

***Атомни ядра: основни  
градивни клетки  
на материята***

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# Фемтосвят

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- Единици SI

- Единица за дължина - метър

- ✓ нанометър =  $10^{-9}\text{m}$

- ✓ фемтометър =  $10^{-15}\text{m}$

- ✓ ангстрьом ( $\text{\AA}$ ) =  $10^{-10}\text{m}$

- ✓ ферми =  $10^{-15}\text{m}$

# Пространствени размери и динамика

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- Атомен радиус = 0.1 nm
- Радиус на ядрото =  $1.2 \times A^{1/3}$   
 $A=125 \quad R(^{125}\text{Sn}) = 6.0\text{fm}$
- Енергия на връзката на атома  $\approx \text{eV}$
- Енергия на връзката на ядрото  $\approx \text{MeV}$

## Процеси

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- Съставното ядро живее  $10^{-14}$  сек.
- Преки ядрени реакции – характерно време  $10^{-22}$  сек.
- Честота на въртене –  $10^{20}$ - $10^{21}$  Hz
- Вибрационна честота  $5 \times 10^{21}$  Hz

# Взаимодействия

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- Атом

- **Электромагнитно**  
взаимодействие

- отрицательно зарядени  
**электроны**

- **И**

- положително зарядени

- **протоны**

- Ядро

- Взаимодействие  
между неутрони и  
протоны

1. **Силно**

2. **Электромагнитно**

3. **Слабо**

# Перспективи

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**99%**

от видимата материя във Вселената е  
концентрирана в атомните ядра

ФЕМТО ТЕХНОЛОГИИ

Ядрени данни

# Приложения

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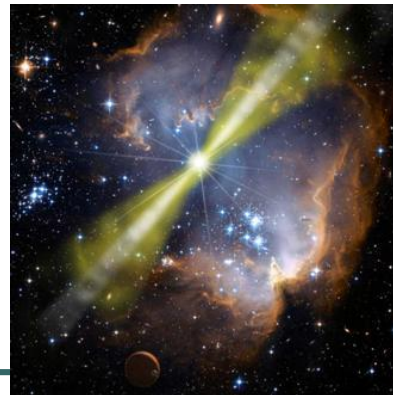
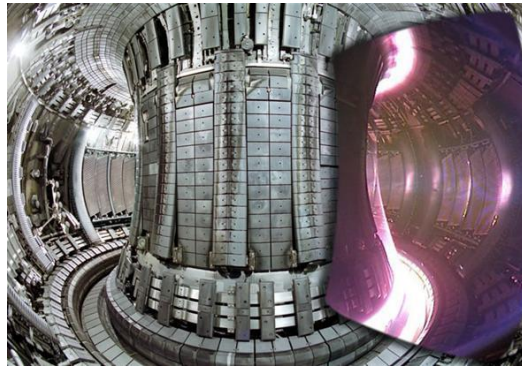
- 1942 г. – първи ядрен реактор
- 1945 г. – ядрен взрив
- 1953 г. – термоядрен взрив
- 1954 г. – първа атомна централа

# Importance of nuclear data

**Applications:** fission and fusion, nuclear medicine, object and material analysis, radiation protection , nuclear safety and security

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**Science:** astrophysical reactions, reactions and structure of nuclei, basic physics





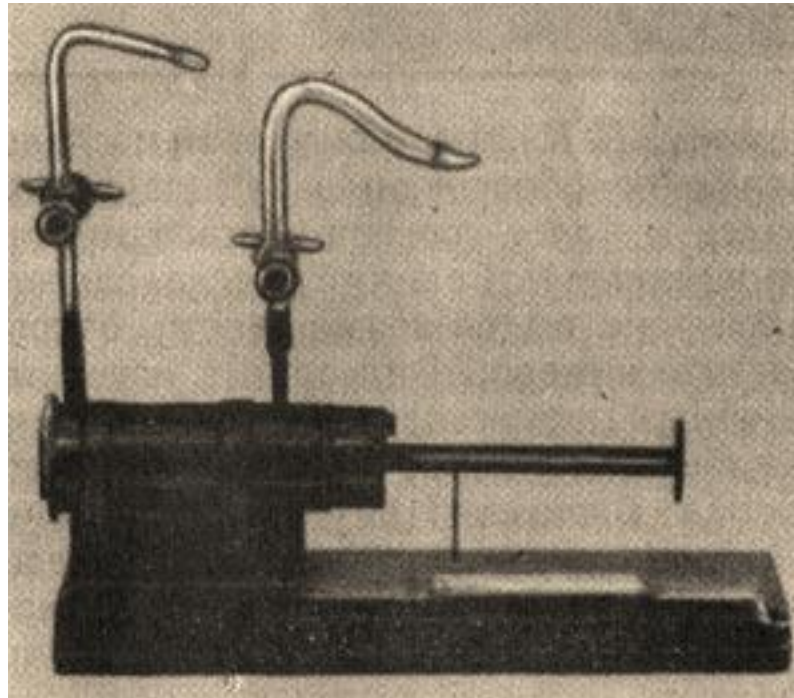
# История

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- **7 март 1911**, Ръдърфорд, доклад “Разсейване на  $\alpha$ - и  $\beta$ - лъчи и структура на атома”
- **1919** – откриване на протона
- **1932** – откриване на неутрона
- **1932** – идея за неутрон - протонния състав на ядрото

**История  
ускорител на Ръдърфорд  
дължина 18 см, ширина 2 см, височина 6 см**

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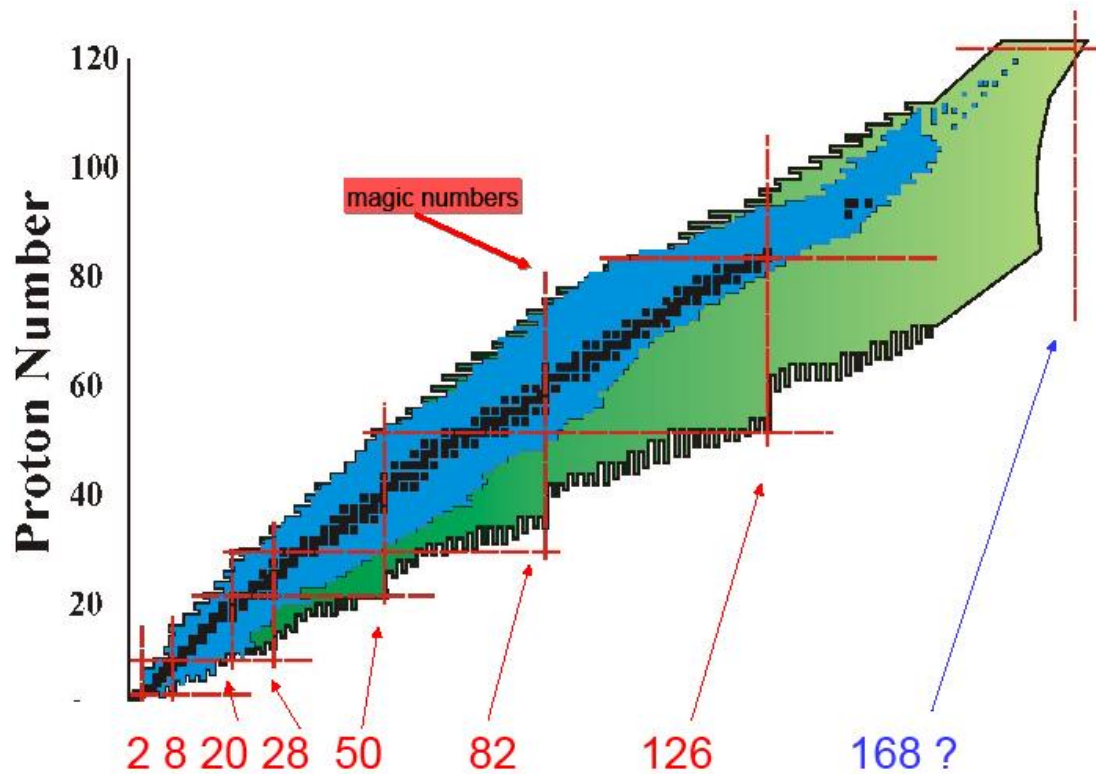


# Паметник на младия Ръдърфорд в колежа Нелсън

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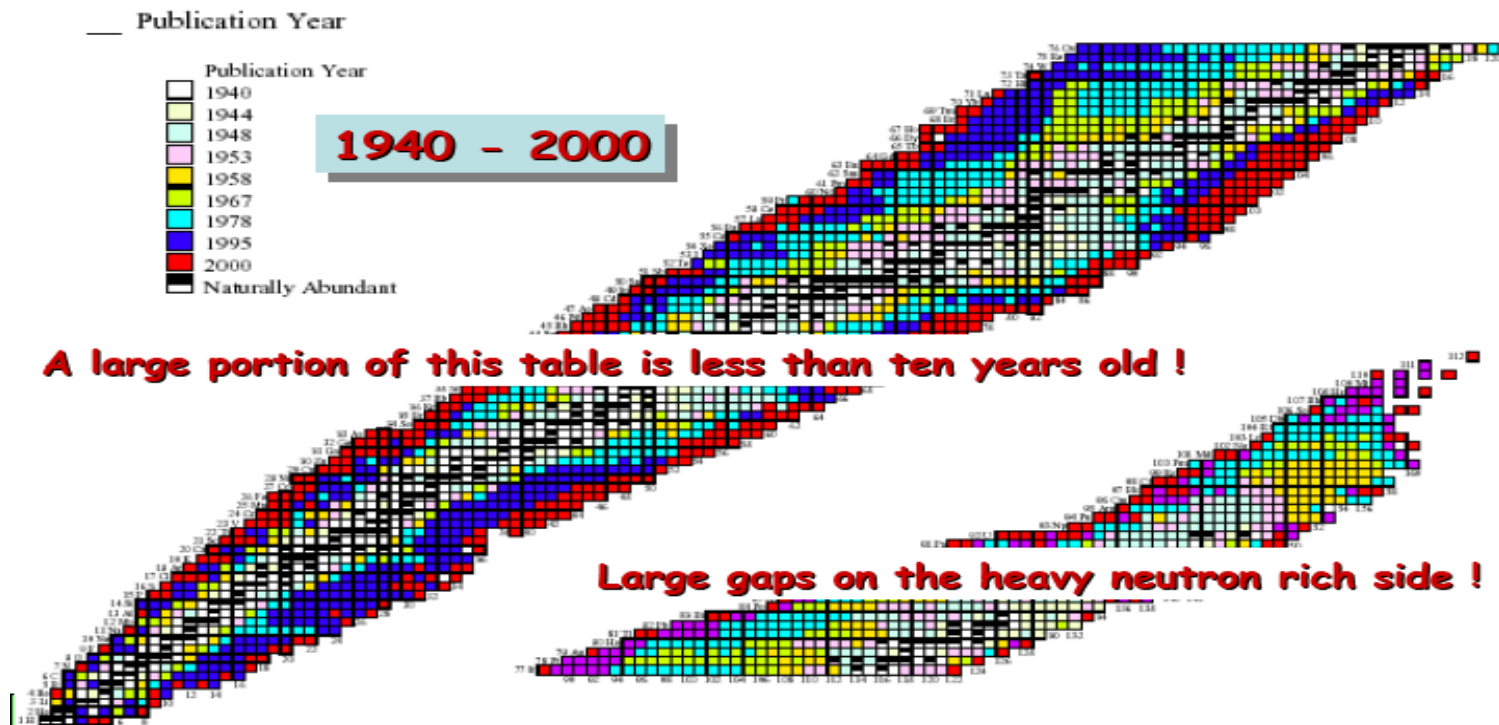


# Таблица на изотопите

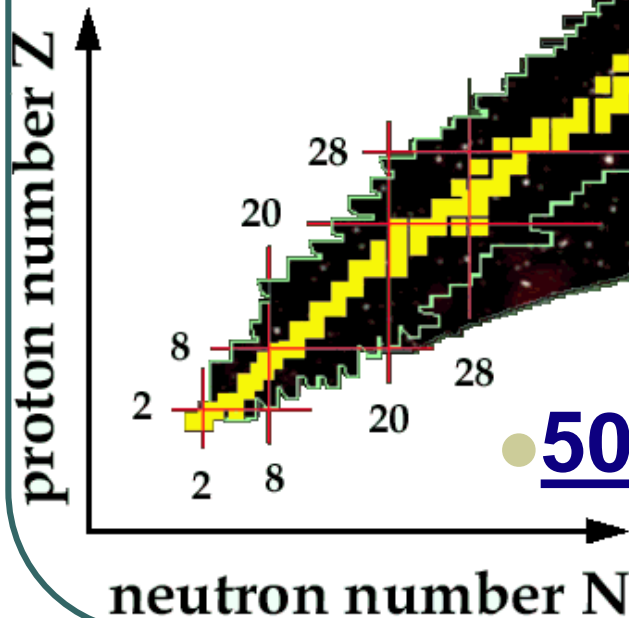


# Таблица на изотопите

## Evolution of the *Table of Isotopes*



# A huge research potential: the nuclear chart



- 250 стабилни ядра
- 2000 изкуствено получени
- 5000 to 7000 очаква се да бъдат получени

# Ядрена Структура

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Едночатишно движение

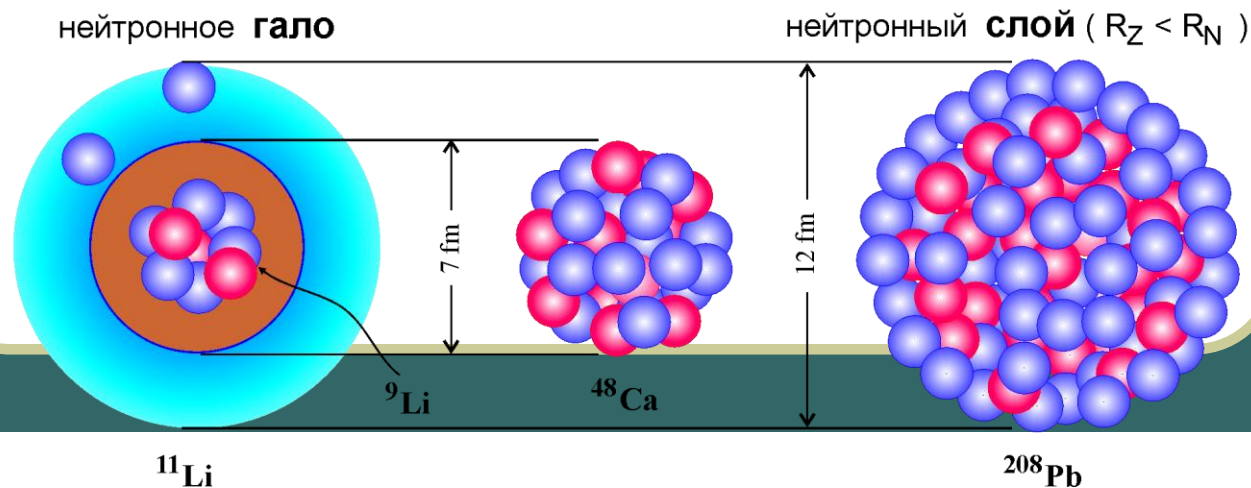
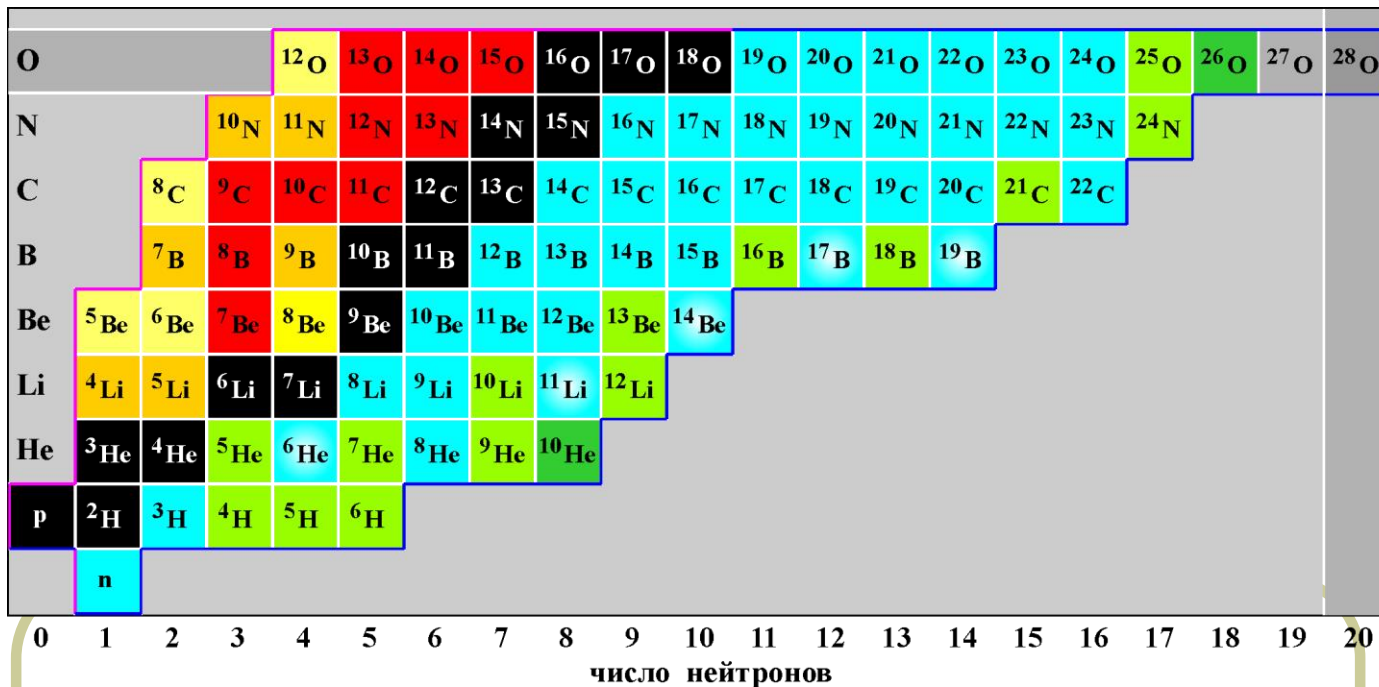
От частици към квазичастици

Колективни възбуждания

Някои примери за разрешаване на модерни проблеми в ядрената структура



# Ореол (Halo)





# Фундаментални изследвания

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- Прецизно определяне на структурата на стабилните ядра
- Изследване на ядра с аномален брой протони или неутрони
  - т.н. ЕКЗОТИЧНИ ЯДРА

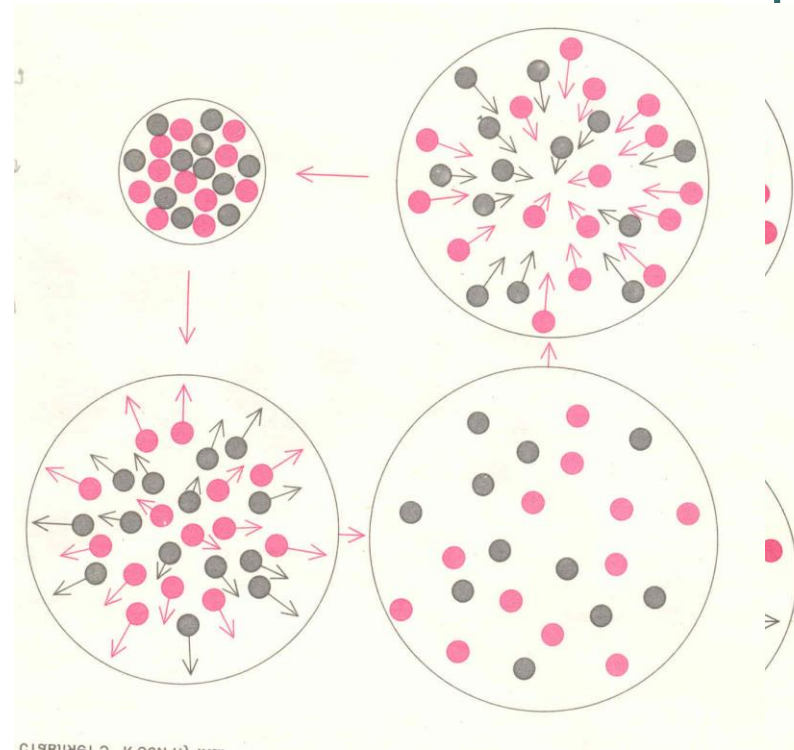
# Едночастично и колективно движение в ядрата

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- 1944 – предсказано е съществуването на гигантски диполен резонанс
- 1949-1950 слоест модел на ядрото

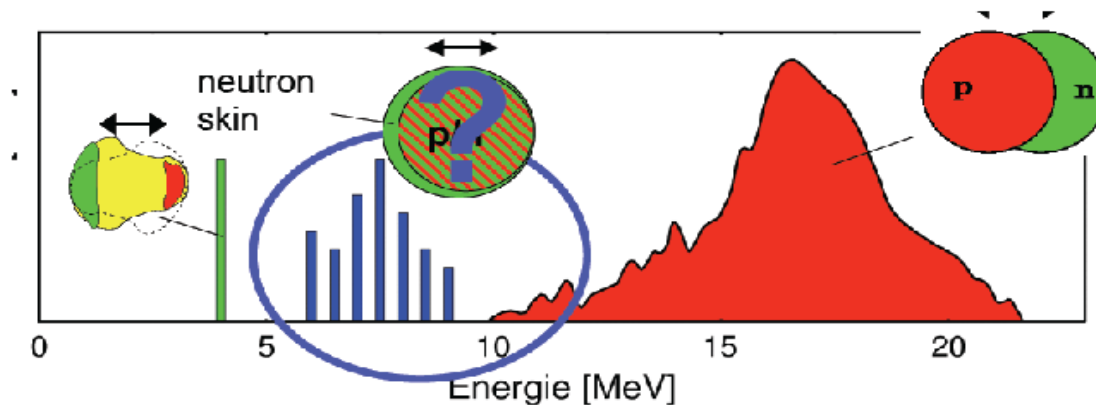
# Колективни свойства - Гигантски Резонанси

1. Монополен резонанс
2. Диполен резонанс –  $5 \times 10^{21} \text{ Hz}$
3. Квадруполен резонанс –  $3 \times 10^{21} \text{ Hz}$



# Диполни възбуждания

## Electric Dipole response in Nuclei



- Giant Dipole Resonance (GDR)
- Two-Phonon excitation ( $2^+ \otimes 3^-$ )
- Pygmy Dipole Resonance (PDR)

# Едночастично движение Средно поле в ядрото

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- Уравнение на Шрьодингер
- Спин-Орбитално взаимодействие
- Потенциал на Уудс-Саксон
- Слоест подход към многочастичната задача
- Модел на Хартри-Фок

# Уравнение на Шрьодингер

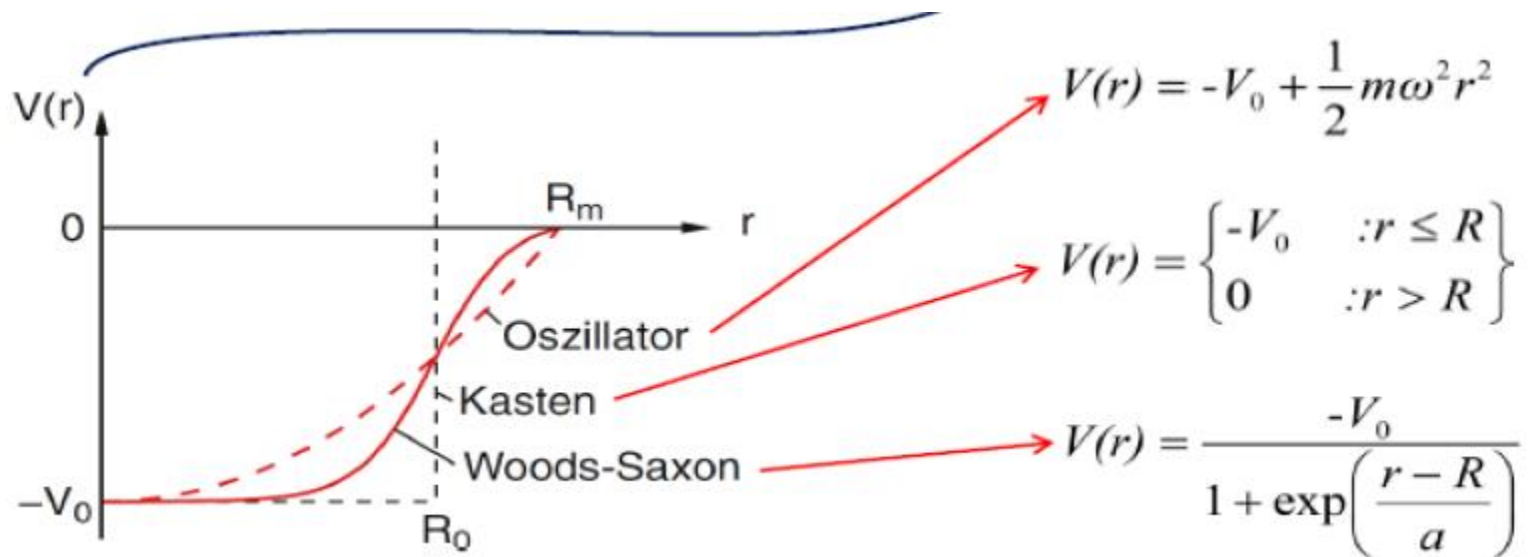
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- Едночастично уравнение на Шрьодингер

$$\left(-\frac{1}{2m}\Delta + V(\mathbf{r}) - E\right)\psi = 0$$

При сферична симетрия,  
пространственат вълнова функция  
може да бъде заменена от:

$$\psi_{nlm} = \frac{u_{nl}(r)}{r} \times Y_{lm}(\theta, \varphi)$$



# Слоест подход към многочастичната задача

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- Най-общо Хамилтонианът на системата може да се запише в следния вид:

$$H_0\Phi = \left\{ \sum_{i=1}^A h_i \right\} \Phi = \sum_{i=1}^A \left\{ -\frac{\hbar^2}{2m} \nabla_j^2 + V(x_j) \right\} \Phi = E\Phi$$

- Вълновата функция на системата може да се представи като Слейтерова

$$\Phi = \frac{1}{\sqrt{N!}} \begin{vmatrix} \psi_1(x_1) & \psi_1(x_2) & \dots & \psi_1(x_N) \\ \psi_2(x_1) & \psi_2(x_2) & \dots & \psi_2(x_N) \\ \dots & \dots & \dots & \dots \\ \psi_N(x_1) & \psi_N(x_2) & \dots & \psi_N(x_N) \end{vmatrix}$$



# Резултати

едночастична схема

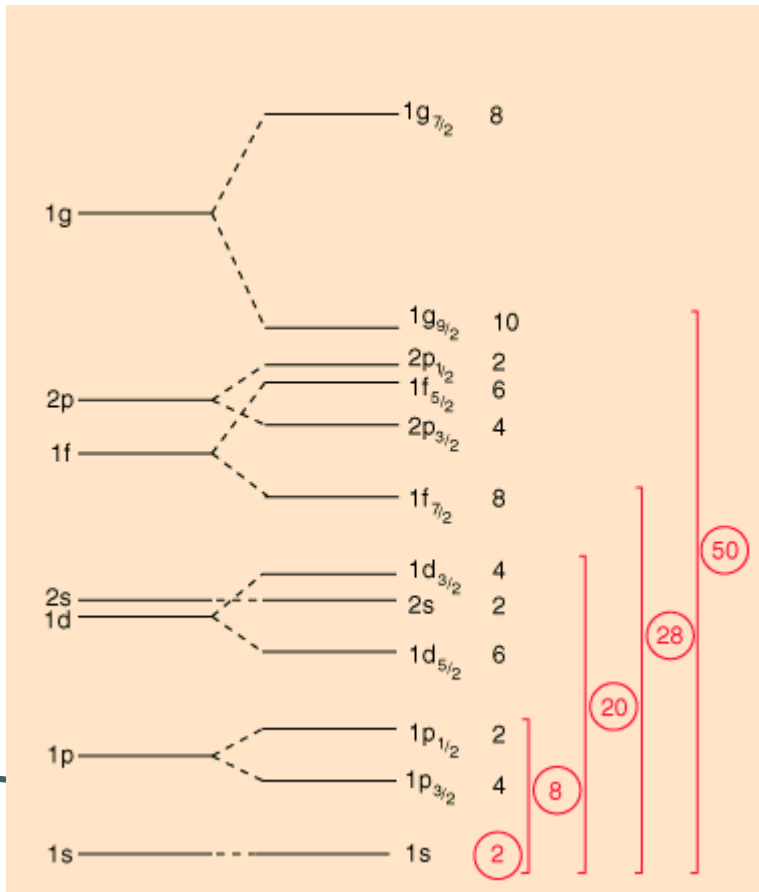
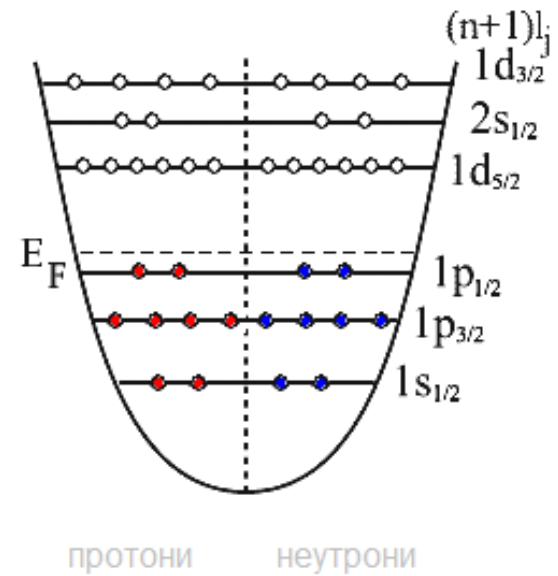
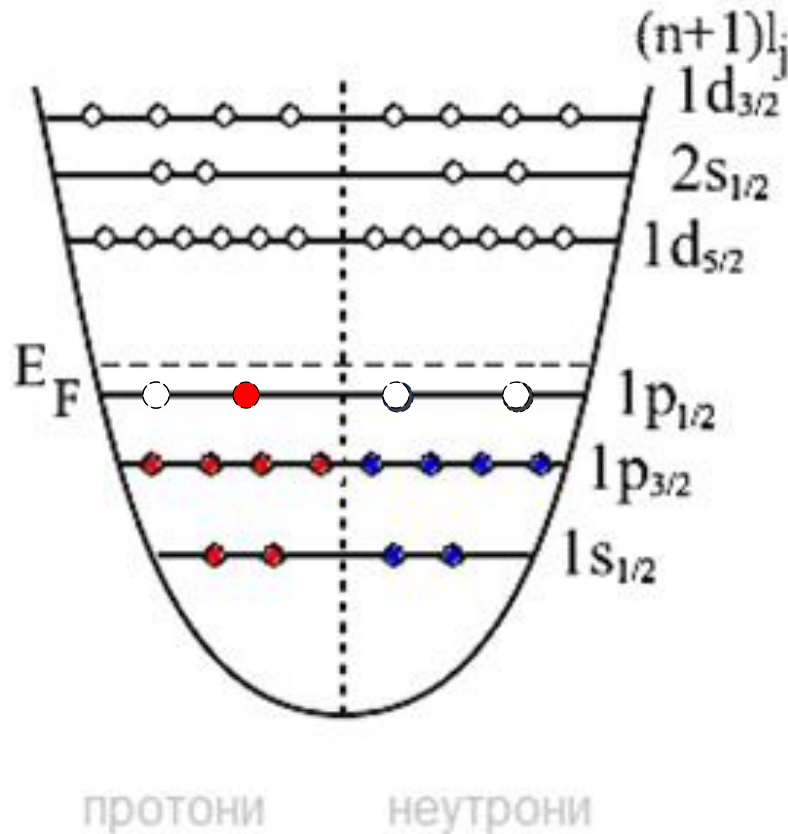


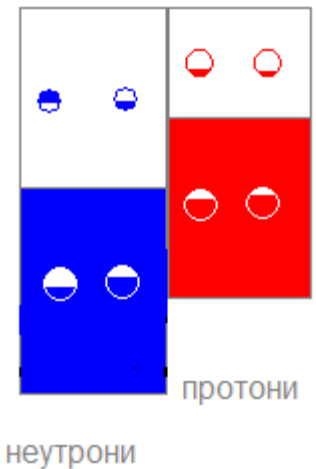
Схема на запълване на  $^{16}\text{O}$



# Квазичастично Приближение на случайните фази



1. Едночастични възбуждания
2. Двучастични възбуждания
3. Квазичастици



# Сдвояване

## Н. Н. Боголюбов, В. Г. Соловьев

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$$H_{s.p.} = \sum_{j,m} (E_0(j) - \lambda) a_{jm}^\dagger a_{jm}$$

$$H_{pair} = - \sum_{j,j',m,m'} G(jm, j-m; j'm', j'-m') a_{jm}^\dagger a_{j-m}^\dagger a_{j'-m'} a_{j'm'}$$

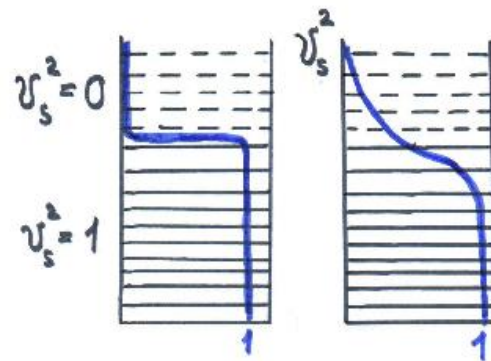
$$\beta_{jm} = u_j a_{jm} + (-1)^{j-m} v_j a_{j-m}^\dagger$$

$$u_j^2 + v_j^2 = 1$$

$$\begin{aligned}
 C_j &\xrightarrow{u_j^2} \text{gap parameter} \\
 \lambda &\xrightarrow{} \text{chemical potential} \\
 \varepsilon_j &= \frac{1}{2} \left( \frac{E_0(j) - \lambda}{\sqrt{C_j^2 + (E_0(j) - \lambda)^2}} \right) \xrightarrow{} \text{quasiparticle energy}
 \end{aligned}$$

$$N = \sum_{jm} \langle g.s. | a_{jm}^\dagger a_{jm} | g.s. \rangle = 2 \sum_j v_j^2$$

$$C_j = \sum_{j',m'} G(jm, j-m; j'm', j'-m') \frac{C_{j'}}{\sqrt{C_{j'}^2 + (E_0(j') - \lambda)^2}}$$

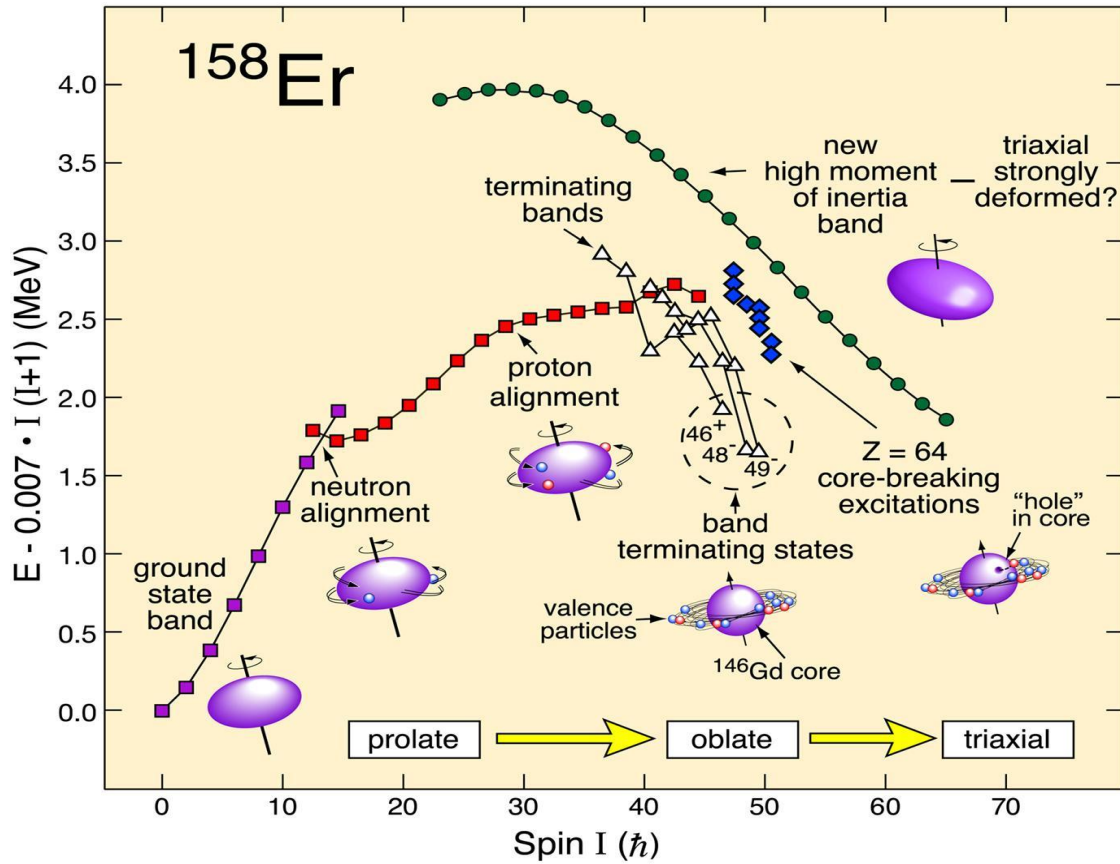


$$\alpha_s^+ = u_s a_s^+ + v_s \sigma_s a_{\bar{s}}$$

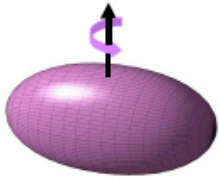
$$\alpha_s |g.s.\rangle = 0$$

$$|g.s.\rangle = \prod_s (u_s - v_s a_s^+ a_{\bar{s}}^+) |0\rangle$$

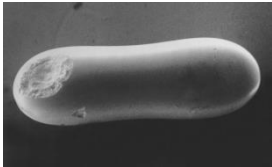
# Сдвояване



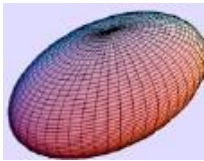
# Exotic nuclear shapes



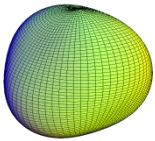
Superdeformation  
Hyperdeformation



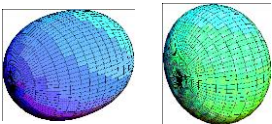
Jacobi  
shapes



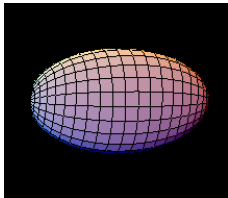
Triaxial shapes  
3-dimensional rotation



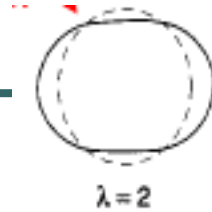
Higher-order shapes  
(with high-rank  
symmetry) :  
tetrahedral, octahedral



Shape  
coexistence



dynamic  
deformation  
vibrations etc.



quadrupole

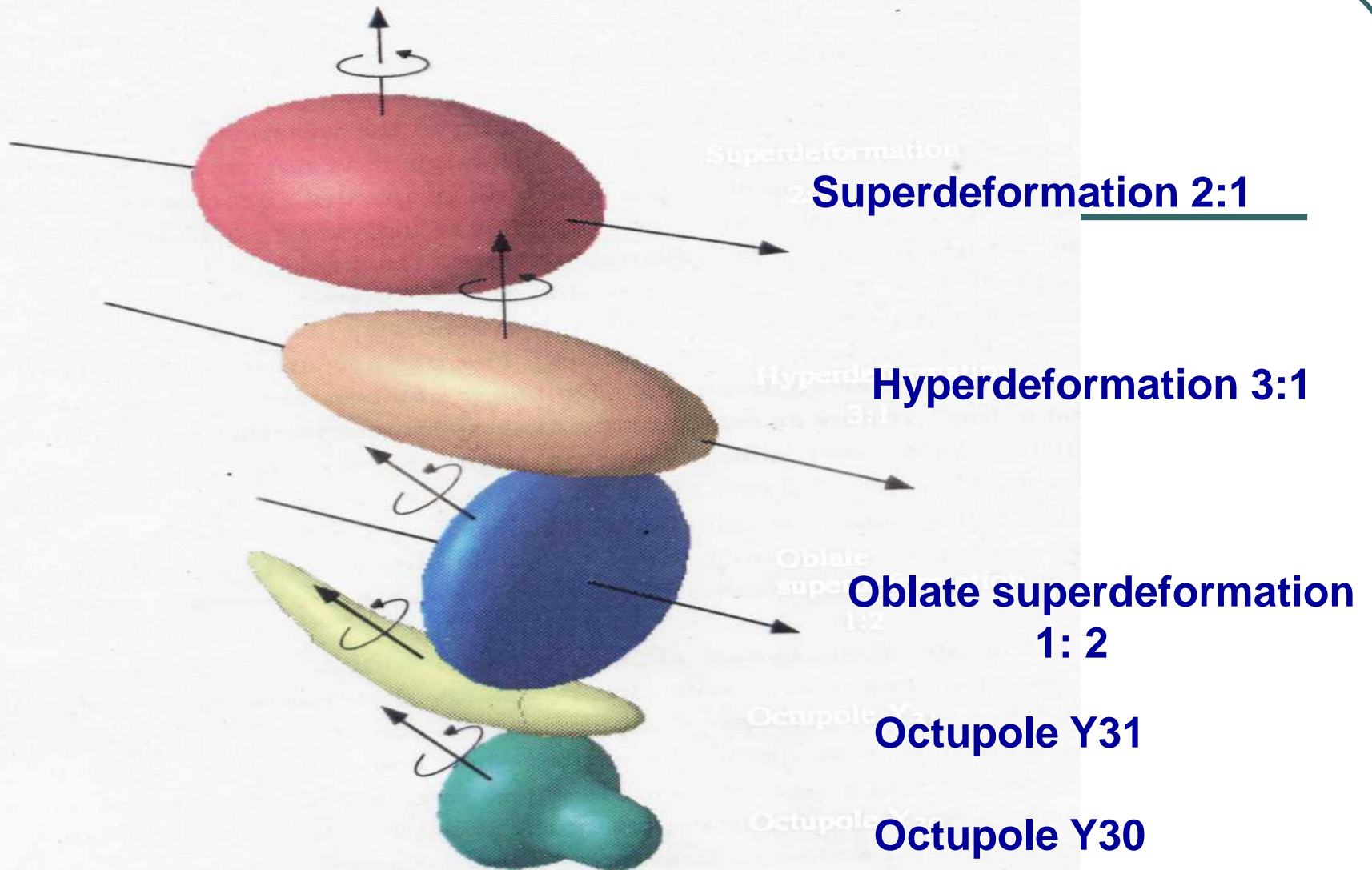


octupole



hexadecapole

- the largest deformations at the highest spins
- fusion-evaporation with intense n-rich RIB
- high-spin spectroscopy
- $\gamma$ -ray spectroscopy at  $S^3$
- in-flight production of exotic nuclei
- shape coexistence (at low spin)
- low-energy Coulomb excitation
- EXOGAM, EUROBALL, AGATA + VASILISA



Various exotic shapes of nuclei. Exotic orbitals appears in the region far from the stability line provides many types of deformations.

# Структура на ядрата

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- Атомните ядра могат да имат различна форма: сферична, oblate (като летяща чиния), prolate (като топка за бейзбол), триаксиални (крушовидна форма).
- Pd изотопи правят преход от почти сферични ядра при  $^{96-102}\text{Pd}$  към деформирани при  $^{120}\text{Pd}$ .

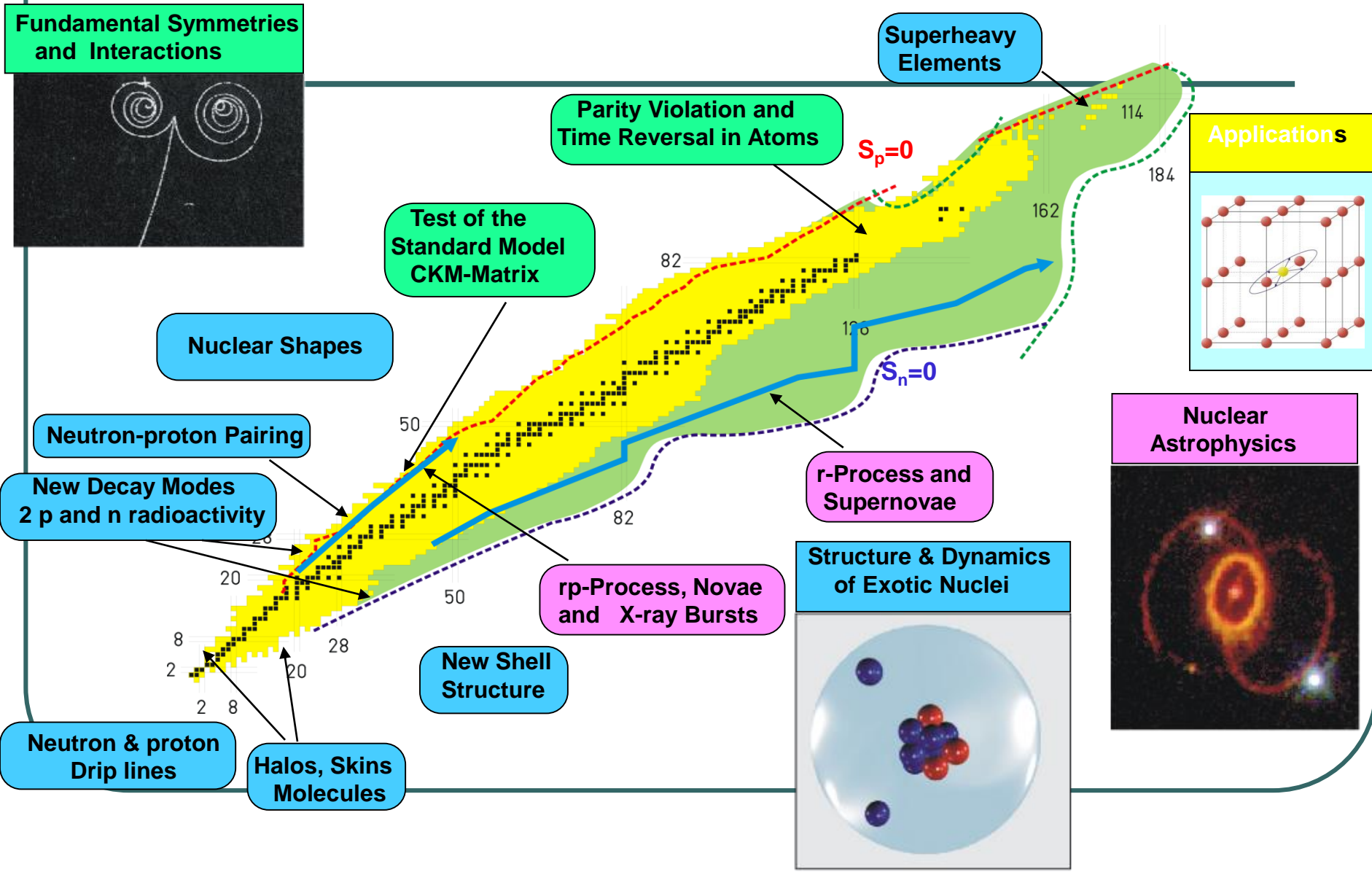


# Структура на ядрата

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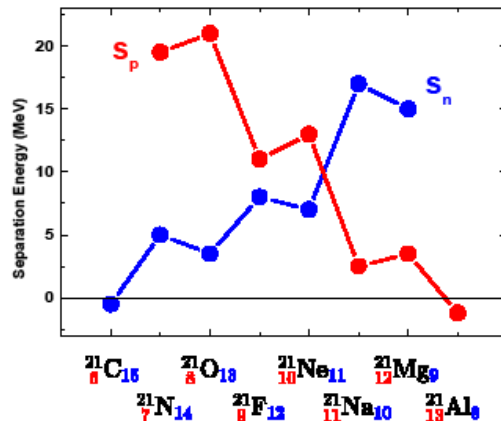
•Този преход при различните вериги от изотопи протича различно: най-често постепенно, но деформацията може да се случи и внезапно или да се премине през т.нар. гама мекота или през стабилни триаксиални форми.

# Physics with Exotic Nuclei



# Physics with Exotic Nuclei

## DEFINITION OF THE DRIPLINES



The **nuclear binding** in nuclei with an extreme excess of neutrons or protons may **not be sufficient** to bind the last neutron or proton

the dripline can be defined as the limits where **neutron  $S_n$**  or **proton  $S_p$**  separation energies cross zero

$$S_n = \text{BE}(N, Z) - \text{BE}(N - 1, Z)$$

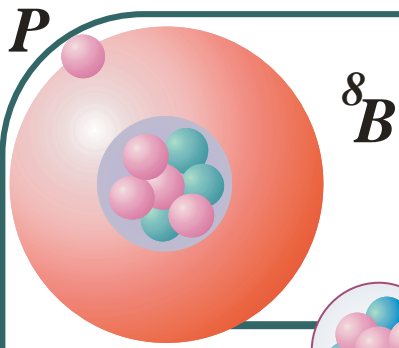
$$S_p = \text{BE}(N, Z) - \text{BE}(N, Z - 1)$$

The unbound nuclei :

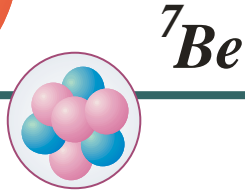
- can have fairly **long lifetimes** along the proton dripline (because of the **Coulomb barrier**).
- extremely **short lived** beyond the neutron dripline ( **absence of the Coulomb barrier** )

**the proton dripline** has been reached for elements up to  **$Z = 83$**   
**the neutron dripline** has been reached for elements up to  **$Z < 10$**

# Exotic Nuclei



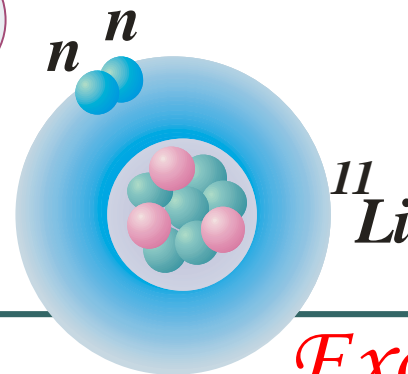
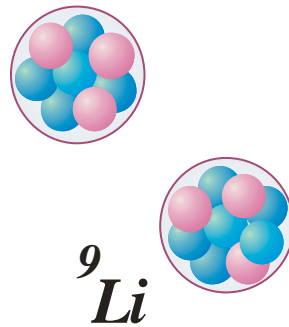
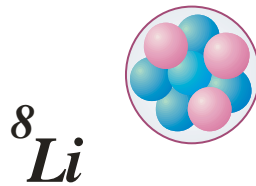
$$\langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2} = -0,49\text{fm}$$



$$\langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2} = 0,1\text{fm}$$

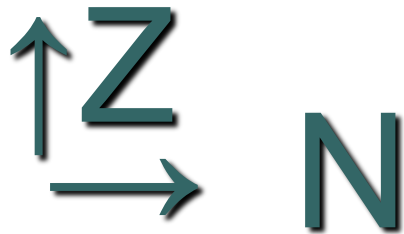


# Stable Nuclei

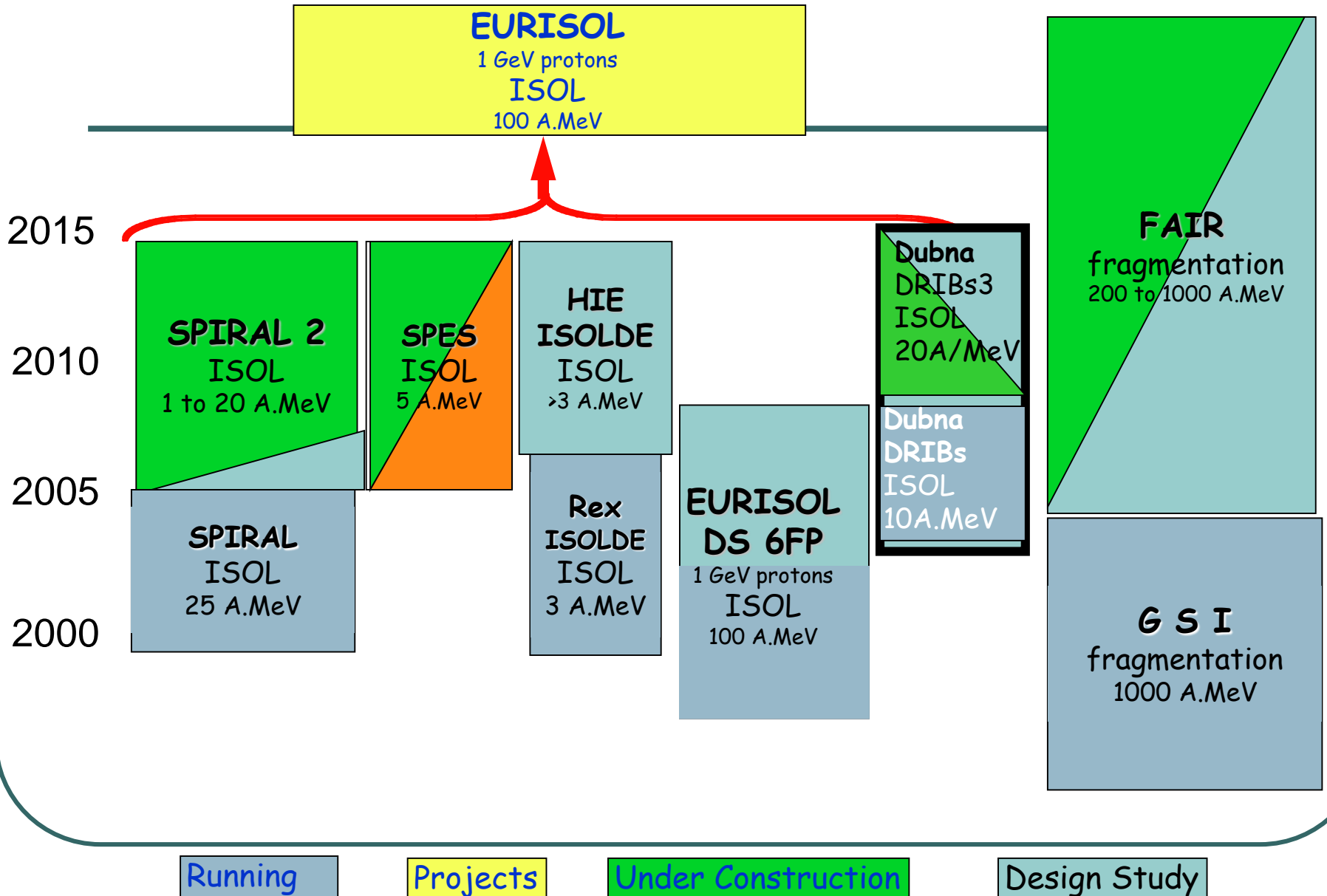


# Exotic Nuclei

$$\langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2} = 0,96\text{fm}$$

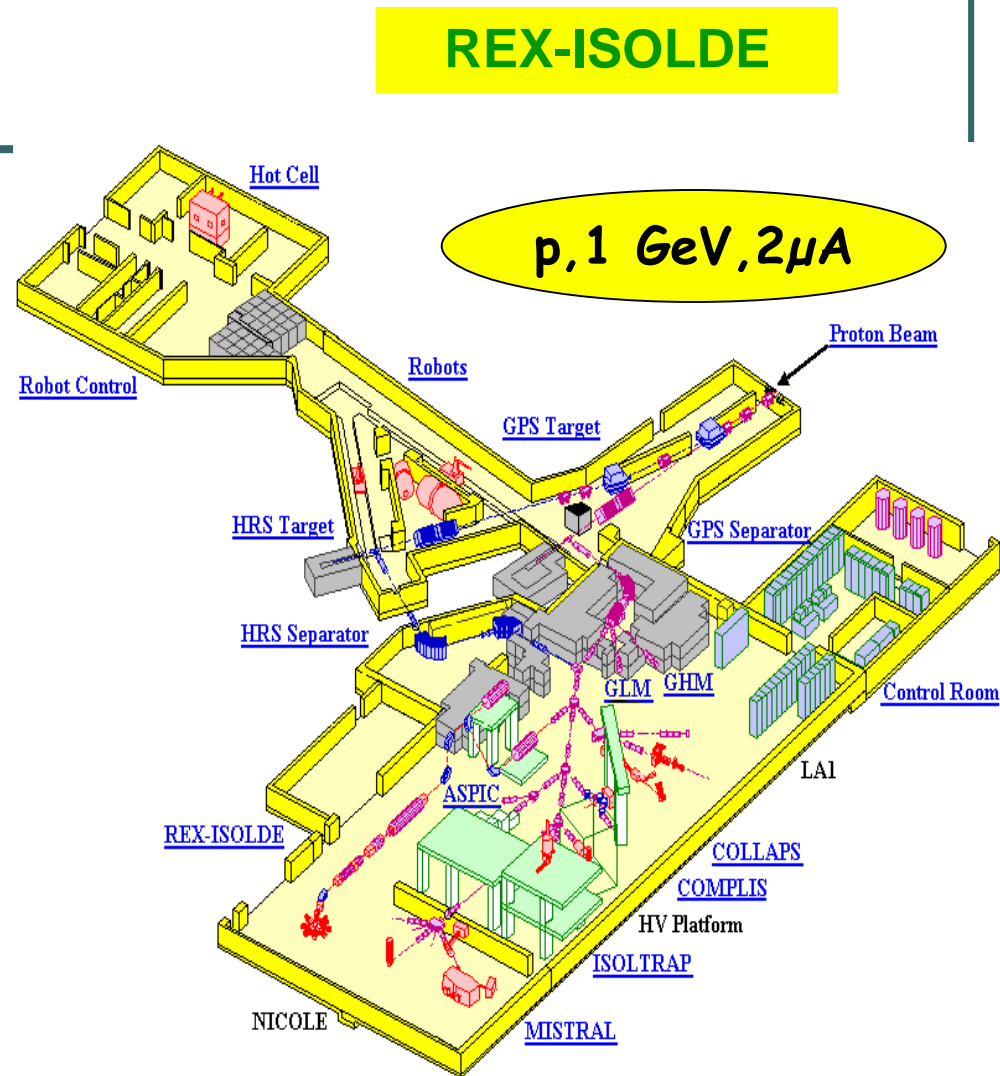


# European RNB Facilities - NuPECC Road Map



# ISOL Facilities

- ISOL method born in Europe (N.Bohr Institute 1951)
- Isolde@CERN 40years of Physics
- Production of more **600** isotopic beams
- Target –ion source technology
- Laser ion source, traps
- Purity and mass separation
- Manipulating « exotic ions »



HIE-ISOLDE Project : Energy & intensity upgrade

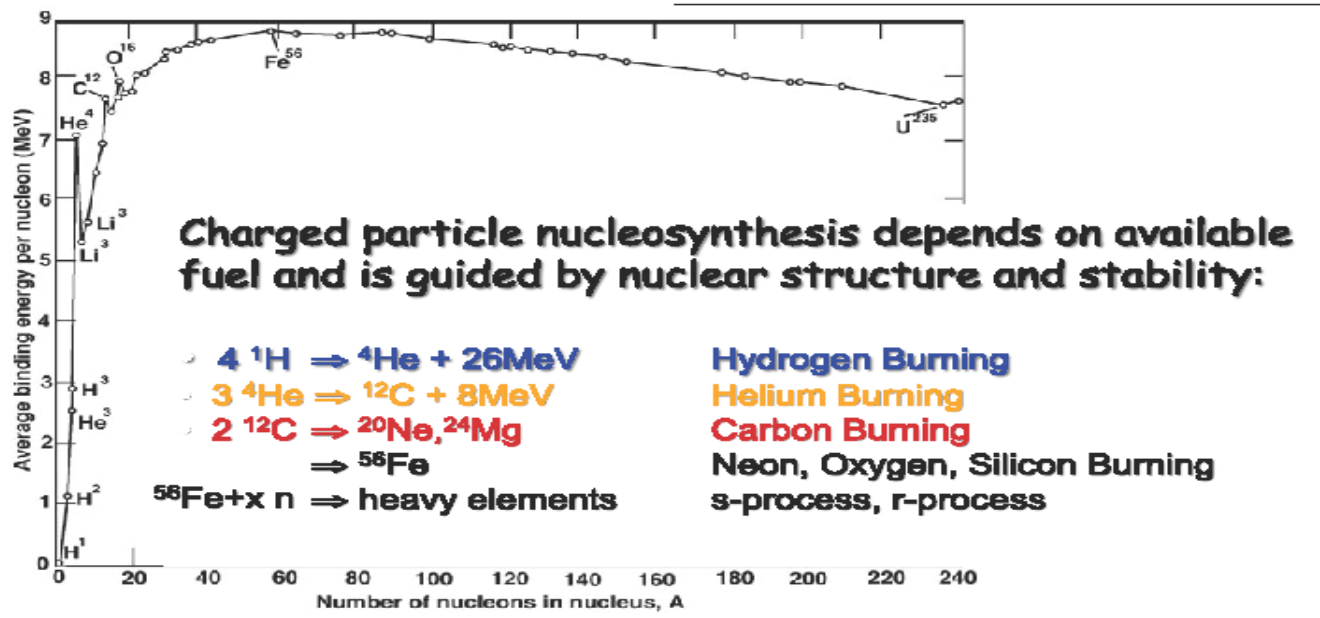
# Letter of Intent to the ISOLDE for experiments

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- To perform HIE-ISOLDE and MINIBALL experiments to study MSSs of **radioactive nuclei** from mass  **$A \approx 130-140$  and  $70-80$  regions**

# Nucleosynthesis

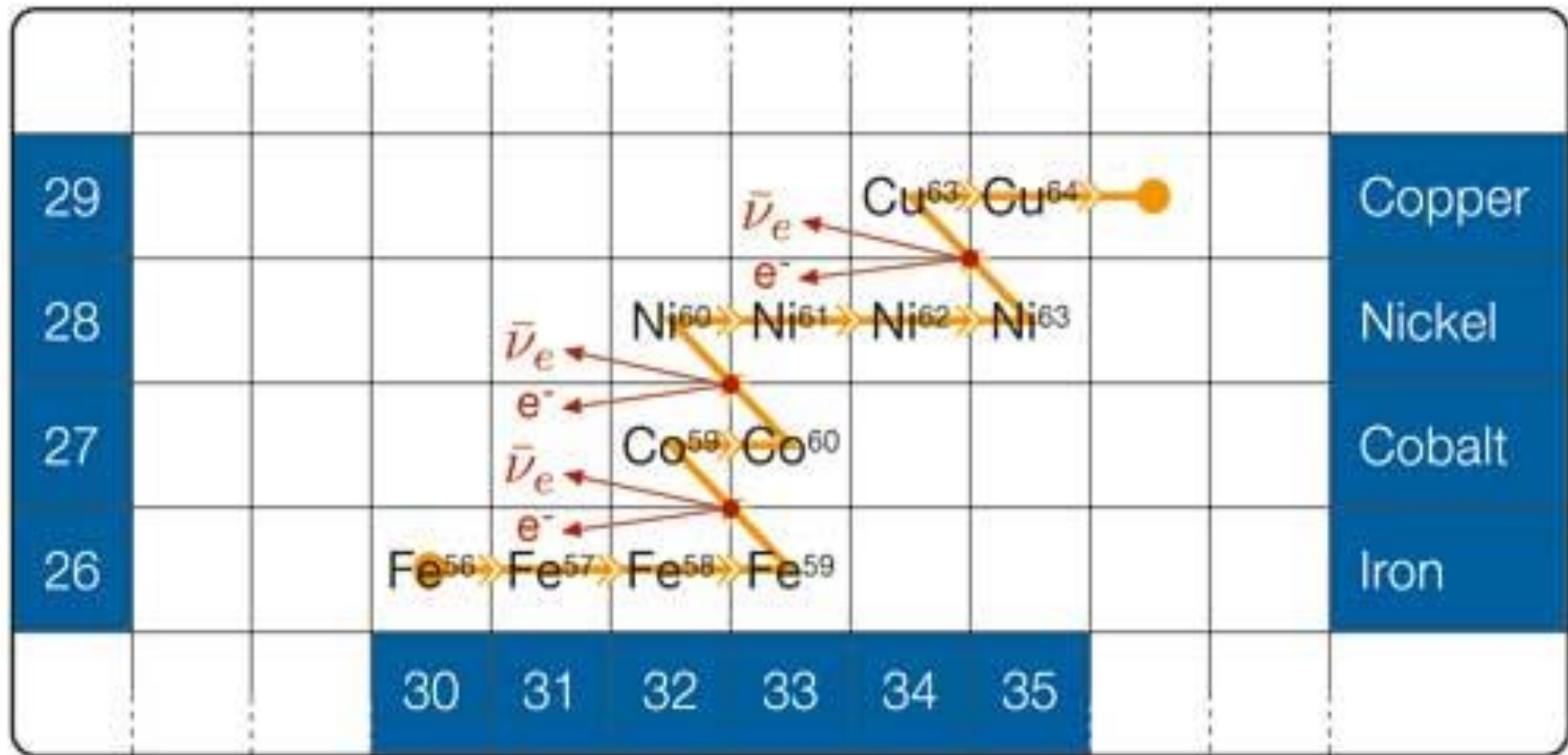
## Nucleosynthesis Processes in Stars





• s- Process •

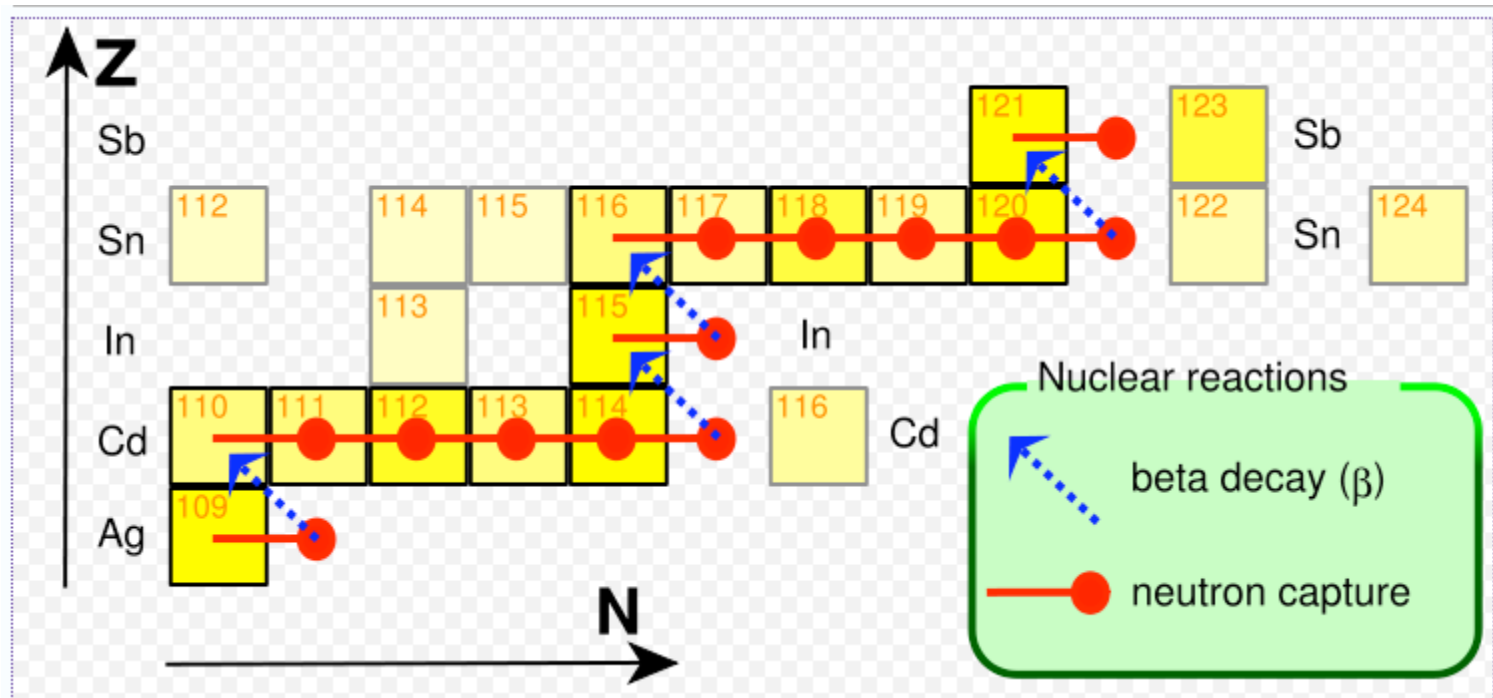
• Number of Protons •



• Number of Neutrons •

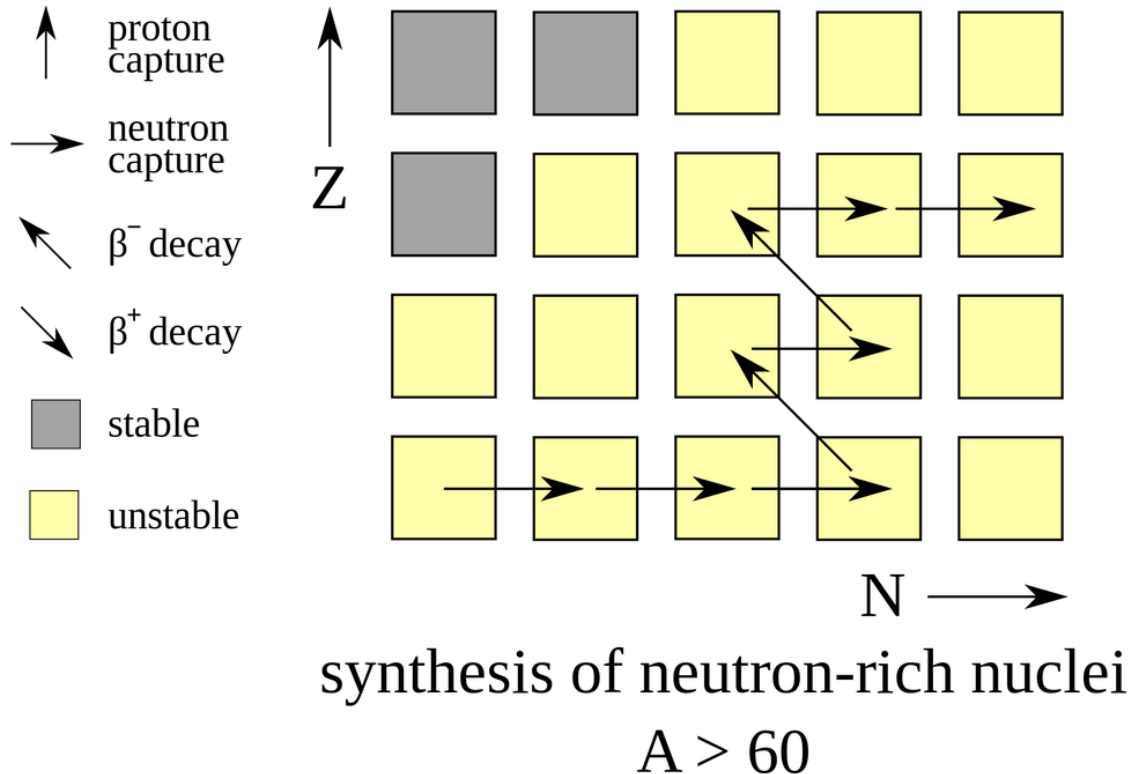
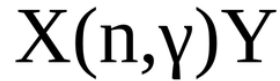
**S-process slow-neutron-capture-process is a nucleosynthesis process that occurs at relatively low neutron density and intermediate temperature conditions in stars. Under these conditions heavier nuclei are created by neutron capture, increasing the atomic weight of the nucleus by one. A neutron in the new nucleus decays by beta-minus decay to a proton, creating a nucleus of higher atomic number. The rate of neutron capture by atomic nuclei is slow relative to the rate of radioactive beta-minus decay, hence the name.**

# S-Process Nucleosynthesis



# r-process

rapid neutron captures

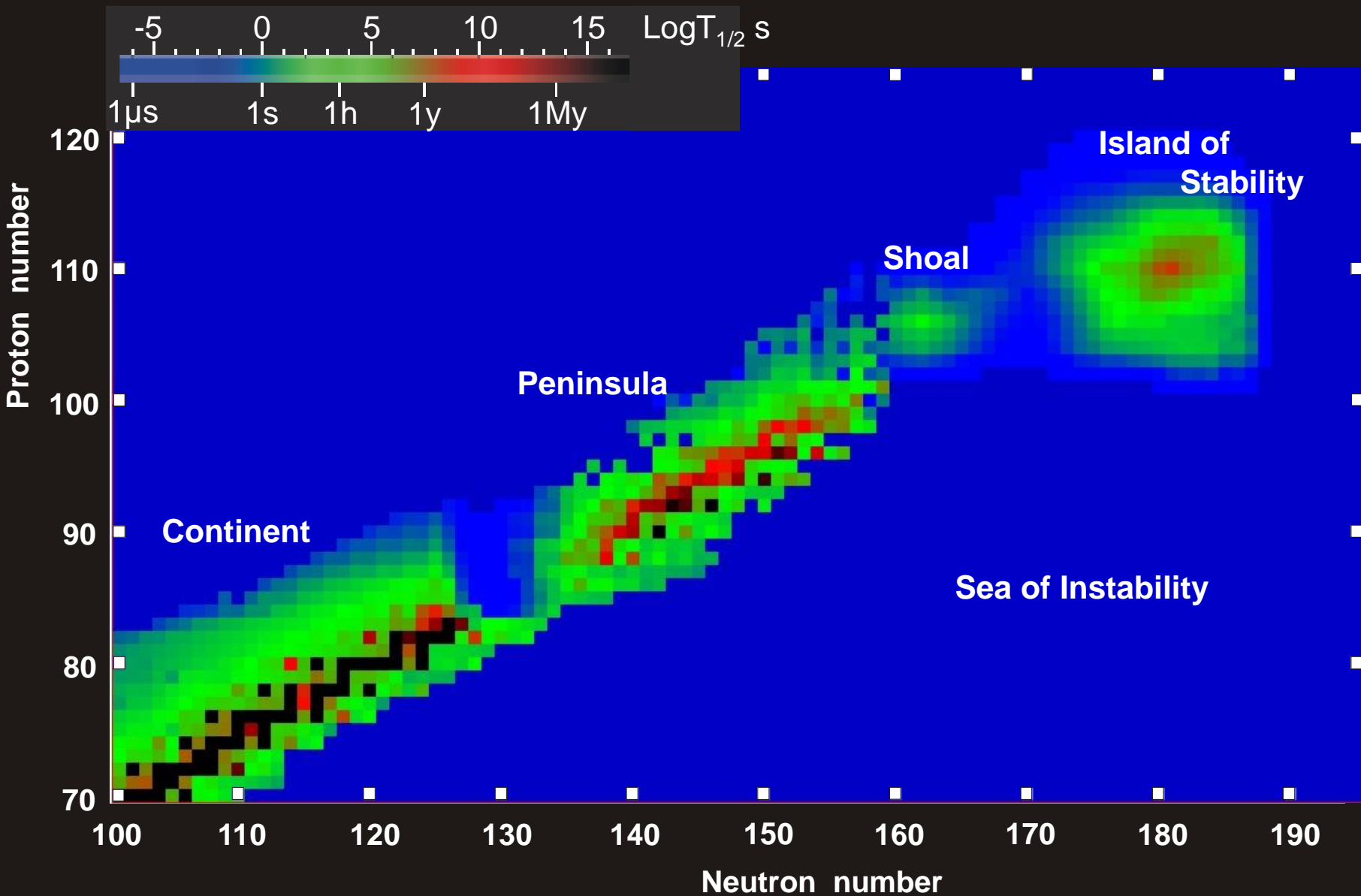


The r-process is a nucleosynthesis process, that occurs in core-collapse supernovae (see also supernova nucleosynthesis), and is responsible for the creation of approximately half of the neutron-rich atomic nuclei heavier than iron. The process entails a succession of rapid neutron captures (hence the name r-process) by heavy seed nuclei, typically  $^{56}\text{Fe}$  or other more neutron-rich heavy isotopes. The other predominant mechanism for the production of heavy elements is the s-process, which is nucleosynthesis by means of slow captures of neutrons, primarily occurring in AGB stars. The s-process is secondary, meaning that it requires preexisting heavy isotopes as seed nuclei to be converted into other heavy nuclei. Taken together these two processes account for a majority of galactic chemical evolution of elements heavier than iron.

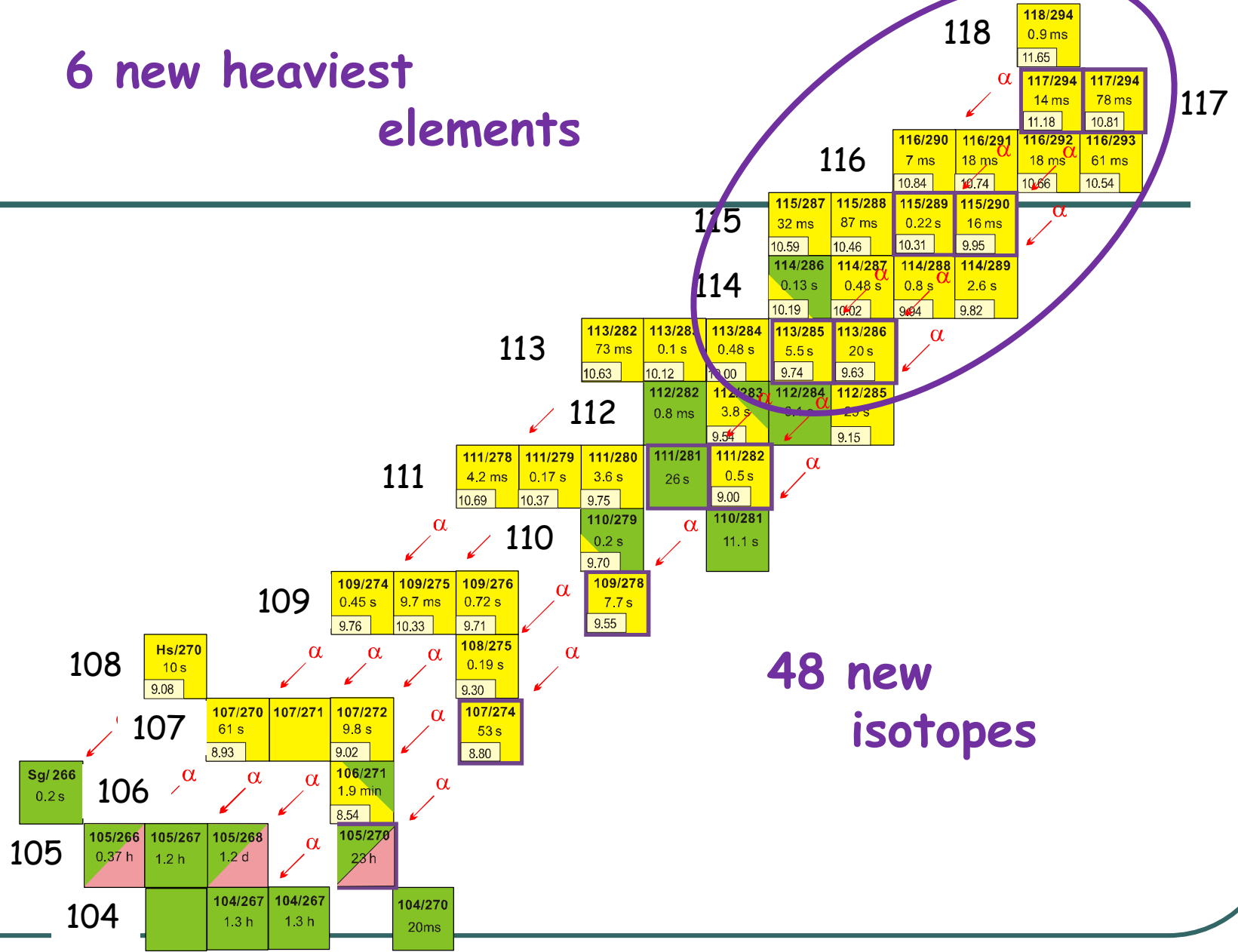
Asymptotic Giant Branch (AGB)

New lands

Microscopic theory



# 6 new heaviest elements



48 new isotopes

# Synthesis of new isotope of Element 118

Z=118

|                        |     |  |  |  |           |
|------------------------|-----|--|--|--|-----------|
| 294<br>0.9 ms<br>11.65 | 295 |  |  |  | 299<br>CN |
|------------------------|-----|--|--|--|-----------|

$\alpha$



116

|                      |                       |                       |                       |
|----------------------|-----------------------|-----------------------|-----------------------|
| 290<br>7 ms<br>10.84 | 291<br>18 ms<br>10.74 | 292<br>18 ms<br>10.66 | 293<br>80 ms<br>10.54 |
|----------------------|-----------------------|-----------------------|-----------------------|

$\alpha$



114

|                        |                        |                      |                    |
|------------------------|------------------------|----------------------|--------------------|
| 286<br>0.13 s<br>10.19 | 287<br>0.48 s<br>10.02 | 288<br>0.8 s<br>9.94 | 289<br>2 s<br>9.82 |
|------------------------|------------------------|----------------------|--------------------|

$\alpha$



112

|                       |                      |                      |                     |
|-----------------------|----------------------|----------------------|---------------------|
| 282<br>0.8 ms<br>9.54 | 283<br>3.8 s<br>9.54 | 284<br>0.1 s<br>9.15 | 285<br>29 s<br>9.15 |
|-----------------------|----------------------|----------------------|---------------------|

$\alpha$



110

|                      |             |
|----------------------|-------------|
| 279<br>0.2 s<br>9.70 | 281<br>11 s |
|----------------------|-------------|

...with heaviest target  $^{251}\text{Cf}$  from ORNL (USA)

Approved by IUPAC

## Start of the Name Approval Process for the Elements of Atomic Number 114 and 116

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- **flerovium** (symbol **Fl**) for element number **114**  
and the name
- **livermorium** (symbol **Lv**) for element number **116**.

December 1st 2011. The President of IUPAC, Professor Nicole J. Moreau **announced the proposed names for the elements with atomic numbers 114 and 116.**

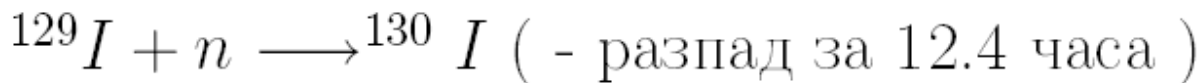
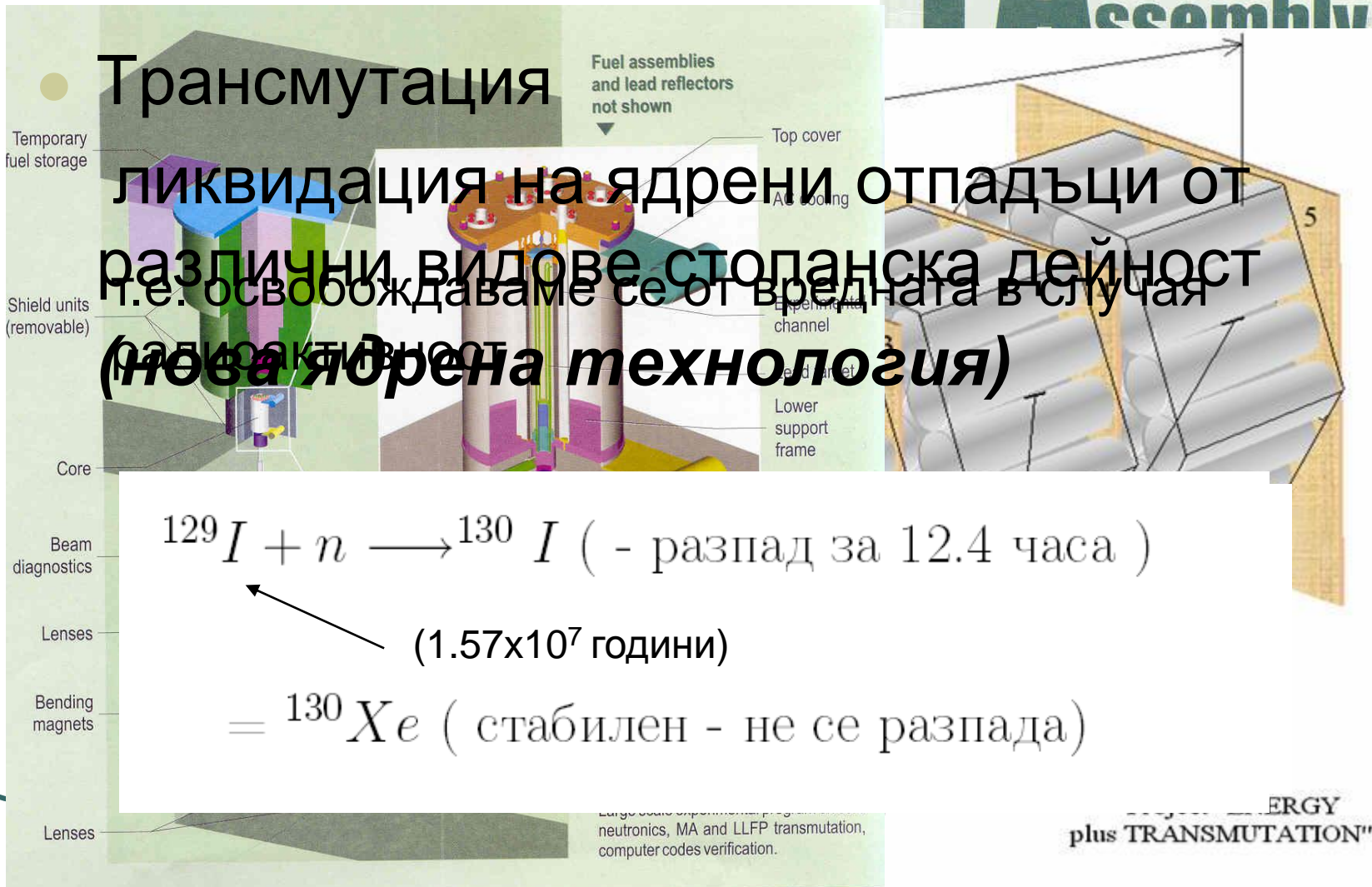


# Приложения

# Subcritical Assembly

## Трансмутация

ликвидация на ядрени отпадъци от различни видове стопанска дейност т.е. освобождаваме се от вредната в случая радиосактивност (нова ядрена технология)



(1.57x10<sup>7</sup> години)



Large scale experiments in  
neutronics, MA and LLFP transmutation,  
computer codes verification.

ENERGY  
plus TRANSMUTATION"

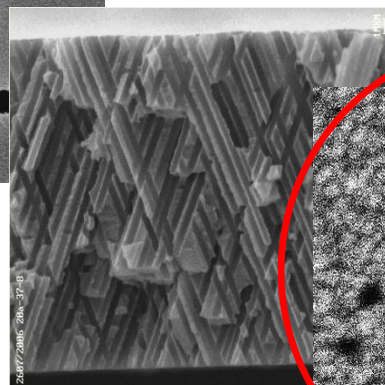
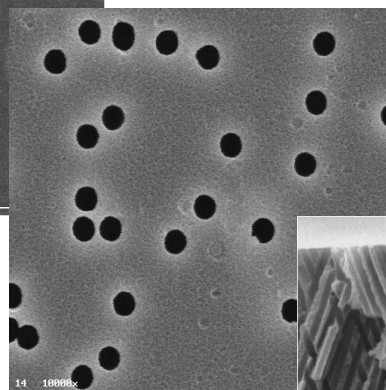
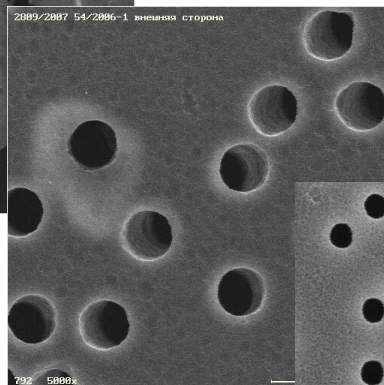
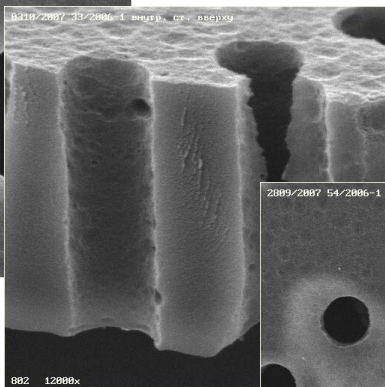
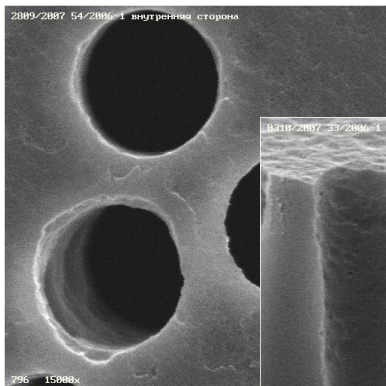
V  
et

DS

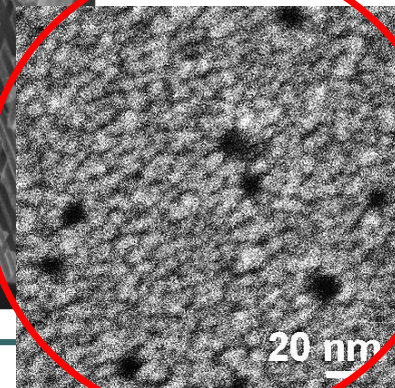


# Micro- and nanoporous materials

**Micrometers**



**Nanometers**

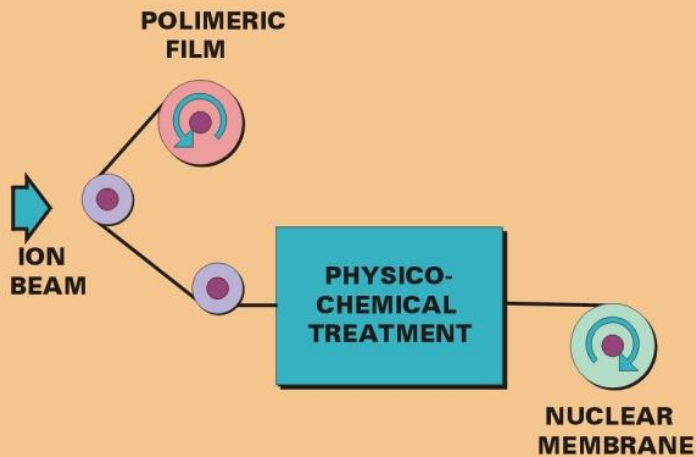


“Making things small is a great deal today”

# NUCLEAR TRACK MEMBRANES

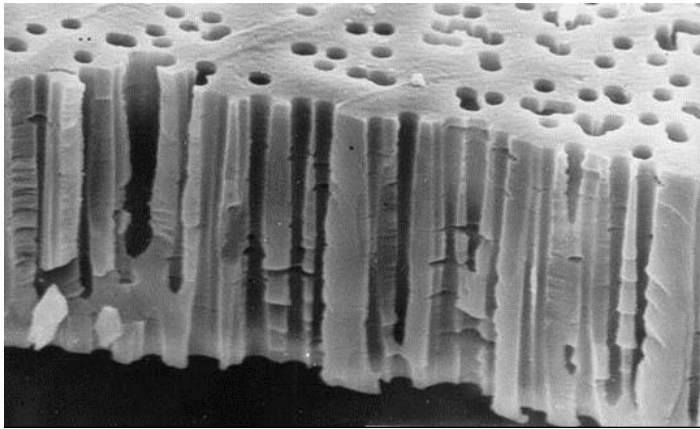
At the Joint Institute for Nuclear Research an advanced technology has been developed to produce nuclear membranes by using unique multicharged ion cyclotrons.

On the basis of this technology the nuclear membranes can be produced from various polymeric films.

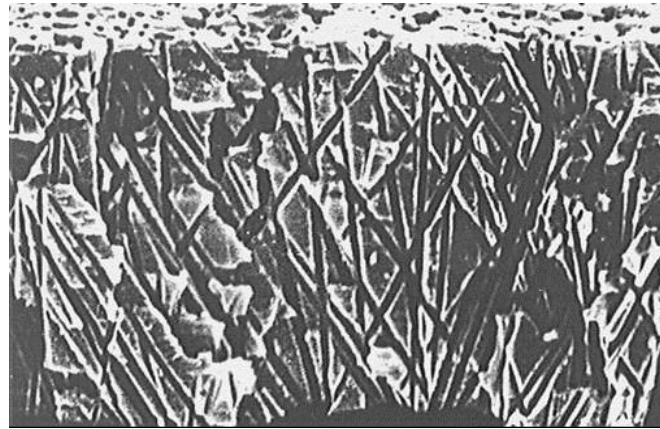


**Scheme of nuclear membrane manufacture**

## Various shapes of pore channels in track membranes



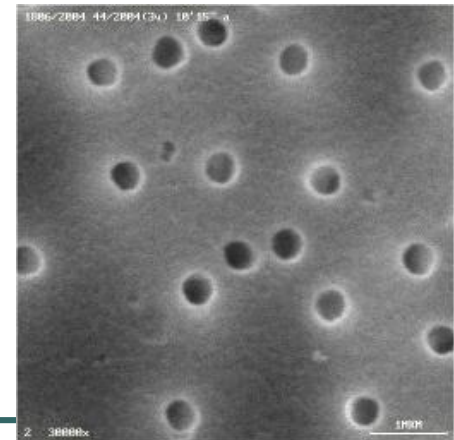
10  $\mu\text{m}$



10  $\mu\text{m}$

### Main properties:

- Track-etched membranes are true size nano- or microporous membranes with a closely-controlled pore size distribution
- Pore diameter ranges from 15 nm to 10  $\mu\text{m}$
- Pore density ranges from 1 to  $10^{10}$   $\text{cm}^{-2}$
- Thickness: from 5 to 23  $\mu\text{m}$



# INDUSTRIAL APPLICATIONS OF TRACK-ETCH MEMBRANES

Process filtration (water, pharmaceuticals, beverages, etc)



Laboratory filtration (analytical works)

Cell culture

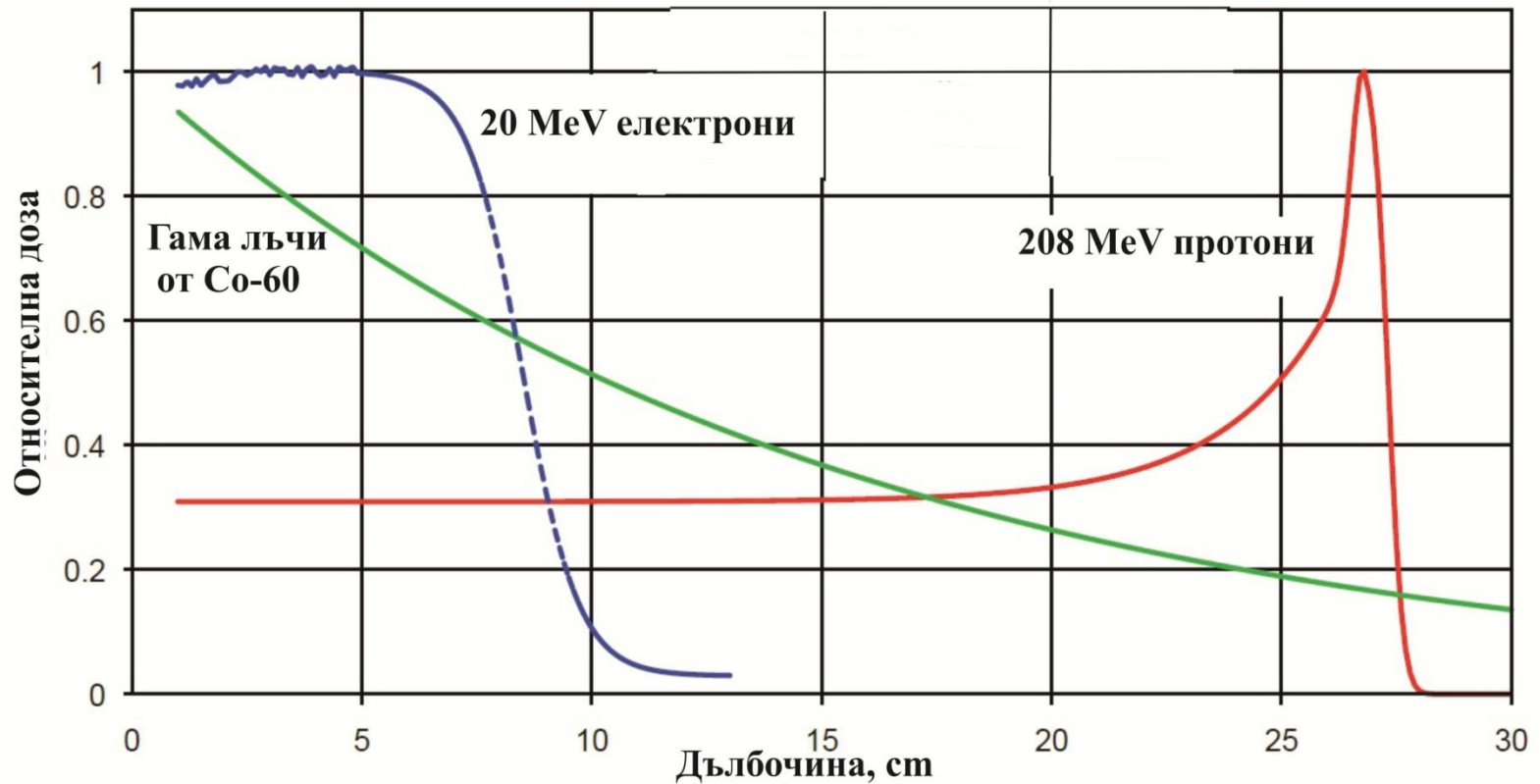


# ПРИЛОЖЕНИЯ НА ЯДРЕНИТЕ МЕТОДИ В МЕДИЦИНАТА

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- За производството на PET изотопи се използват циклотрони, ускоряващи **протони до енергия 16-18 MeV** и **деутрони до енергия: 8-9 MeV**. Така например за производството на  $^{18}\text{F}$  се използва реакцията:
  - $p + ^{18}\text{O} \rightarrow ^{18}\text{F} + n$
  - енергията на протоните е **8-17 MeV**.

# ПРИЛОЖЕНИЯ НА ЯДРЕНИТЕ МЕТОДИ В МЕДИЦИНАТА





# Синхротронът за лъчетерапия с въглеродни йони, Япония



# Производство на радионуклиди в България

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- По време на най-активния работен период на изследователския реактор са произвеждани разнообразни радионуклиди като
- $^{18}\text{F}$ ,  $^{42}\text{K}$ ,  $^{24}\text{Na}$ ,  $^{35}\text{S}$ ,  $^{45}\text{Ca}$ ,  $^{51}\text{Cr}$ ,  $^{59}\text{Fe}$ ,  $^{60}\text{Co}$ ,  $^{64}\text{Cu}$ ,  $^{82}\text{Br}$ ,  $^{86}\text{Rb}$ ,  $^{90}\text{Y}$ ,  $^{142}\text{La}$ ,  $^{169}\text{Yb}$ ,  $^{182}\text{Ta}$ ,  $^{192}\text{Ir}$ ,
- намиращи приложение в промишлеността и медицината



# Производство на радионуклиди в България

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- ИЯИЯЕ е закупил циклотрон с максимална енергия на протонния сноп в диапазона 15 - 24 MeV
- PET изотопи -  $^{18}\text{F}$ ,  $^{124}\text{I}$ ,  $^{64}\text{Cu}$ ,  $^{68}\text{Ge}/^{68}\text{Ga}$
- SPECT изотопи -  $^{123}\text{I}$ ,  $^{111}\text{In}$ ,  $^{67}\text{Ga}$ ,  $^{99\text{m}}\text{Tc}$

*Thank You*

