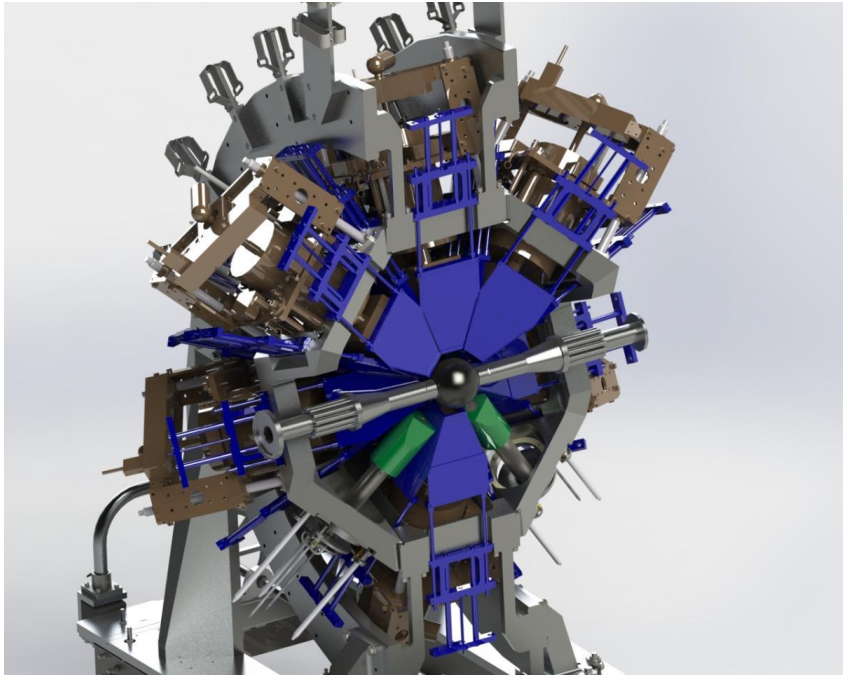


# Estudio de Núcleos Exóticos



Bruno Olaizola  
IEM-CSIC



# Summary

- Typical nuclear physics experiment
  - Before the experiment
  - During the experiment
  - After the experiment
- Examples of nuclear physics experiments
  - Nuclear structure
  - Fundamental symmetries
  - Nuclear astrophysics
  - Nuclear medicine
  - Solid state/biology

# Before the experiment

# Have an idea



# Have an idea

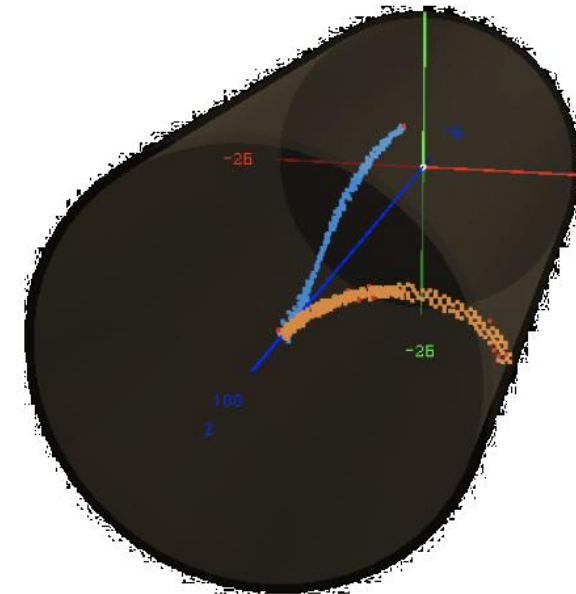
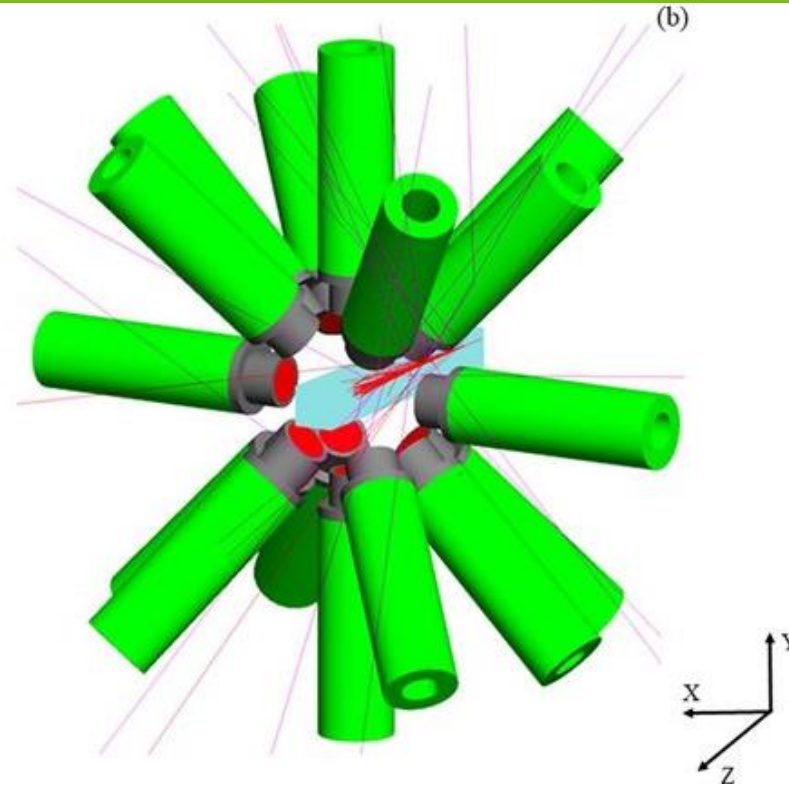


- Read 100s of papers
- Think you have had a novel idea
- Realize it was done already in USSR in the 70's
- Read another 100 papers
- Have another idea
- Realize it is impossible to do
- Re-read 100s of papers and read another 100 new ones
- Come up with an idea that is feasible and has not been done

**EUREKA!!**

# Design your experiment

- Which nucleus am I going to measure?
- Which properties?
- Which detectors do I need for that?
  - How many?
  - Where do I position them?
- Use Geant4 to simulate your experiment
  - Is it feasible?
  - How much beamtime would I need?



# Experiment proposal

- Experiments are very expensive
- Beamtime is very competitive
- Write detailed experimental proposal
- Defend it in front of an international committee of experts
  - They are mean and ask very difficult questions
- Only the most interesting and feasible are approved



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Exploring shape coexistence across  $N=60$  in  $^{100}\text{Sr}_{62}$  using IDS

January 5, 2022

B. Olaizola<sup>1</sup>, S. S. Bhattacharjee<sup>2</sup>, R. Kanungo<sup>3</sup>, A. Algora<sup>4</sup>, A. Andreyev<sup>5</sup>, Y. Ayyad<sup>6</sup>, M.J. Borge<sup>7</sup>, J.A. Briz<sup>8</sup>, R. Caballero-Folch<sup>3</sup>, C. Costache<sup>9</sup>, J. Cubiss<sup>5</sup>, S. J. Freeman<sup>1</sup>, L.P. Gaffney<sup>10</sup>, A. Illana<sup>11</sup>, P. Jones<sup>12</sup>, U. Koester<sup>13</sup>, R. Lică<sup>1,9</sup>, N. Marginean<sup>9</sup>, C. Mihai<sup>9</sup>, R. E. Mihai<sup>9</sup>, C. Page<sup>5</sup>, J. Pakarinen<sup>11</sup>, S. Pascu<sup>9</sup>, V. Petousis<sup>2</sup>, Z. Podolyak<sup>14</sup>, M. Stryczyk<sup>11</sup>, A. Turturica<sup>9</sup>, M. Veselsky<sup>2</sup>, N. Warr<sup>15</sup>, K. Wimmer<sup>16</sup>, Z. Yue<sup>5</sup>

<sup>1</sup>ISOLDE-EP CERN, <sup>2</sup>Technical University in Prague, <sup>3</sup>TRIUMF, <sup>4</sup>IFIC Valencia, <sup>5</sup>University of York, <sup>6</sup>Universidad de Santiago, <sup>7</sup>CSIC Madrid, <sup>8</sup>Universidad Complutense de Madrid, <sup>9</sup>IFIN-HH Bucharest, <sup>10</sup>University of Liverpool, <sup>11</sup>University of Jyväskylä, <sup>12</sup>Themba LABS, <sup>13</sup>ILL Grenoble, <sup>14</sup>University of Surrey, <sup>15</sup>Universität zu Köln, <sup>16</sup>GSI Darmstadt

Spokesperson: B. Olaizola [bruno.olaizola@cern.ch]

Spokesperson: S. S. Bhattacharjee [Soumendu.Bhatt@cvut.cz]

Contact person: Razvan Lică [razvan.lica@cern.ch]

**Abstract:** This proposal aims to locate excited  $0^+$  state(s) in  $^{100}\text{Sr}_{62}$  in order to unravel the nuclear structure responsible for the sudden change in deformation characteristic of the region. The excited states of Sr isotopes will be populated via  $\beta$  and  $\beta$ -n decay using  $^{100,101}\text{Rb}$  beams at the ISOLDE Decay Station (IDS). The  $0^+$  state(s) will be firmly identified using  $\gamma - \gamma$  angular correlations and by directly observing E0 transitions using the SPectrometer for Electron DETection (SPEDE) ancillary detector. Secondary goals include measuring the  $P_n / P_{2n}$  values and nuclear level lifetimes by using fast-timing LaBr<sub>3</sub>(Ce) detectors. The proposed experimental data will provide critical information about the shape co-existence beyond  $N = 60$  in Sr isotope.

**Requested shifts:** [11] shifts, (split into [1] runs over [1] years)

**Installations:** IDS with 5 clovers and SPEDE

CERN-INTC-2022-007 / INTC-P-622  
05/01/2022



# Detector testing

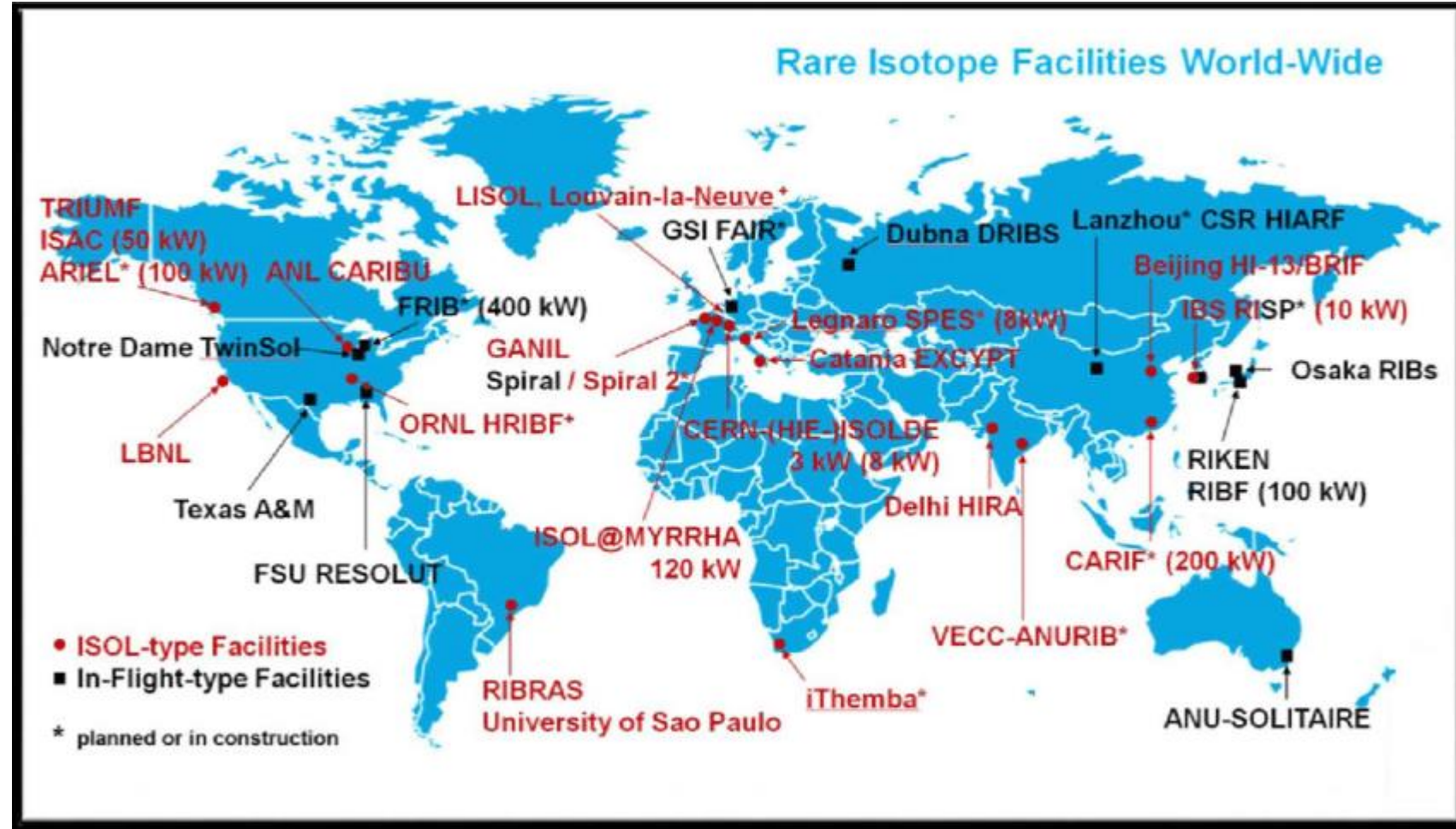
- Detectors:
  - Testing
  - Characterization
  - Optimization
- Electronics
- Data Acquisition System (DAQ)





# Shipment and travel

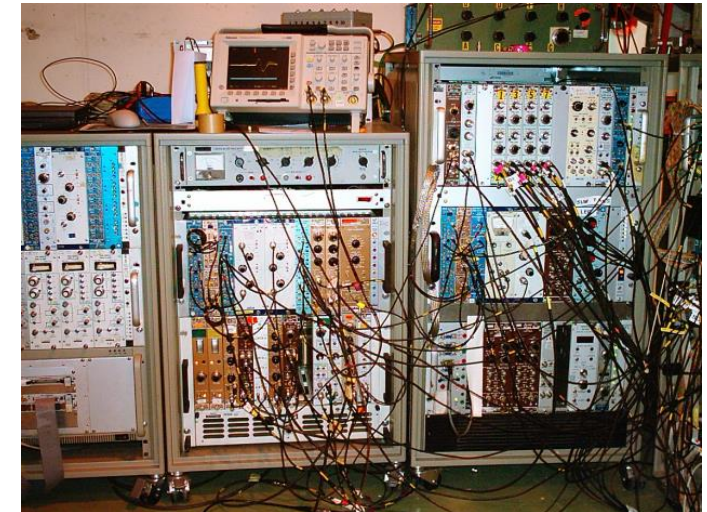
- Only a few laboratories around the world
- Shipping expensive scientific equipment is not trivial
- Large group of people travel to the lab



# During the experiment

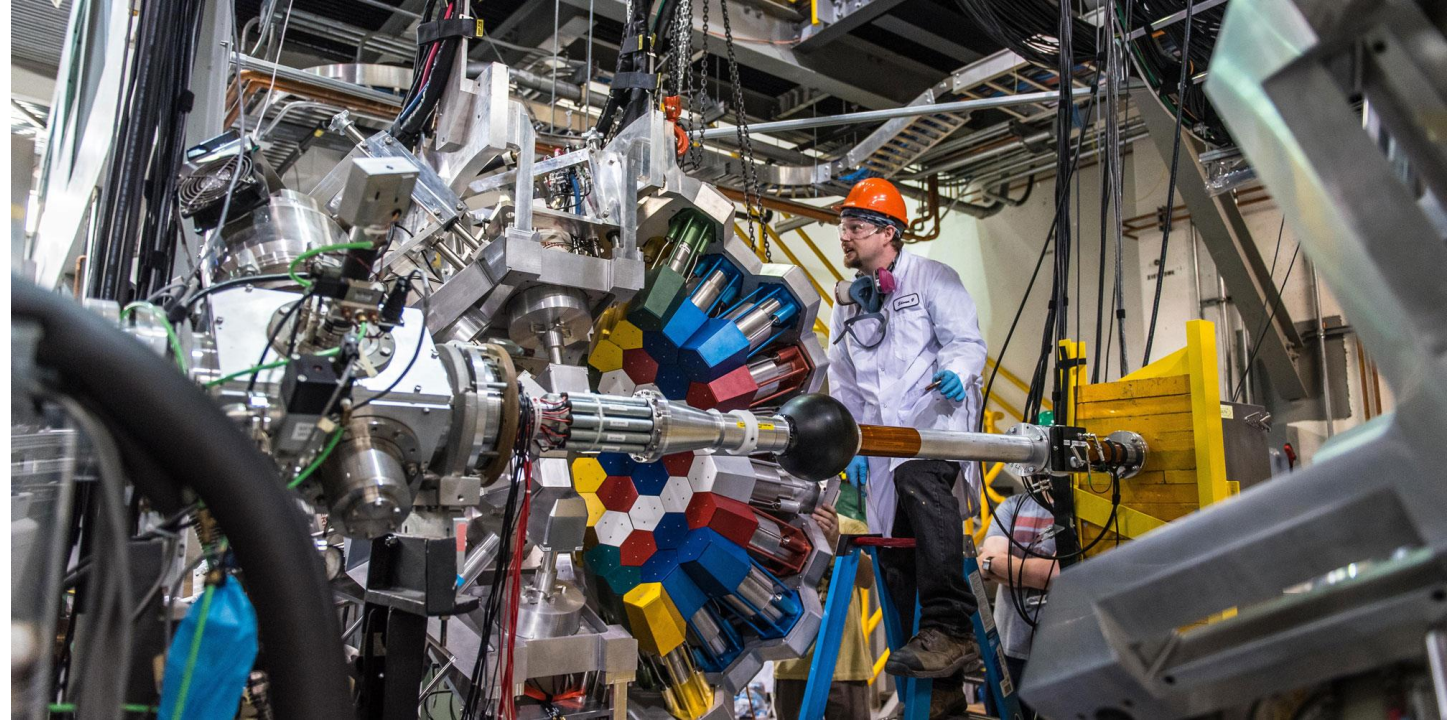
# Setting up

- Set up all the equipment
- Cross fingers everything works
- Spend the night fixing what it does not



# Permanent large detector arrays

- International laboratories have large permanent setups that international users run experiments with



# Beamtime

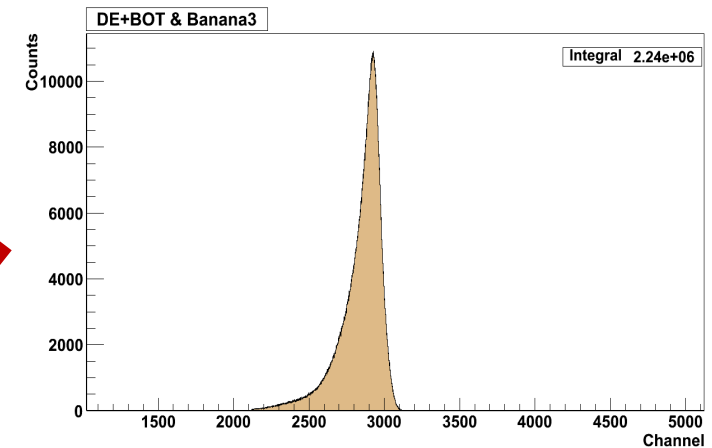
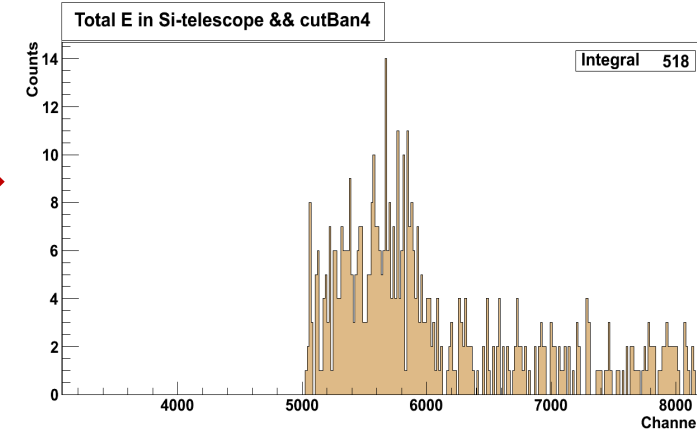
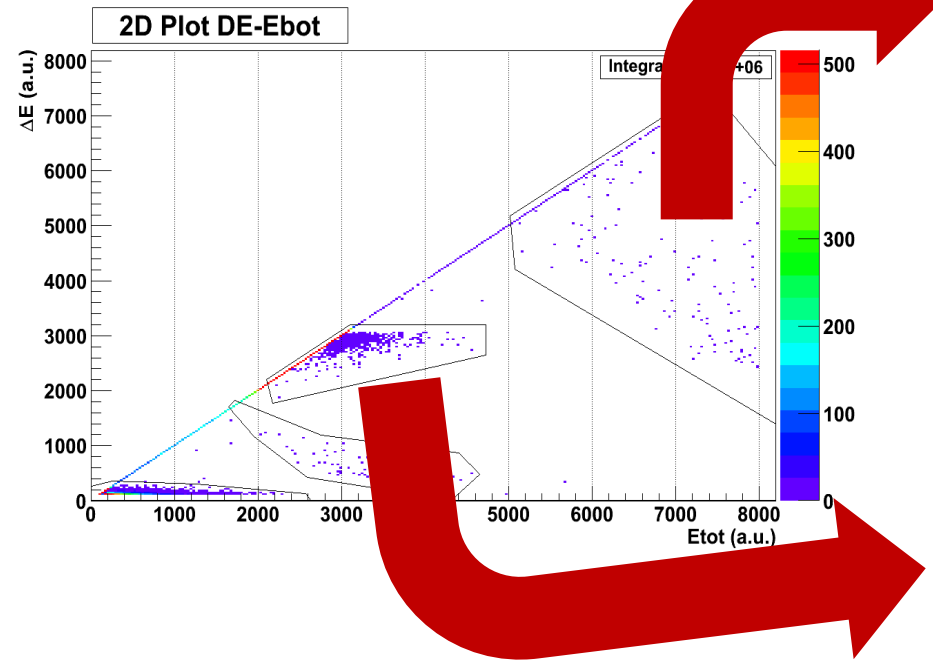


- The actual experiment: the beamtime
- It runs 24/7: 8-hour shifts
- Typical experiment runs for 5-7 days

# After the experiment

# Data analysis

- Modern nuclear experiments collect large amount of data (TBs)
- Need to be sorted and filtered
- Some programming skills are needed
- Most common C++ for ROOT
- Analysis usually led by PhD students



# Present in conferences

- As analysis progress, results are shared with the community
- Disseminate your new findings
- Engage on interesting discussions
- Network
- Travel to cool places



**The 5-th International Conference on Quarks and Nuclear Physics**  
 Beijing , September 21-26, 2009  
<http://tpcs.f.ihep.ac.cn/QNP09/index.htm>

**International Advisory Committee:**  
 N. Brambilla (Munich), S. Brodsky (SLAC),  
 V. Burkert (JLab), F. Close (Oxford),  
 D. Diakonov (Galeata), A. Dobado (Madrid),  
 A. Faessler (Tuebingen), A. Gal (Hebrew U.),  
 R. Jaffe (MIT), H. T. S. Lee (Argonne),  
 Ulf-G. Meissner (Bonn-Juelich), M. Oka (Tokyo),  
 E. Oniz (Valencia), J. E. Ribeiro (Lisbon),  
 D. O. Riska (Helsinki), M. Soyeur (Saclay),  
 T. Sugitate (Hiroshima), A. W. Thomas (JLAB),  
 H. Toki (Osaka), W. Weise (Munich),  
 U. Wiedner (Bochum), S. N. Yang (Taipei),  
 K.T. Chao (Peking U.), H. S. Chen (IHEP, Beijing),  
 W. Q. Shen (Shanghai), W. L. Zhan (Lanzhou),  
 Z. Y. Zhang (IHEP, Beijing)

**Local organizing committee:**  
 Chair: Y. F. Wang,  
 Co-chairs: Q. Zhao, B. S. Zou,  
 H. C. Chiang, Y. B. Dong, M. Huang,  
 G. X. Peng, P. N. Shen, S. Jin,  
 X. Y. Shen, C. Z. Yuan (IHEP, Beijing),  
 W. Q. Chao (CCAST), Y. X. Liu, B. Q. Ma,  
 S. L. Zhu (Peking Univ.),  
 P. F. Zhuang (Tonghua Univ.),  
 J. P. Ma (ITP), Z. T. Liang (Shandong),  
 Y. G. Ma (Shanghai)  
 Scientific Secretary: Lei Dang  
 Administrative Secretary: Tie Jun Deng

**Topics:**

- Effective Field theories
- Non perturbative QCD and models
- Hadron spectroscopy
- Hadron probes
- Matter under extreme conditions
- New and planned experimental facilities
- Recent applications to fundamental physics

Early information enquiry can be sent to: [qnp2009@ihep.ac.cn](mailto:qnp2009@ihep.ac.cn).

**HAWAII 2014**  
 FOURTH JOINT MEETING OF THE NUCLEAR PHYSICS DIVISIONS OF  
 American Physical Society and the Physical Society of Japan

October 7 – 11, 2014  
 HILTON MAWAOOLA VILLAGE, MAWAOOLA ISLAND  
<http://hawaii2014.org> | <http://www.aps.org> | <http://www.psj.jp>

**Winter Nuclear & Particle Physics Conference**

**WNPPC 2023**



# Publication

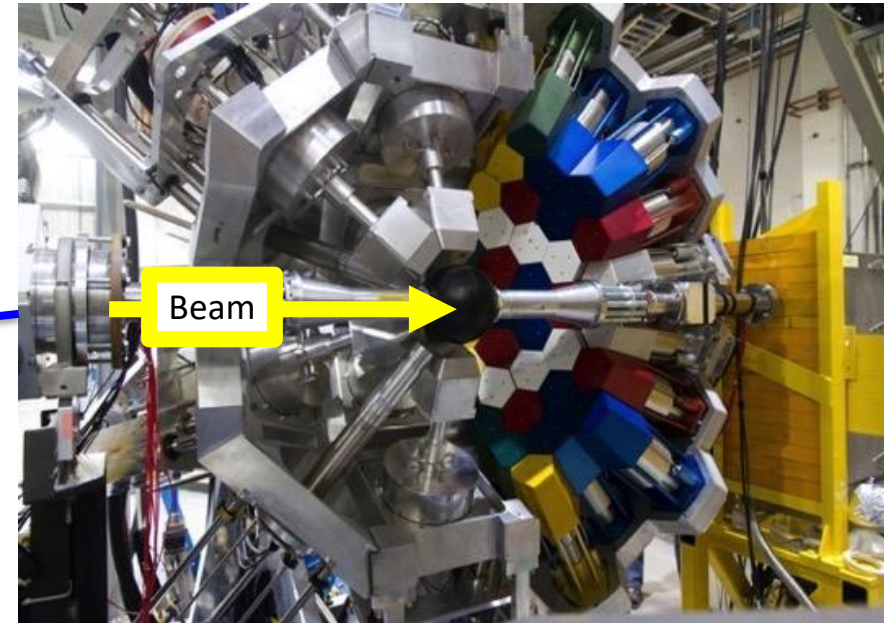
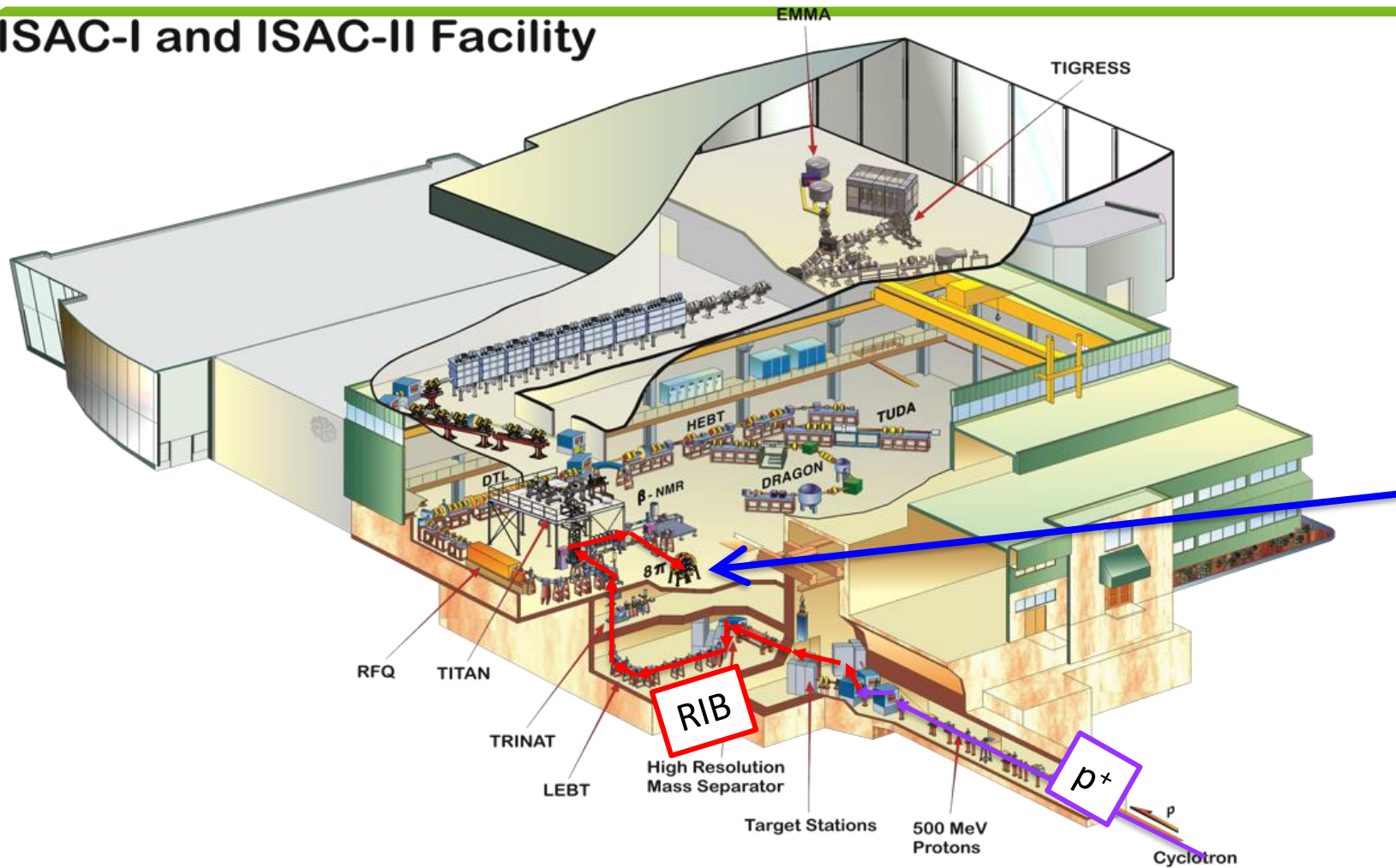
- The final step of research is to publish the results on peer-reviewed journals
- (And defend PhD thesis)



# Examples of nuclear physics experiments

# Decay experiments

## ISAC-I and ISAC-II Facility



# Nuclear structure

# Nuclear Shell model

● El núcleo exhibe estructura de capas

- Capas cerradas= « numeros mágicos »
- Nucleones de Valencia esenciales
- El modelo de capas es la base para explicar la espectroscopia nuclear

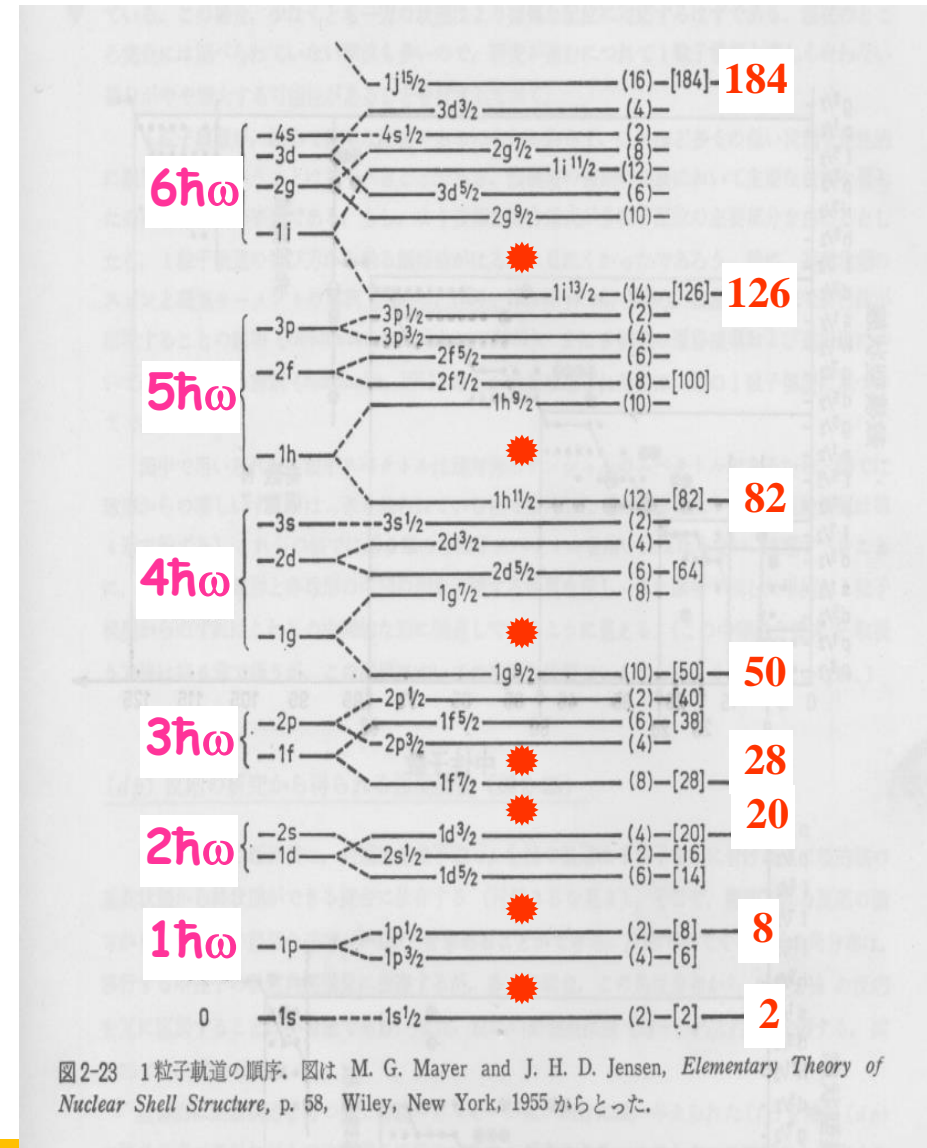
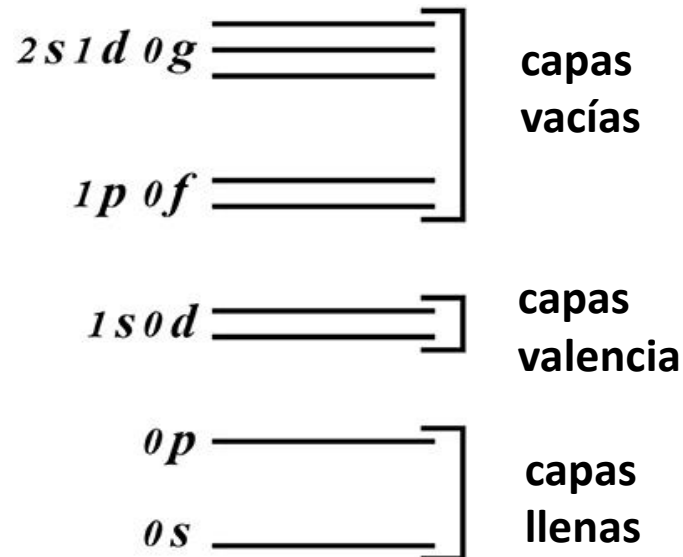
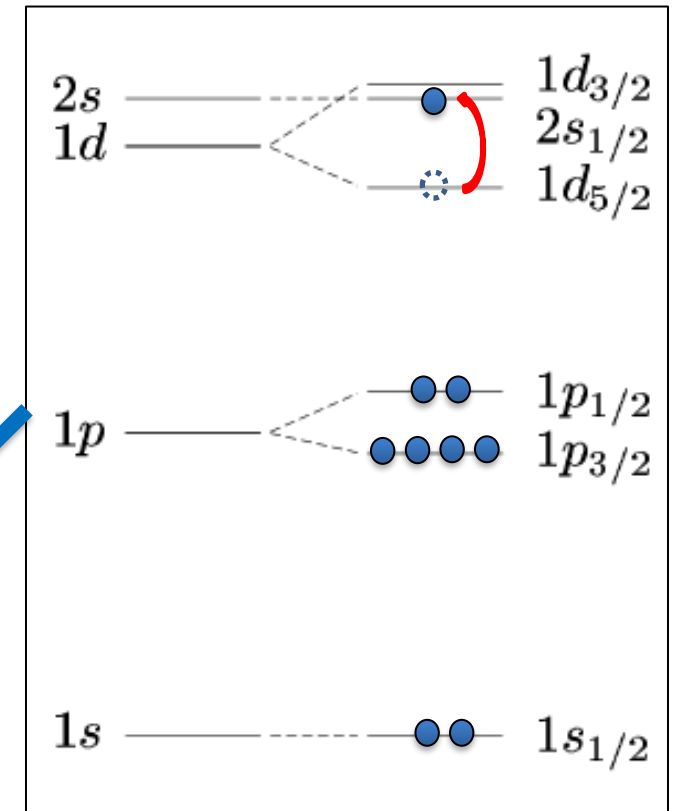
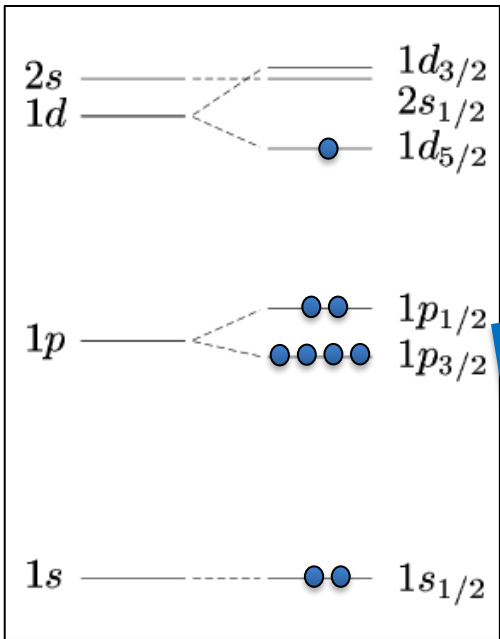
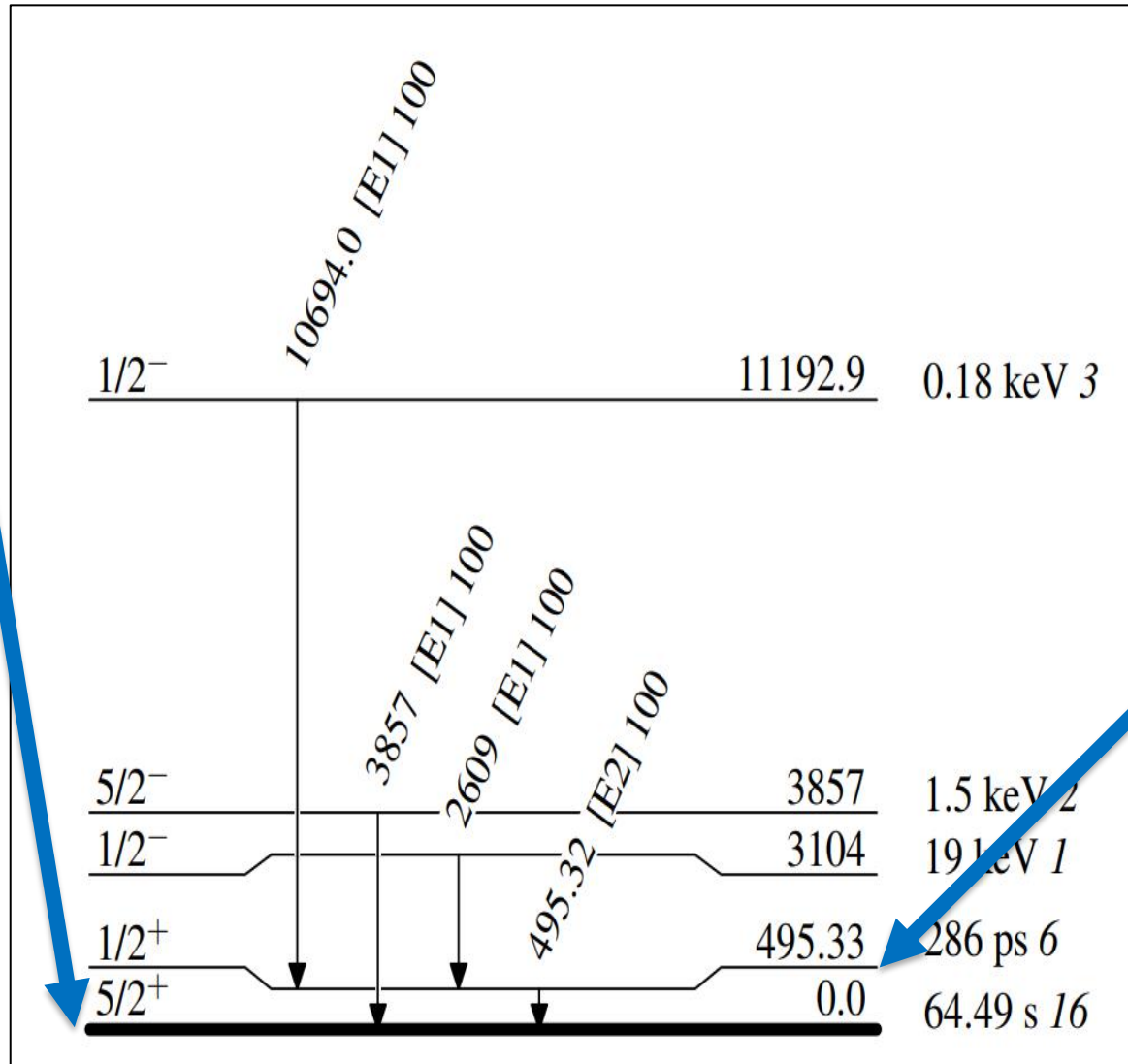
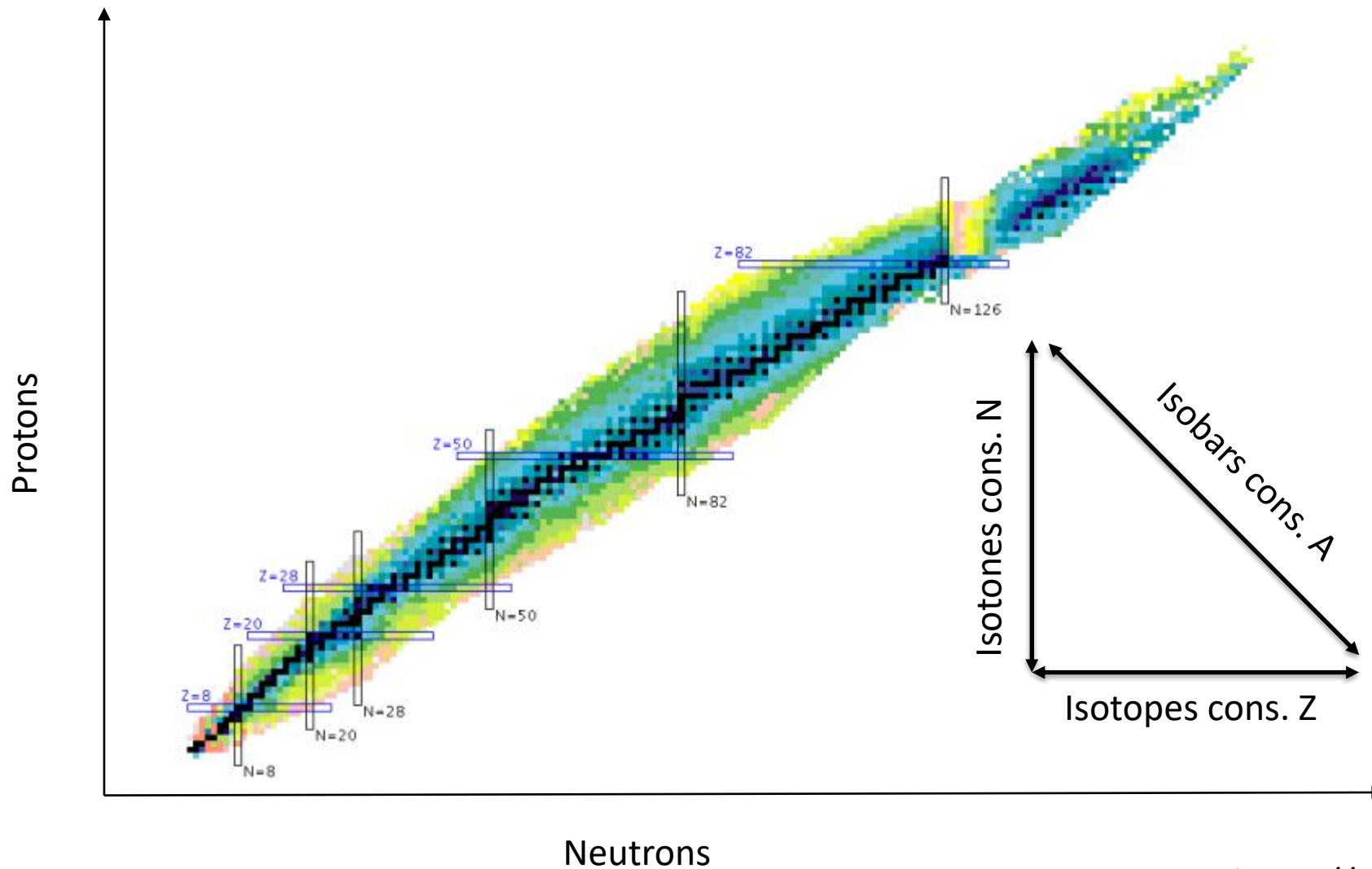


図 2-23 1 粒子軌道の順序. 図は M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure*, p. 58, Wiley, New York, 1955 からとった.

# Nuclear Shell model

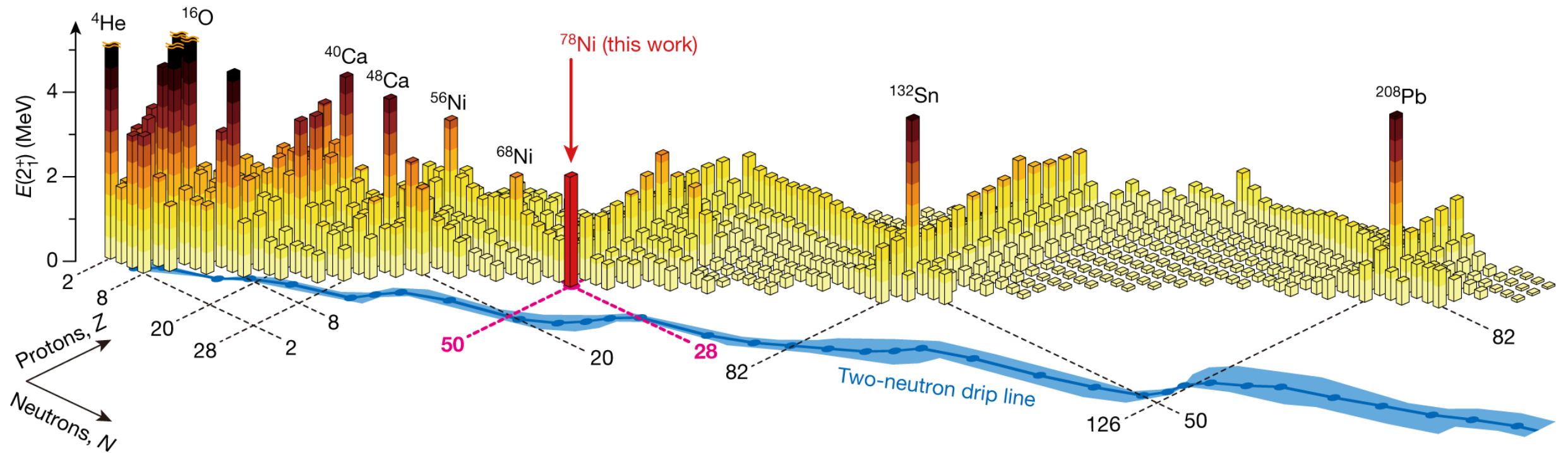


# Nuclear chart



<https://www.nndc.bnl.gov/>

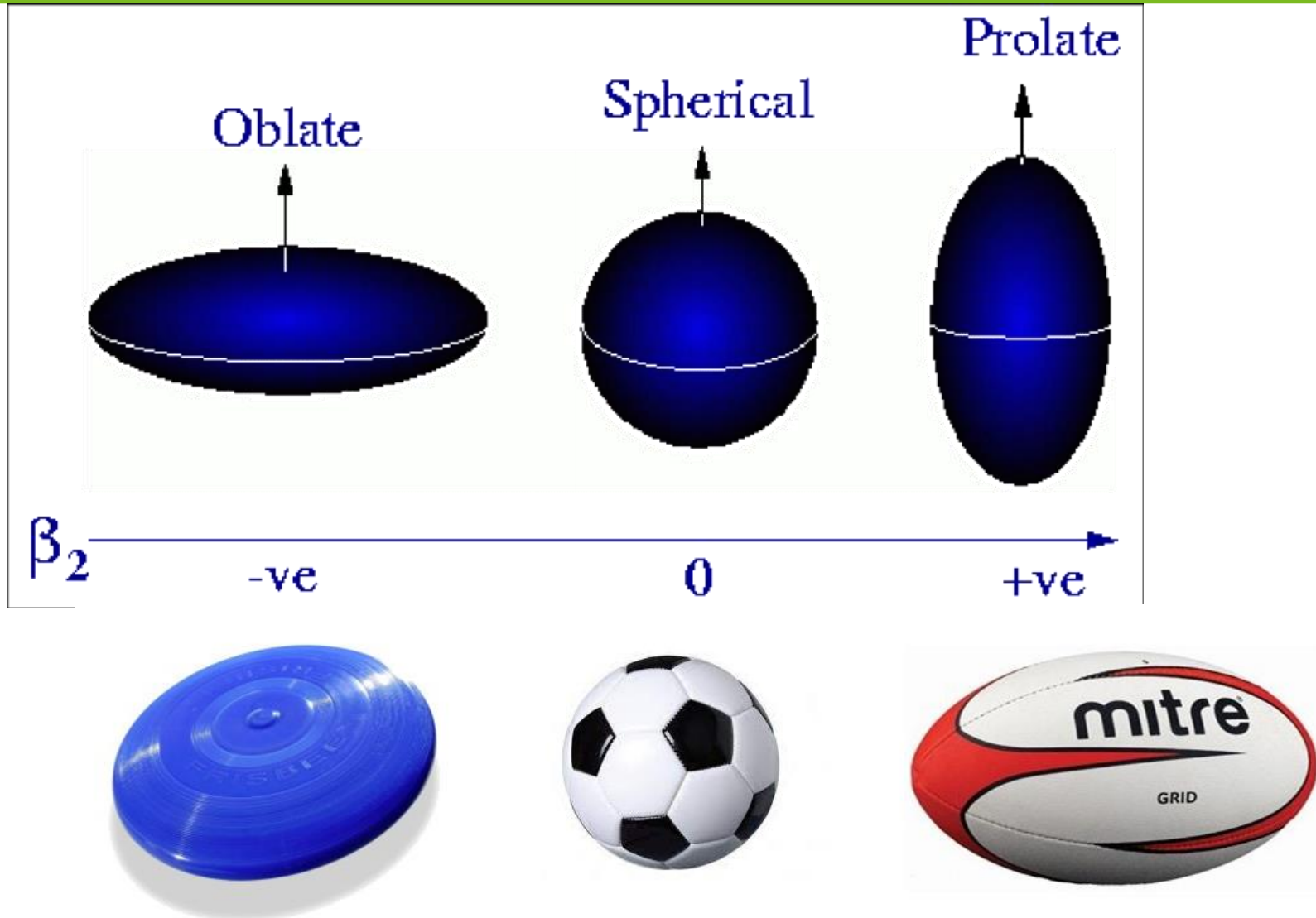
# Data analysis



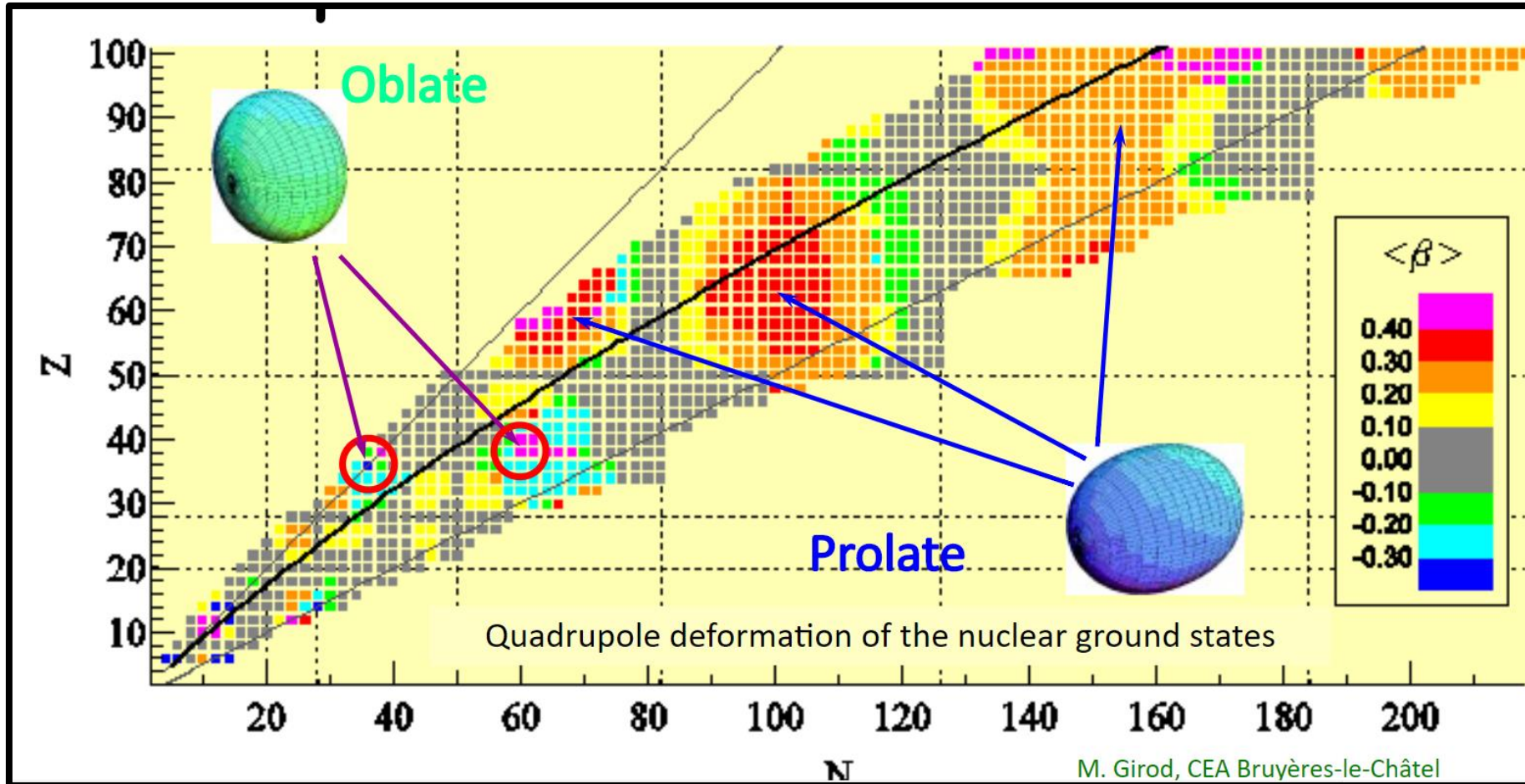
- Check closed shells by measuring energy of first excited states
- Turns out, far from stability new magic numbers appear
- Some “standard” magic numbers may disappear



# Deformation

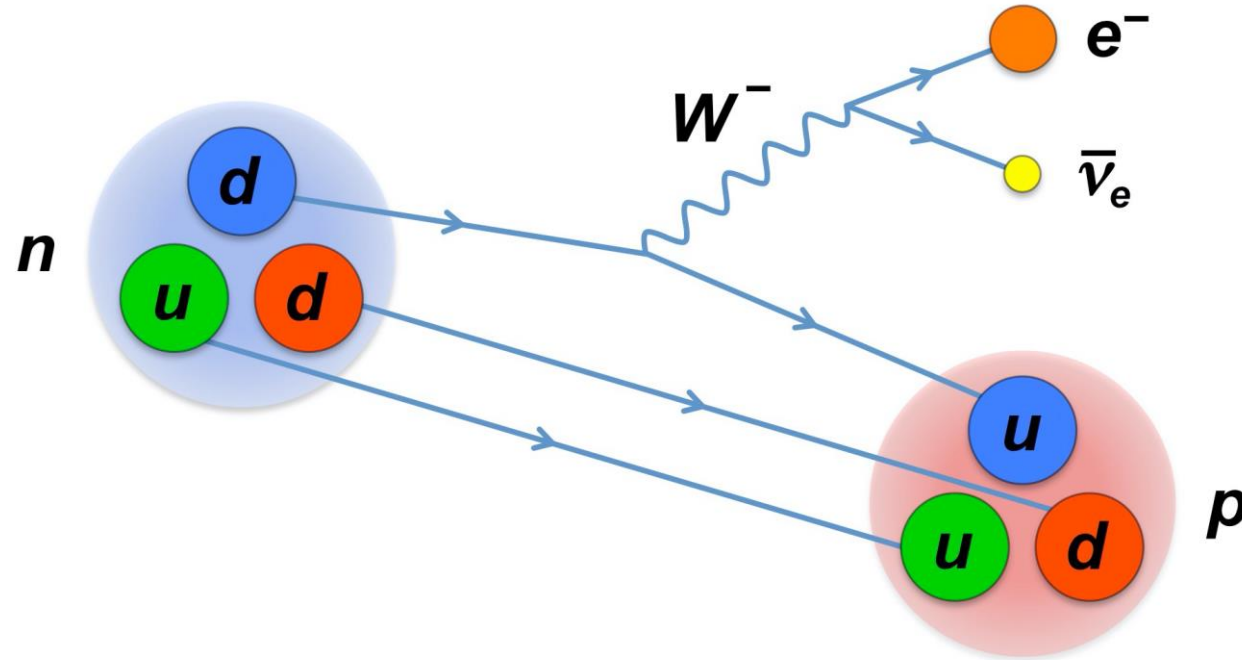


# Deformation is a common phenomenon



# Fundamental symmetries

# Beta decay



- Protons and neutrons are made of quarks
- In beta decay, a *down* quark becomes an *up* one
- They interact via the weak force

# The Standard Model of particle physics

The Cabibbo–Kobayashi–Maskawa (CKM) matrix plays a central role in the Standard Model and underpins all quark flavour-changing interactions:

weak interaction eigenstates  $\neq$  quark mass eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle + V_{ub}|b\rangle$$

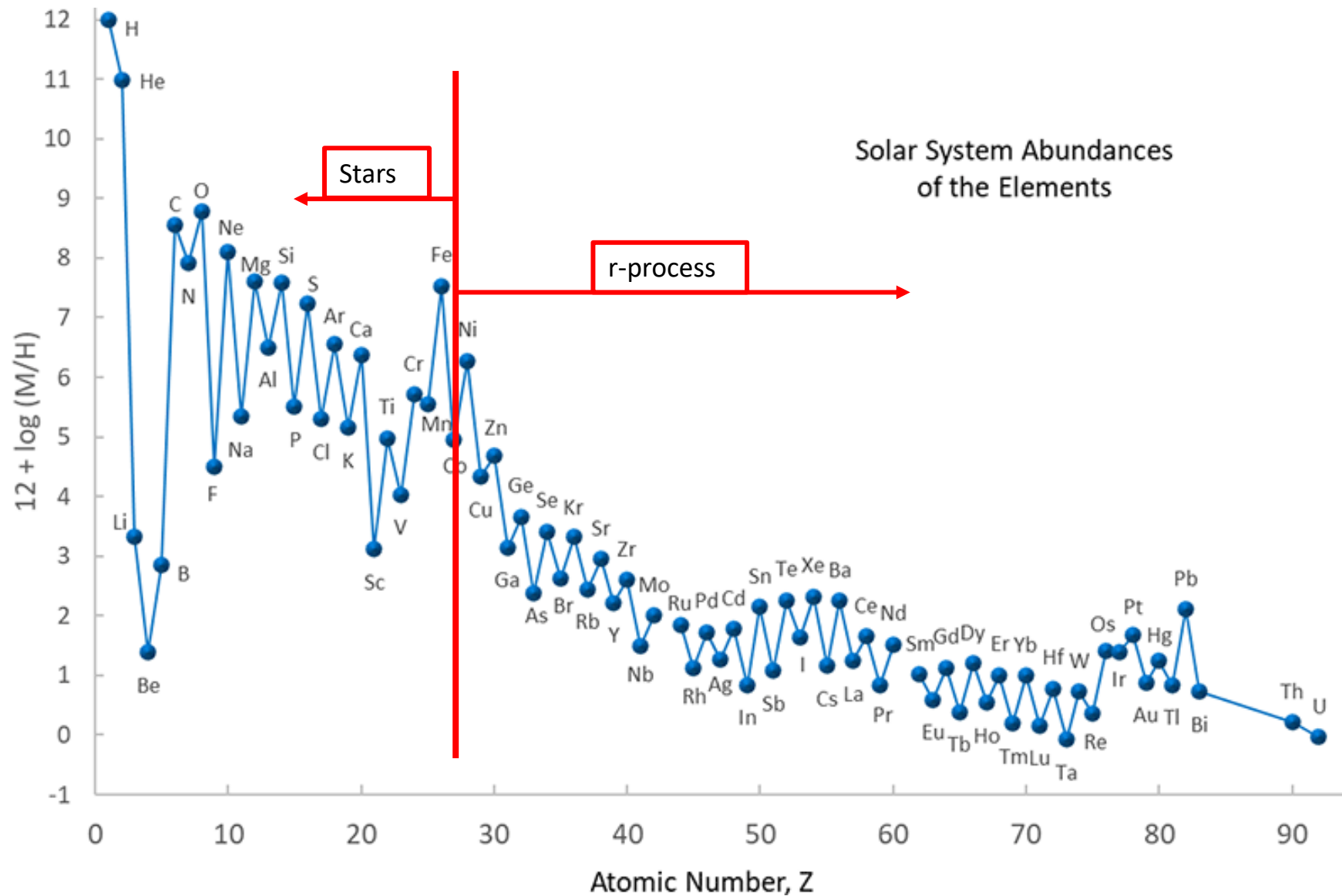
In the Standard Model the CKM matrix describes a unitary transformation:

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

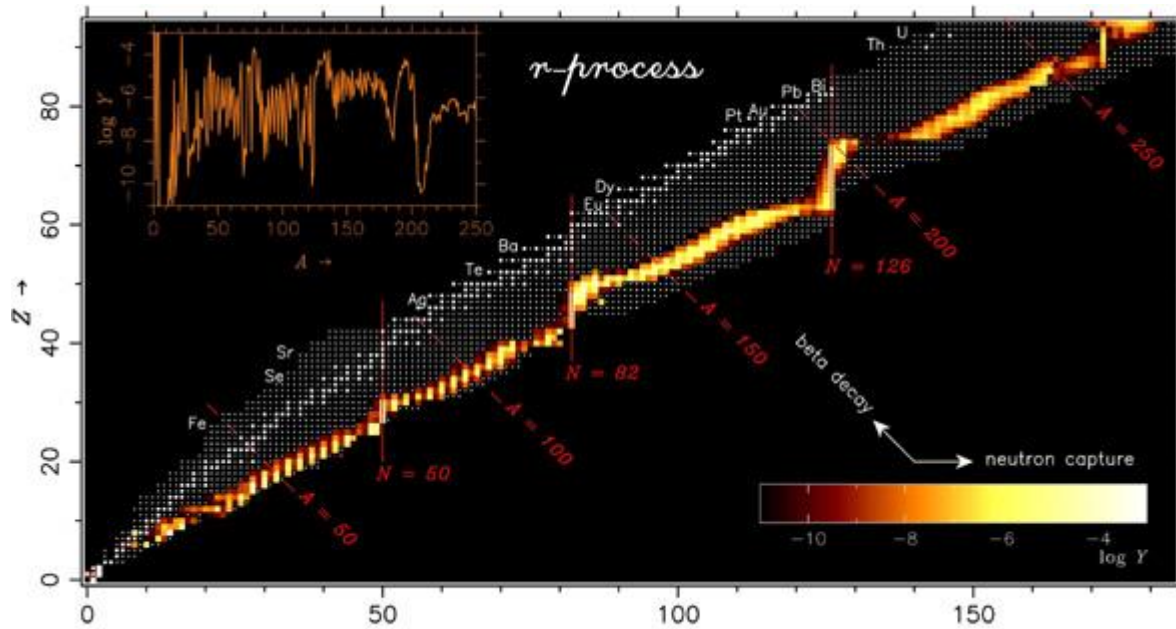
- Superaligned beta decays (beta decay between two special nuclei) is a pure transformation between *up* and *down* quarks
- We measure some nuclear properties (lifetime, nuclear mass, decay probability)
- Most precise measurement of the  $V_{ud}$  term

# Nuclear astrophysics

# Solar abundance

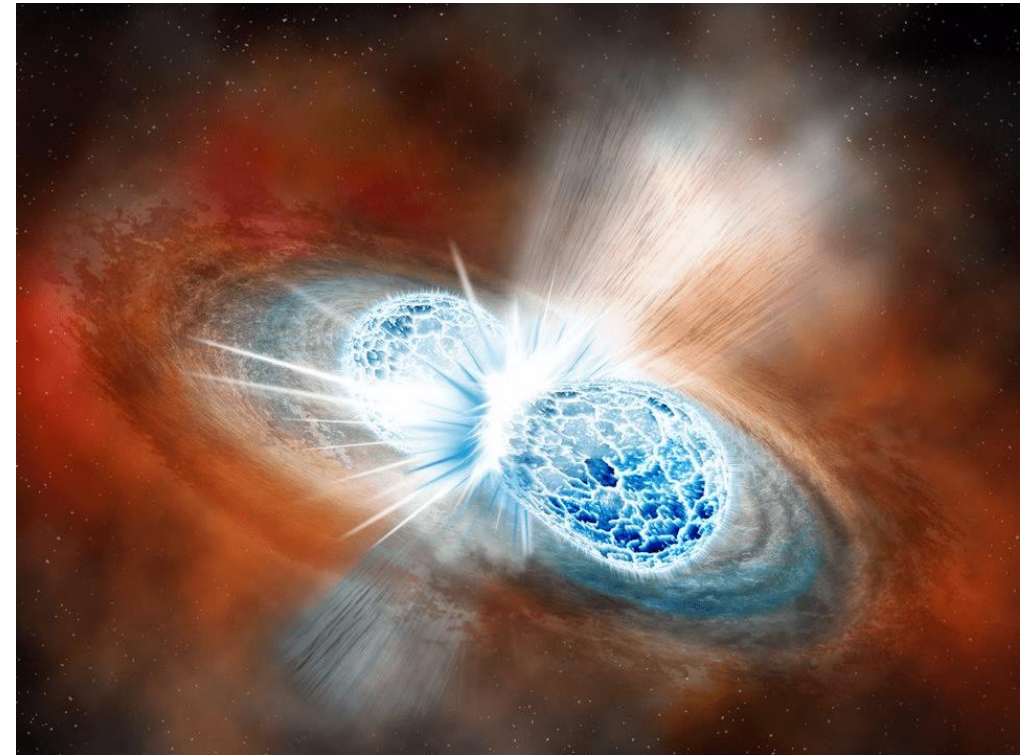


# r-process



- Rapid neutron-capture process
- Neutron star mergers
- Competition between beta decay and neutron absorption
- Most relevant observables:
  - Beta decay half life (g.s. and isomers)
  - Neutron emission
  - Neutron capture cross section

<http://www.ph.sophia.ac.jp/~shinya/research/research.html>



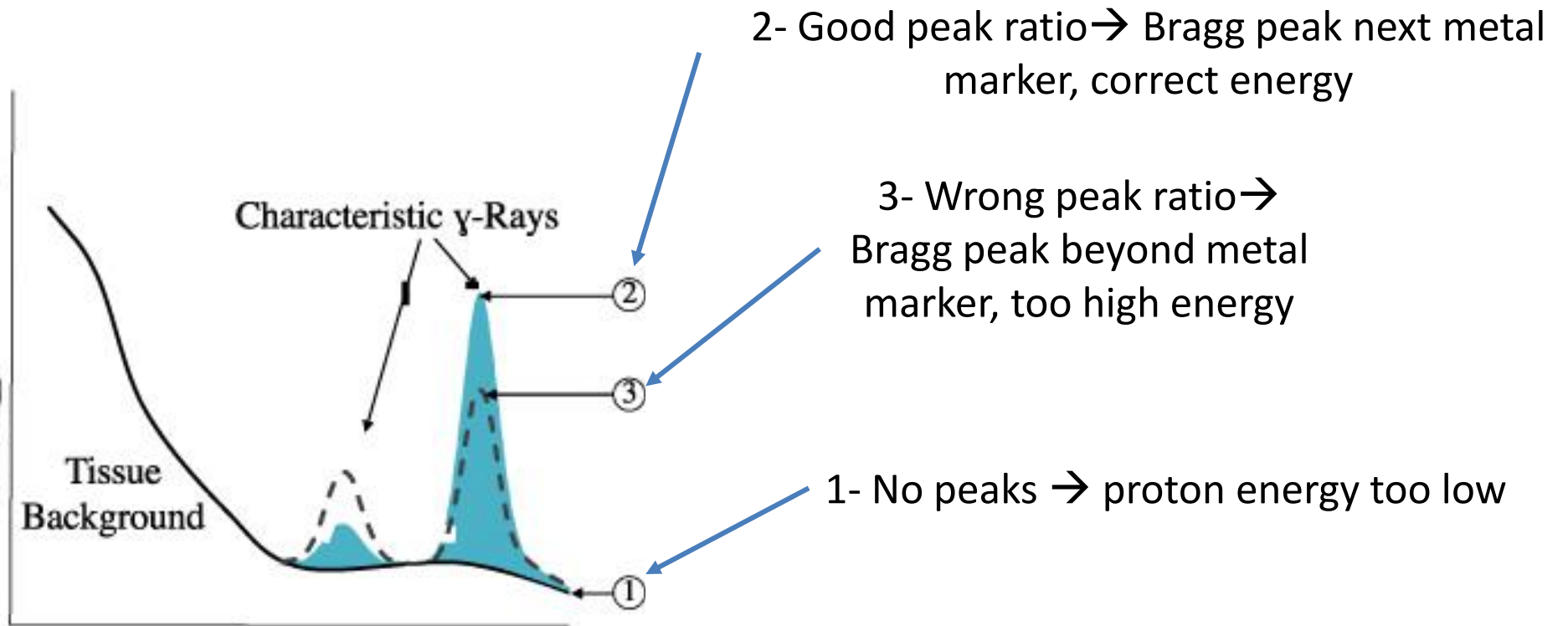
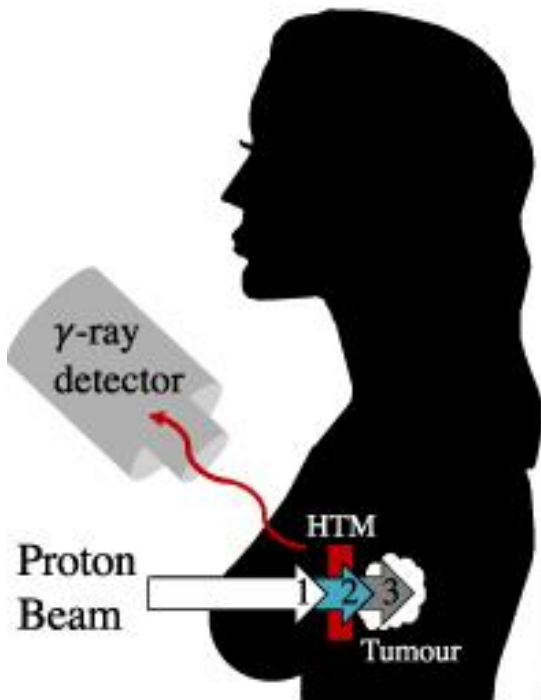
<https://physicsworld.com/a/merging-neutron-stars-create-more-gold-than-collisions-involving-black-holes/>



# Nuclear medicine

# Proton therapy range verification

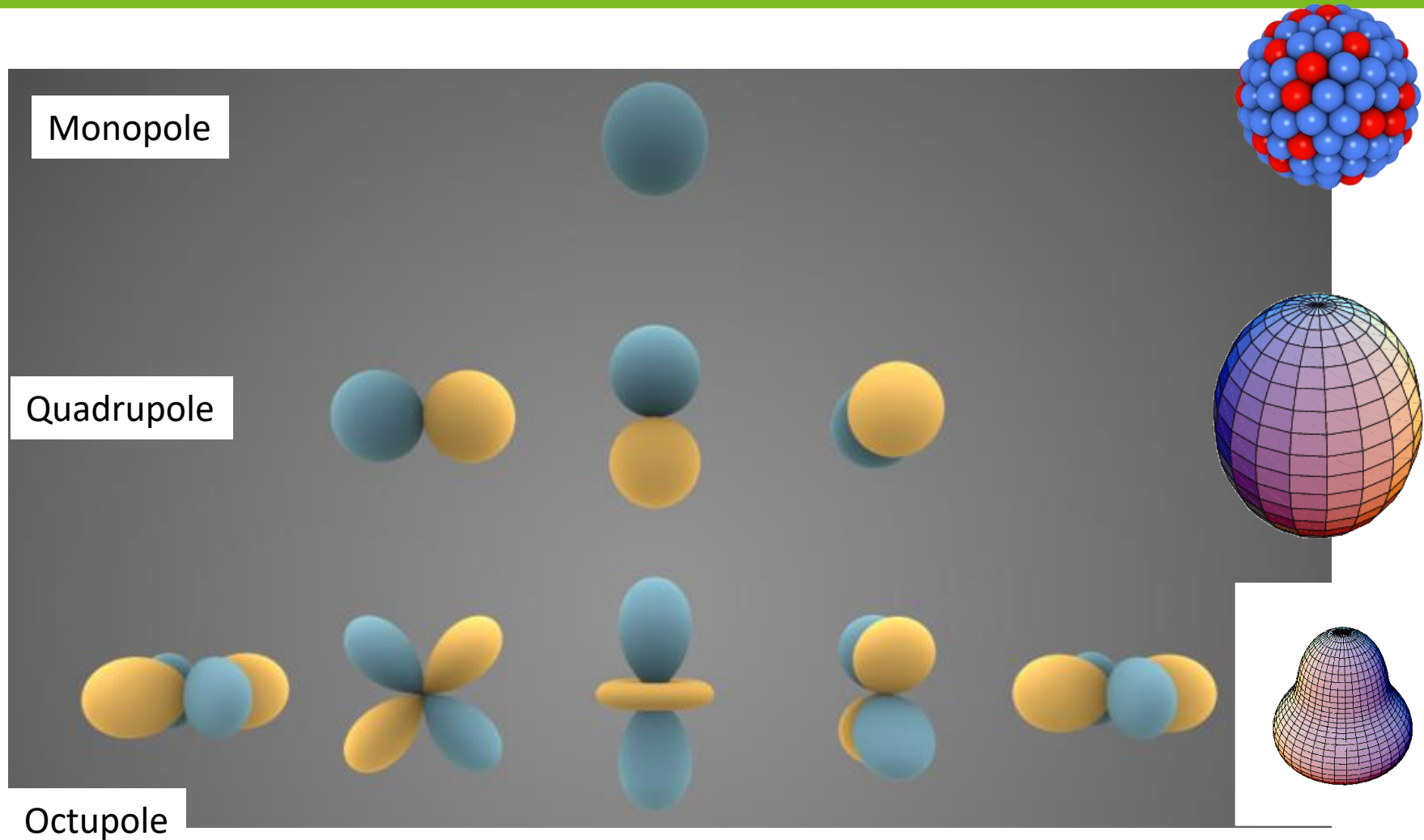
- We insert a metal foil (Mo) in front of the tumor
- Nuclear reaction with  $p^+$  emits characteristic gamma rays
- Ratio between peaks depends on  $p^+$  energy



C Burbadge et al 2021 *Phys. Med. Biol.* 66 025005

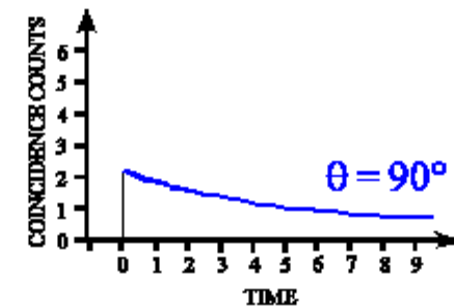
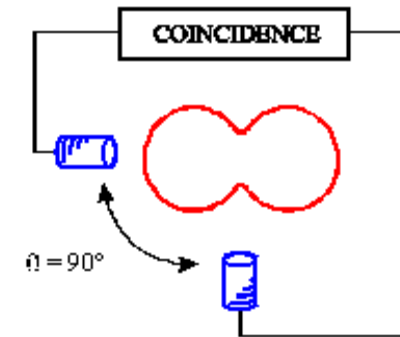
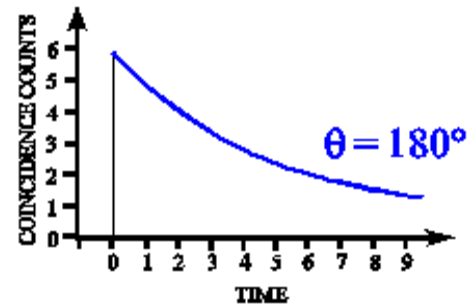
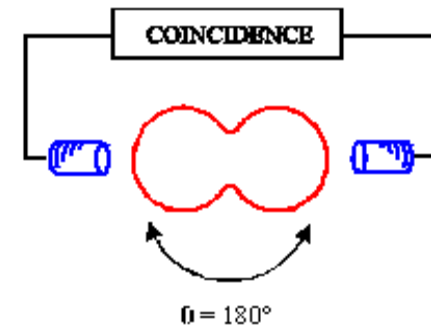
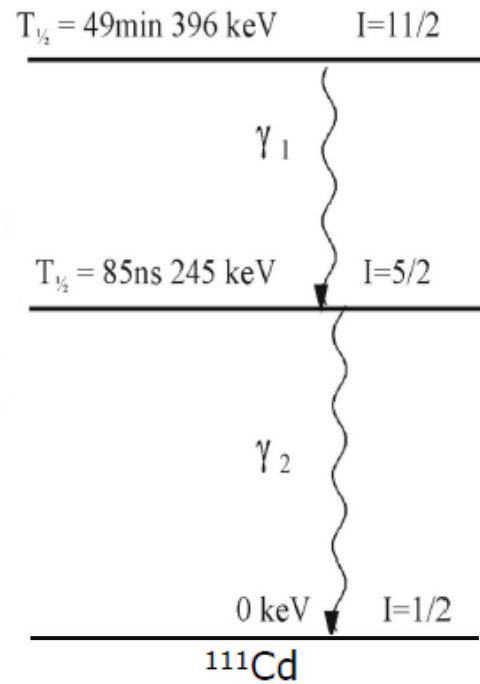
# Solid state and biology

# Multipole radiation



# PAC Spectroscopy

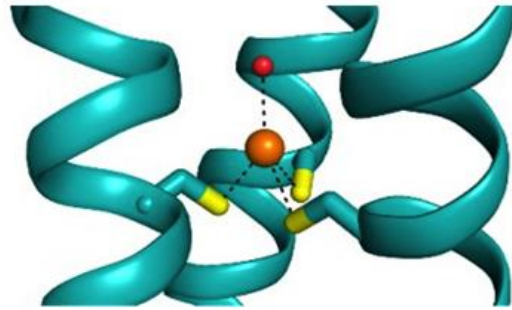
$\gamma$  -  $\gamma$  angular correlation



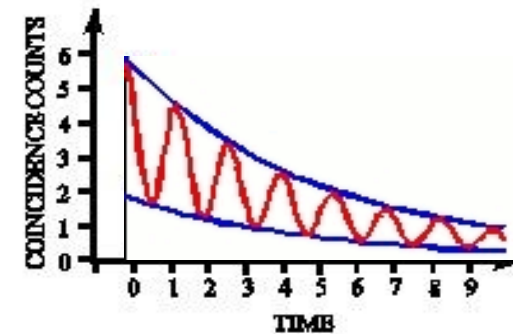
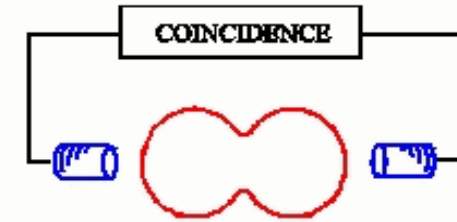
(www.uni-leipzig.de)

# Perturbed angular correlation

Now if the electric/magnetic field is created by other atoms in a molecule then the Perturbed  $\gamma$  -  $\gamma$  angular correlation is a very sensitive probe!

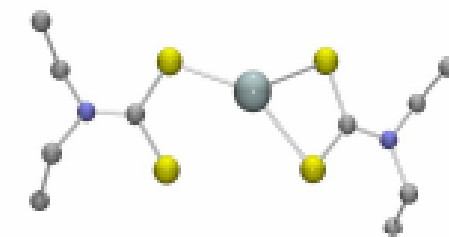
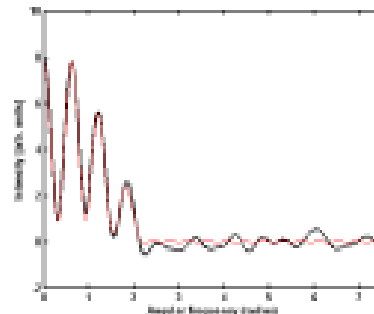
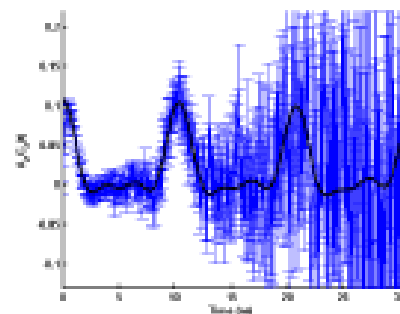
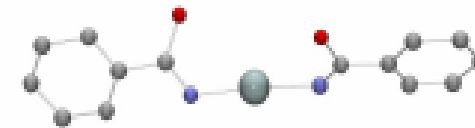
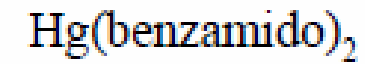
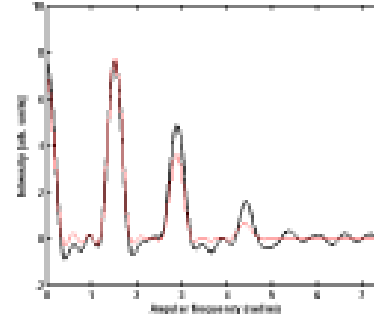
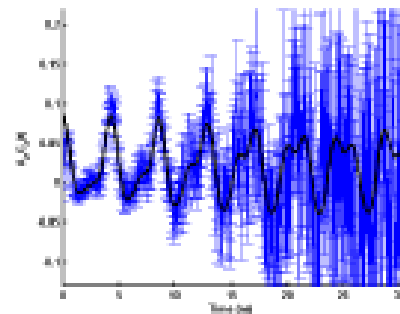
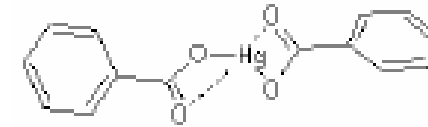
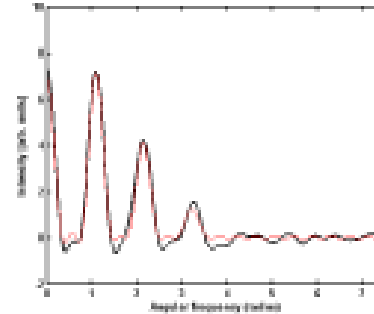
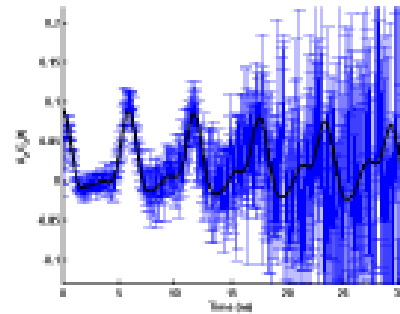


- This technique requires detectors with good energy resolution and excellent timing resolution.
- LaBr<sub>3</sub> scintillators are the ideal choice.



(www.uni-leipzig.de)

# PAC Spectroscopy reveals coordination chemistry



# Summary

- Typical nuclear physics experiment
  - Before the experiment
  - During the experiment
  - After the experiment
- Examples of nuclear physics experiments
  - Nuclear structure
  - Fundamental symmetries
  - Nuclear astrophysics
  - Nuclear medicine
  - Solid state/biology



# Nuclear physics masters

**CURSO 2023-2024**

Destinado a:  
Futuros investigadores. Profesionales de la física médica, radiología, radiactividad ambiental, técnicas nucleares de análisis, desarrollos tecnológicos, fechados con isótopos radiactivos, centrales nucleares.

**Máster Interuniversitario en Física Nuclear**

Participan:

- Universidad de Sevilla (coordinadora)
- Universidad Autónoma de Madrid
- Universidad de Barcelona
- Universidad Complutense de Madrid
- Universidad de Granada
- Universidad de Salamanca
- Instituto de Estructura de la Materia (CSIC Madrid)
- Instituto de Física Corpuscular (CSIC Valencia)
- CIEMAT, Madrid



**Contenidos:**  
Física nuclear experimental. Estructura nuclear. Reacciones nucleares. Técnicas experimentales en física nuclear. Física nuclear aplicada I (materiales y medio ambiente). Física nuclear aplicada II (energía y aplicaciones biomédicas). Radioprotección. Física hadrónica. Astrofísica nuclear. Mecánica cuántica relativista. Teorías de muchos cuerpos en física nuclear. Interacciones débiles.

Información en: <http://master.us.es/fisicanuclear>  
[http://www.us.es/estudios/master/master\\_M082](http://www.us.es/estudios/master/master_M082)



ERASMUS MUNDUS JOINT MASTER DEGREE IN **NUCLEAR PHYSICS**

Co-funded by the Erasmus+ Programme of the European Union

[www.emm-nucphys.eu](http://www.emm-nucphys.eu) [nucphysinfo@us.es](mailto:nucphysinfo@us.es)

THREE DIFFERENT PATHS OFFERED

- 1 EXPERIMENTS IN LARGE ACCELERATORS
- 2 THEORETICAL NUCLEAR PHYSICS
- 3 APPLICATIONS AND SMALL ACCELERATORS

MORE THAN 25 ASSOCIATED PARTNERS!

**REGISTER NOW!**  
[www.emm-nucphys.eu](http://www.emm-nucphys.eu)

Candidates who want to apply for an Erasmus Mundus scholarship can do it until 15th January 2023

**15 SCHOLARSHIPS AVAILABLE TO COVER PARTICIPATION\*, TRAVEL & INSTALLATION, AND SUBSISTENCE COSTS!**

\*Participation costs: 4.500 € / year for programme-country students ; 9.000 € / year for partner-country students





# Any questions?

You can always contact me at  
[bruno.olaizola@csic.es](mailto:bruno.olaizola@csic.es)