PEKING UNIVERSITY 北京大学 物理学院

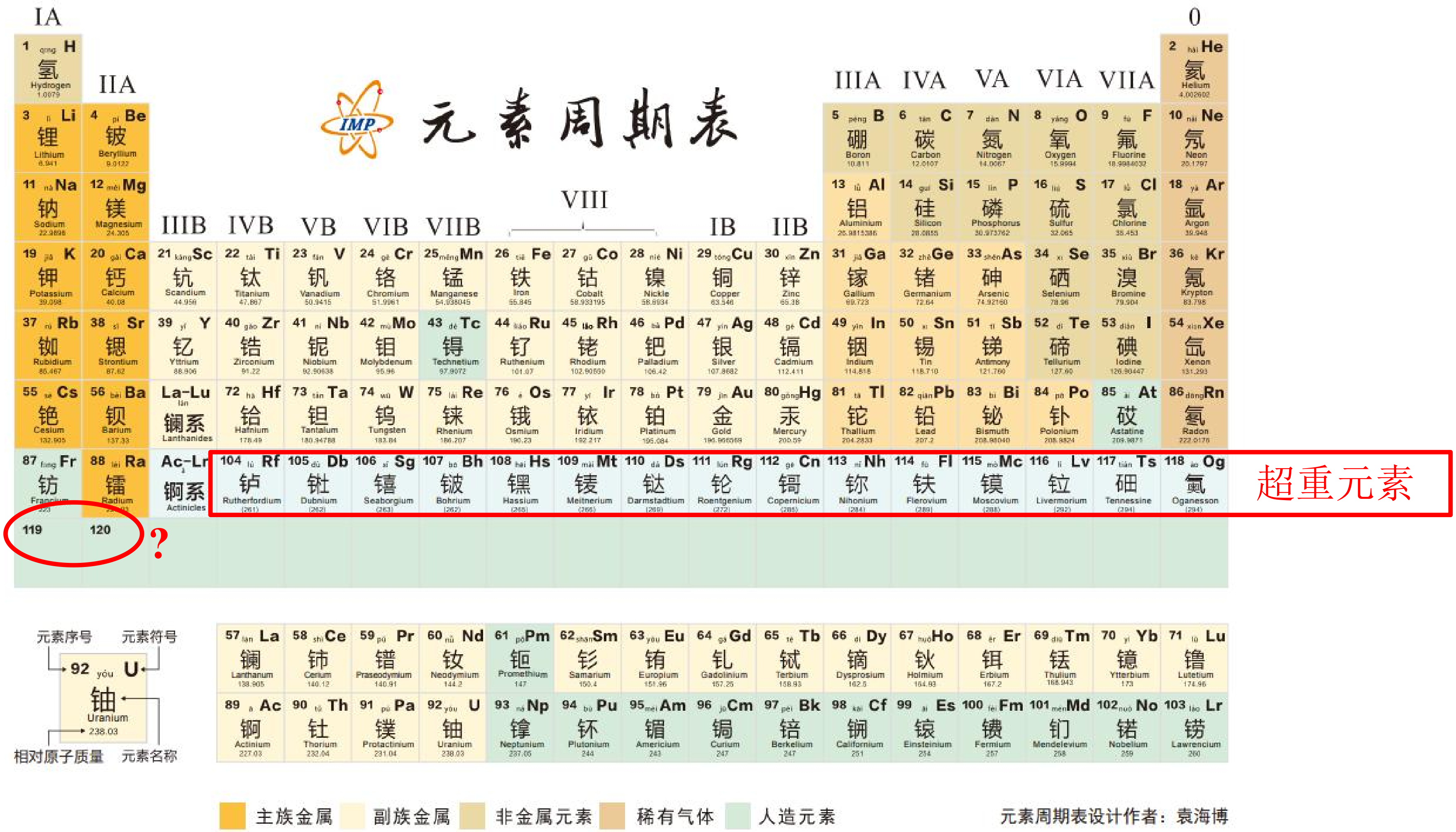
走向核素版图的边缘

Towards the edge of nuclear landscape

许甫荣

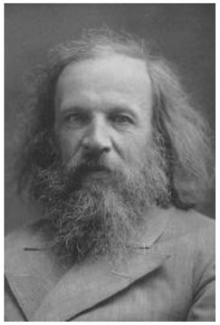
I. 核物理发展历史（重要里程碑）

II. 当前核物理前沿



元素周期表
IMP
IA
IIA
IIIB IVB VB VIB VIIB VIII IB IIB
IIIA IVA VA VIA VIIA
0
超重元素
119
120
?
元素序号
元素符号
92 yóu U
铀
Uranium
238.03
相对原子质量
元素名称
主族金属
副族金属
非金属元素
稀有气体
人造元素
元素周期表设计作者：袁海博

Classification of elements



Dmitri Ivanovich Mendeleev

(1834－1907年)

Regularities in the chemical properties of the elements

ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,4.
			Fe=56	Rn=104,4	Ir=198.
			Ni=Co=59	Pl=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	Ga ?=68	Ur=116	Au=197?
	C=12	Si=28	Ge ?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		Sc ?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

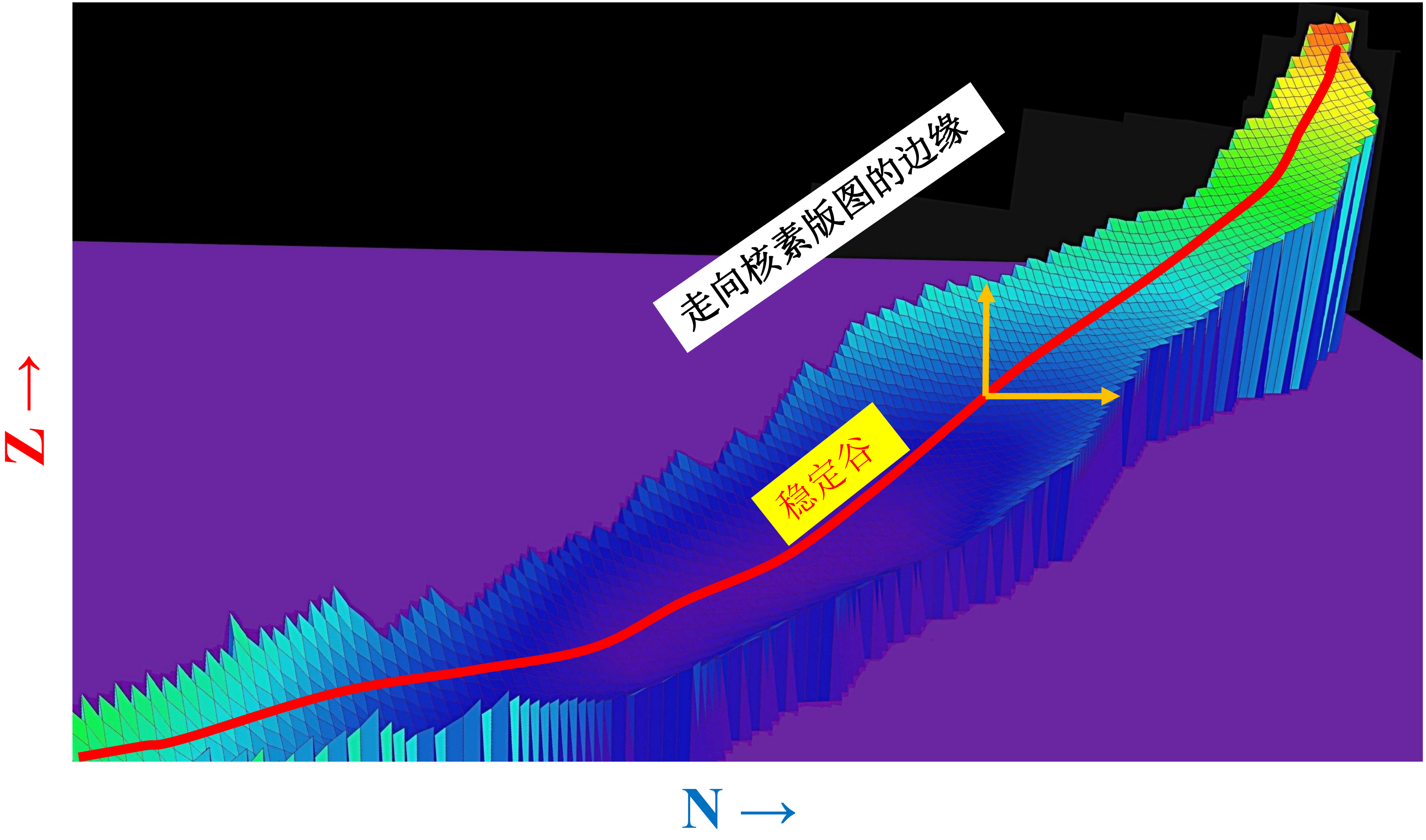
Д. Менделѣевъ (1869)

The place of an element in the table is given by the number **Z** (=atomic number, from Atom**Z**ahl)

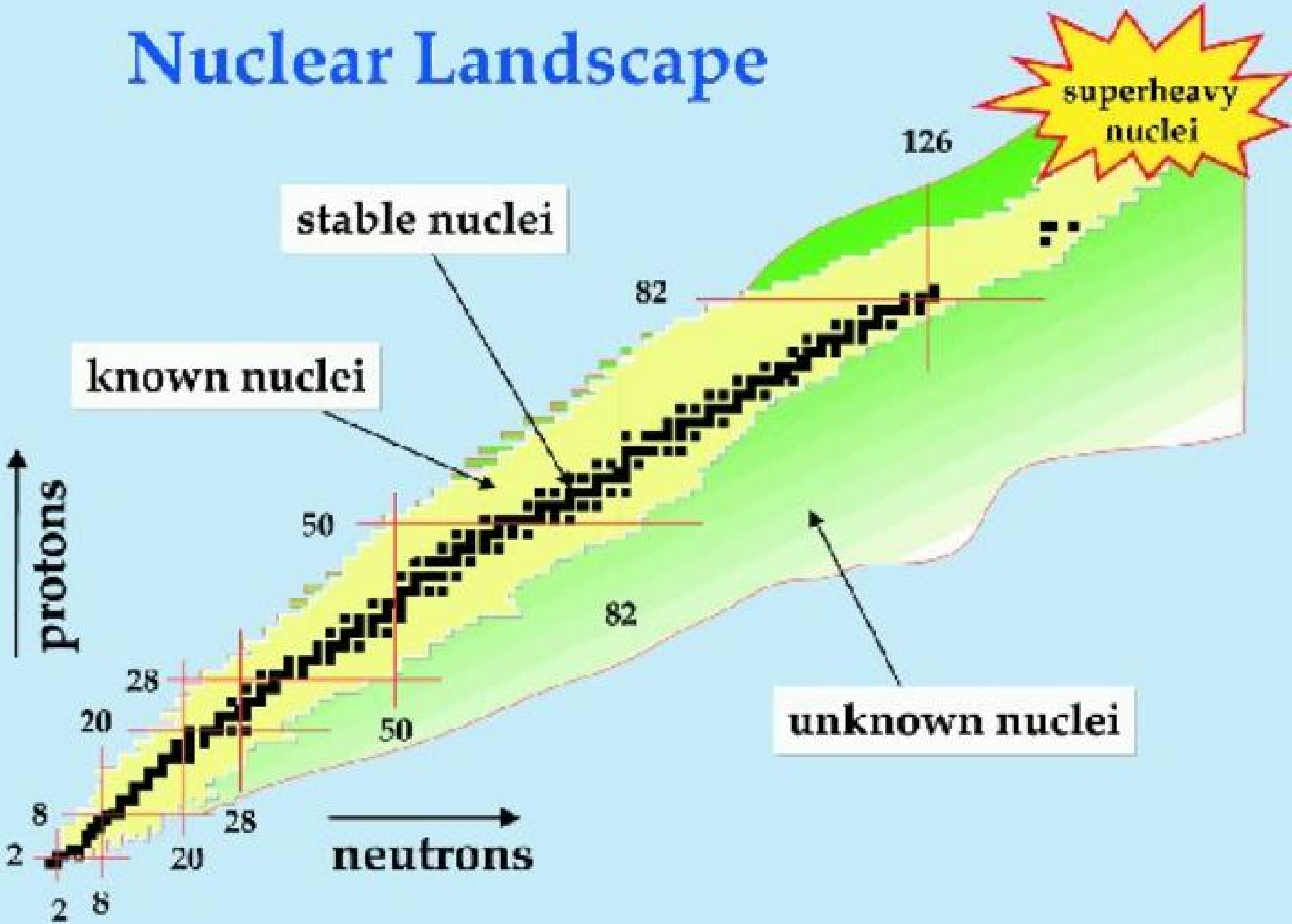
前后20年，1869年门捷列夫发现了元素周期律：元素质量+化学性质

给当时未知元素留空位，预言未知元素：比如，氦、氖、氩、氪、氙和氡

核素版图 Nuclear Landscape



Nuclear Landscape

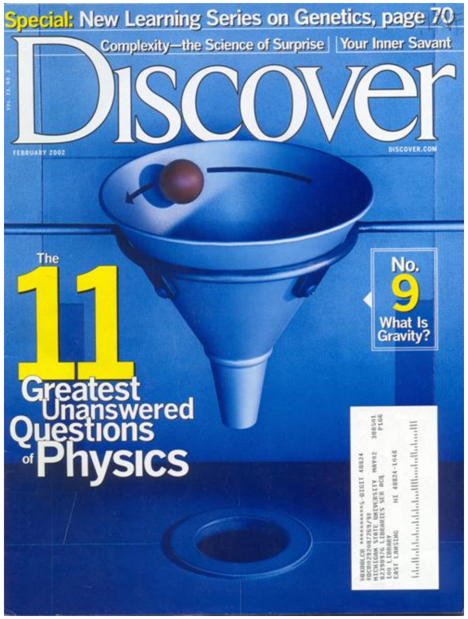


What is the Universe made of ?

- About 95% are of the dark matter and dark energy (don't know exactly what they are)
- Nuclear astrophysics attempts to study the rest 5%

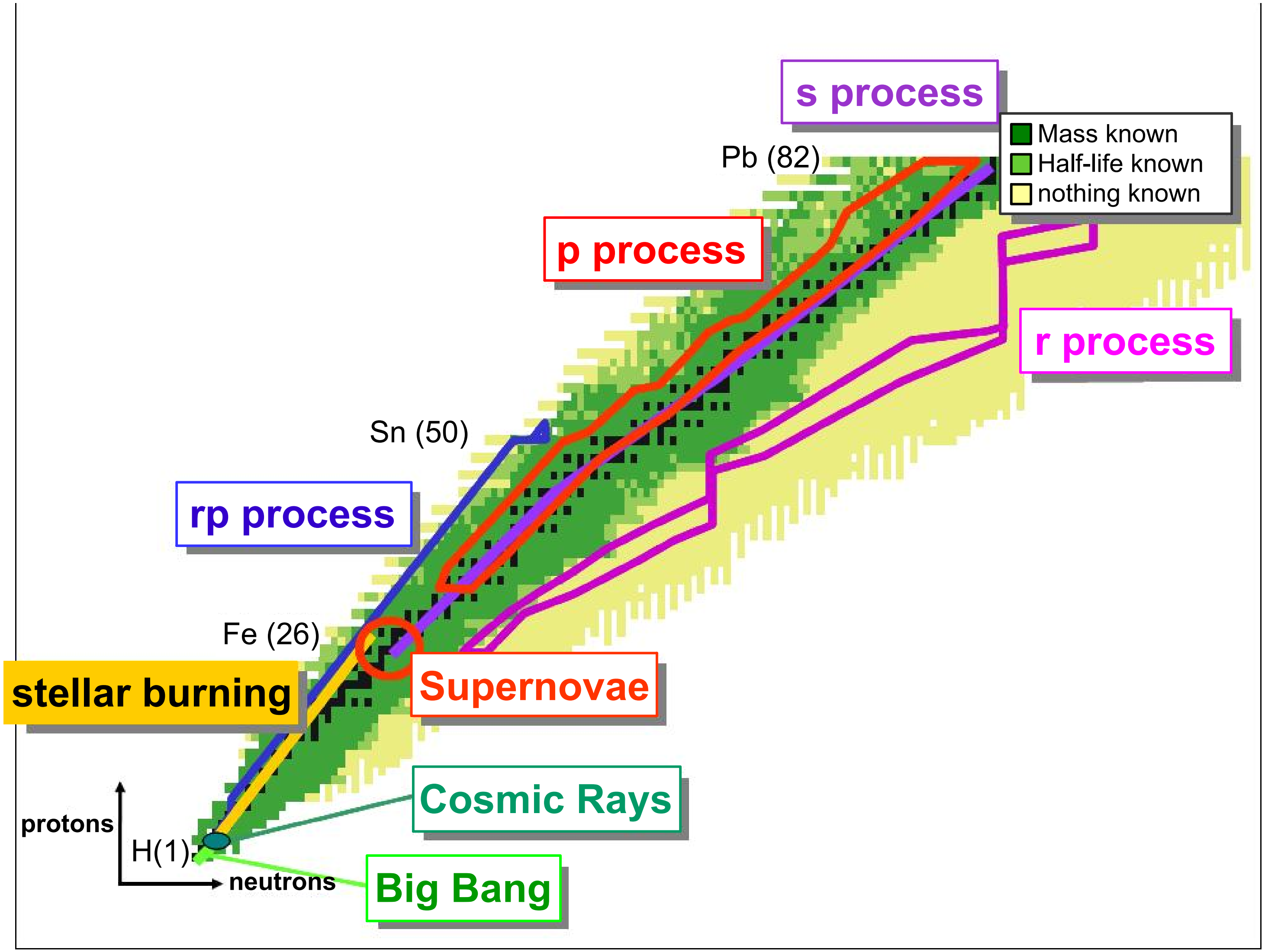
The USA National Academy of Science Report listed 11 questions of physics

- The Question # 3: How were the elements from iron to uranium made?



宇宙时间	主　要　事　件	距今时间
~0	奇点，宇宙大爆炸	~150 亿年
10^{-43}秒	普朗克时间，四种力统一	~150 亿年
10^{-6}秒	强子时间，四种力分离	~150 亿年
2 秒	夸克囚禁时间，粒子产生	~150 亿年
3 分	辐射时间，合成氦	~150 亿年
1 万年	物质时间，宇宙变成物质为主	~150 亿年
70 万年	脱耦时间，宇宙变成透明	~150 亿年
~20 亿年	星系开始形成	~130 亿年
30 亿年	星系开始成团	~120 亿年
40 亿年	前银河系吸积	~110 亿年
41 亿年	第一代恒星形成	~109 亿年
50 亿年	第二代恒星形成	~100 亿年
100 亿年	第三代恒星形成，原太阳星云形成	~50 亿年
104 亿年	原太阳星云吸积	~46 亿年

核天体物理：Element production



PHYSICAL REVIEW LETTERS **123,** 212501 (2019)

Editors' Suggestion　Featured in Physics

Location of the Neutron Dripline at Fluorine and Neon

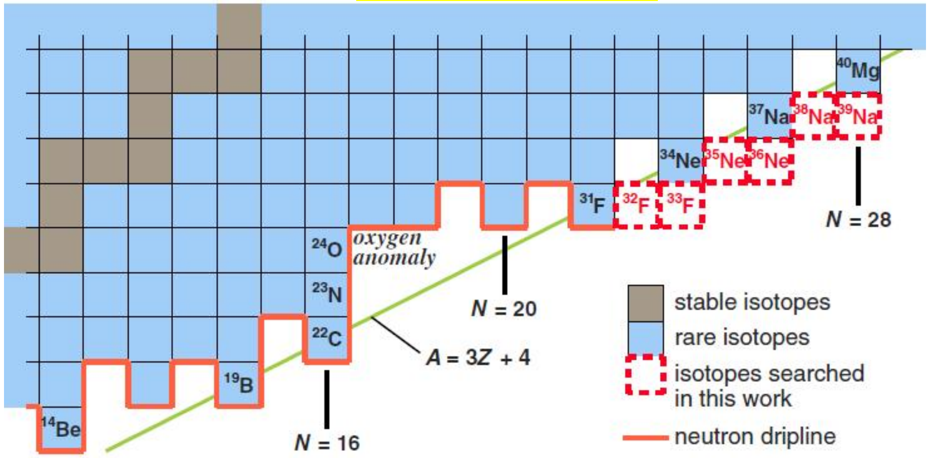
D. S. Ahn,[1] N. Fukuda,[1] H. Geissel,[5] N. Inabe,[1] N. Iwasa,[4] T. Kubo,[1,*,†] K. Kusaka,[1] D. J. Morrissey,[6] D. Murai,[3] T. Nakamura,[2] M. Ohtake,[1] H. Otsu,[1] H. Sato,[1] B. M. Sherrill,[6] Y. Shimizu,[1] H. Suzuki,[1] H. Takeda,[1] O. B. Tarasov,[6] H. Ueno,[1] Y. Yanagisawa,[1] and K. Yoshida[1]

[1]*RIKEN Nishina Center for Accelerator-Based Science, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

美国物理学会选出的“2019年物理学发生的十大事件”

4. 中子滴线得到延伸

走向边缘

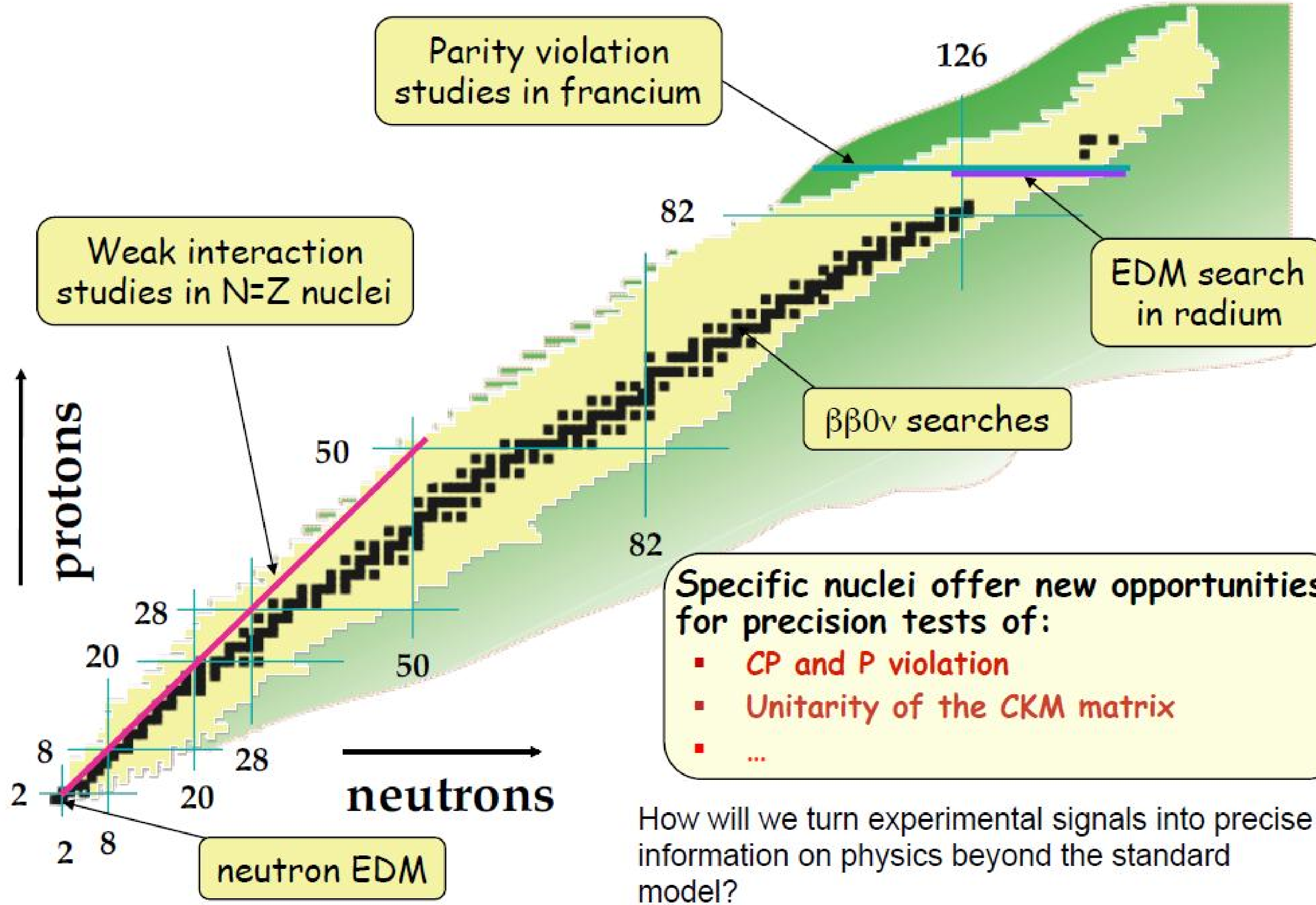


中子滴线停滞在元素周期表的前8个元素的中子滴线（**粉线**）已经20年。2019年，日本科学家将中子滴线延伸至氟（F）和氖（Ne）（**绿线**）

物理学家希望下一个元素的滴线不要再等上20年。下一代稀有同位素装置计划在两年内投入使用，可能会将滴线延伸至镁元素，即元素周期表中的第12号元素。

与粒子物理交叉

Testing the fundamental symmetries of nature

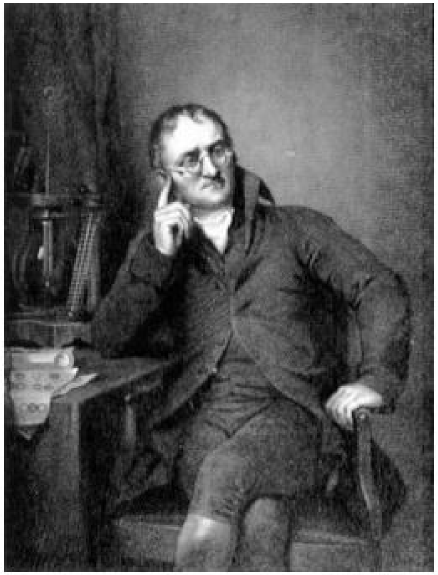


Specific nuclei offer new opportunities for precision tests of:

- CP and P violation
- Unitarity of the CKM matrix
- …

How will we turn experimental signals into precise information on physics beyond the standard model?

Constituents of matter



John Dalton

1803 :
-matter is made of **atoms**

-atoms of the same element are identical

Dalton's billiard ball, 1803

-atoms of an element can combine with those of other elements to form compounds

-atoms of different elements have different masses

I. 核物理发展历史（重要里程碑）

At the dawn of the 20th century

（1824-1907年）

"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

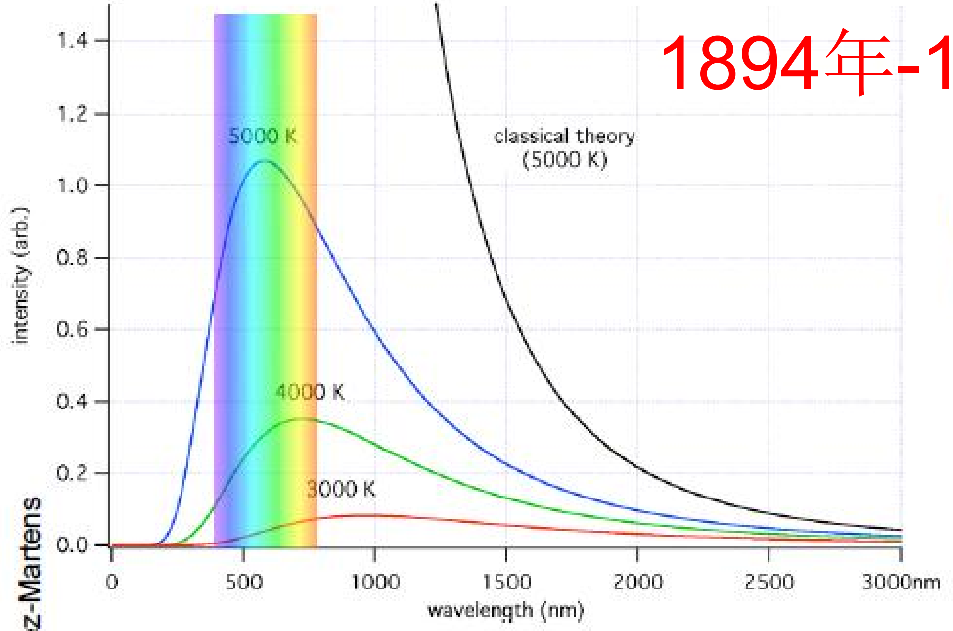
William Thomson (Lord Kelvin), 1900

British Association for the advancement of Science

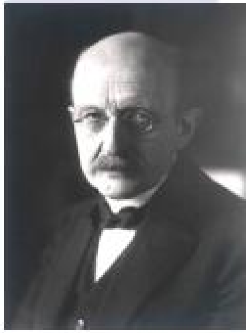
A few clouds in the sky.....

ultraviolet catastrophe: spectral distribution of

thermal radiation from matter



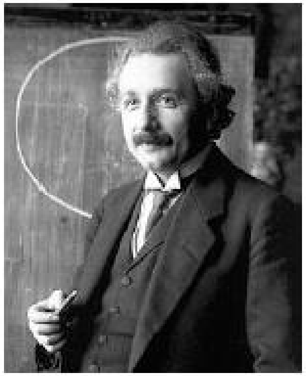
1894年-1900年



Max Planck

Matter can only absorb or emit radiation energy in discrete packets proportional to the frequency of the radiation: energy **quanta**

According to A. Einstein, Planck's quantization arises from the granular nature of light: light is made up of **photons**

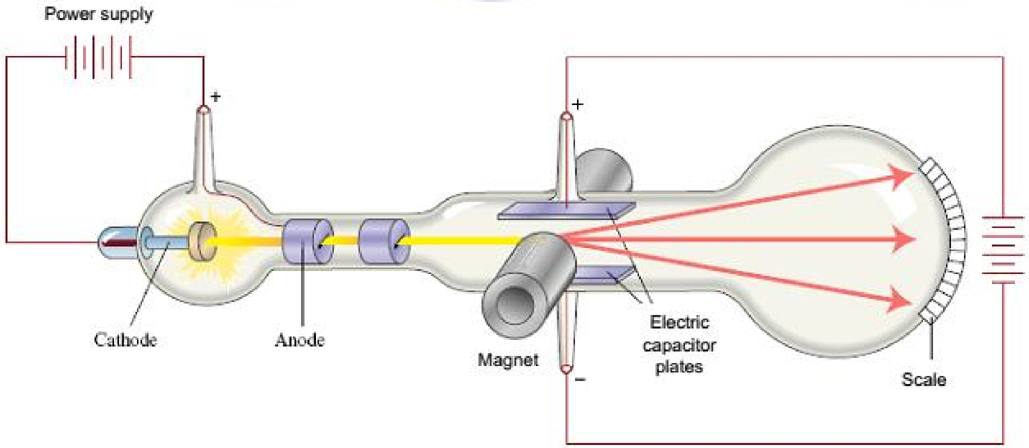


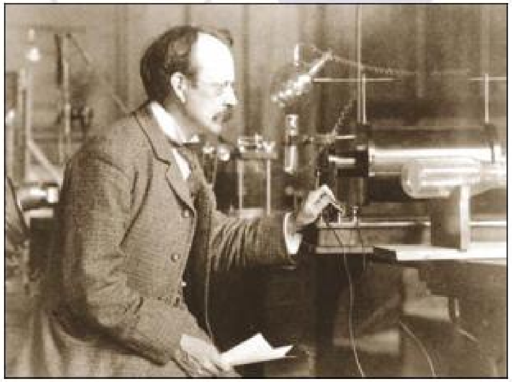
Albert Eisntein

EJC2011, A. Lopez-Martens

1898年

Atoms are no longer indivisible !

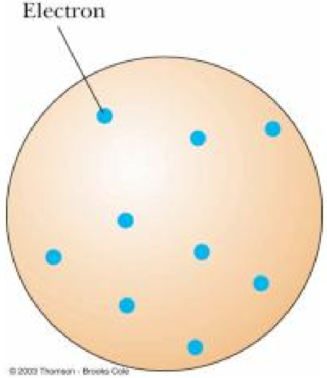




John Joseph Thomson

J.J. Thomson measures the charge/mass ratio of the charged particles

1898: J.J. Thomson concludes that what he calls ‘corpuscules’ (= electrons) are the constituents of atoms



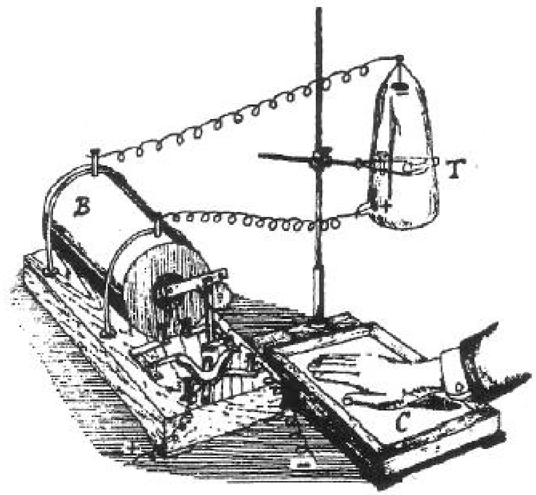
‘plum pudding’ model

1895年

From cathode rays to X rays

1895 W. Röntgen discovery of X rays

Wilhelm Röntgen



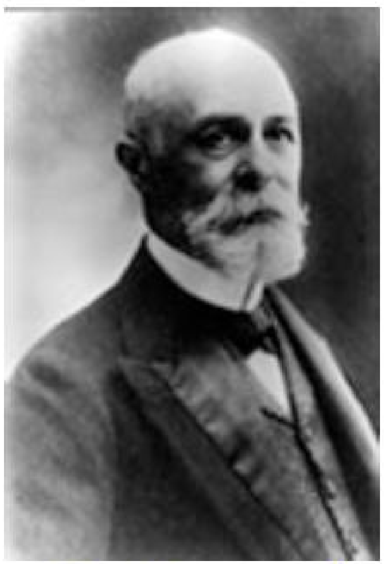
W. Röntgen receives the 1st Nobel Prize in Physics in 1901

EJC2011, A. Lopez-Martens

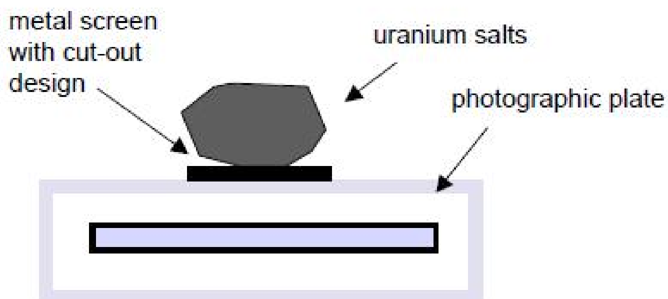
1896年

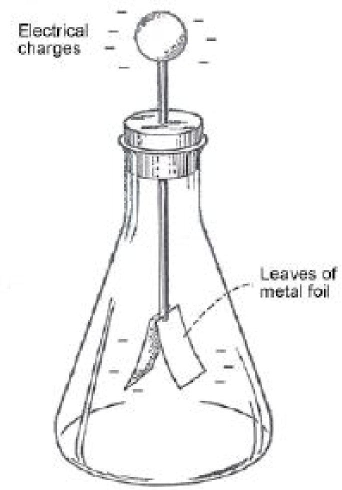
From X rays to Uranium rays

1896 H. Becquerel discovery of a new kind of radiation emitted by Uranium



Henri Becquerel





Uranium rays ionize the air and cause the discharge of an electroscope

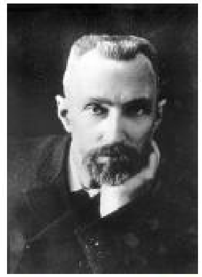
Nobel Prize in Physics (1903)

From Uranium rays to radioactivity

1898年

1898 Marie & Pierre Curie

Marie Curie



Pierre Curie

extraction of polonium and radium

Laboratory at the Ecole de Physique et Chimie industrielle de Paris

EJC2011, A. Lopez-Martens

M. Curie calls the radiation:
'radioactivity'

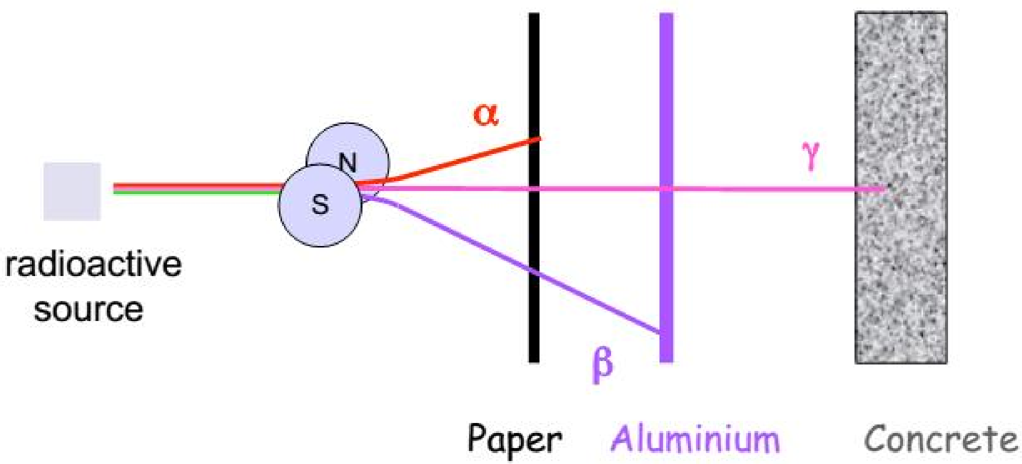
因为天然放射性方面的贡献，居里夫妇跟贝克勒尔同一年分享一半 Nobel Prize in Physics (1903)

居里夫人，1911年，因发现元素钋和镭再次获得诺贝尔化学奖

1908年Noble化学奖，这个工作是得化学Noble的主要基础，通过alpha decay后，元素蜕变别的元素.

Radioactivity is manifold

1898	E. Rutherfod	alpha, beta radiation
1900	P. Villard	gamma radiation



α = hélium ion He^{2+}

β= high energy e^-

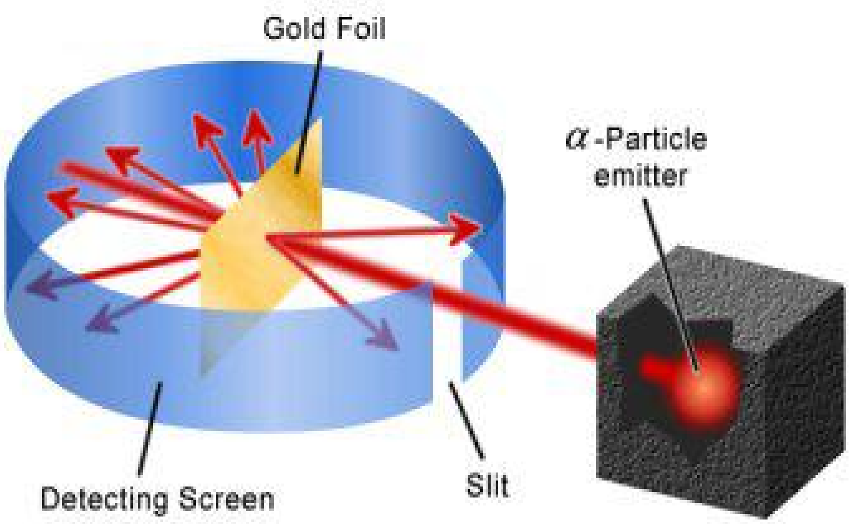
γ= photons - like X rays

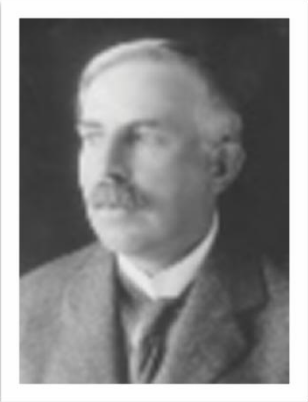
EJC2011, A. Lopez-Martens

Ernest Rutherford

Paul Villard

- 1908: H. Geiger 和 E. Marsden 在研究 α 粒子散射实验中发现，**约每 8000 个 α 粒子，就有一个被大角度散射。**





E. Rutherford (1871 - 1937)

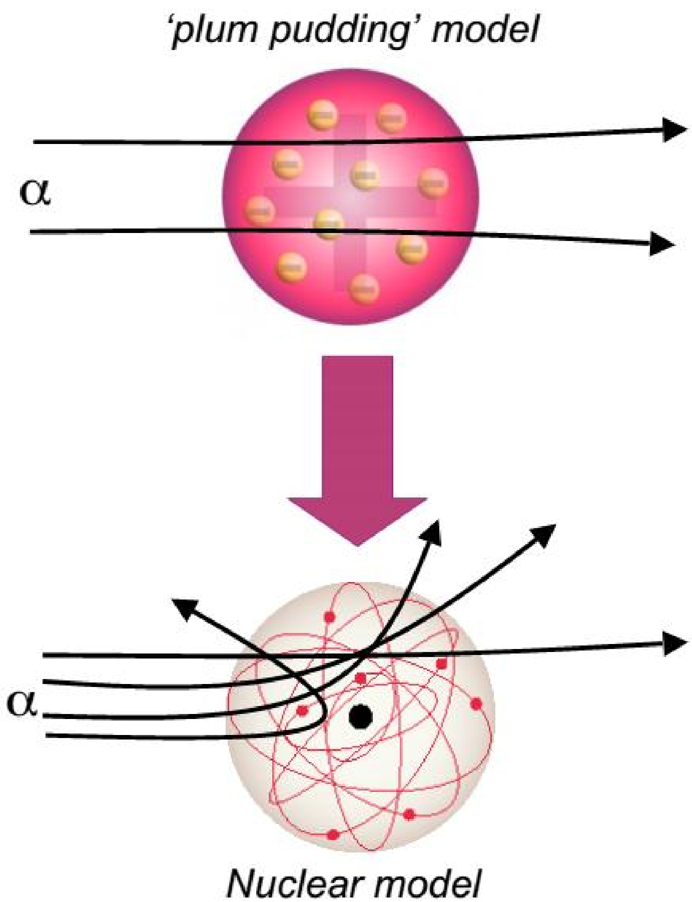
H. Geiger, *Proceedings of the Royal Society of London A* 81, 174 (1908).

E. Rutherford, *Philosophical Magazine* 21, 669 (1911).

> "It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you! "

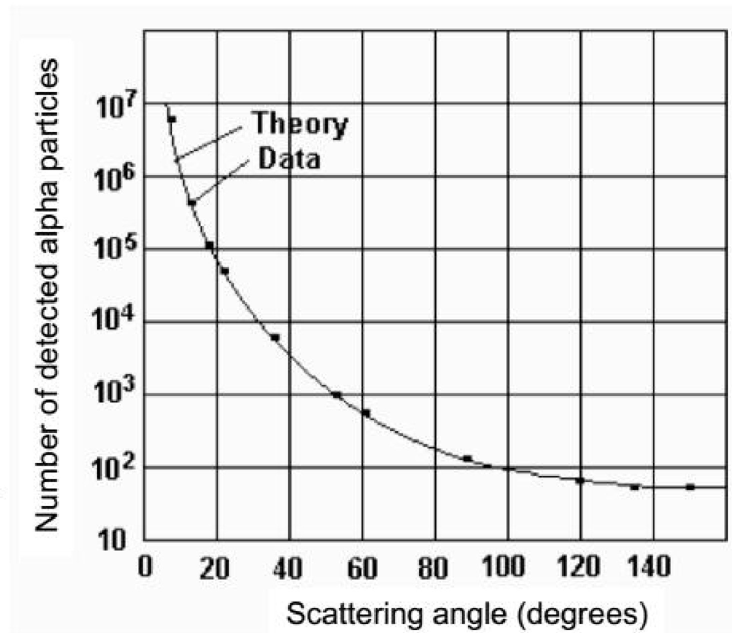
1911年，形成有核原子模型概念

The nucleus is born !

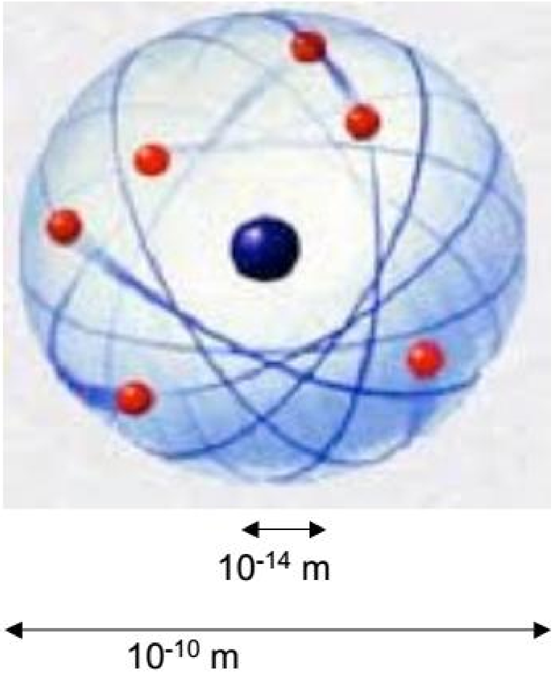


EJC2011, A. Lopez-Martens

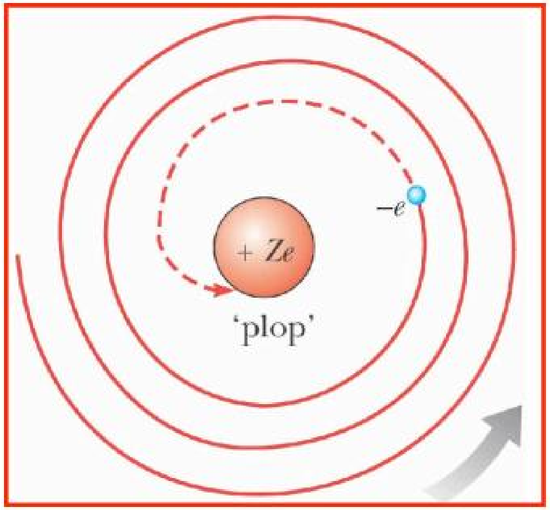
Philosophical Magazine Series 6, vol. 21 May 1911, p. 669-688



Consequences of Rutherford's model



Matter is empty !



The atom is unstable !

1913年波尔原子模型

Bohr solves the problem with Planck's quanta

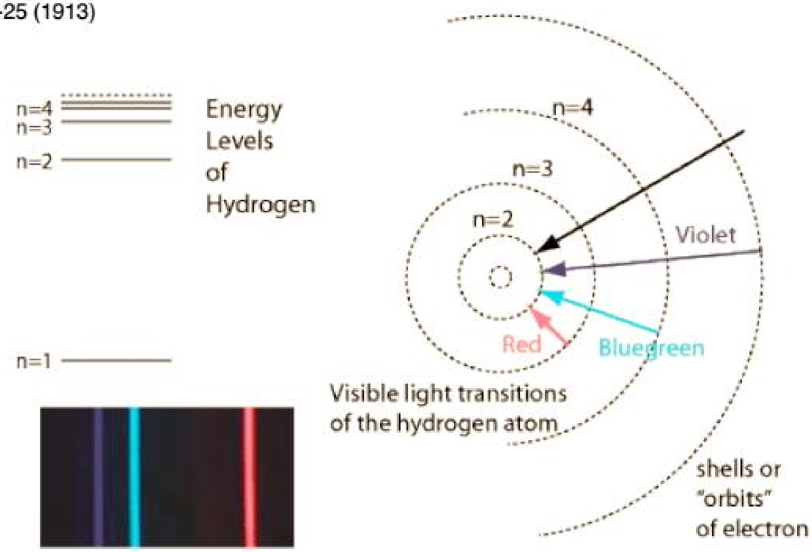
- angular momentum is quantized ⇔ only certain orbits of energy E_n (n=1,2,3,...) are allowed
- n is the principal quantum number
- electronic jumps from one orbit to another are accompanied by the emission (or absorption) of a photon of given wavelength

Niels Bohr

1922年 诺贝尔物理学奖

Philosophical Magazine **26**, 1-25 (1913)

$E_n \propto -Q^2/n^2$

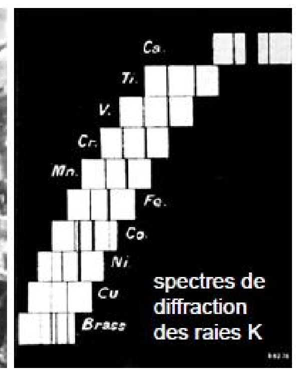


EJC2011, A. Lopez-Martens

在玻尔原子模型基础上，莫塞莱提出了原子序数的概念，解释元素化学性质由核外的电子壳层排序确定的，推动了原子物理的发展。

一战爆发以后，莫塞莱辞去了他在牛津大学的工作，入伍成为一位工程兵军官。1915年，莫塞莱阵亡，年仅27岁。如果没阵亡，很可能诺贝尔奖。 因为他的阵亡，英国政府制定了新的参战资格政策。

The periodic table finds its thread



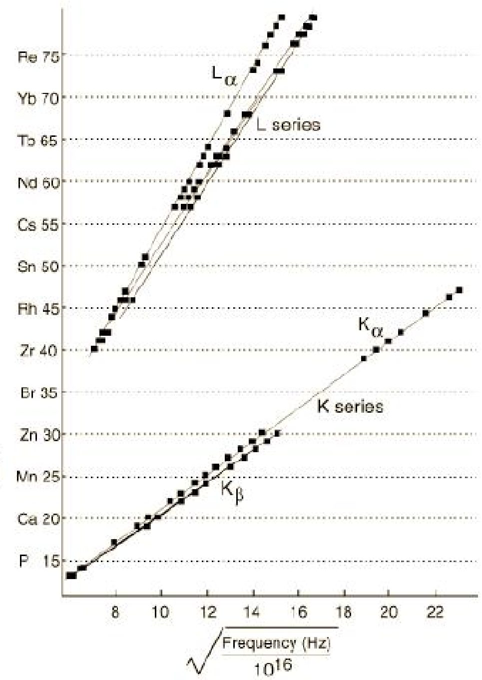
1914 Henry Moseley

Measurement of the high frequency spectra of many elements

⇨ atomic number Z = charge of the nucleus

⇨ regularities of the periodic table explained in terms of filling of electronic shells

EJC2011, A. Lopez-Martens



Adapted from Moseley's original data (H. G. J. Moseley, Philos. Mag. (6) 27:703, 1914)

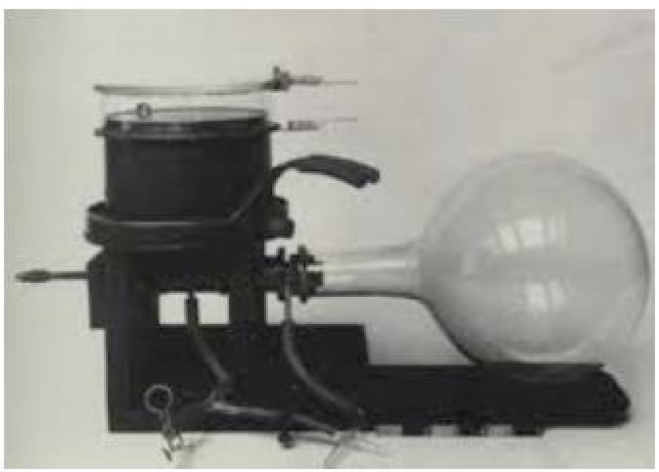
The alchemists of the 20th century

1919 E. Rutherford — 1st artificial transmutation

α + Nitrogen $\rightarrow$ Hydrogen

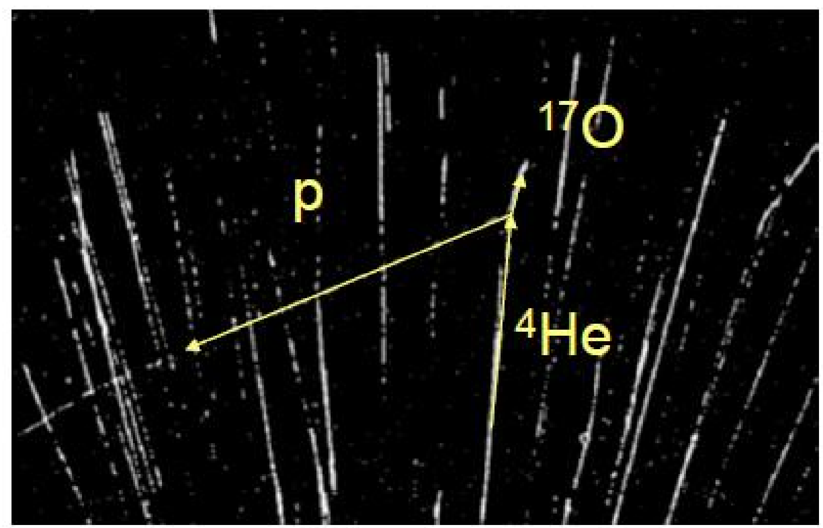
Rutherford calls H^+ proton 发现质子

1924 P. Blackett visualizes the transmutation $\alpha + {}^{14}N \rightarrow {}^{17}F^* \rightarrow {}^{17}O + p$



Cloud chamber (C.T.R. Wilson, 1912)

EJC2011, A. Lopez-Martens



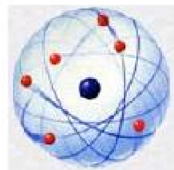
P. Blackett 1948 云雾室实验工作得 Nobel Prize

核物理早期二个代表性人物

100 years ago...

" The scattering of α and β particles by matter and the structure of the atom"

Philosophical Magazine Series 6, vol. 21 May 1911, p. 669-688



EJC2011, A. Lopez-Martens

Rutherford被誉为核物理之父

The Nobel Prize in Chemistry 1911 was awarded to Marie Curie *"in recognition of her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element"*.

1898年： 英国科学家 汤姆逊 发现电子

1911年： 卢瑟福 α背散射实验 原子模型

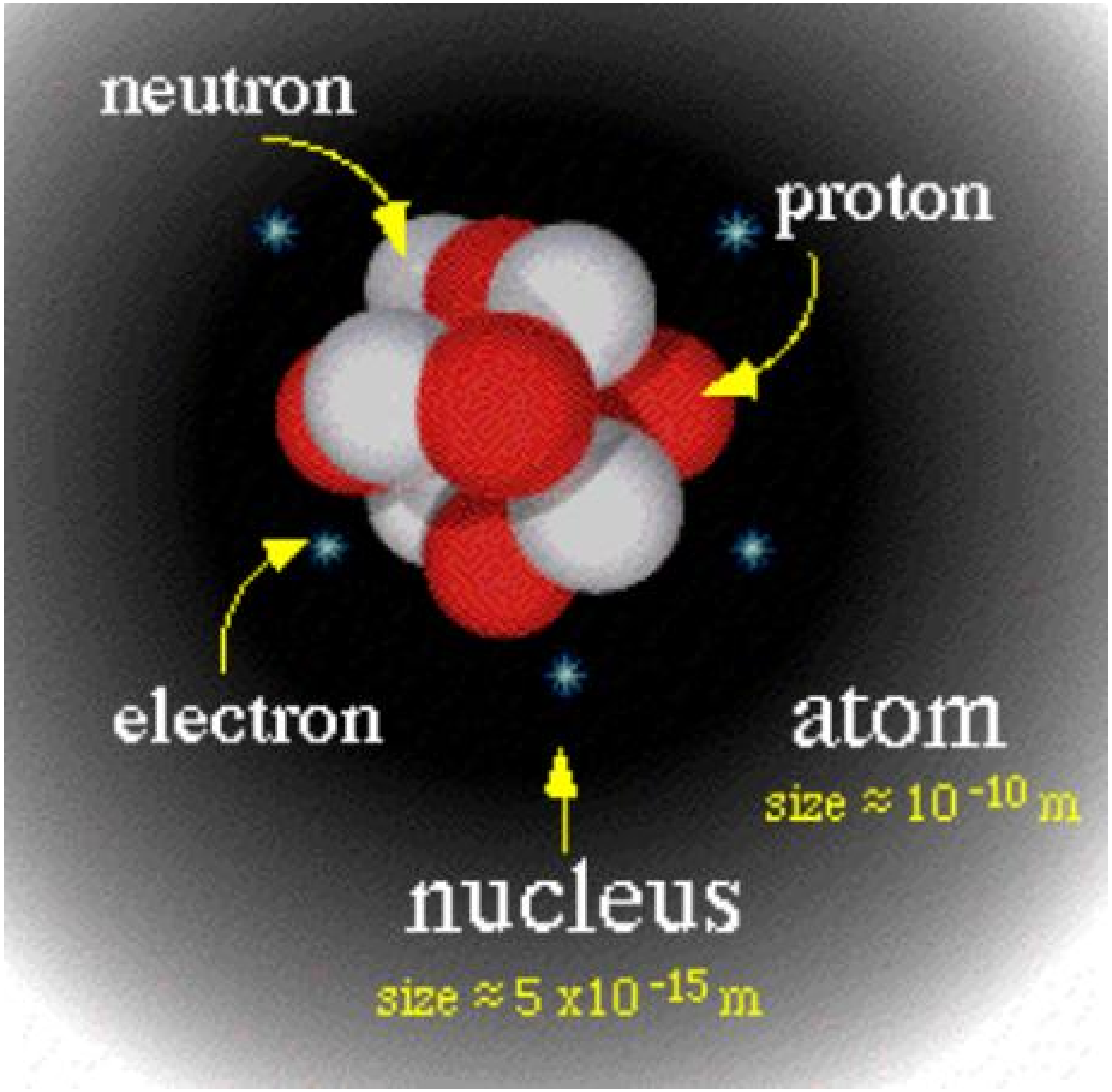
1913年： N.玻尔 量子论 建立玻尔原子模型

1919年 (实验1917, 发表1919)： 卢瑟福 发现质子

1932年： 查德威克 发现中子

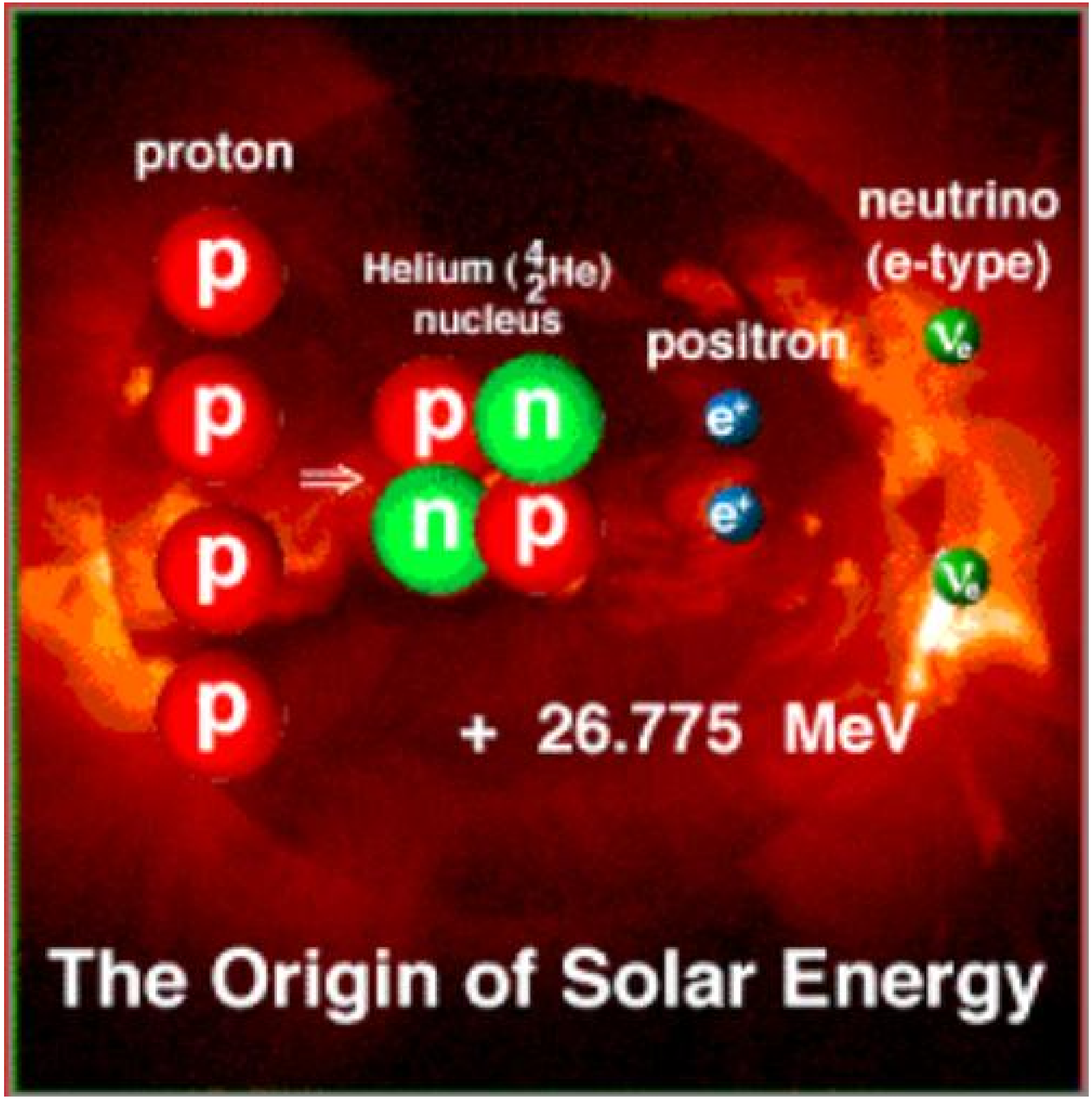
原子和原子核模型的建立

原子核结构



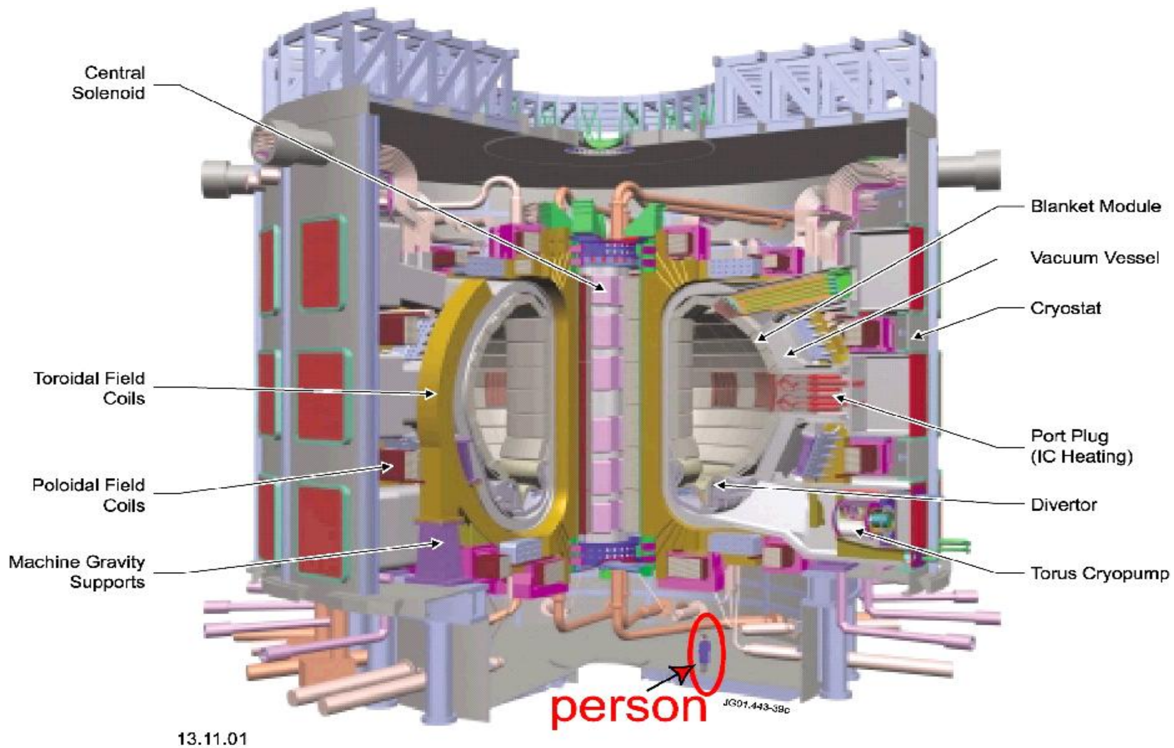
neutron
proton
electron
atom
size ≈ 10 -10 m
nucleus
size ≈ 5 x10 -15 m

太阳能源

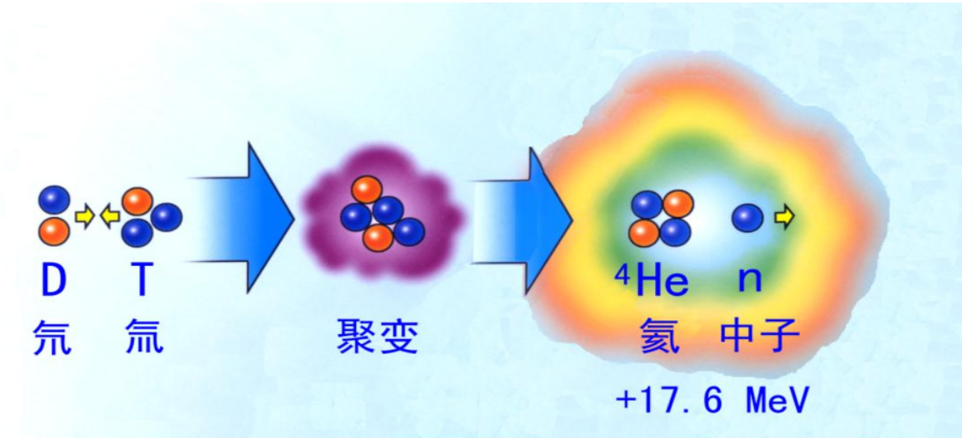


proton
p
p
p
p
Helium ($^4_2$He) nucleus
p n
n p
positron
e^+
e^+
neutrino (e-type)
ν_e
ν_e
+ 26.775 MeV
The Origin of Solar Energy

ITER装置



Central Solenoid
Toroidal Field Coils
Poloidal Field Coils
Machine Gravity Supports
Blanket Module
Vacuum Vessel
Cryostat
Port Plug (IC Heating)
Divertor
Torus Cryopump
person
13.11.01



D
T
氘
氚
聚变
⁴He
n
氦
中子
+17.6 MeV

核物理发展的几个里程碑

液滴模型（Gamow提出概念，1935年由Weizsacker数学化，Bethe和N. Bohr贡献）

$$E_B = a_V A - a_S A^{2/3} - a_A \frac{(A-2Z)^2}{A^{1/3}} - a_C \frac{Z(Z-1)}{A^{1/3}} + \delta(A,Z)$$

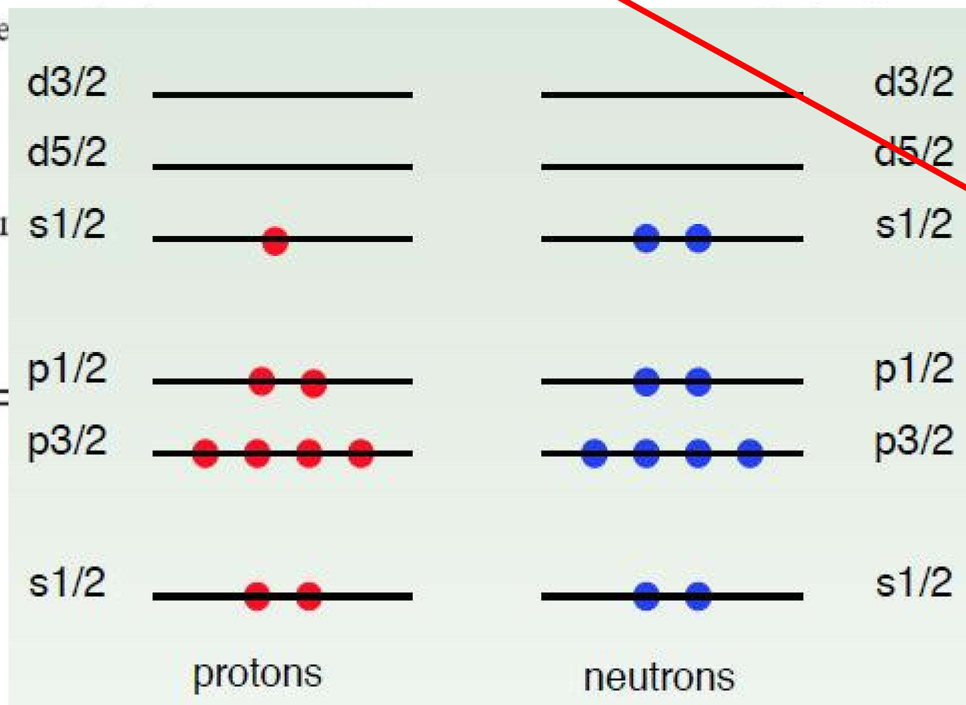
Volume term

Pairing term

For pairing ter

$\delta(A,Z) =$

where



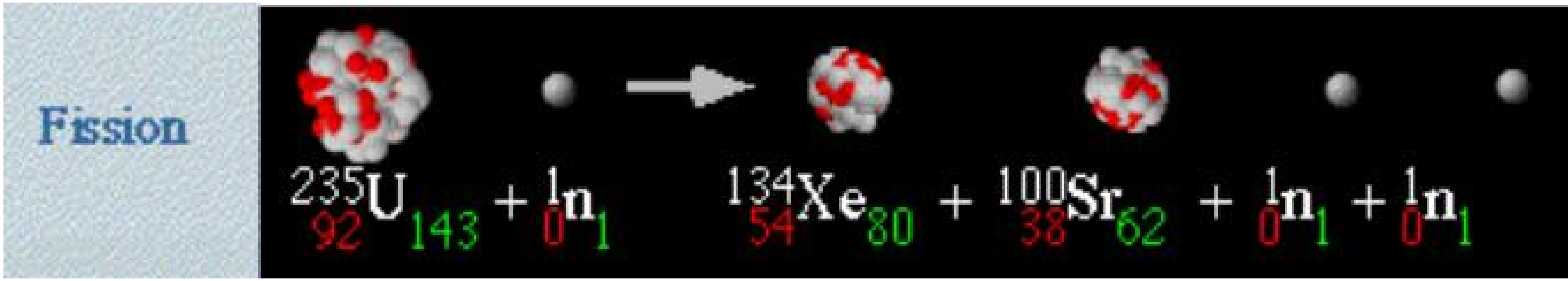
$$\frac{|N-Z|^2}{A^{1/3}}$$

量子力学的Pauli不相容原理

裂变发现，N. Bohr用液滴模型，马上意识到裂变产生能量！

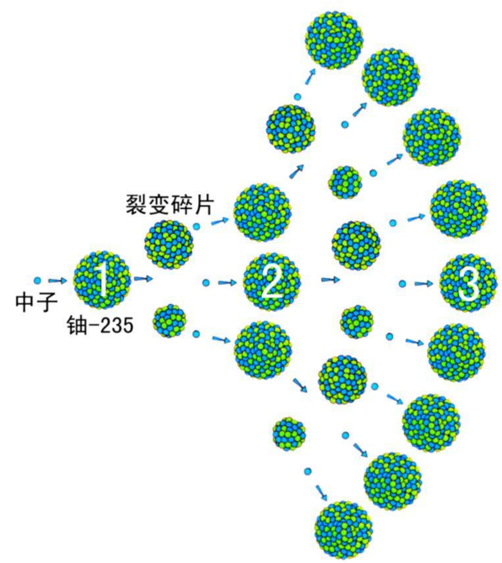
Q1: 对称能（Asymmetry or Wigner term)物理原因是什么？

核裂变的发现（1938年：哈恩，迈特纳）



$$B(A,Z) = a_{vol}A - a_{surf}A^{2/3} - a_{comb}Z(Z-1)A^{-1/3} - a_{sym}(A-2Z)^2A^{-1}$$

裂变：核能



裂变链式反应

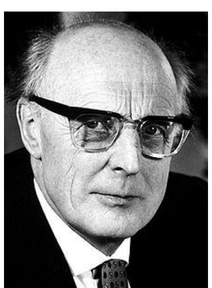
费米：第一个反应堆

Nuclear Shell Model

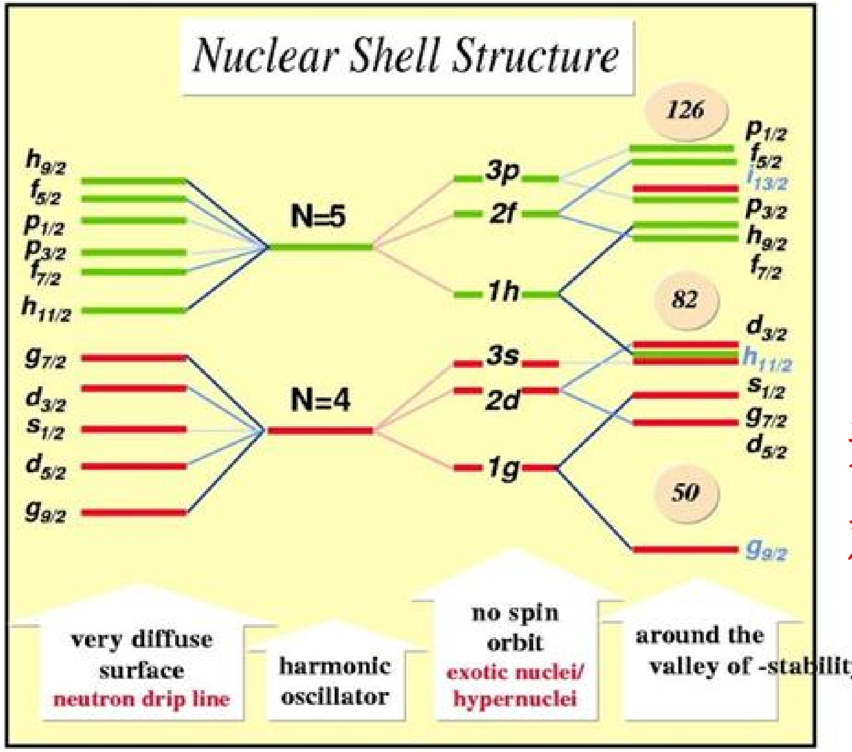
（概念1932年已经提出，1949年发展， 1963 Nobel prize ）

Eugene Paul Wigner

Maria Goeppert-Mayer



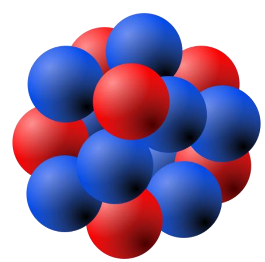
J. Hans D. Jensen

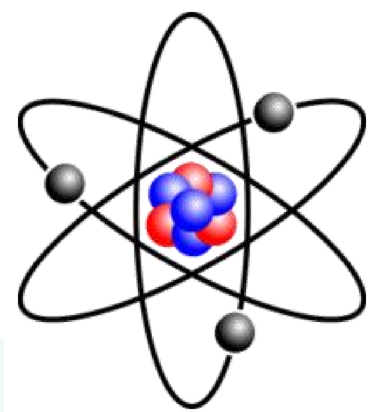


Spin-orbit coupling

幻数

开启了核结构的微观量子理论研究





从Liquid drop model: 原子核总是球形的！

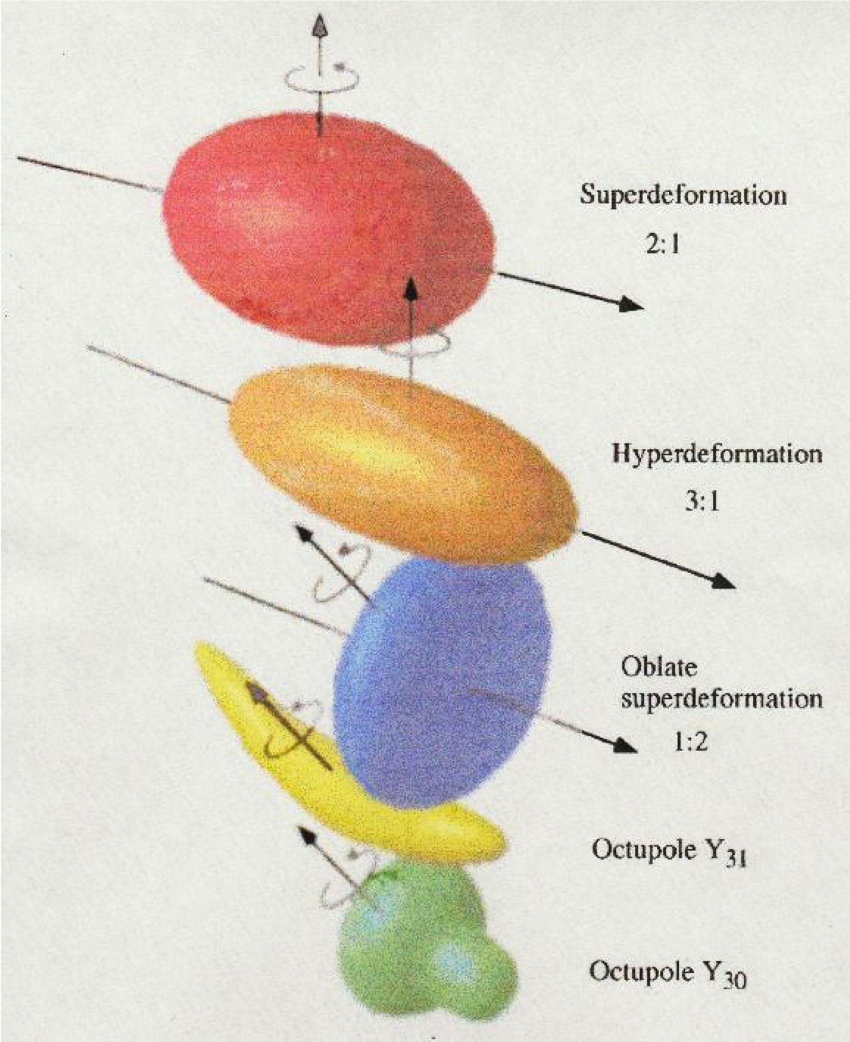
高速转动原子核

The Nobel Prize in Physics 1975

Aage Niels Bohr

Ben Roy Mottelson

Leo James Rainwater



The Nobel Prize in Physics 1975

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 1975 in equal shares to Professor **Aage Bohr**, Denmark, to Professor **Ben Mottelson**, Denmark and to Professor **James Rainwater**, USA, **for the discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of the structure of the atomic nucleus based on this connection.**

Aage Niels Bohr

Ben Roy Mottelson

Leo James Rainwater

III. 目前的核物理前沿

1. 超重元素

2. 滴线区原子核

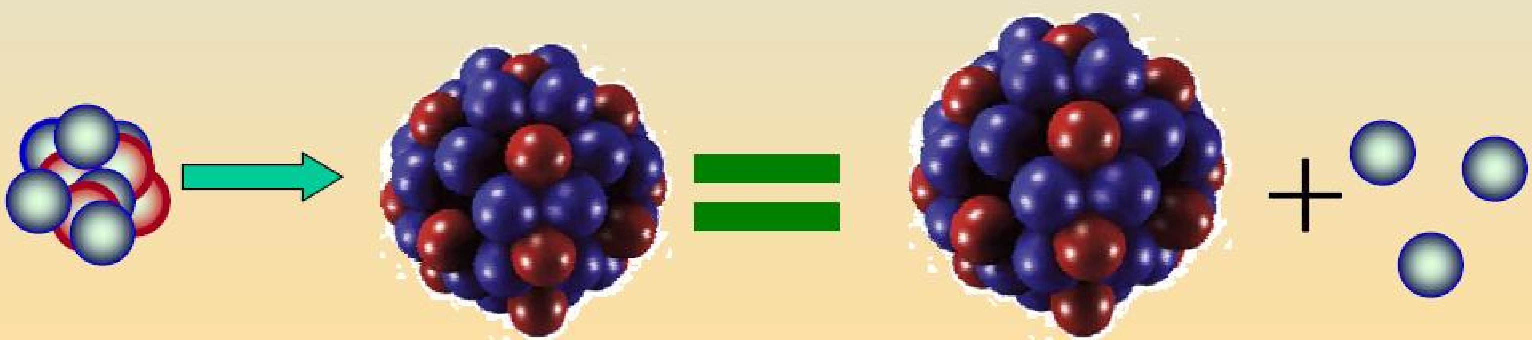
3. 与基本对称性相关的精确测量

4. 新理论手段

5. 实验核天体物理

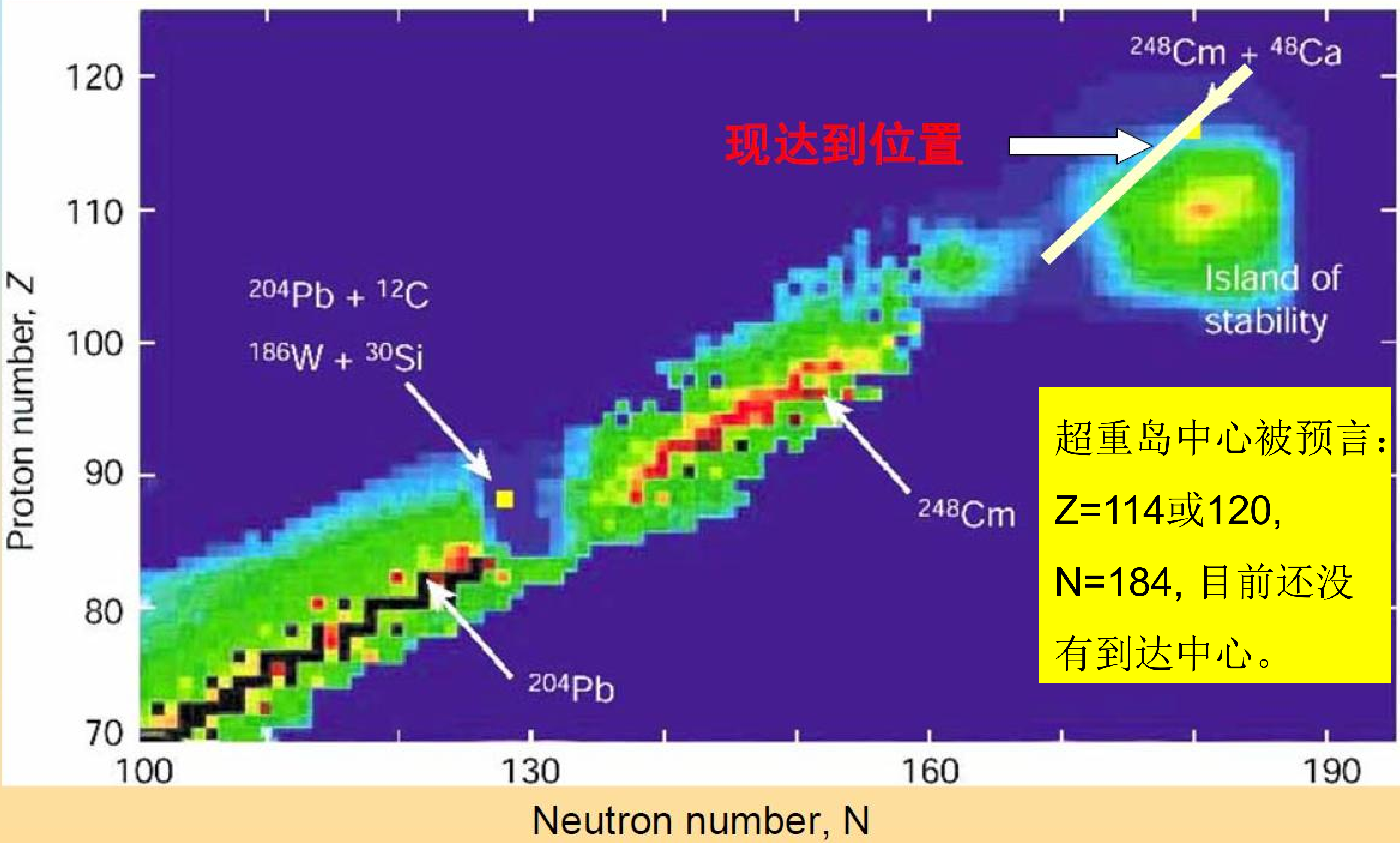
超重元素合成的途径

熔合反应——利用一定能量的炮弹原子核轰击靶原子核，两者熔合在一起，形成一个新的原子，它的原子序数为弹核与靶核之和。新原子核有一定的激发能，一般通过发射中子退激发。



$$^{48}Ca + {}^{244}Pu = {}^{289}114 + 3n$$

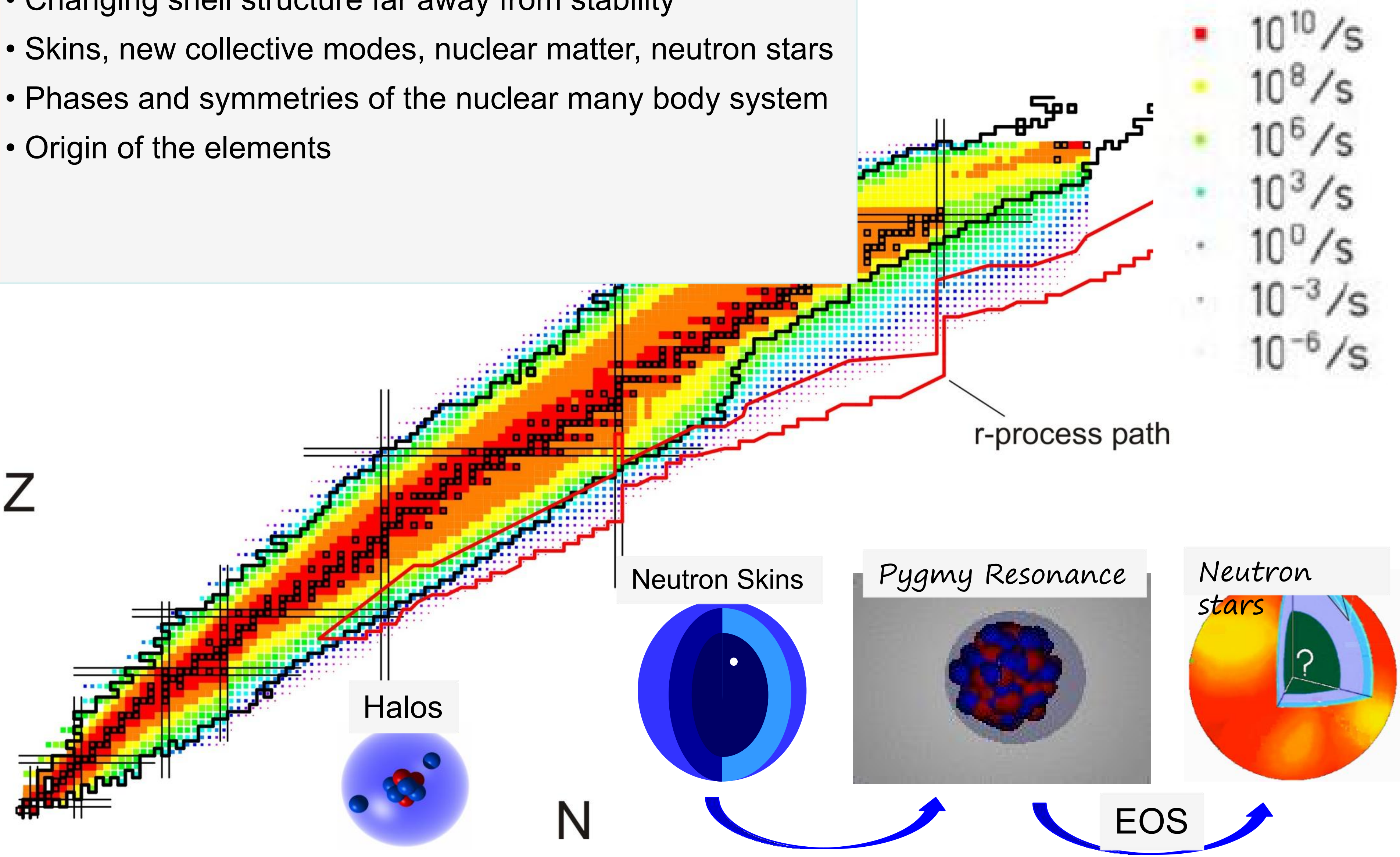
•超重元素的合成



超重岛中心被预言：Z=114或120，N=184，目前还没有到达中心。

Challenging physics

- Quest for the limits of existence
- Halos, Open Quantum Systems, Few Body Correlations
- Changing shell structure far away from stability
- Skins, new collective modes, nuclear matter, neutron stars
- Phases and symmetries of the nuclear many body system
- Origin of the elements

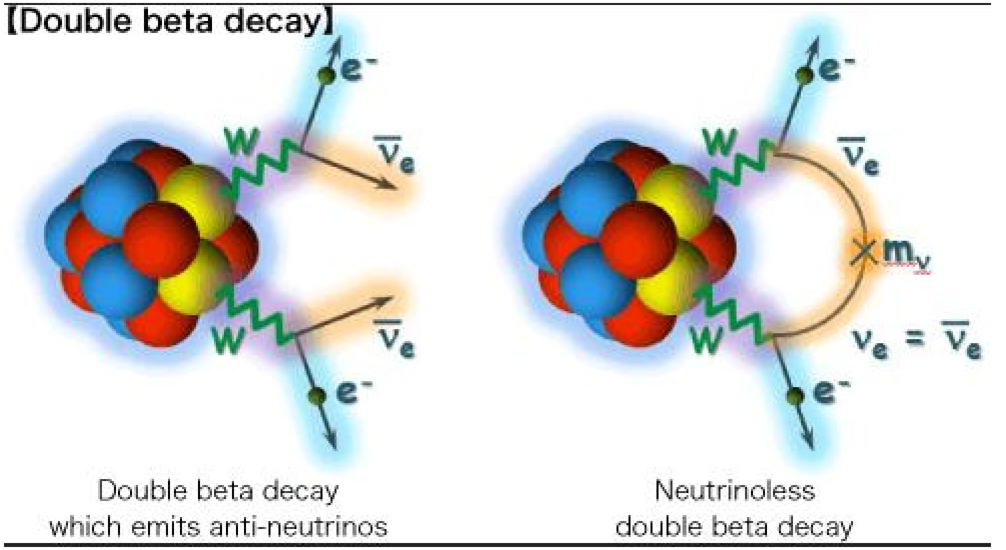


无中微子双β衰变（0νββ）

Neutrino is its own antiparticle?
(Majorana Fermion)

$^{136}Xe \rightarrow {}^{136}Ba + 2e^- \ (+\ 2\bar{\nu}\ ?\ )$

（利用精确的能量守恒关系）



预言衰变寿命: $\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}|M^{0\nu}|^2|f(m_i, U_{ei})|^2$

$G^{0\nu}$ phase-space factor (or kinematic factor); $f(m_i, U_{ei}) = g_A^2 \frac{\langle m_\nu \rangle}{m_e}$

$M^{0\nu}$ nuclear matrix element

（核物理第一性原理计算，非常依赖于母核、子核波函数）

物理可观测量:

Free space ⇨ **effective space, 利用场论重整化方法(Goldstone diagrams)**

暗物质粒子（WIMPs）与原子核散射：暗物质直接测量

Step 1: 场论扩展 $\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \cdots$

WIMP质量：1 — 100 GeV

PHYSICAL REVIEW LETTERS **128,** 072502 (2022)

Ab Initio Structure Factors for Spin-Dependent Dark Matter Direct Detection

B. S. Hu,[1,*] J. Padua-Argüelles,[1,2,†] S. Leutheusser,[1,3,‡] T. Miyagi,[1,§] S. R. Stroberg,[4,∥,¶] and J. D. Holt[1,5,**]
[1]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[2]*Perimeter Institute, 31 Caroline Street North, Waterloo, Ontario N2L 2Y5, Canada*
[3]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[4]*Department of Physics, University of Washington, Seattle, Washington 98195, USA*
[5]*Department of Physics, McGill University, Montréal, Quebec City H3A 2T8, Canada*

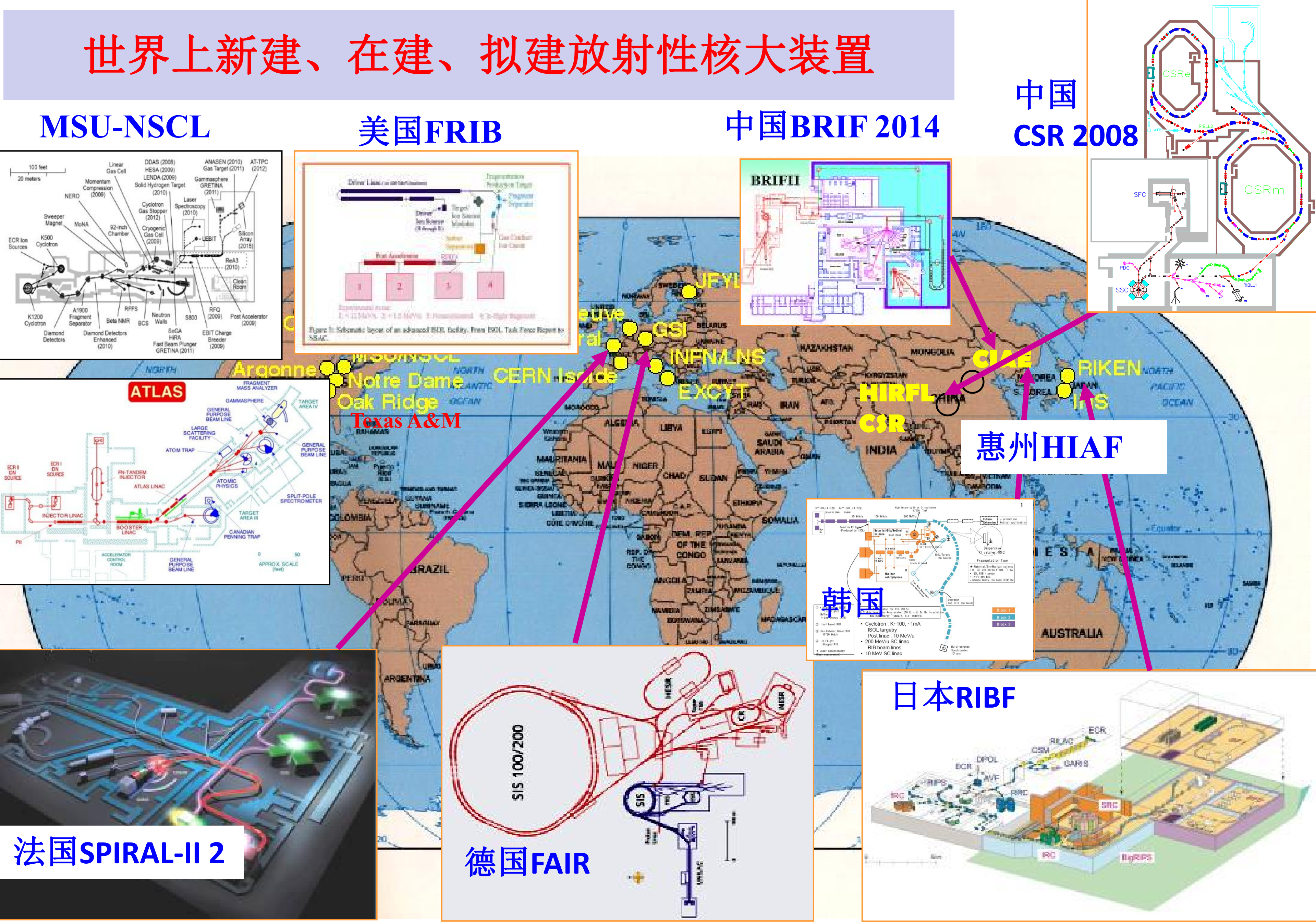
目标 — 为暗物质实验直接测量提供：

1）暗物质粒子与原子核散射的最佳侯选核

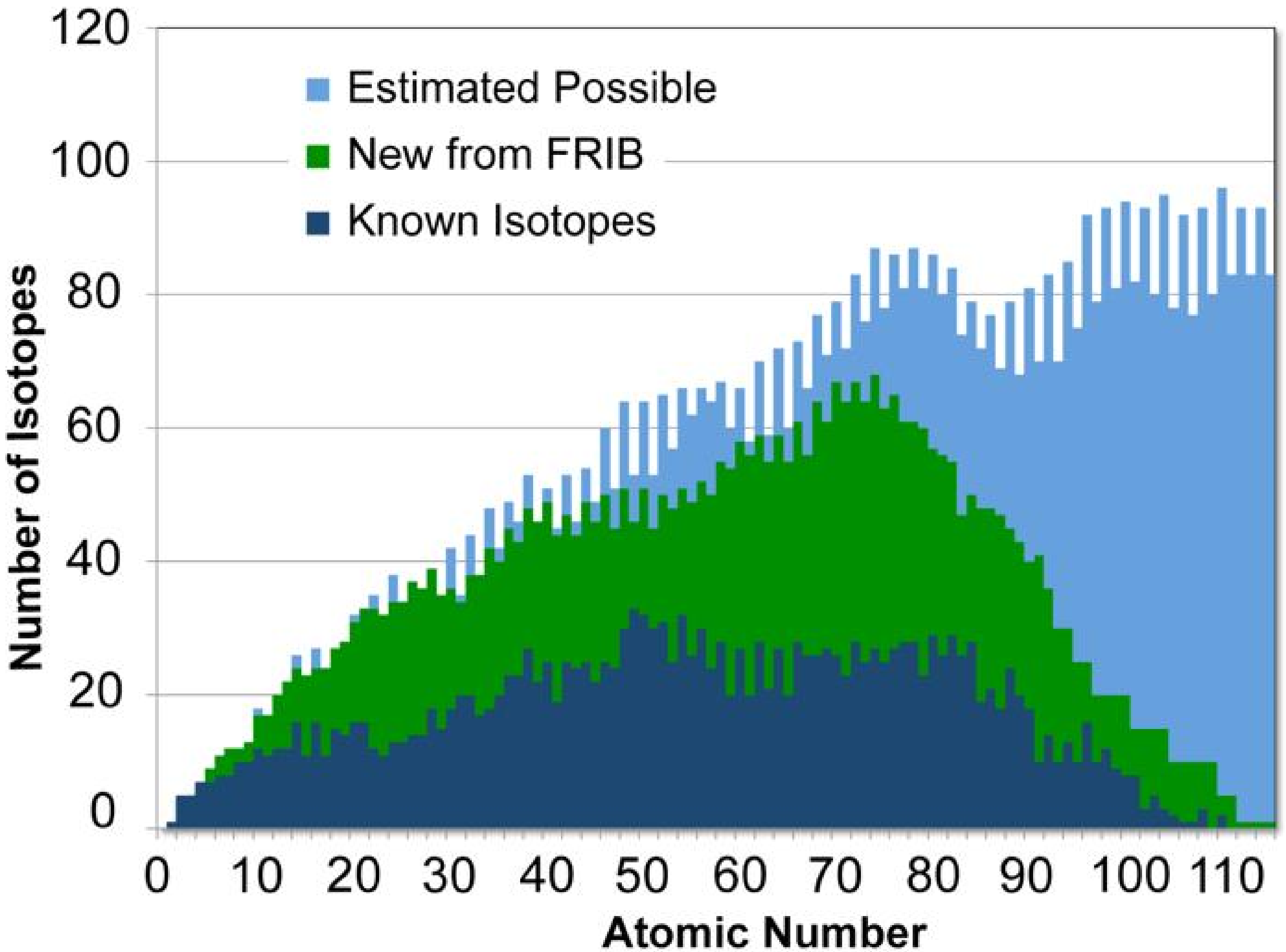
2）散射截面

3）最佳能区

世界上新建、在建、拟建放射性核大装置



The Number of Isotopes Available for Study



- Estimated Possible: Erler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, to be published, based on a study of EDF models
- "Known" defined as isotopes with at least one excited state known
- Below Z=90 FRIB will be able to make >80% of all possible isotopes

核物理的新理论方法

核理论的二个最基本问题

1. 核力（Nuclear Force, 强相互作用）
2. 强关联量子多体体系的求解（many-body problems)

$$\hat{H}_{int} = \sum_{i<j}^{A} \frac{(\vec{p}_i - \vec{p}_j)^2}{2mA} + \sum_{i<j}^{A} V_{NN,ij} + \sum_{i<j<k}^{A} V_{NNN,ijk}$$

写出来难，处理起来难

最好从QCD出发，但目前还不是很成功…

Physics World公布2022年十大年度突破性成果

Courtesy: IOP Publishing

01 迎来超冷化学的新时代

02 观测到理论预言的四中子状态

两院院士评选“2022年中国/世界十大科技进展新闻”揭晓

中国科学报 2023-01-12 11:01 发表于北京

2022年世界十大科技进展新闻

01 首个完整人类基因组序列公布

⋮

10 科学家发现“四中子态”存在最明确证据

四中子共振态（Tetraneutron）

（大概60年前，猜想）

Home About Us News Archive Copyright Privacy Policy Contact Us Newsletter RSS

SCI NEWS

HOME ASTRONOMY SPACE EXPLORATION ARCHAEOLOGY PALEONTOLOGY BIOLOGY PHYSICS MED

Physicists Observe Elusive Four-Neutron System: Tetraneutron

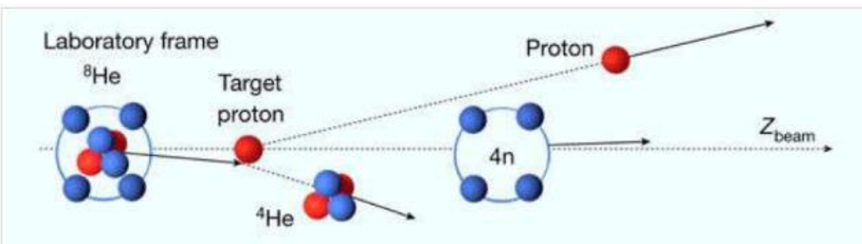
Jun 23, 2022 by Enrico de Lazaro « Previous |

Published in
Physics

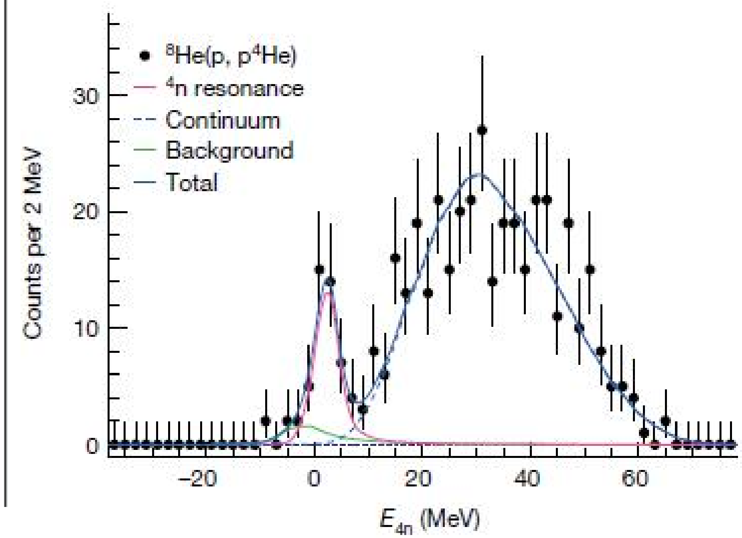
Tagged as
Alpha particle
Helium
Helium-4
Helium-8
Neutron
Proton
SAMURAI
Tetraneutron

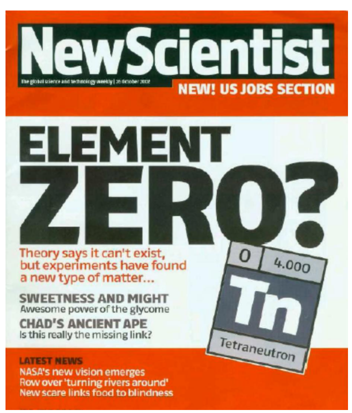
Follow
You Might Like

Physicists using the Superconducting Analyzer for Multi-particles from Radio Isotope Beams (SAMURAI) in Japan have experimentally observed a resonance-like structure consistent with a tetraneutron state after 60 years of experimental attempts to clarify its existence.



M. Duer *et al*., Nature 606, 678 (2022)



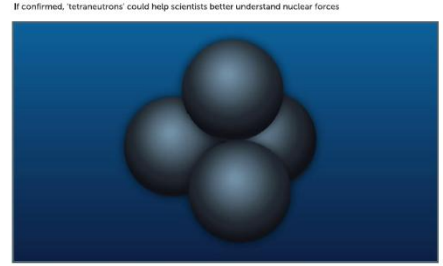


ScienceNews
INDEPENDENT JOURNALISM SINCE 1921

NEWS PHYSICS

Physicists may have finally spotted elusive clusters of four neutrons

If confirmed, 'tetraneutrons' could help scientists better understand nuclear forces



Four neutrons may form a short-lived agglomeration called a tetraneutron (illustrated).
SONJA BATTENBERG/TUM

By Emily Conover
JUNE 22, 2022 AT 11:00 AM

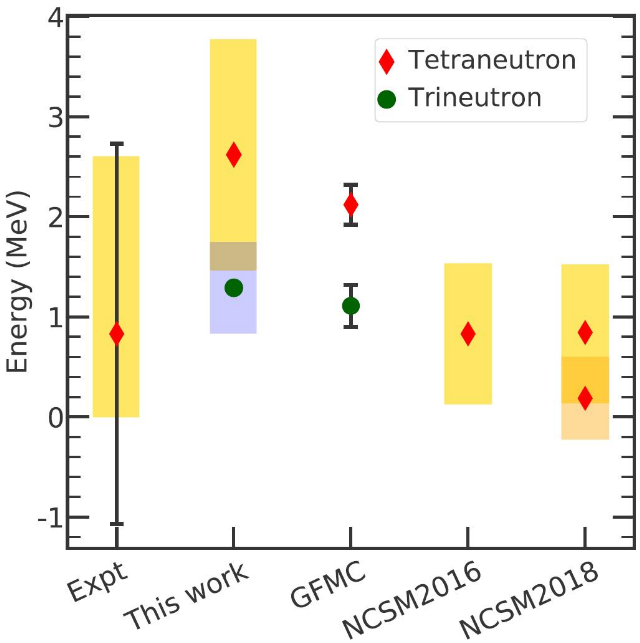
Chiral EFT N^3LO + NCGSM, 考虑更多的强关联：Gamow 自然基

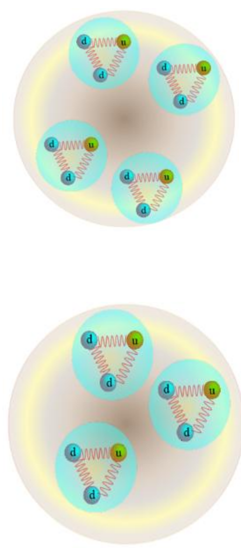
PHYSICAL REVIEW C **100**, 054313 (2019)

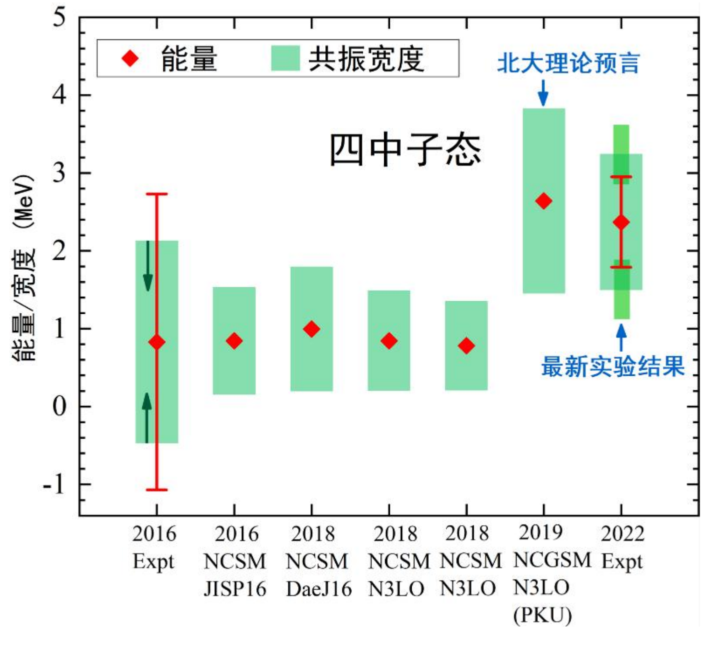
Ab initio no-core Gamow shell-model calculations of multineutron systems

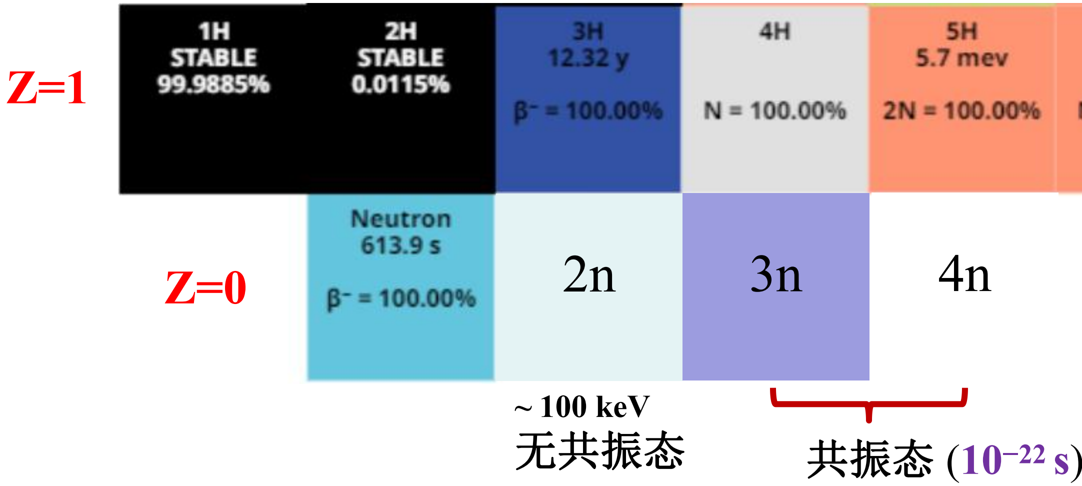
J. G. Li,[1] N. Michel,[2,3] B. S. Hu,[1] W. Zuo,[2,3] and F. R. Xu[1,*]

[1]School of Physics, and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
[2]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[3]School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China







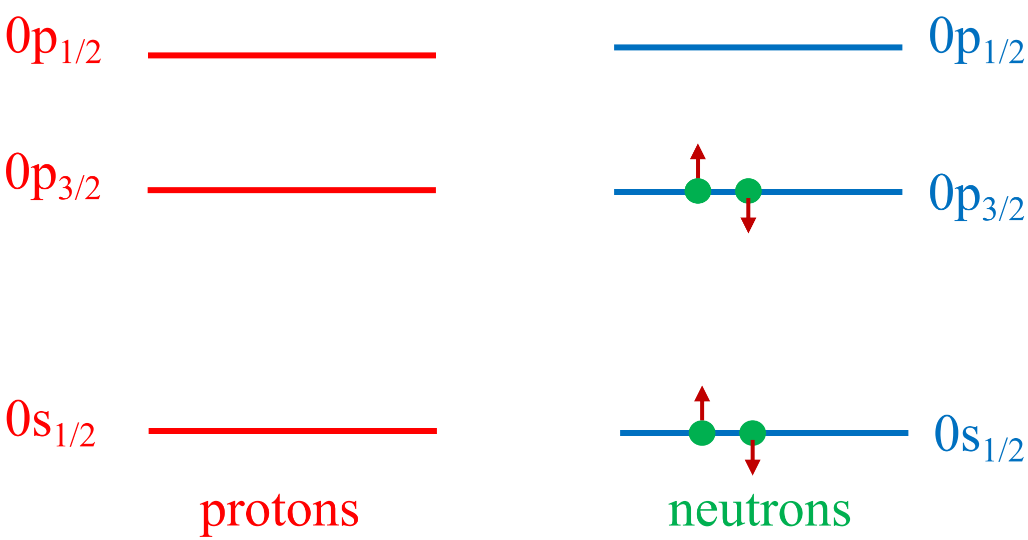


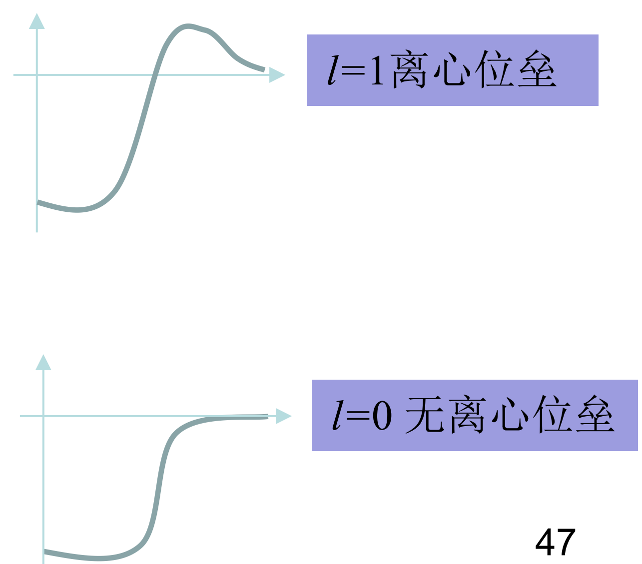
发现4n体系的重要性：

1）核力（nn）

2）纯中子物质

…





小结

历史：在量子力学建立初期，核物理起非常重要的作用

- 核物理还有许多事情要做！
- 新一代大型先进核设施建设将给我们带来空前的机遇，同时对理论是挑战！
- 还会有新的激动人心的新发现！

Brief History of Nuclear Physics

1896: discovery of radioactivity by Becquerel
1898: separation of Radium by Maria and Pierre Curie; discovery of α, β, γ rays
1911: nucleus as a central part of an atom – Rutherford
1913: Soddy and Richards elucidate the concept of nuclear mass: isotopes are born
1919: Rutherford carries out first transmutation ($He+N \rightarrow p+O$)
1923: Georg von Hevesy uses radioactive tracers in biology
1928: theory of alpha decay by Gamow
1929: cyclotron (Ernest Lawrence); Rasetti discovers spin J=1 for ^{14}N
1930: Pauli predicts neutrino; Dirac predicts antimatter
1932: discovery of the neutron by Chadwick; discovery of positrons by Anderson
1934: Fermi theory of beta decay; Baade and Zwicky predict neutron stars
1935: nuclear (strong) force through meson exchange – Yukawa
1936: John Lawrence treats leukemia with ^{32}P
1938: stars are powered by nuclear fusion (Gamow, von Weizsäcker, Bethe): pp, CNO
1939: nuclear fission (Hahn, Strassman, Meitner, Frisch); Bohr, Wheeler explain fission
1940: McMillan and Abelson produce a new element ($n+^{238}U \rightarrow ^{239}U \rightarrow ^{239}Np \rightarrow ^{239}Pu$)
1942: first self-sustaining fission reaction (Fermi); Manhattan project (Oppenheimer)
1945: atomic bomb
1947: pi meson discovered in Bristol (by studying cosmic ray tracks)
1948: Big Bang nucleosynthesis (Alpher, Bethe, Gamow)
Electricity generated at the X-10 Graphite Reactor in Oak Ridge

1949: nuclear shell model (Mayer, Jensen)
1951: nuclear collective model (Bohr, Mottelson, Rainwater)
1952: hydrogen bomb (Teller, Ulam); Hoyle resonance predicted
1954: proton therapy at Berkeley
1956: experimental evidence for antineutrino (Reines, Cowan)
prediction and discovery of parity violation (Lee, Yang, Wu)
1957: stellar nucleosynthesis (Burbidge, Burbidge, Fowler, Hoyle)
1958: nuclear superconductivity (Bohr, Mottelson, Pines)
1961: first PET scan at Brookhaven
1964: quarks proposed (Gell-Mann, Zweig)
1967: discovery of neutron stars (Hewish, Shklovsky, Bell)
1969: intrinsic structure of the proton (SLAC)
1972: color charge and quantum chromodynamics (Fritsch, Gell-Mann)
1978: discovery of the gluon (DESY)
1982: chiral symmetry on the lattice (Ginsparg, Wilson)
1983: discovery of W and Z intermediate vector bosons (CERN)
1995: top quark discovered (Fermilab)
1999: discovery of particle stability of ^{31}F (RIKEN)
2001: neutrino oscillations (Super-Kamiokande, SNO)
2002: element Z=118 produced in Dubna
2005: quark–gluon liquid of very low viscosity discovered at RHIC
2008: discovery of ^{40}Mg at MSU https://www.youtube.com/watch?v=tJsam4z715c

|| CUSTIPEN Homepage || 中文版本

- Home
- Policies
- Application Form
- Governing Board
- Conferences and Workshops
- Visitors
- Information
- Publications
- Photo Gallery
- Contact Persons
- Jobs Info
- News and Events

About CUSTIPEN

Purpose:
Deliver an international venue for research on the physics of nuclei during an era of experimental investigations on rare isotopes.

Location:
Peking University, Beijing, China

US Participation:
Provide travel and local support for visits of U.S.-based physicists to CUSTIPEN

China Participation:
Provide local support for China-based physicists at CUSTIPEN

Synopsis:
The China-U.S. Theory Institute for Physics with Exotic Nuclei (CUSTIPEN) has been established in order to facilitate collaborations between U.S. and Chinese scientists whose main research thrust is in the area of the physics of nuclei. U.S. participation in CUSTIPEN is in the form of travel grants and subsistence grants to those individuals who are interested in collaborating with Chinese scientists.


谢 谢
2023.04.21 科大