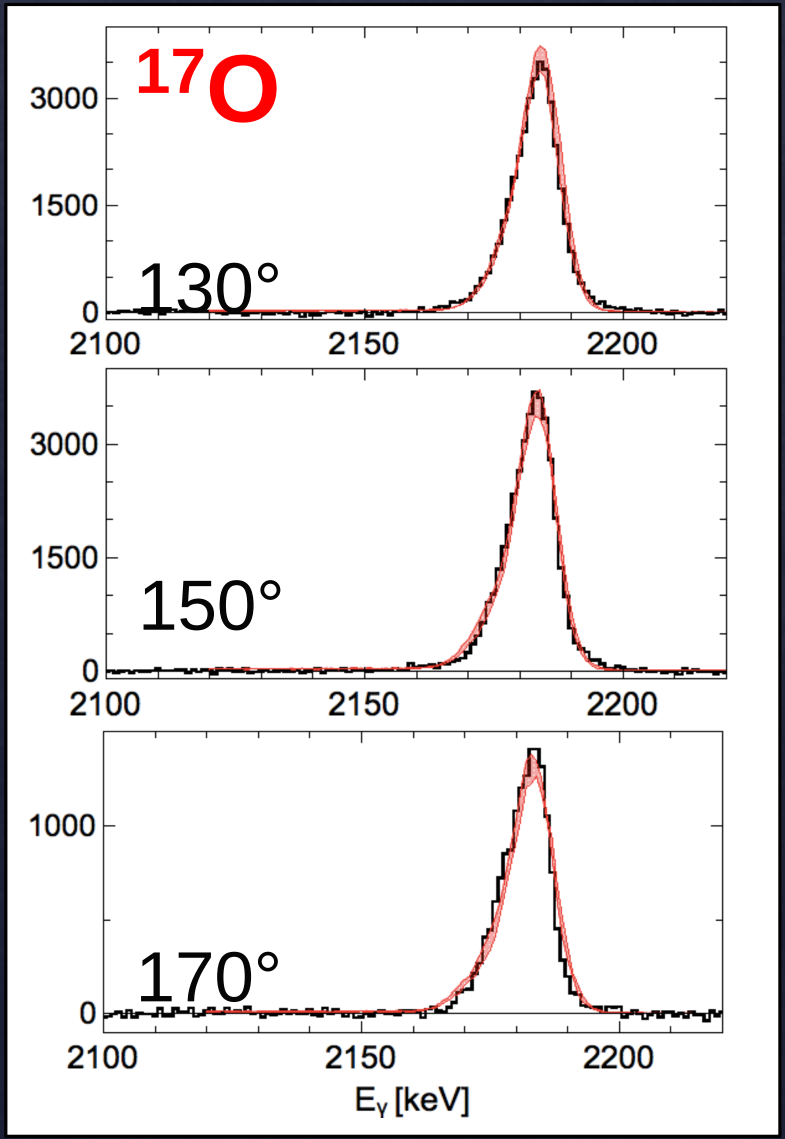




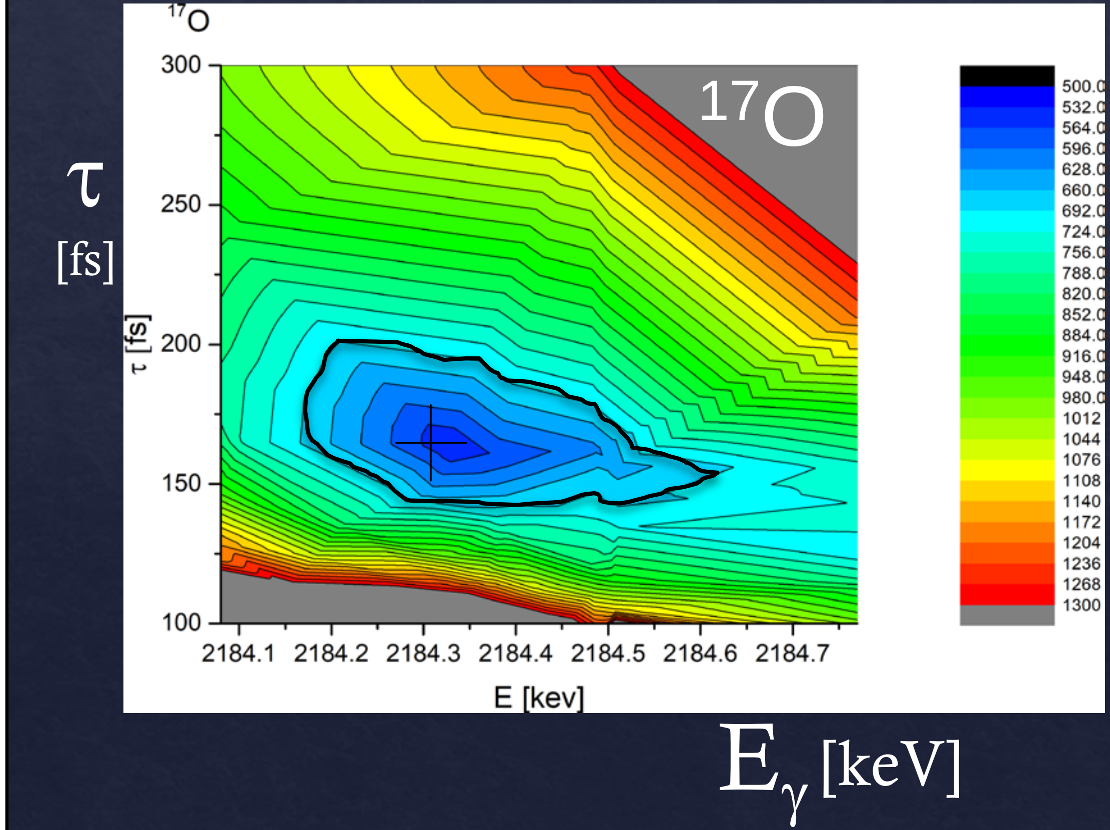
τ > 400 fs

Literature Eγ = 2371(1) keV

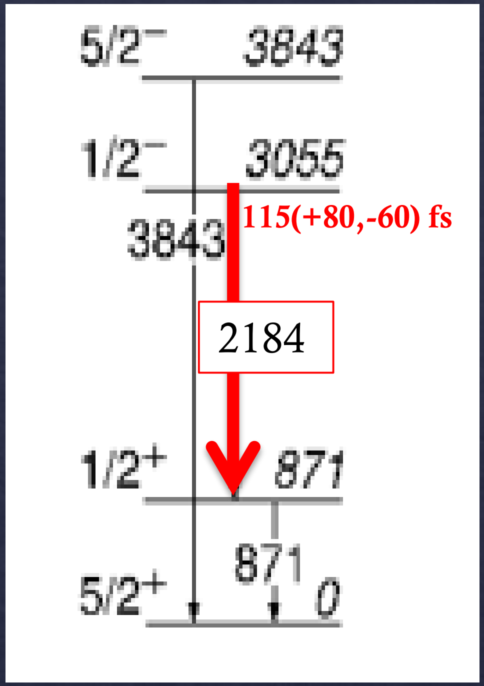
TEST of KNOWN Lifetimes in the 100s femtoseconds region



^{18}O (7 MeV/A) + ^{181}Ta target (6 mg/cm^2)



Literature Eγ = 2184.48(20) keV

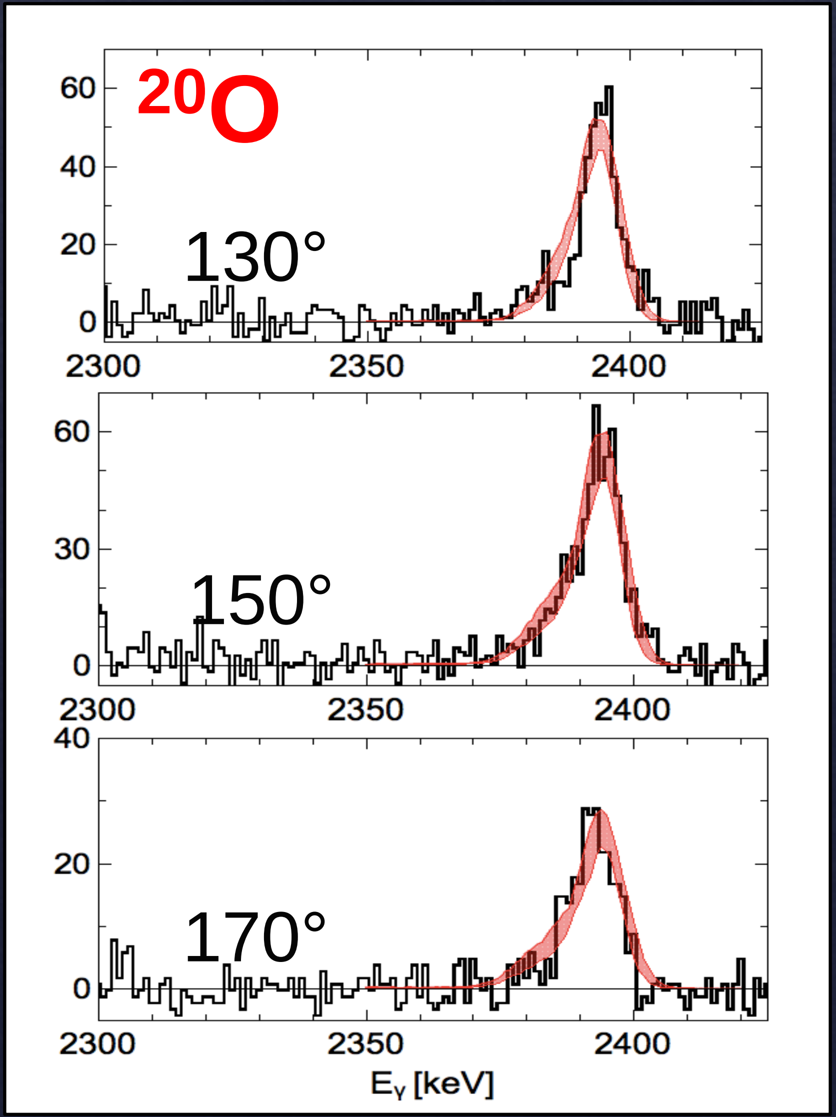


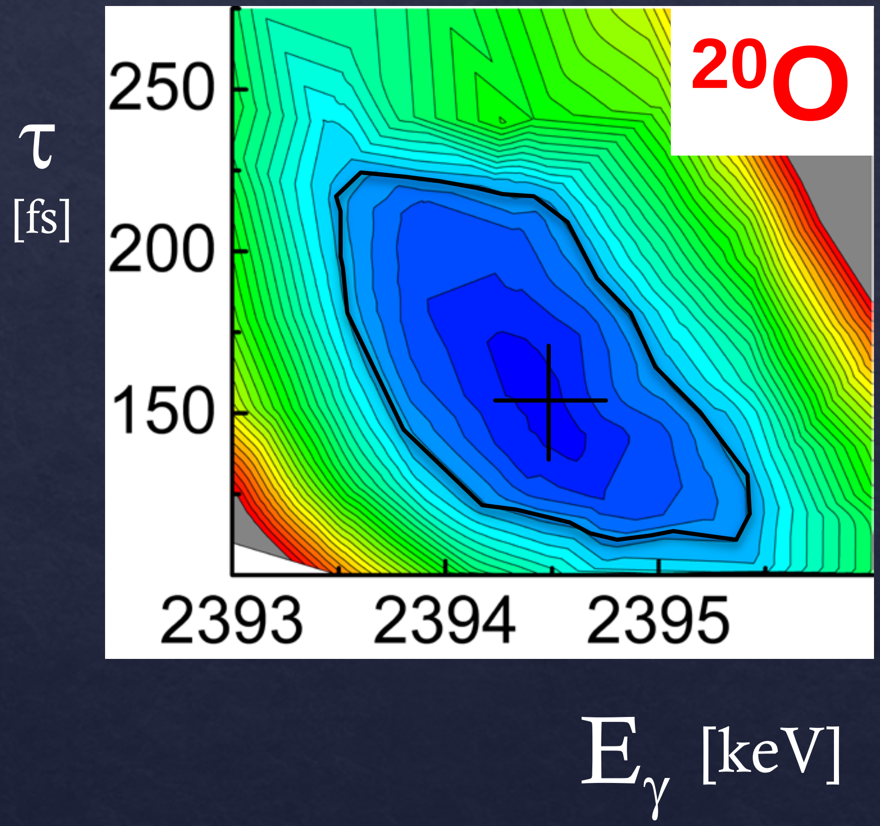
$$\tau = 159^{+40}_{-20}\ \text{fs}$$

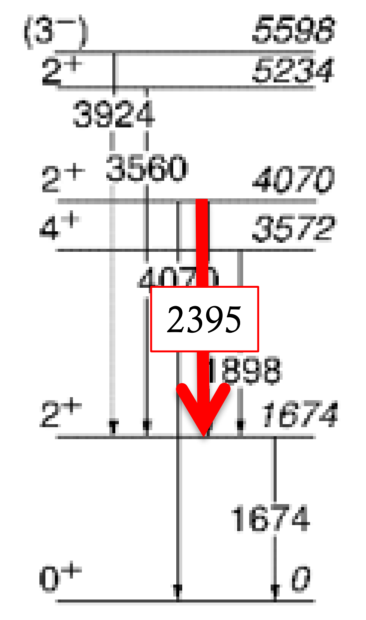
Very old
literature values (1964)
τ = 115(+80,-60) fs

OUR Case of interest – ^{20}O

^{18}O (7 MeV/A) + ^{181}Ta target (6 mg/cm^2)





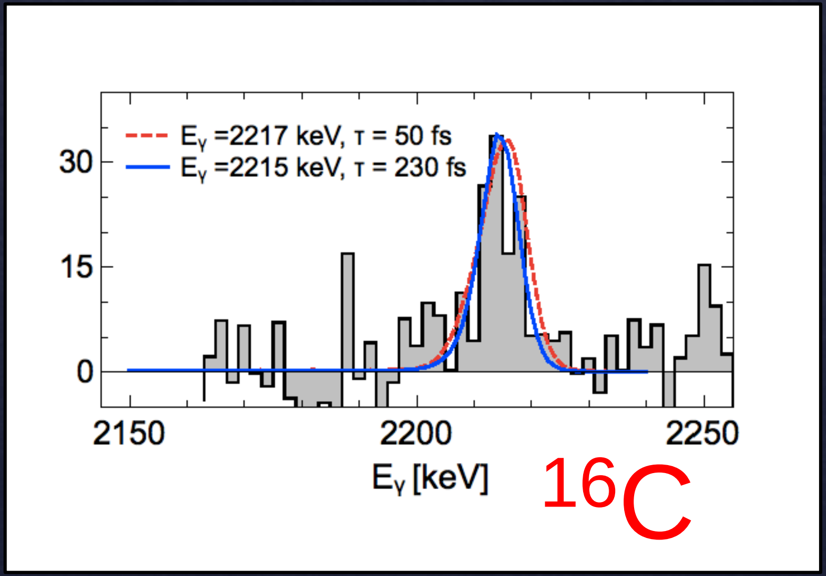


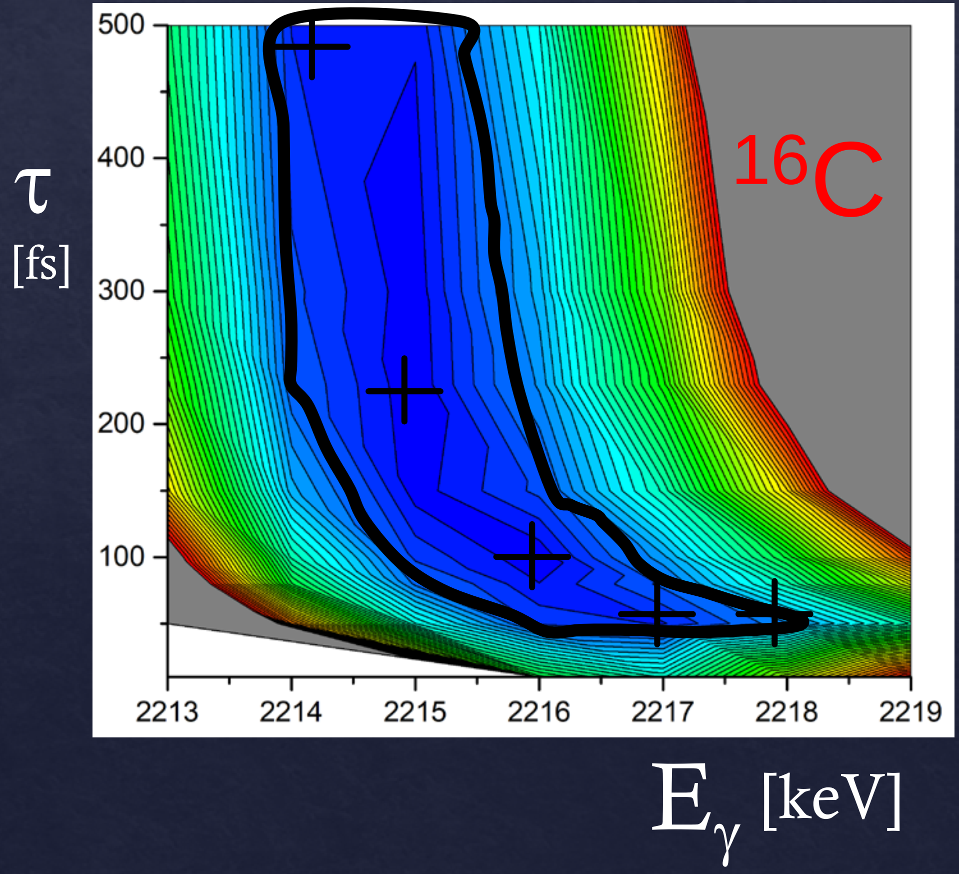
$$\tau = 150^{+80}_{-30}\ \text{fs}$$

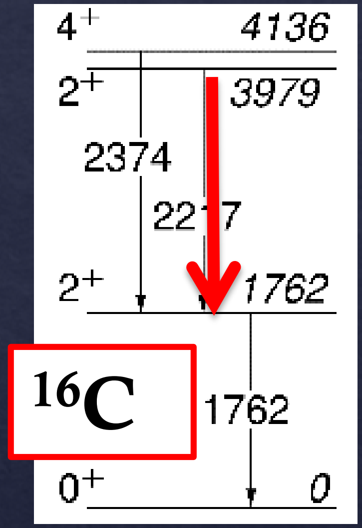
Literature Eγ = 2395(1) keV

OUR Case of interest – ^{16}C

^{18}O (7 MeV/A) + ^{181}Ta target (6 mg/cm^2)

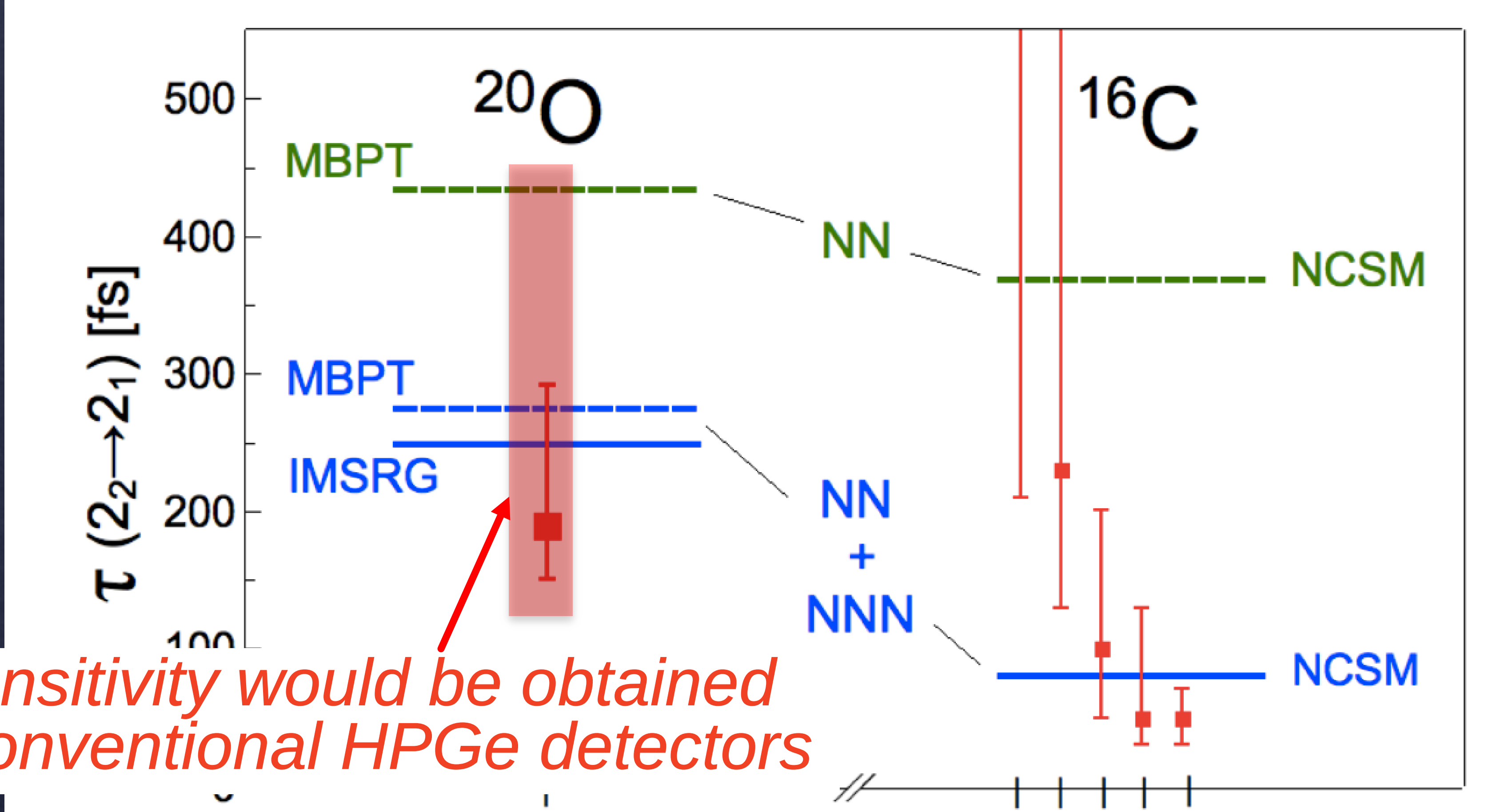






Literature Eγ = 2217(2) keV

Results



NO sensitivity would be obtained with conventional HPGe detectors

For ^{20}O, our result is fully consistent with the *ab initio* calculations which include three-nucleon forces (calculation employing only NN interaction are NOT satisfactory).

Partial lifetimes, with branching taken into account.

NCSM: C. Forssén, et al., J. Phys. G: Nucl. Part. Phys. 40, 055105 (2013).
NN:D.R. Entem and R. Machleidt, Phys. Rev. C 68, 041001(R) (2003); J. Simonis, et al., Phys. Rev. C 93, 011302(R) (2016).

Perspective for future: ^{16}C

In 2019 LoI was presented on AGATA@LNL for stable beams workshop:

M. Ciemała, B. Fornal, S. Leoni, et al.
„Lifetime measurements of excited states in neutron-rich C isotopes” for furthcoming AGATA campaign at Legnaro National Laboratory, Italy.

Setup: PRISMA, AGATA and PARIS

Target: ^{198}Pt, beam ^{18}O

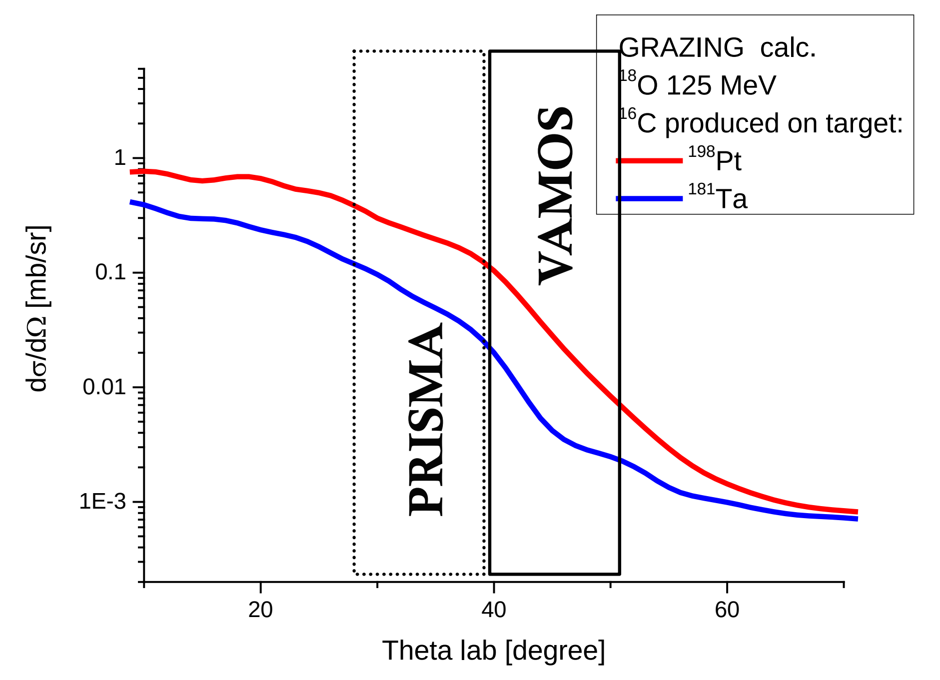
AGATA – Lifetimes of the second 2^+ states: by Doppler Shift Attenuation.

PARIS - high energy g, branches from the second 2^+ state to the ground state and to the first 2^+ state (3979 keV in ^{16}C).

PRISMA – Ion identification, measurement of velocity vector.

One of the physics cases for AGATA white book:

Korten, W., Atac, A., Beaumel, D. et al. Physics opportunities with the Advanced Gamma Tracking Array: AGATA. Eur. Phys. J. A 56, 137 (2020).



Papers published/in preparation:

1. M. Ciemała , S. Ziliani, F.C.L. Crespi, S. Leoni, B. Fornal, A. Maj, et al., „ Testing *ab initio* nuclear structure in neutron-rich nuclei:Lifetime measurements of second 2^+ state in ^{16}C and ^{20}O", Phys. Rev. C 101, 021303(R), 2020.
2. M. Ciemała, S. Ziliani, F.C.L. Crespi, S. Leoni, B. Fornal, A. Maj, et al., „ *Accessing tens-to-hundreds femtoseconds nuclear state lifetimes with low-energy binary heavy-ion r*" submitted to EPJA (description of the method) *https://arxiv.org/abs/2012.05180*
3. S. Ziliani, M. Cimała, F.C.L. Crespi, S. Leoni, B. Fornal, et al. „*Complete spect*
negative-parity states in ^{18}N" (in preparation)

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Proceedings:

1. M. Ciemała et al., Acta Phys. Pol B 50(2019), No. 3, 615
2. S. Ziliani et al., Acta Phys
3. M. Ciemała et al., Acta P
4. S. Ziliani et al., Acta Phys
5. S. Ziliani, Il Nuovo Cimen

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NEWS RELEASE 26-JUN-2020

The nature of nuclear forces imprinted in photons

THE HENRYK NIEWODNICZANSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

SKANER

FIZYKA

Natura sił jądrowych odciśnięta w fotonach

Naukowcy z Instytutu Fizyki Jądrowej PAN wraz ze współpracownikami potwierdzili konieczność uwzględnienia oddziaływania trójnukleonowego w opisie elekromagnetycznych przejść w jądrze atomowym tlenu ^{20}O

Conclusions

- Tested experimentally the impact of the NNN interactions to nuclear structure observables.
- Novel method, together with the most sophisticated experimental setup, lead to the first lifetime measurement of second 2^+ in ^{20}O: 150 fs, fully consistent with *ab initio* calculations including three body interactions.
- Extracted estimates of lifetime of second 2^+ in ^{16}C: it depends on non-shifted gamma-ray energy → new measurement is needed.
- Developed Experimental approach essential for short lifetime measurements in unexplored regions of the nuclear chart, with future intense beams, produced by Isotope Separation On-Line (ISOL) techniques.
- This technique, exploiting EM decays, is new and complementary to other techniques of 3N interaction studies.
- Our work significantly broadens the possibilities for nuclear structure high-precision measurements in hard-to-reach exotic systems.

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AGATA
PARIS
VAMOS
Collaborations

Italian-Polish-French collaboration and AGATA+VAMOS+PARIS setup allowed successful experiment at GANIL.