远离稳定线核的衰变研究

Yanlin Ye

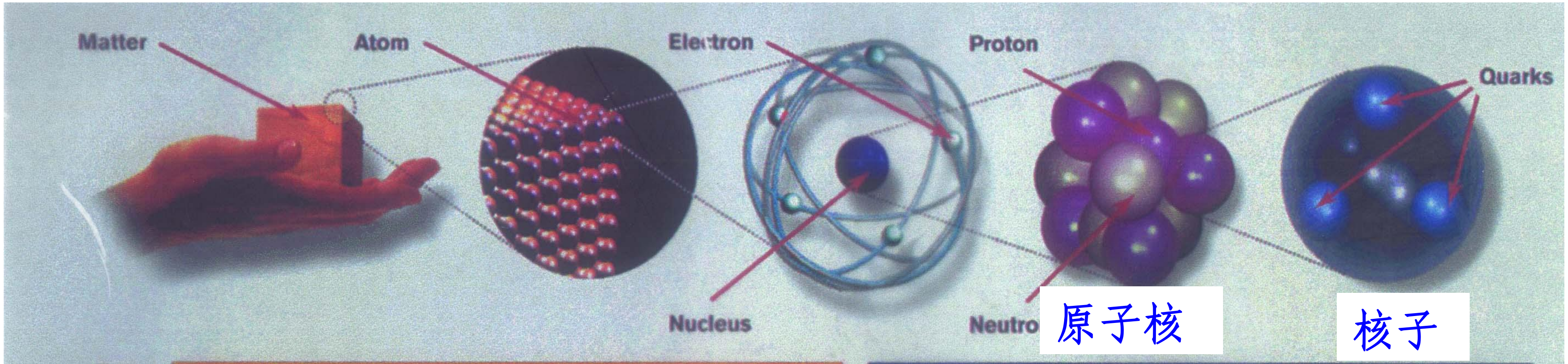
School of Physics and State Key Lab. of
Nucl. Phys.&Tech. Peking University

2013.08.21. 西昌

提 纲

I. RIB物理的一般性问题

II. β 延迟衰变研究



物质世界以层次划分

层次间有关联，但也相互屏蔽和独立，否则层次就消失了。

实验观察是互补互斥的。

每个层次都有独特的结构自由度、有效相互作用和运动规律,。

原子核是独特的微观层次

量子有限多体复杂体系

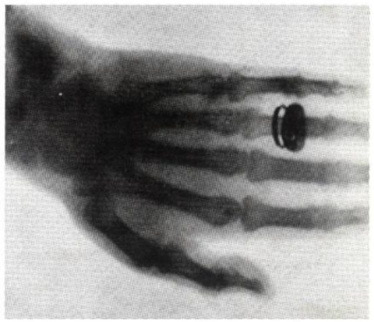
丰富的相互作用、内秉自由度和对称性

宇宙元素、能量变迁;

加速器和射线技术

核科学对人类的生存与发展和国家的地位与安全产生了重大影响，成为衡量综合国力的一项重要标志。

例：



第一张人手X光片

原始创新方式讨论，

以100多年核物理-粒子物理发展为例

（达到诺贝尔奖提名以上）

- 目标型（靠大投入）　（~17项，～19%）
- 探索型（靠制度、环境、兴趣、运气）（~52项，～57%）
- 智慧型（靠小环境和天才群体）（~22项，～24%）

RIB物理创新主要属于探索型和智慧型？

（超重元素合成为目标型）

20多年来RIB物理已有的重要发现

- 壳演化（新幻数；反转岛…)与新的有效相互作用
  monopole part of the tensor force ; 3B interactions; pairing; long and short range correlations；density dependence of the spin–orbit force; couplings to continuum；…
- 滴线区新的结构自由度与玻色子体系
  halo; cluster; molecular; di-neutron;
- 新的集体运动模式
  PDR；shape
- 反应道之间的强关联
  strong couplings;
- 弱流强条件下的新方法与新手段
  SC separator; 0^0 spec.; active T; in-beam γ; Si strip;

（基本是偶然性发现和智慧型创新主导）

怎么做？

张玉虎：

- 小事做大论

  小事做大、小事做细、理论先行？

例：日本人的 **AMD/MO/GTCM**

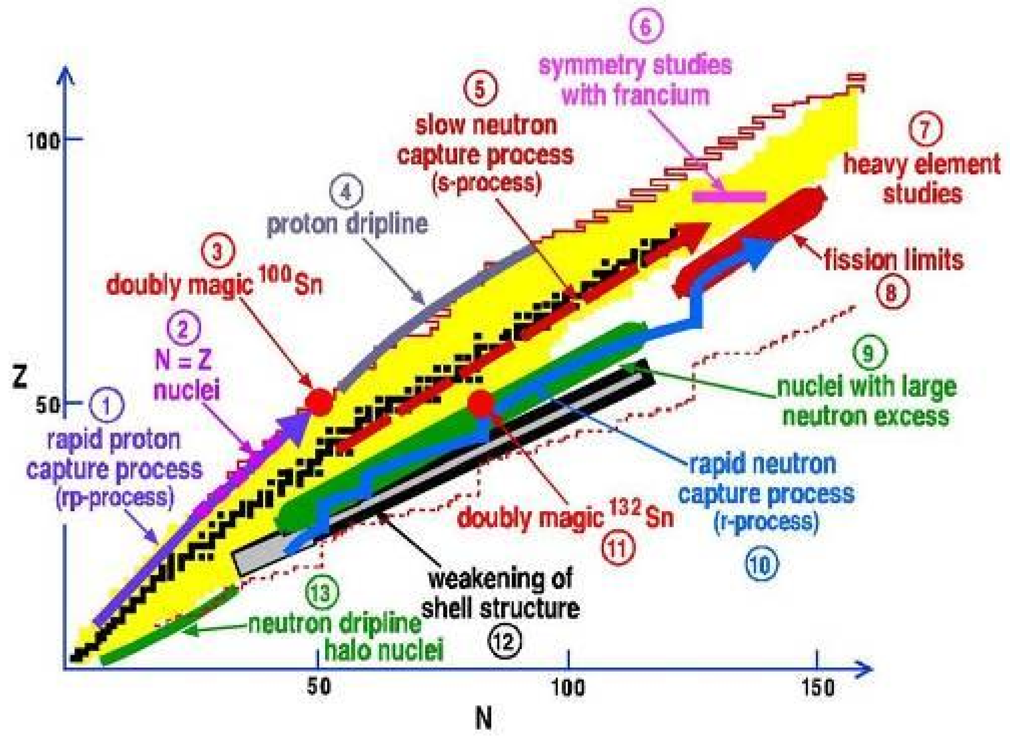
非稳定核区—丰富的科学宝藏和广阔的应用前景

稳定核 ~300

结构自由度和核力比较清楚。

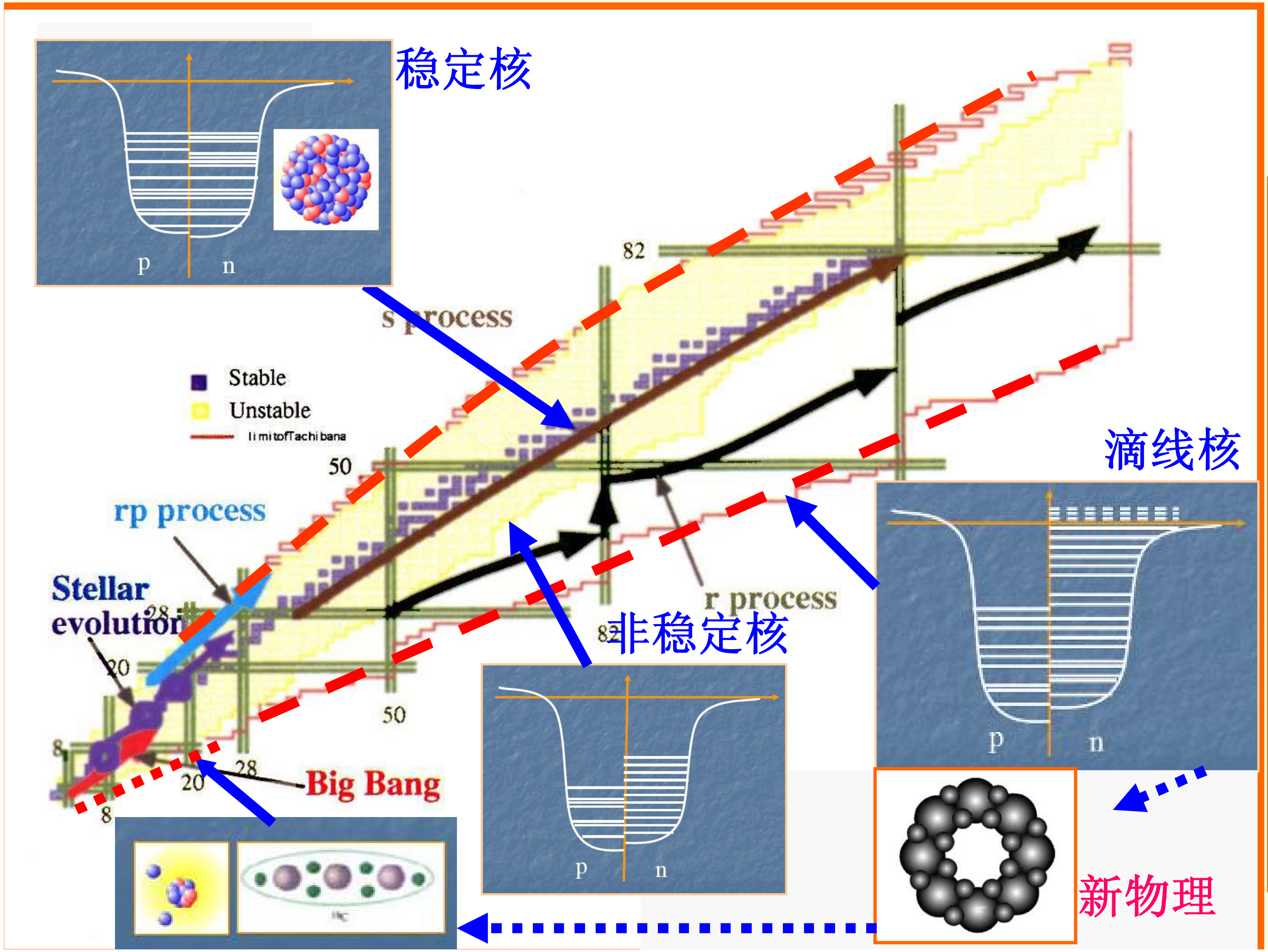
非稳定核—8000~10000

- 发现晕核、新幻数、集团自组织、新有效相互等新现象；
- 与超重核合成和天体演化密切相关；
- 新型储能装置、核材料、核数据等



稳定性极限—非稳定核边界区

对现有核理论的全面挑战



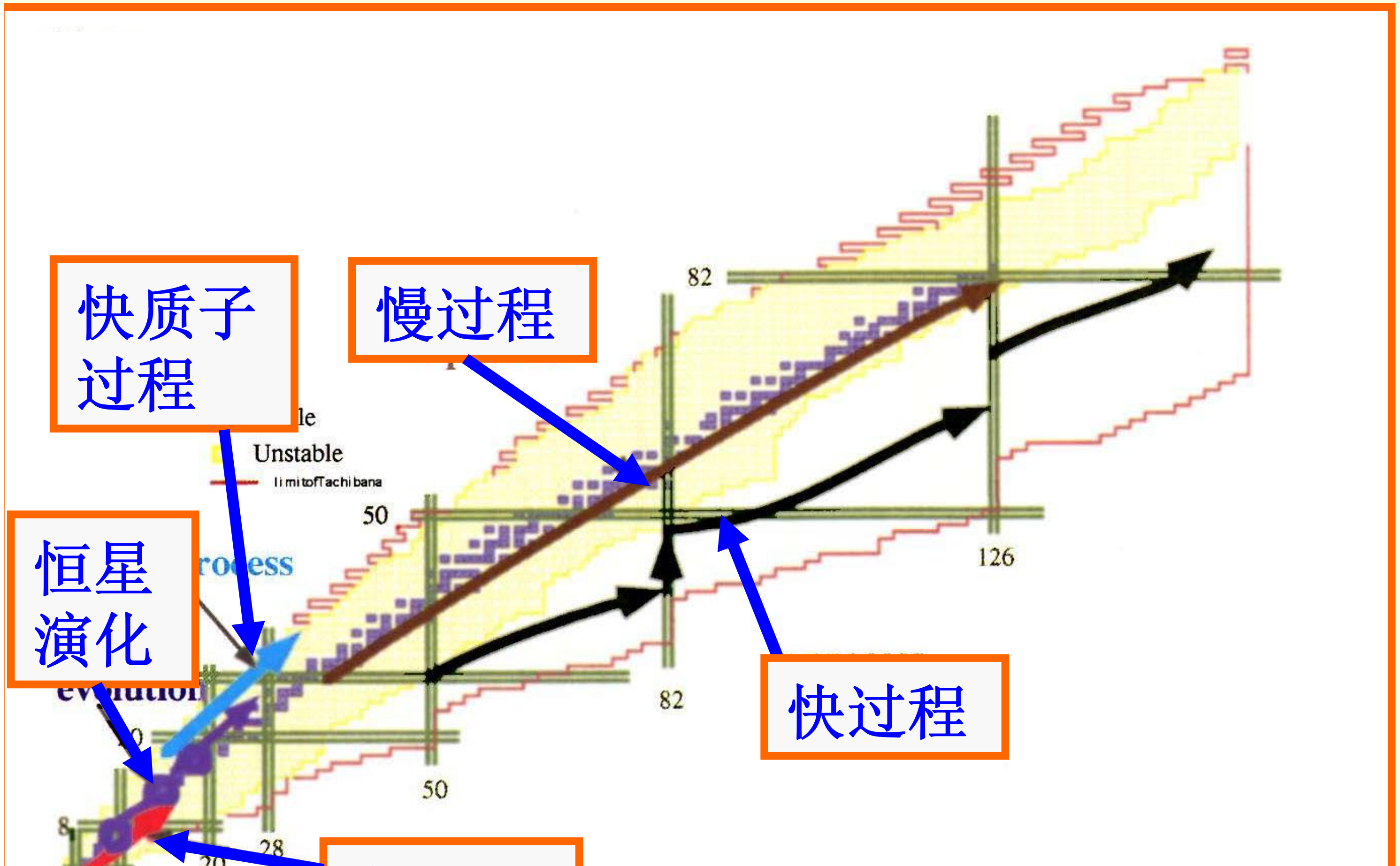
教科书

液滴模型？
V ∞ A（高密）
B ∞ A（饱和）

壳模型　？
幻数与壳层
单粒子结构

反应机制？
复合核反应
直接核反应

与天体核合成和宇观核物质性质密切关联



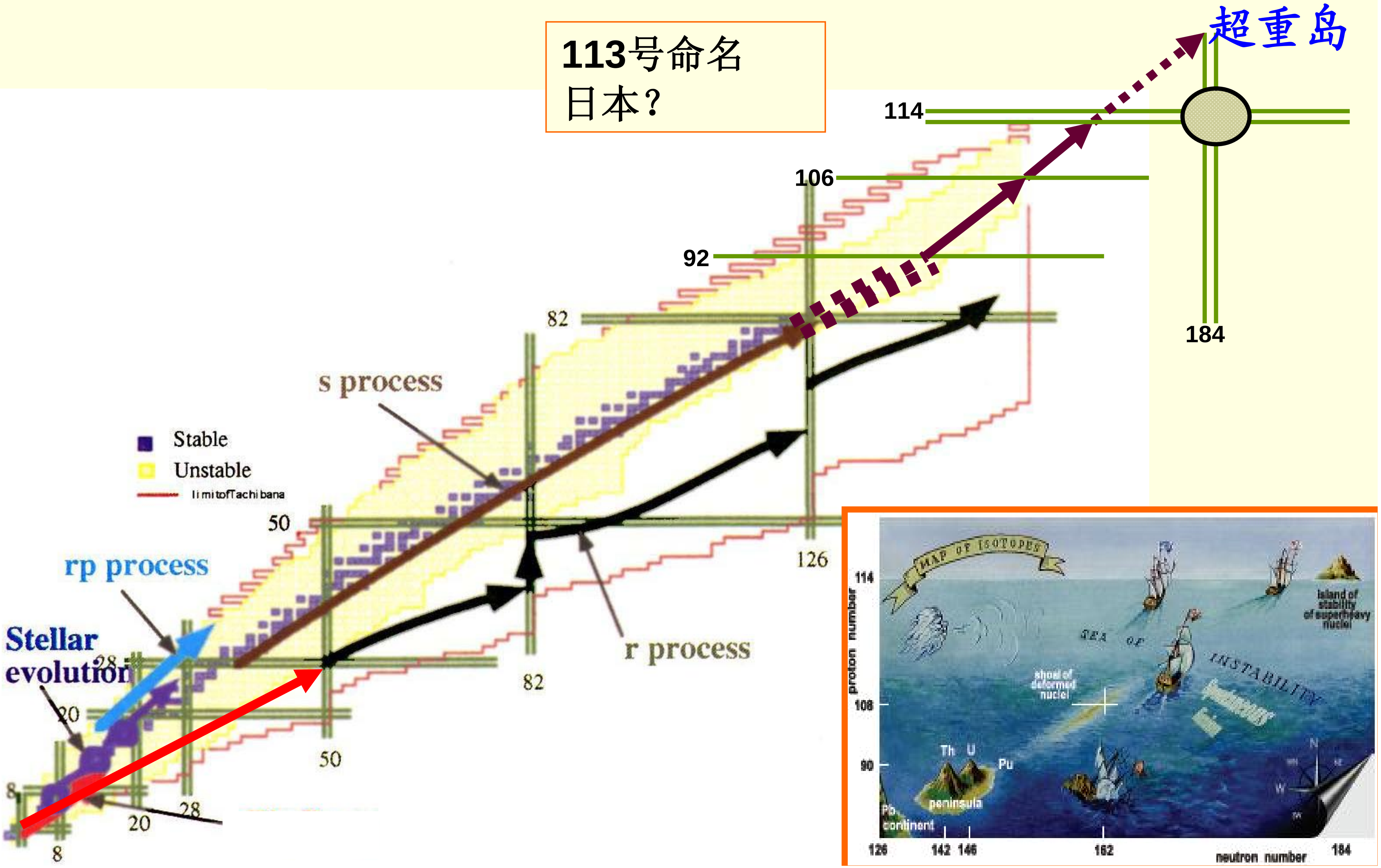
从铁到铀的重元素是如何产生的？

20世纪留给人类的11大物理学谜团，其中第三项：

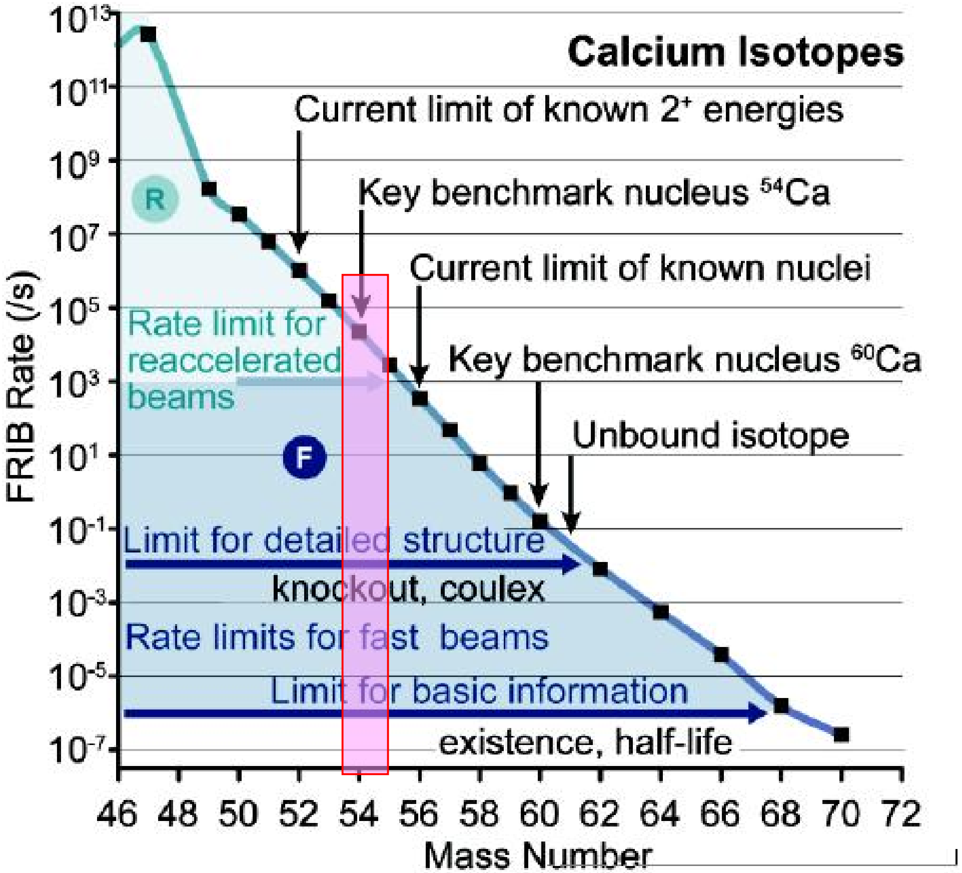
“How were the heavy elements from iron to uranium made?”

与攀登超重岛密切相关

113号命名
日本?



实验和理论的巨大机遇和挑战



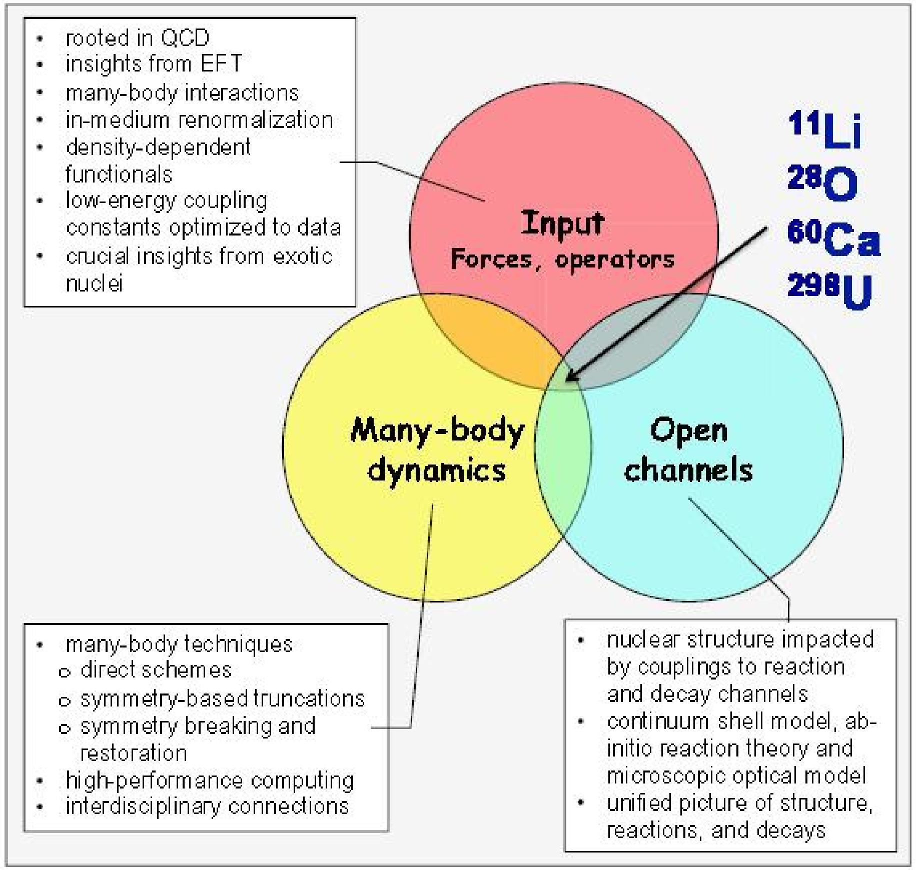
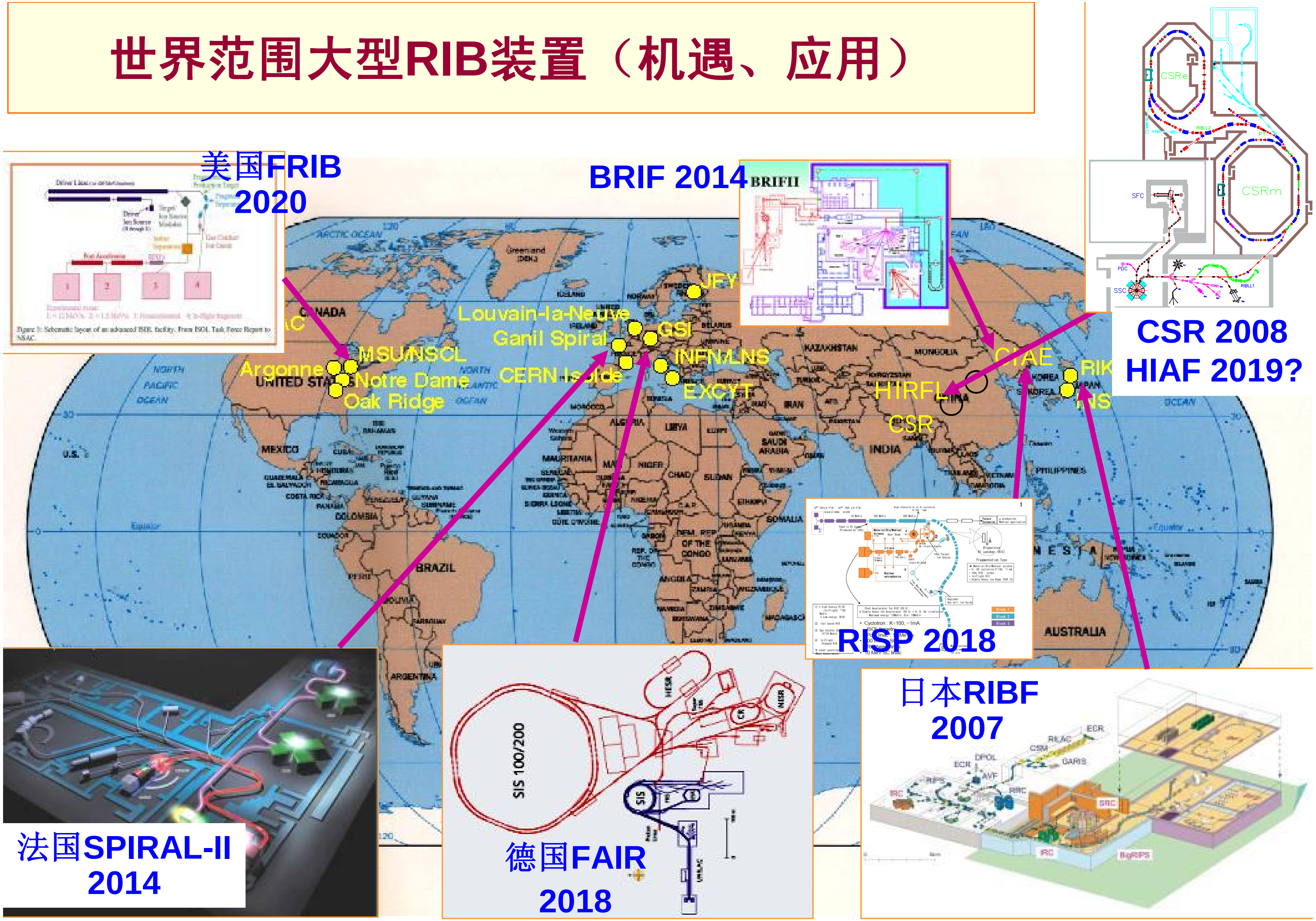


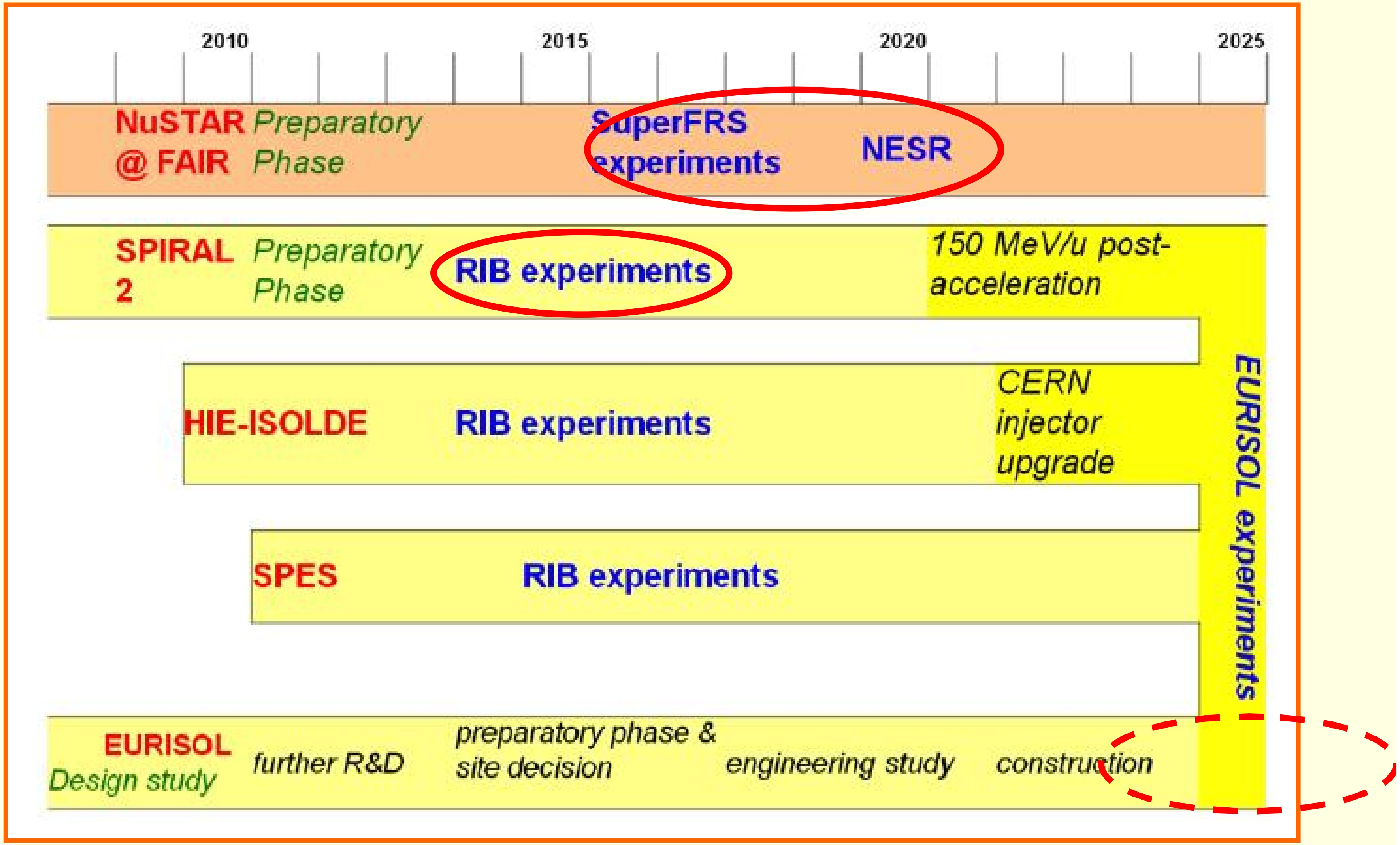
Figure 14. Challenges of the nuclear many-body problem. A comprehensive theoretical framework that would be quantitative, have predictive power, and provide uncertainty quantification must meet three stringent requirements: (i) the input must be quantified and of high quality; (ii) many-body dynamics and correlations must be accounted for; and (iii) the associated formalism must take care of open-quantum-system aspects of the nucleus. Only then can we hope to understand rare isotopes, such as ^{11}Li (two-neutron halo), ^{28}O (doubly-magic, probably unbound), ^{60}Ca (territory for new physics, where *ab initio* theory and DFT meet), and ^{298}U (r-process system, fission recycling participant),

世界范围大型RIB装置（机遇、应用）



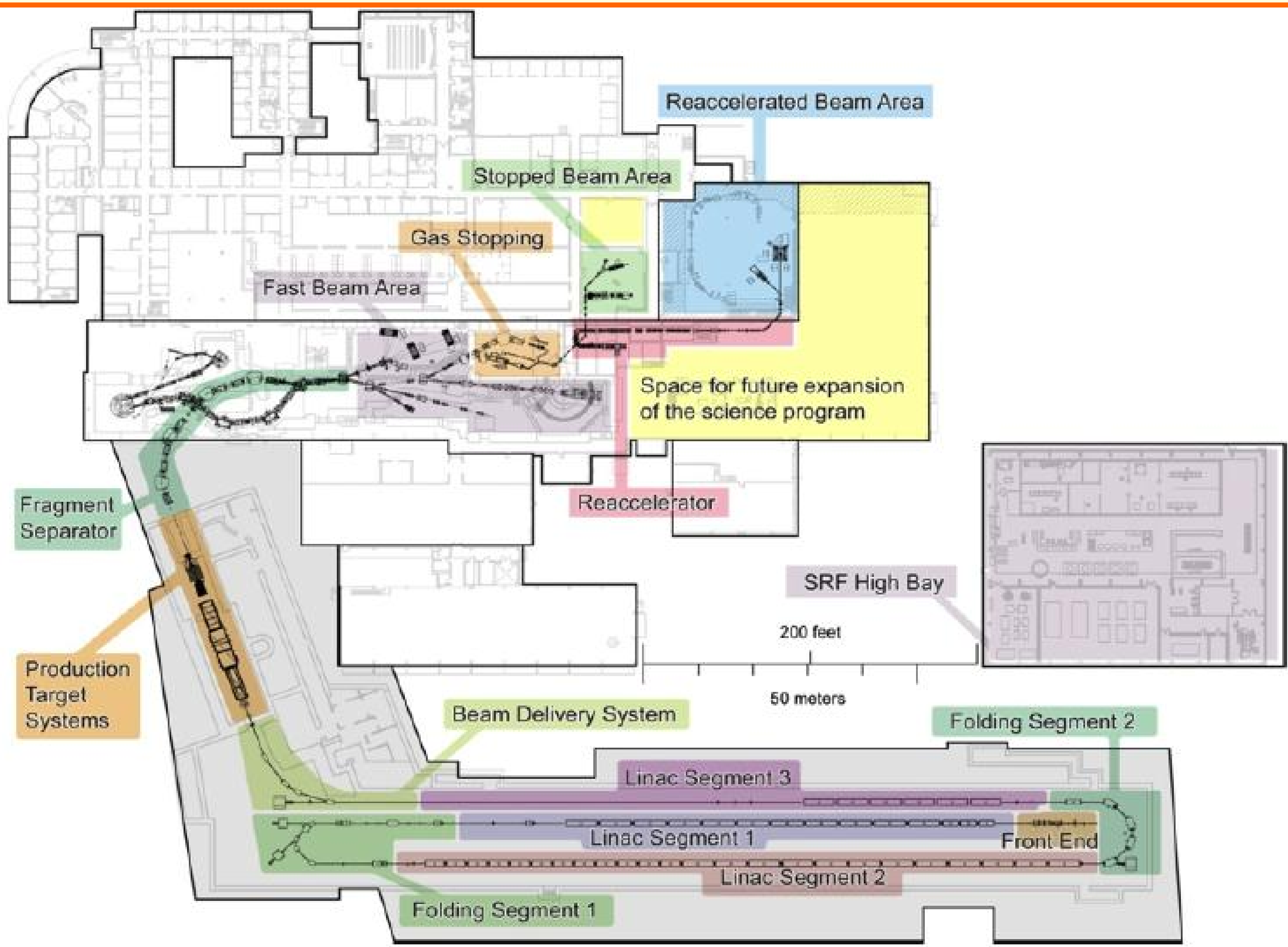
第三代RIB装置：78Ni 1~10 pps

欧洲RIB装置时间表



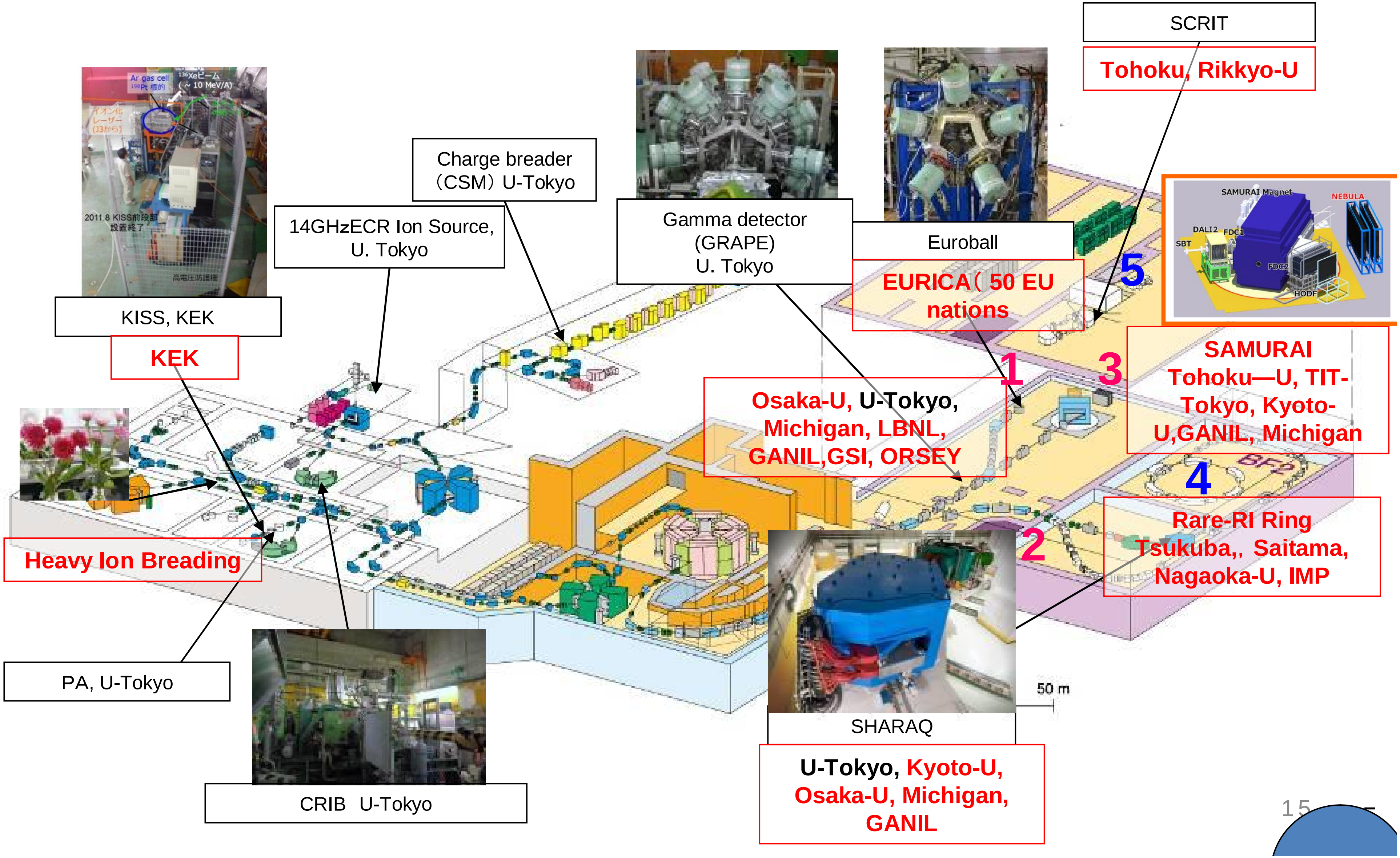
The NuPECC roadmap for RIB facilities.

美国FRIB（2020）



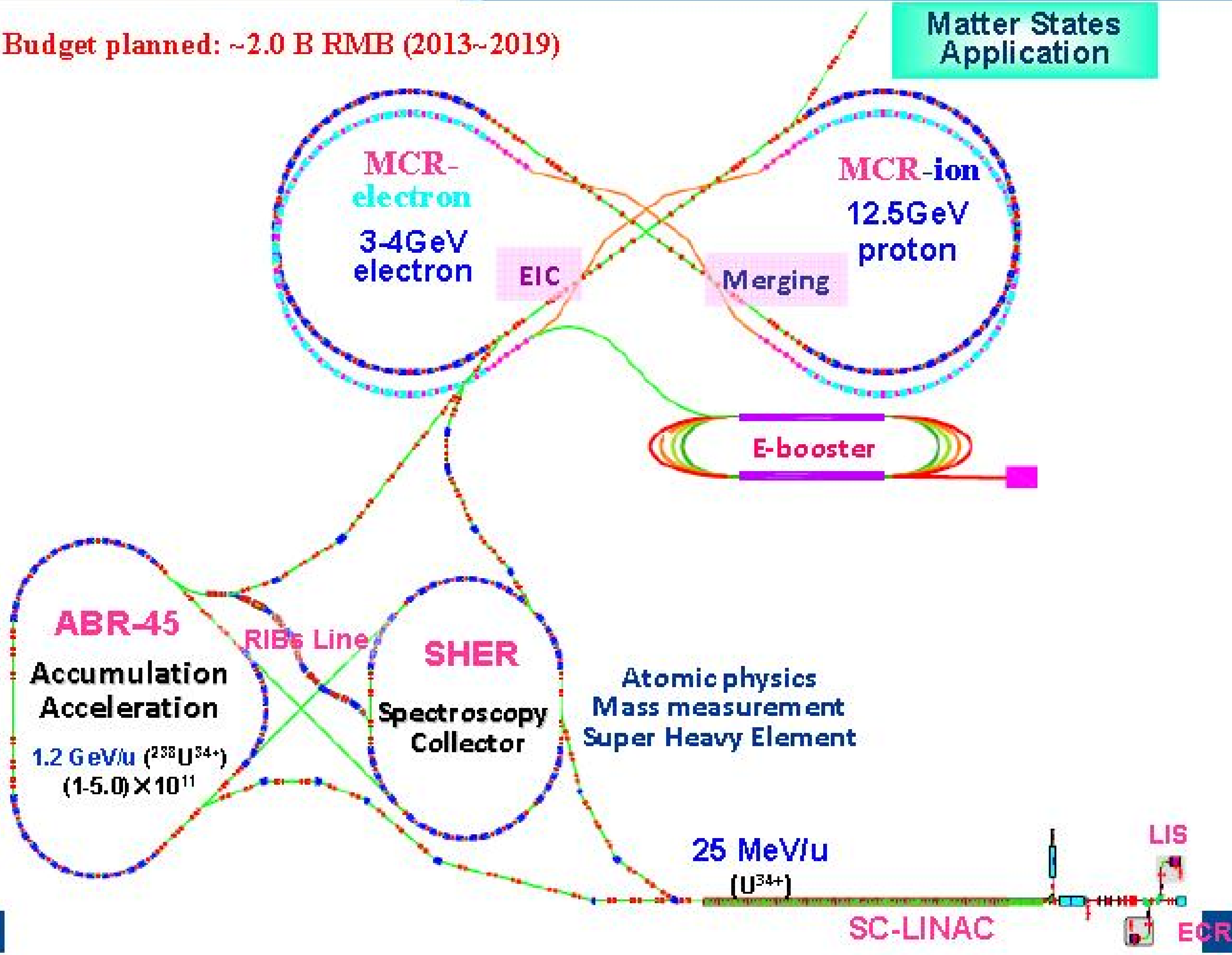
Schematic view of the planned FRIB project.

日本RIBF-International User Facility
(用户群和国际影响)



Future Facility: HIAF

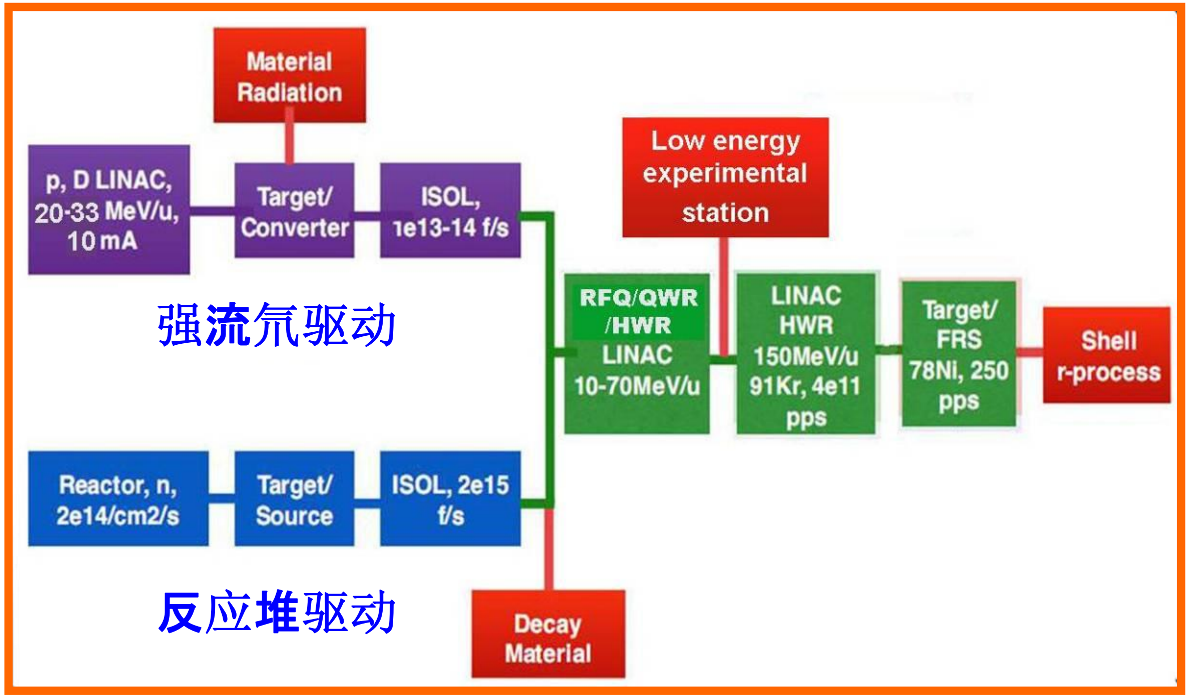
Budget planned: ~2.0 B RMB (2013~2019)



设想的第四代RIB装置 — Beijing ISOL

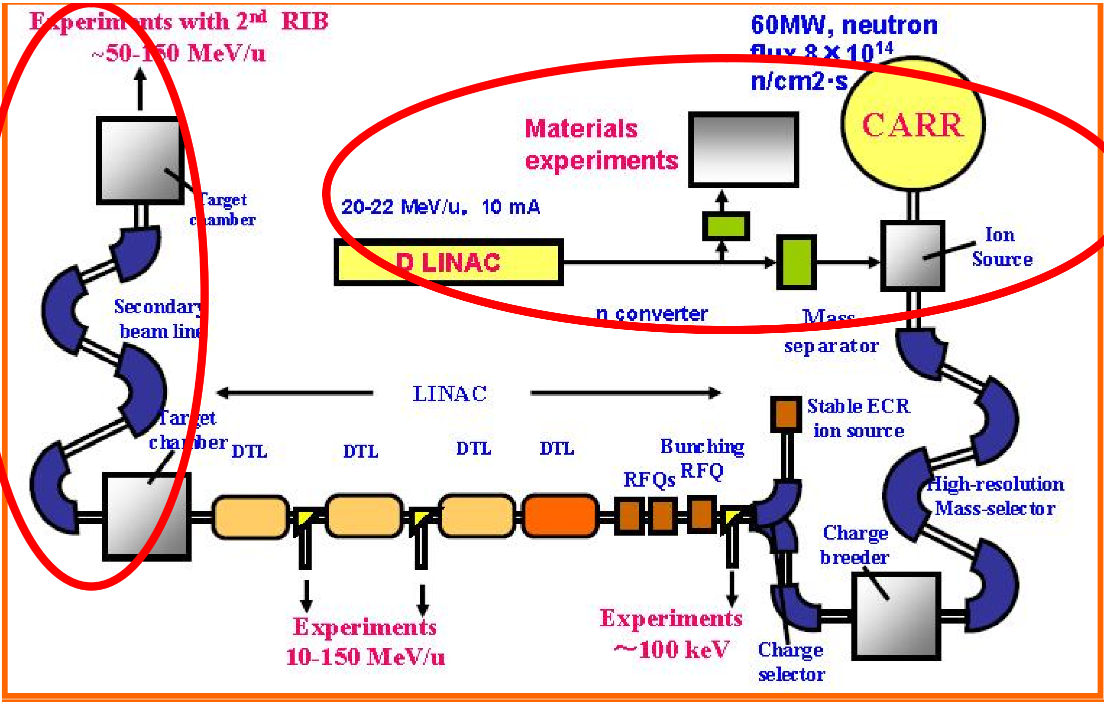
EURISOL → Beijing ISOL

- 强流氘驱动 (IDD) + 反应堆驱动 (RD)
- 在线同位素分离 (ISOL) + 弹核破碎 (PF)
- 基础科学目标（RIB） + 国家重大需求目标（核能材料）

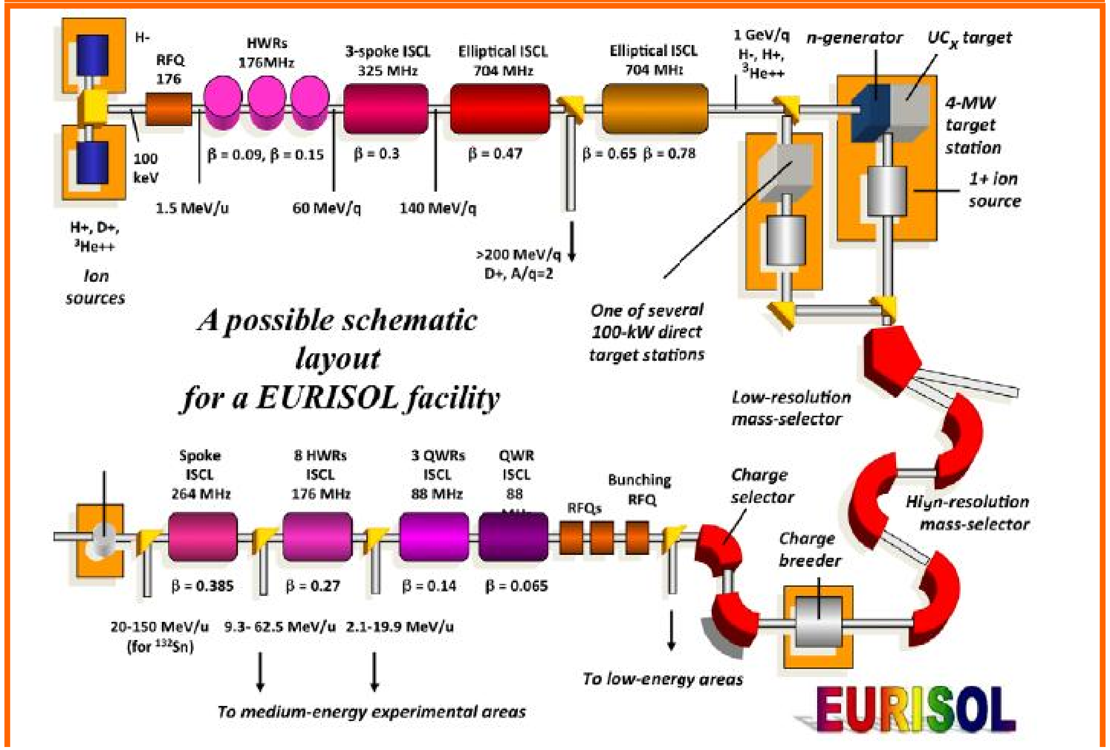


已经召开：
三次国内专家组会议；
两次国际咨询委员会会议

国际反响热烈！

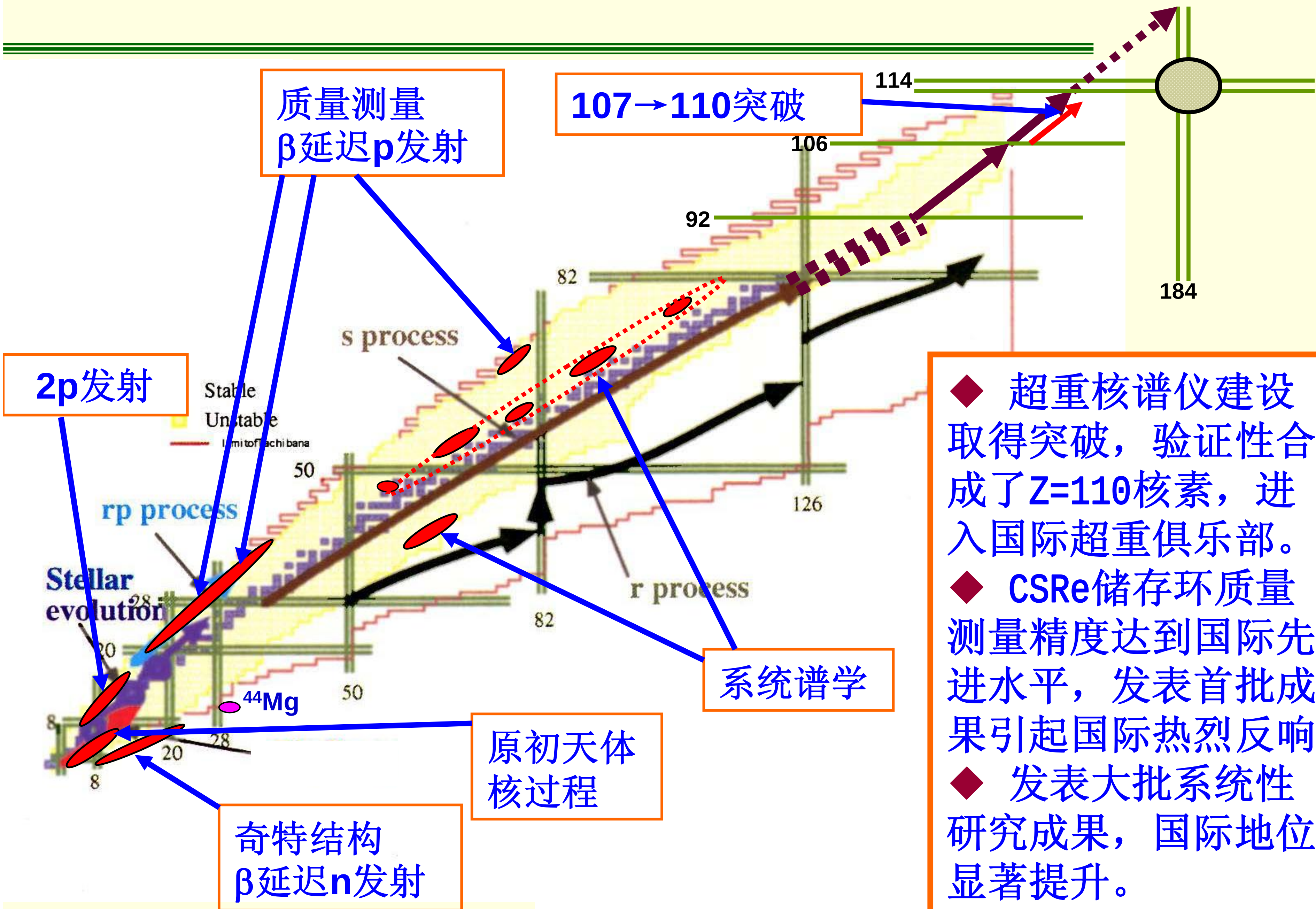


Beijing
ISOL



EURISOL

上一轮“973”项目（2007-2011）重要工作

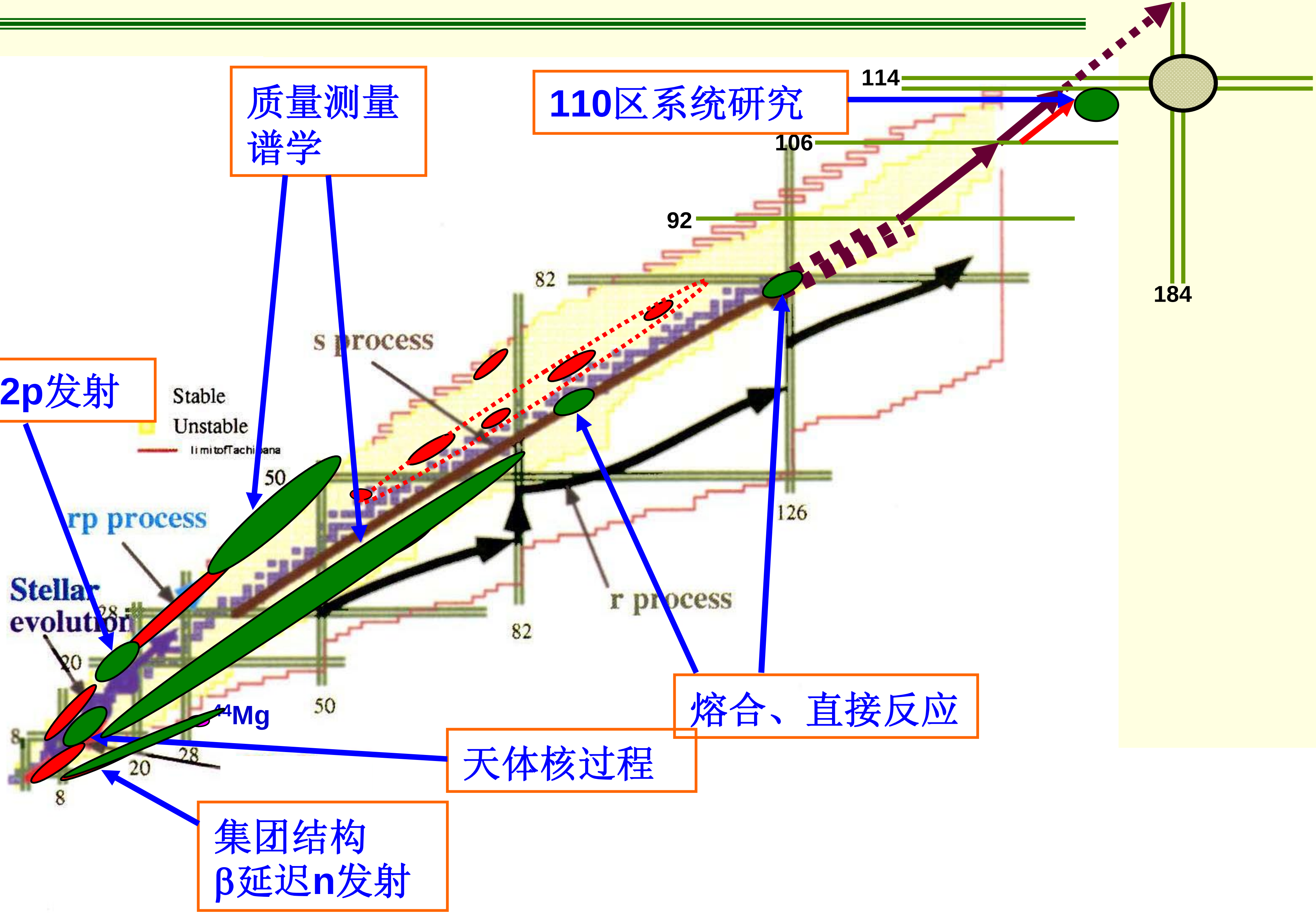


◆ 超重核谱仪建设取得突破，验证性合成了Z=110核素，进入国际超重俱乐部。

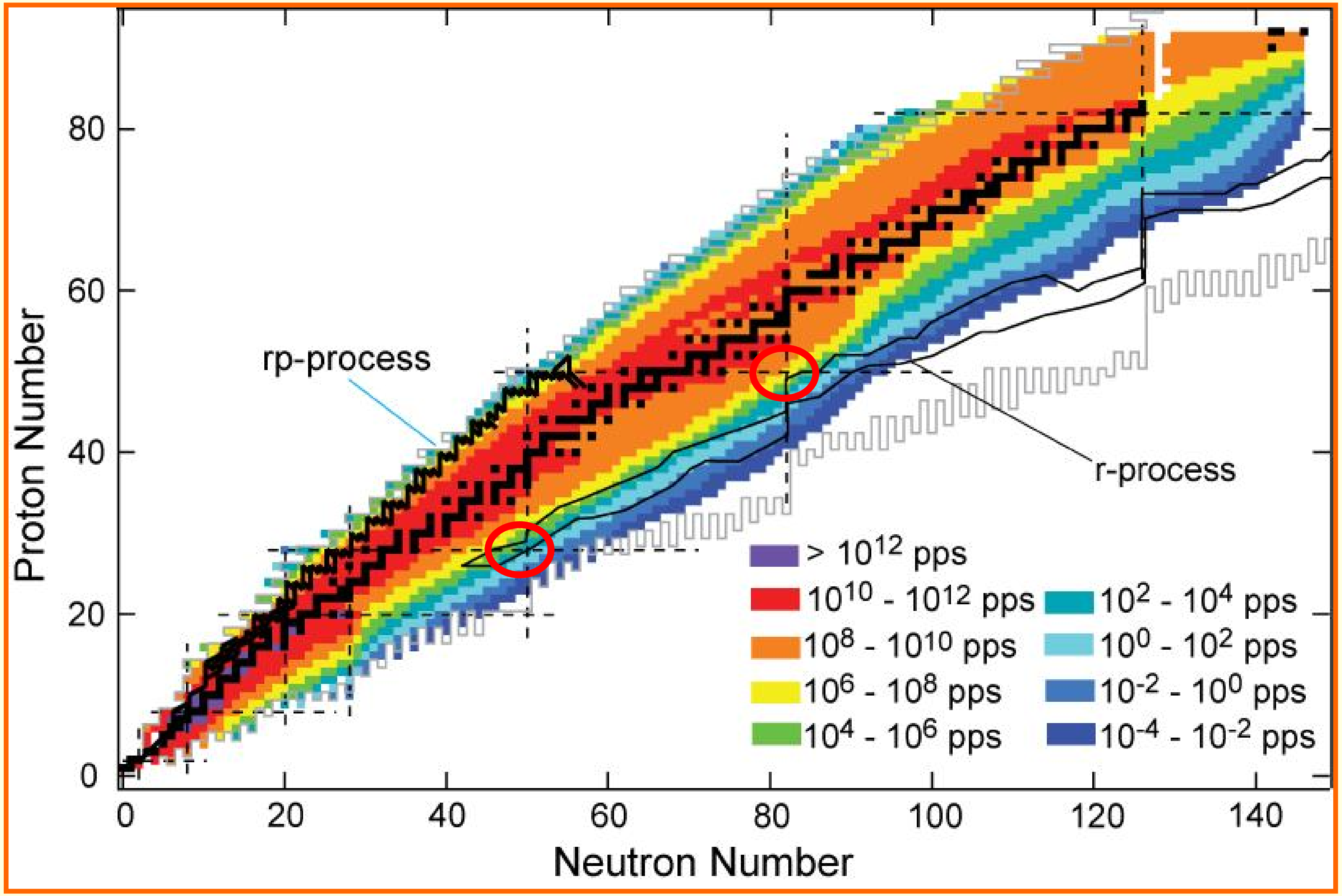
◆ CSRe储存环质量测量精度达到国际先进水平，发表首批成果引起国际热烈反响。

◆ 发表大批系统性研究成果，国际地位显著提升。

新一轮（2013-2017）工作重点



RIB物理还会有30～50年活跃期



The Reach of FRIB

提 纲

I.　RIB物理的一般性问题

II.　β 延迟衰变研究

Phys. Scr. **T152** (2013) 014013 (17pp) doi:10.1088/0031-8949/2013/T152/014013

Beta-delayed particle emission

M J G Borge

Instituto de Estructura de la Materia, CSIC, Serrano 113bis, 28006 Madrid, Spain

REVIEWS OF MODERN PHYSICS, VOLUME 84, APRIL–JUNE 2012

Radioactive decays at limits of nuclear stability

M. Pfützner* and M. Karny

Faculty of Physics, University of Warsaw, Hoża 69, PL-00-681 Warszawa, Poland

Rep. Prog. Phys. **75** (2012) 036301 (21pp) doi:10.1088/0034-4885/75/3/03

Nuclear structure experiments along the neutron drip line

T Baumann[1], A Spyrou[1,2] and M Thoennessen[1,2]

[1] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824-1321, USA

[2] Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824-1321, USA

65% for one page

宇宙物理とRIビーム(bitmap)-E
94.8.20 3:46 PM

核天体过程

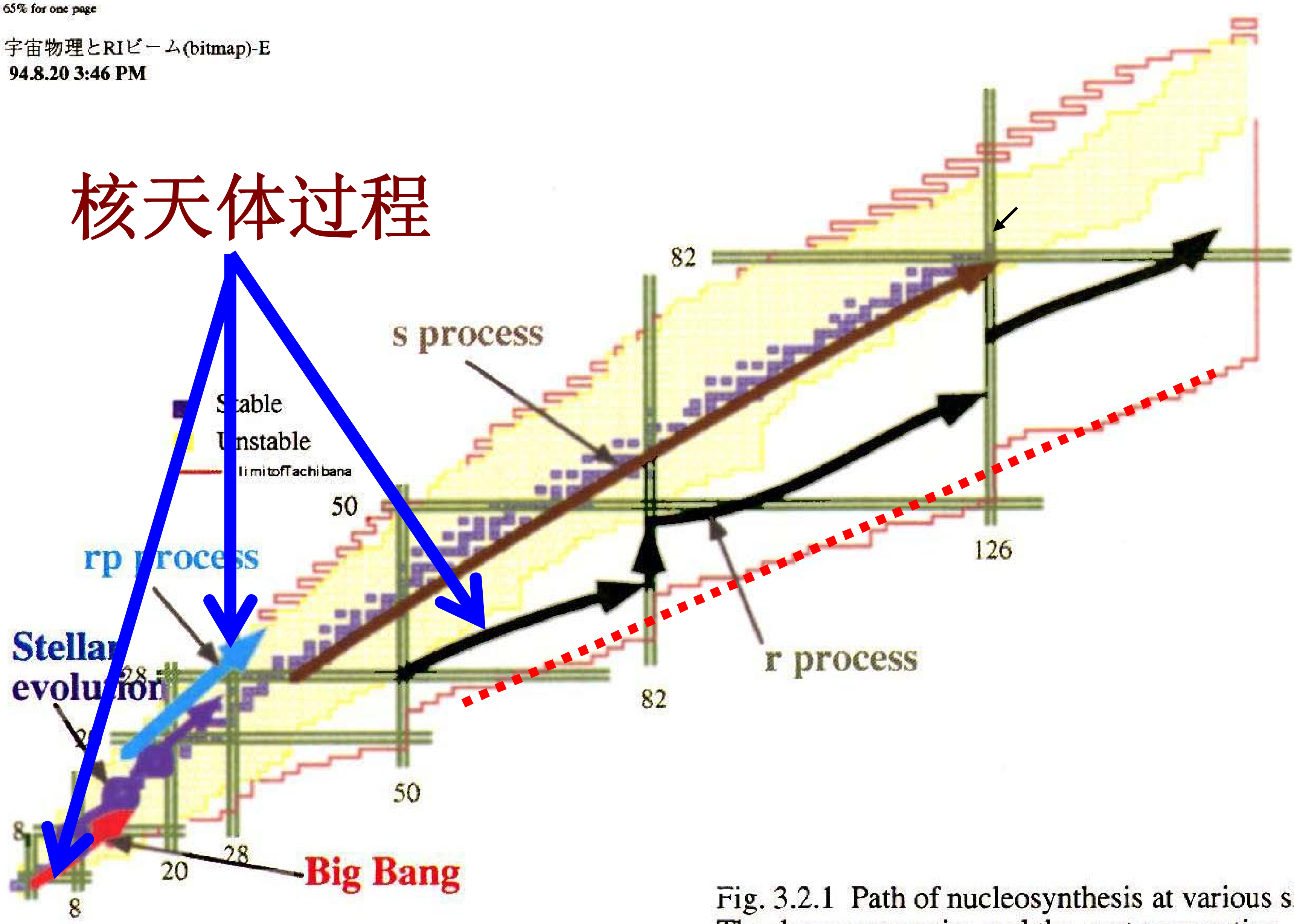
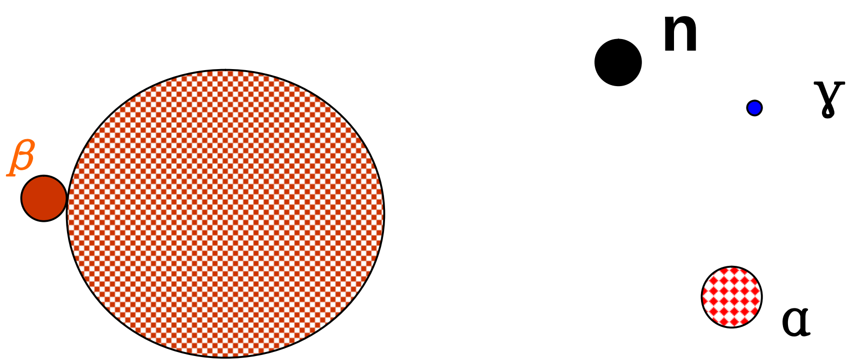


Fig. 3.2.1 Path of nucleosynthesis at various sites. The decay properties and the capture reaction rates of unstable nuclei are essential for understanding these path ways and thus the elemental abundances.

实验观测

- 稳定核：质量、自旋、磁矩、电四级矩。。。
  熔合激发衰变（谱学）；
  直接反应
  多重碎裂
  。。。
- 弱束缚核：质量、自旋、磁矩、电四级矩。。。
  总截面和动量分布；
  β 延迟粒子发射（谱学）
  直接核反应
  。。。


β
n
γ
α

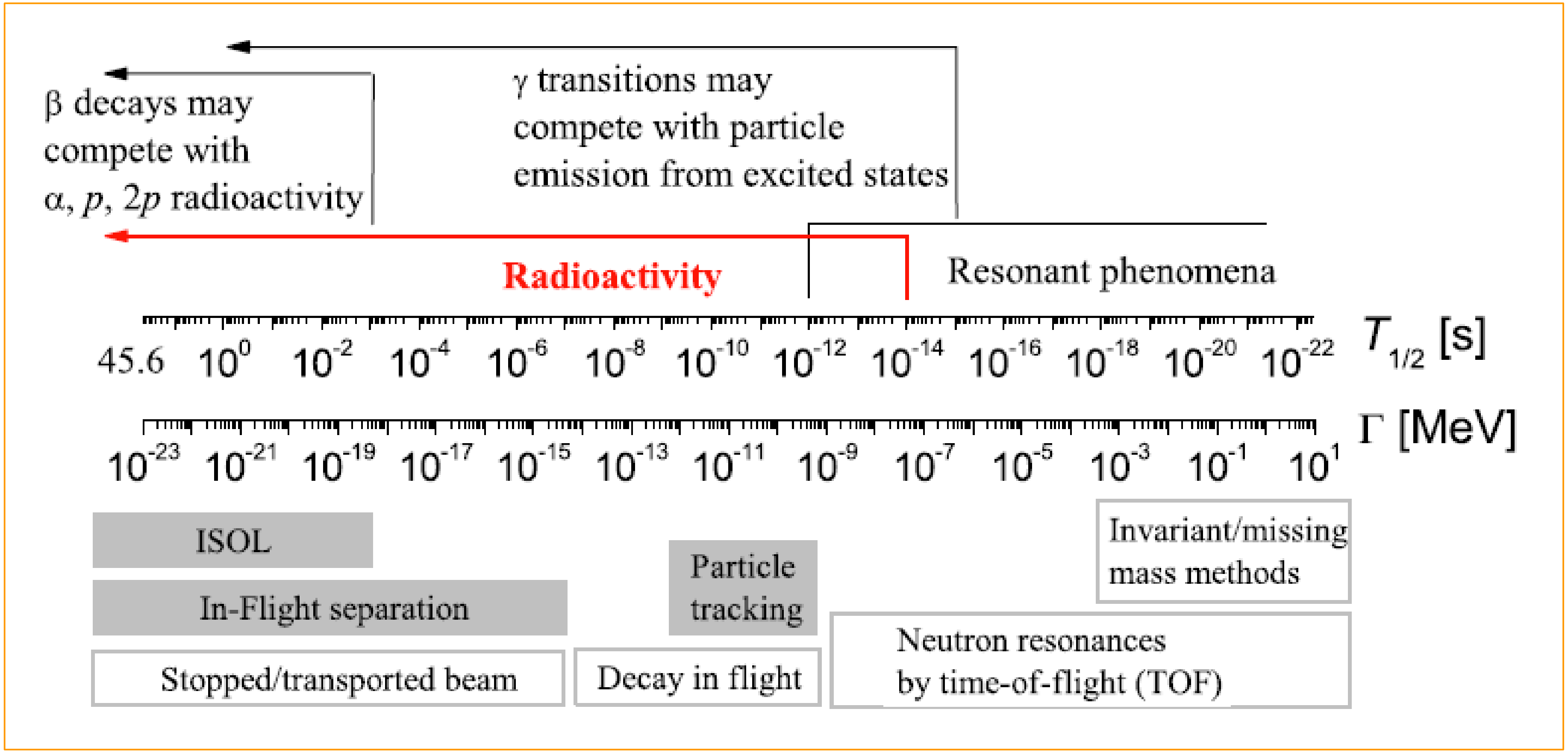
1st β-α: 1916;
1st β-n: 1939;
1st β-p: ~1960;
Now more than 400 β-particle precursors

$$ft = \frac{K}{g_V^2 B_F + g_A^2 B_{GT}}; \quad K = \frac{2\pi^3 \hbar^7 \ln 2}{m_o^5 c^4},$$

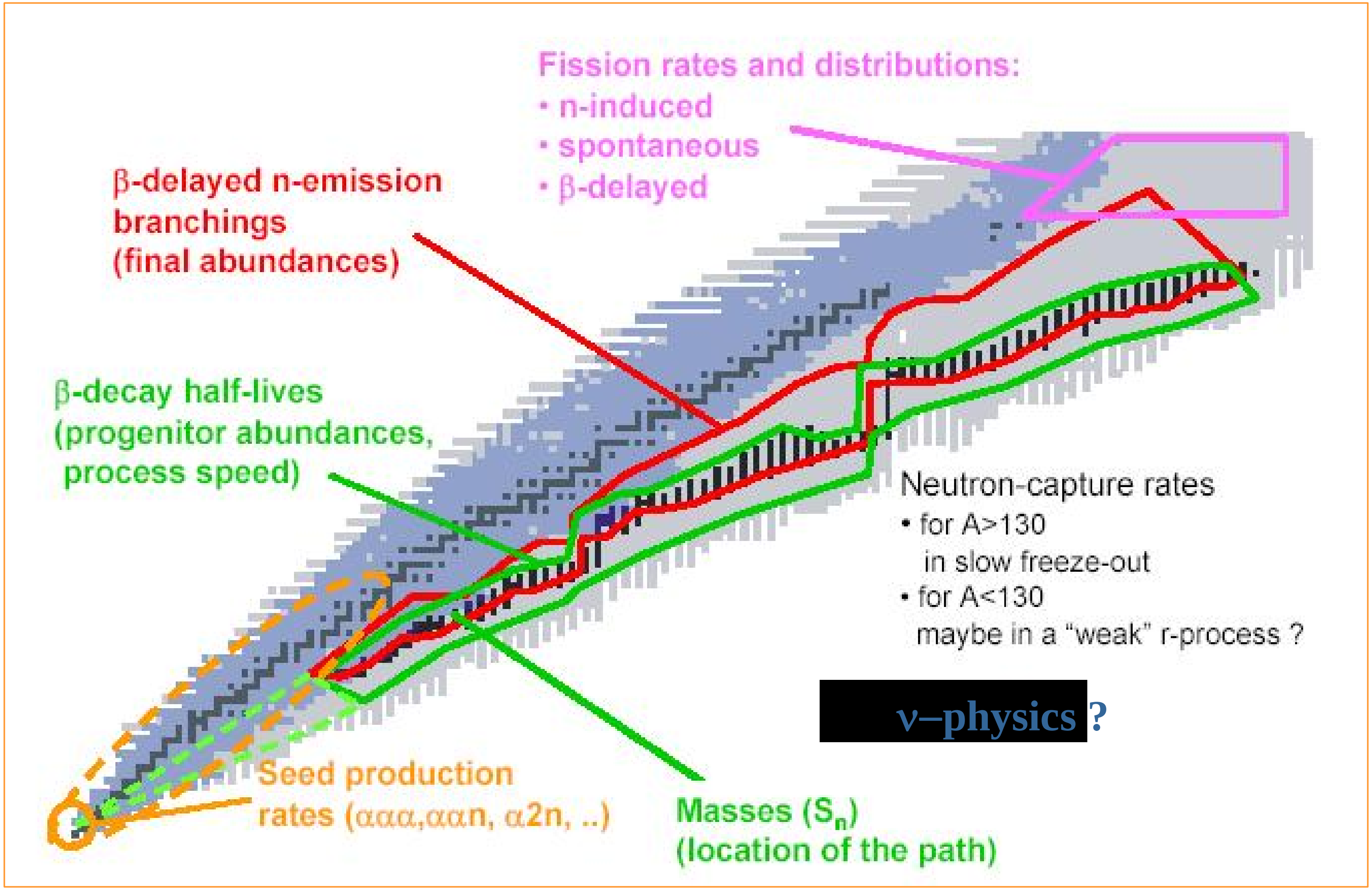
$$B_F = |\langle f|\tau|i\rangle|^2/(2J_i + 1) \quad \Delta J = \Delta T = 0$$

$$B_{GT} = |\langle f|\tau\sigma|i\rangle|^2/(2J_i + 1)$$

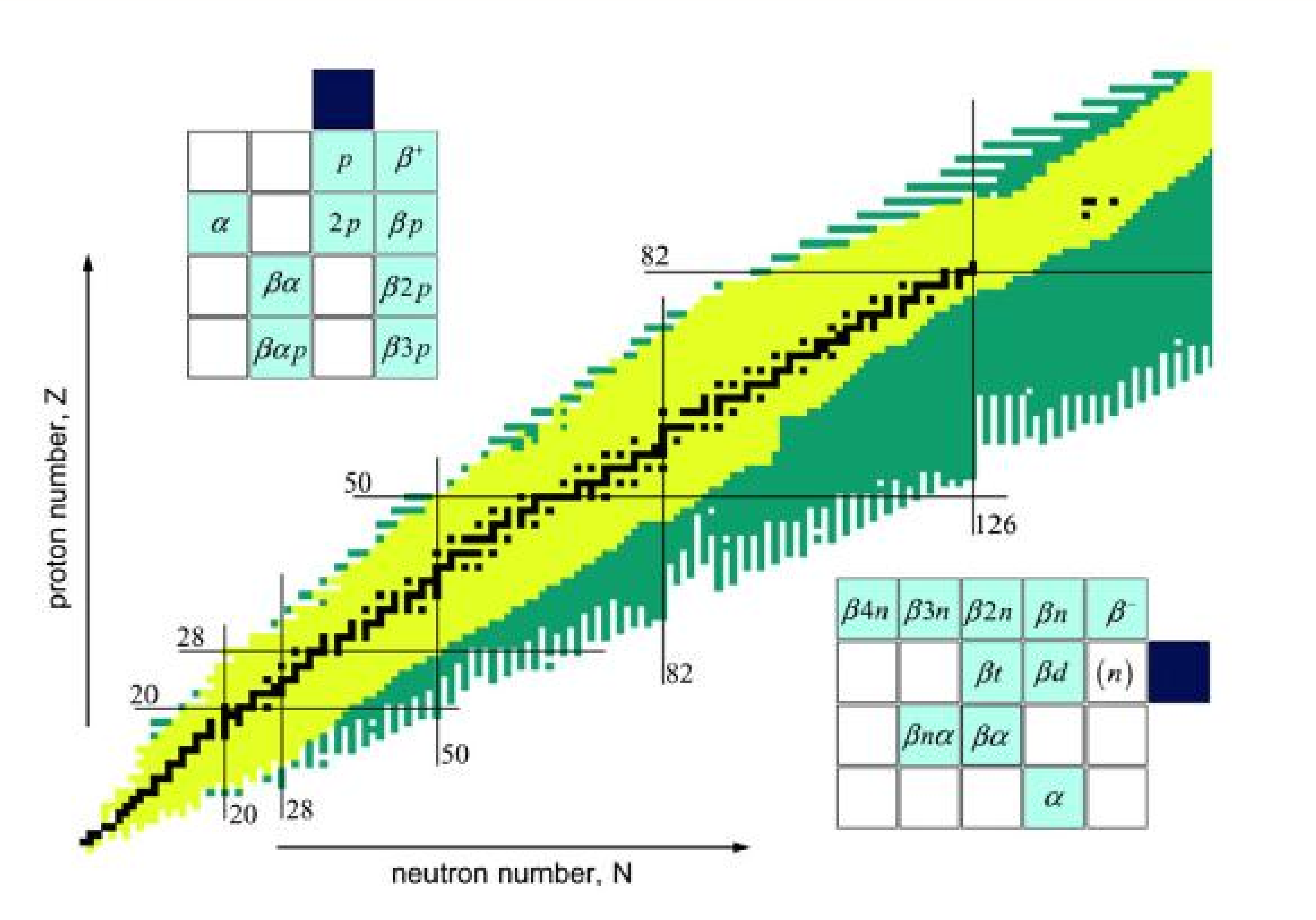
$$\Delta J = 0, \pm 1 \ (0 \nrightarrow 0) \text{ and } \Delta T = 0, \pm 1.$$



β decays may
compete with
α, p, 2p radioactivity
γ transitions may
compete with particle
emission from excited states
Radioactivity
Resonant phenomena
45.6 10^0 10^-2 10^-4 10^-6 10^-8 10^-10 10^-12 10^-14 10^-16 10^-18 10^-20 10^-22
T 1/2 [s]
10^-23 10^-21 10^-19 10^-17 10^-15 10^-13 10^-11 10^-9 10^-7 10^-5 10^-3 10^-1 10^1
Γ [MeV]
ISOL
In-Flight separation
Stopped/transported beam
Particle
tracking
Decay in flight
Invariant/missing
mass methods
Neutron resonances
by time-of-flight (TOF)



Fission rates and distributions:
• n-induced
• spontaneous
• β-delayed
β-delayed n-emission
branchings
(final abundances)
β-decay half-lives
(progenitor abundances,
process speed)
Neutron-capture rates
• for A>130
in slow freeze-out
• for A<130
maybe in a "weak" r-process ?
ν−physics ?
Seed production
rates (ααα,ααn, α2n, ..)
Masses (S_n)
(location of the path)

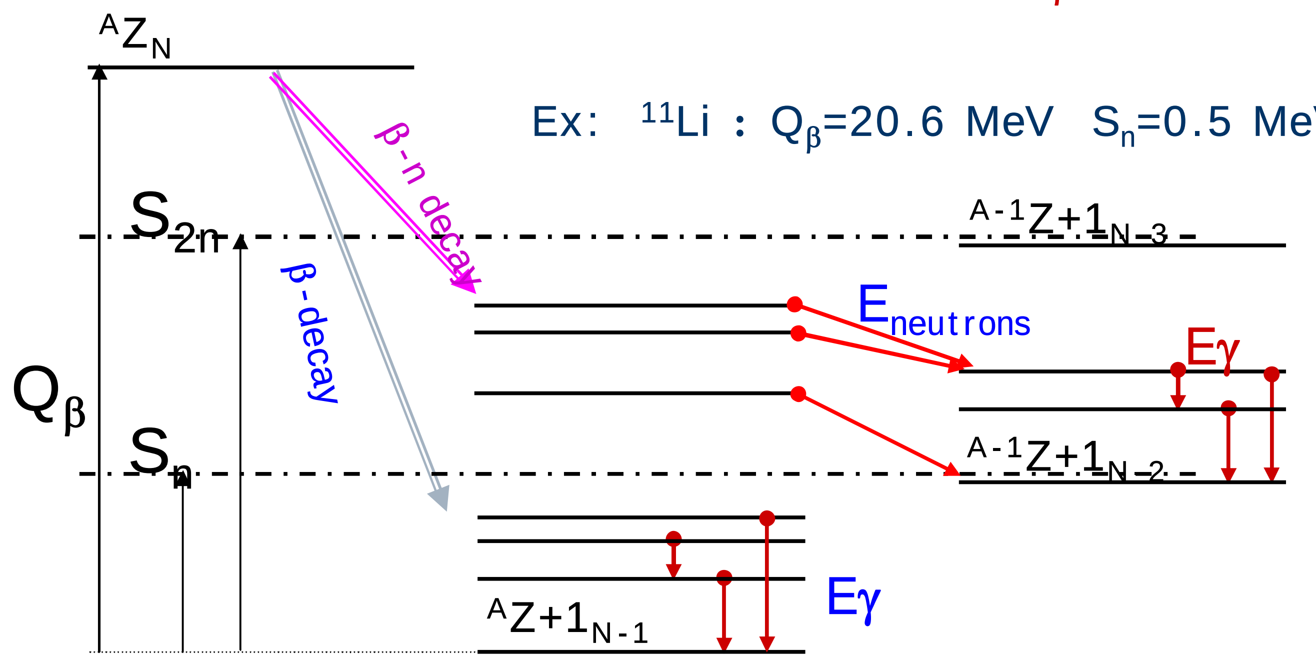


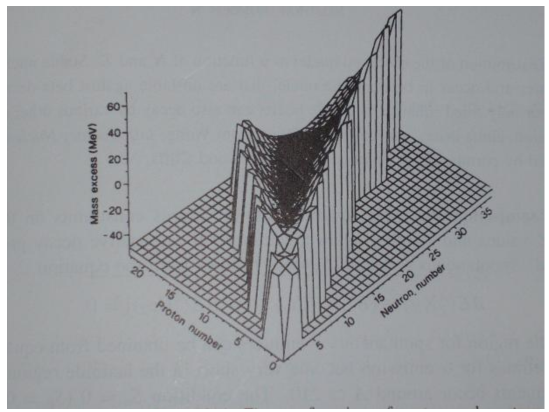
p
β+
α
2p
βp
βα
β2p
βαp
β3p
proton number, Z
82
50
28
20
126
82
50
20
28
β4n
β3n
β2n
βn
β-
βt
βd
(n)
βnα
βα
α
neutron number, N

β 延迟中子衰变

for N>>Z : Q_β , S_n

Ex: ^{11}Li : Q_β=20.6 MeV S_n=0.5 MeV P_n~92%





β-delayed particle emission for unstable nuclei

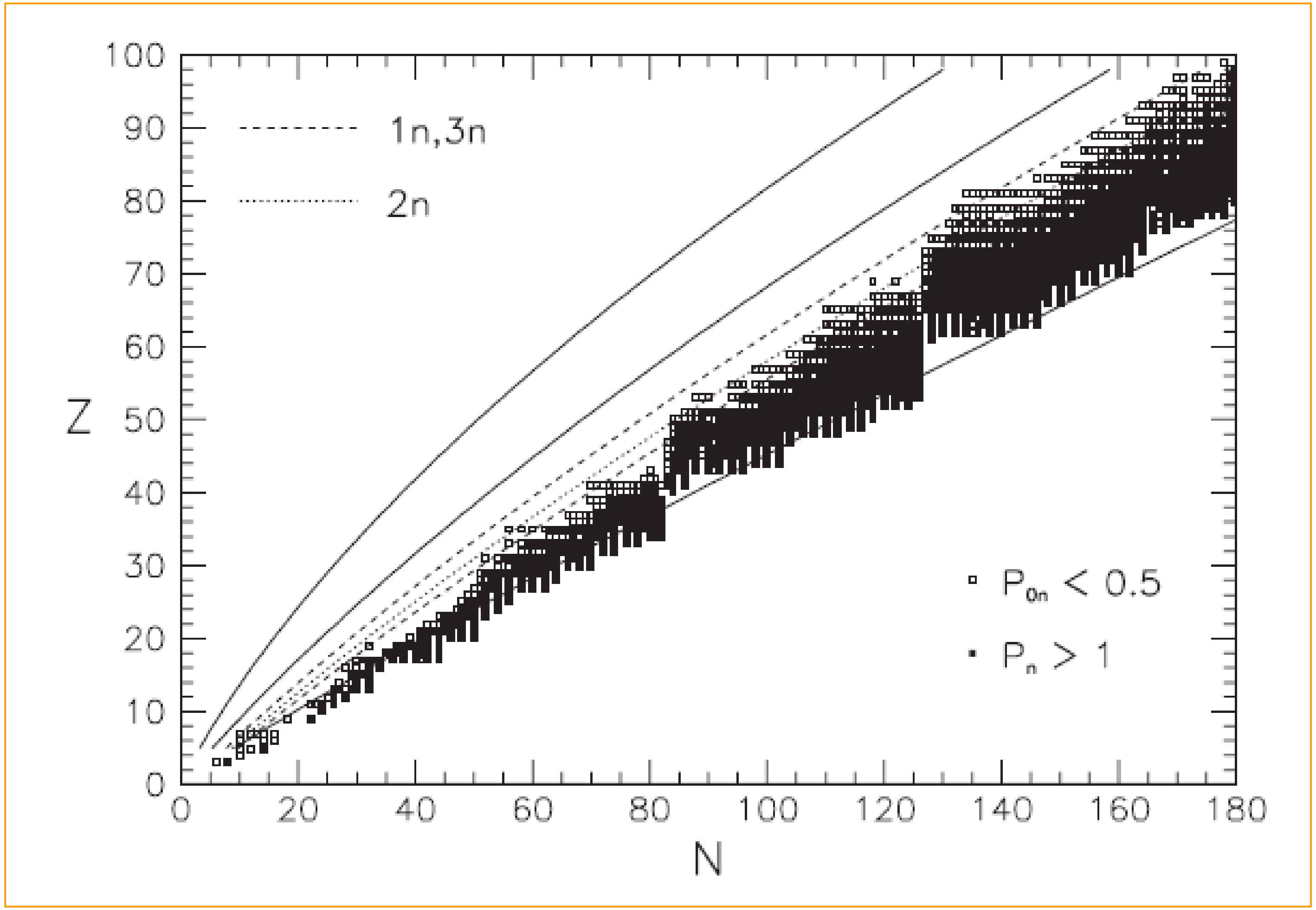


FIG. 18. Nuclei with large beta-delayed neutron-emission probability are marked with an open square if the probability for emitting one or more neutrons is larger than 50% and with a filled square if the average number of emitted neutrons is larger than 1. The P_n

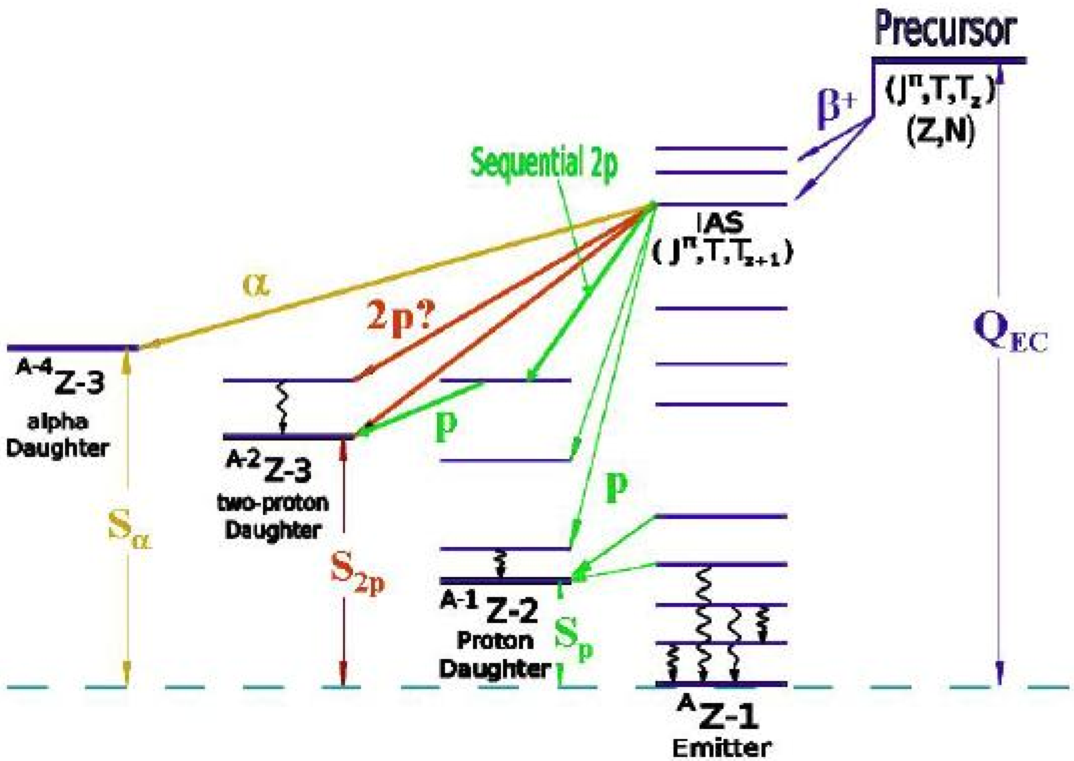
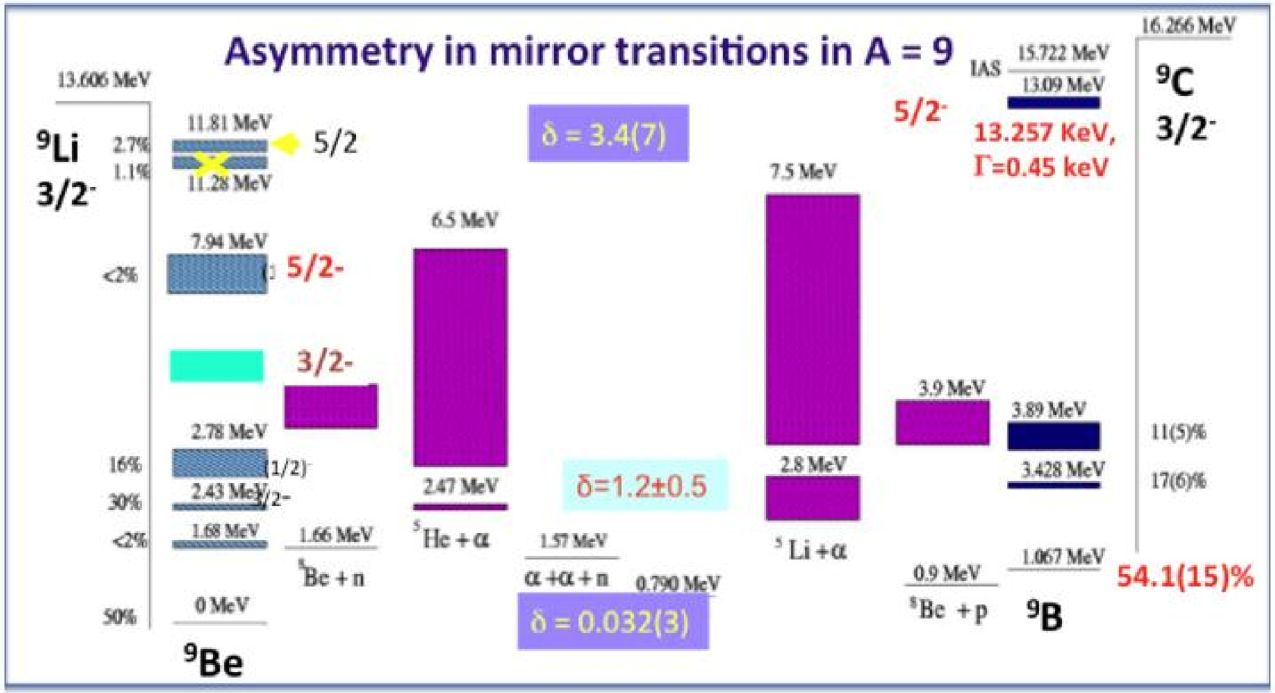
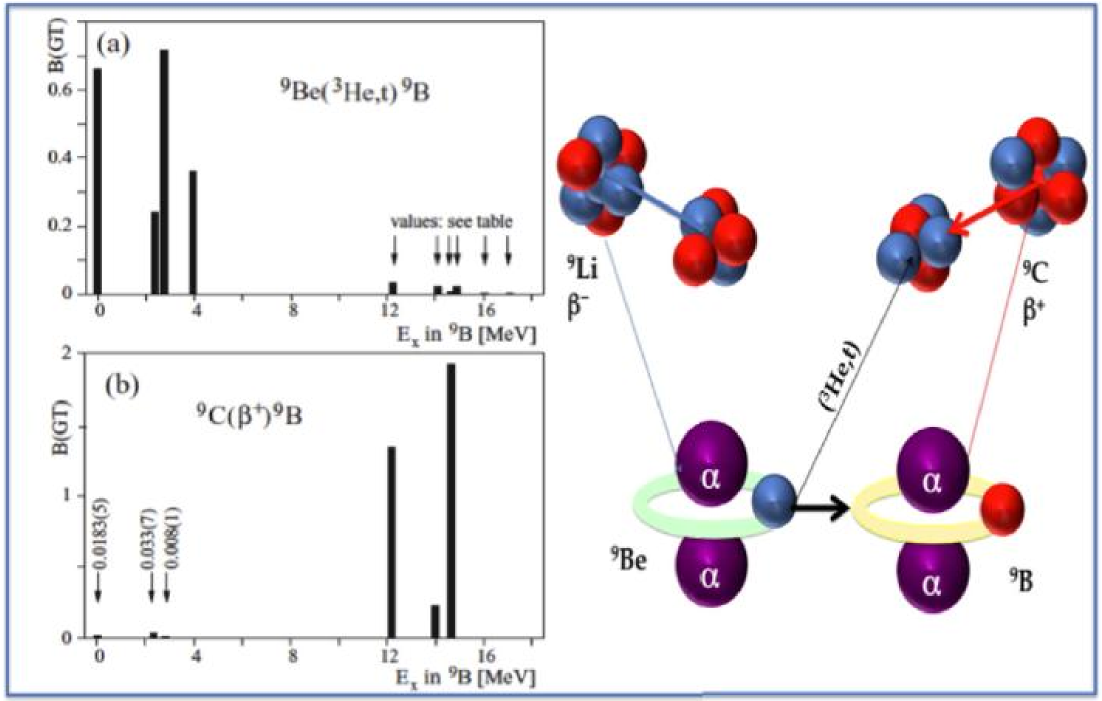


Figure 1. General decay scheme for a $Z > N$ nucleus.



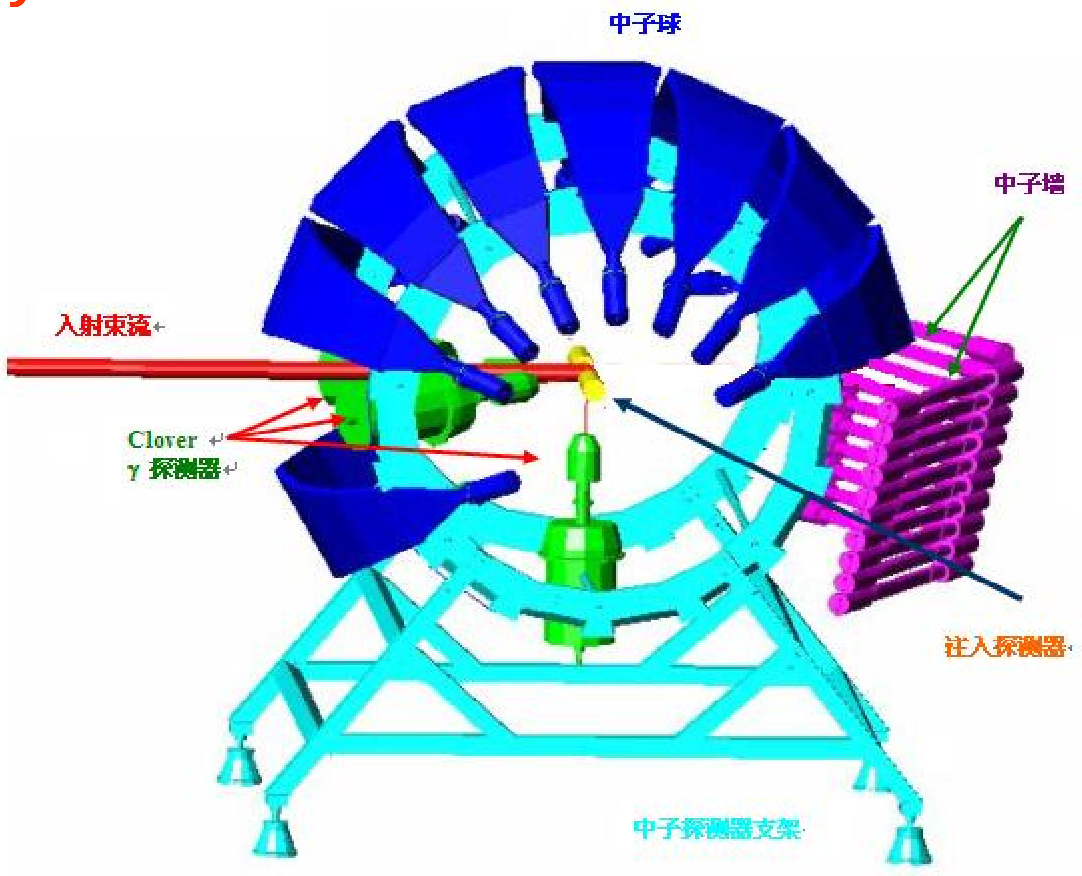
7. On the upper part
ay scheme of the A =
s is shown with the
cay channels and the
ries observed
main transitions
ed in the decay. On
om the BGT
ion for the TZ = 1/2
determined by
e,t)9B reaction [120]
BGT distribution for
= −3/2 case observed
by -decay [82, 121]. Both distributions are consistent with the high dependence of spatial distribution of the populated levels. Large BGT strength between states of similar spatial distribution and very reduced between cluster and non-cluster states. In other words, the cluster character of certain levels seems to be responsible for the BGT distribution.



北大组2002年开始建设中子球

➢Previous facility in 2004

- Neutron Sphere：8 pieces of BC408 ,157cm x 40(20)cm x 2.5cm, covering 30% of 4π。
- Neutron Wall：20 pieces of BC408, 40cm × 5cm × 2.5cm。Covering 2.2% of 4π。
- A set of implantation and β detector



- 3 sets of Clover γ detectors (IMP-Lanzhou）。

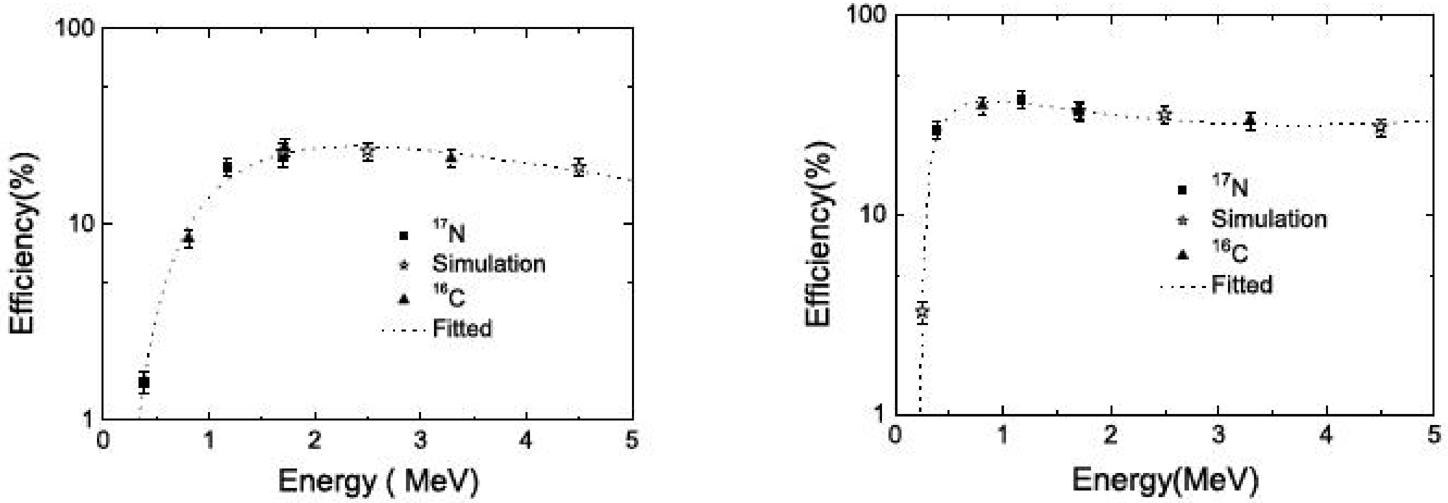
IEEE-TNS-52(2005)473

➢Upgrade 2006

- Neutron sphere: Change the reflection layer (TYVEK1056D), coupling layer and the PMTs (XP2020)
- Neutron wall: Change the reflection layer, coupling layer and the PMTs. Placed inside the sphere.

Table 1
β-delayed neutron peak shape parameters of neutron sphere and neutron wall.

			neutron sphere			neutron wall		
Nucleus	Energy(MeV)	BR(%)	x_0(ns)	Γ(ns)	S	x_0(ns)	Γ(ns)	S
^{17}N	0.383	38	118.4	11.0	0.8	116.9	10.7	0.23
	1.170	50.1	66.8	3.9	0.6	66.5	5.1	0.28
	1.700	6.9	55.3	3.2	0.4	55.6	3.9	0.29
^{16}C	3.29	84.4	40.2	2.7	0.2	40.2	2.0	0.2
	1.715	15.6	55.2	2.9	0.4	55.6	3.4	0.28
	0.808	1.0	80.6	4.1	0.6	80.2	5.6	0.23



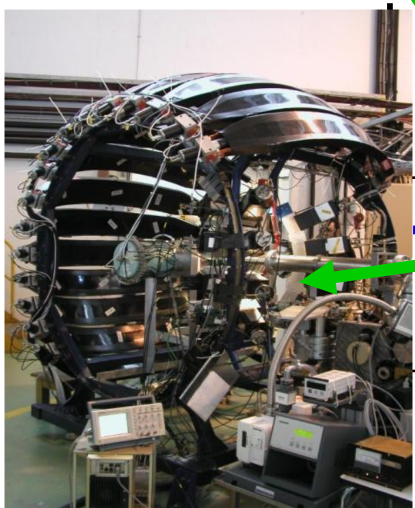
(a) neutron sphere

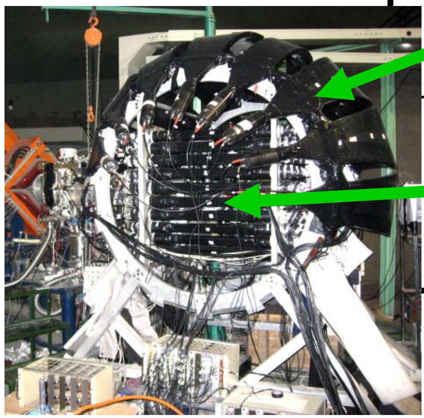
(b) neutron wall

Nucl. Instr. Meth.A 606, 645(2009)

Figure 7. Experimentally determined intrinsic efficiency curves of neutron sphere and neutron walls obtained from in-beam test. The solid curves are fitted results.

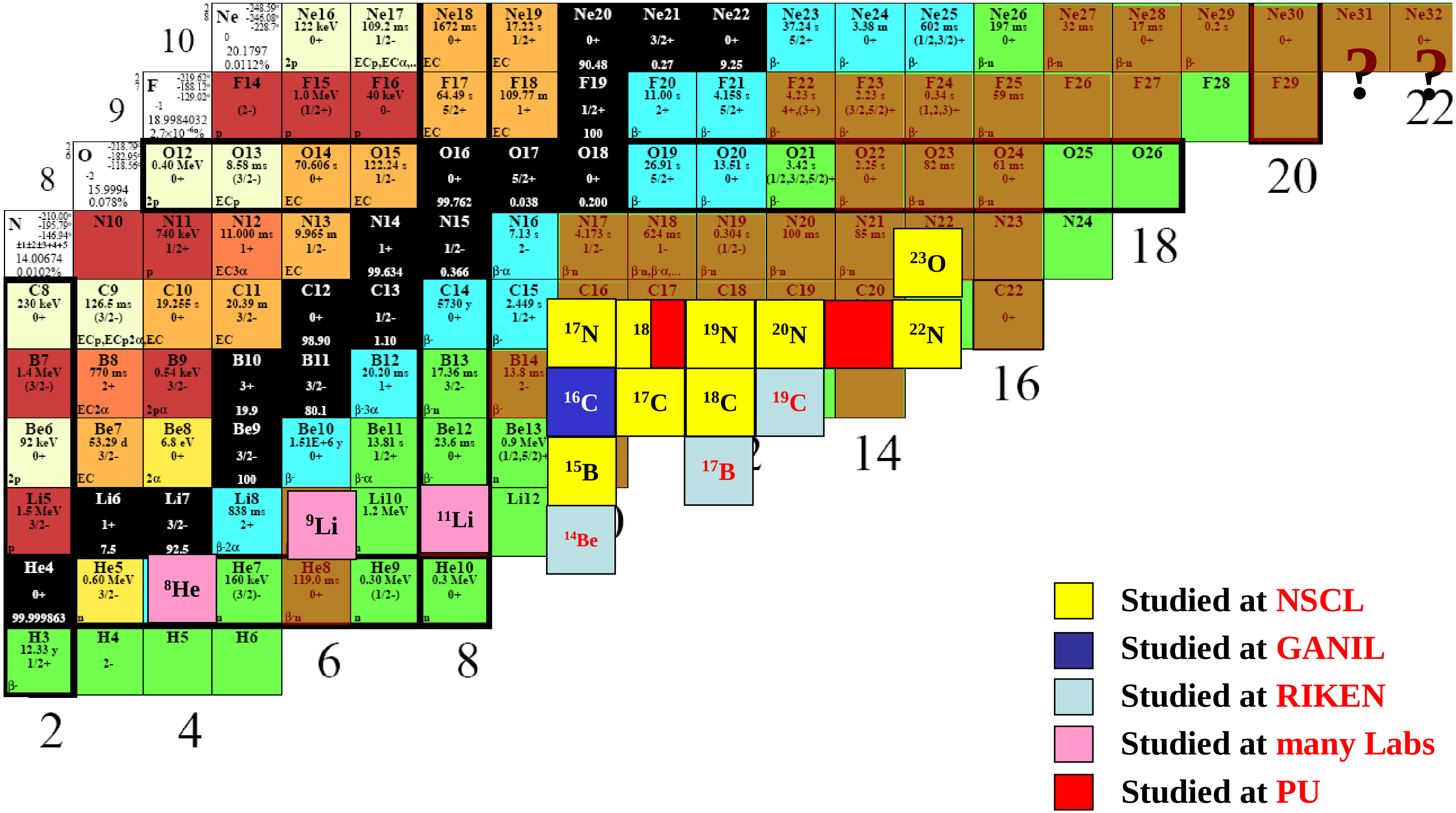
➢ 世界上主要实验探测设备的比较





Array	材料	几何尺寸	片数	R(m)	立体角(%)	本征效率(%)@1MeV	中子测量阈(keV)
NSCL(Ball)	BC412	长：157cm 宽：7.6 cm 厚：2.54 cm	16	1	15	12	800
TONNERRE (Ball)	BC400	长：160cm 宽：20 厚：4 cm^3	32	1.2	45	12	200
北京大学中子球	BC408	长：157cm 中间宽：40cm 两头宽：20cm 厚：2.5cm	8	1	30	14.1	~350
北京大学中子墙	BC408	长：40m, 宽：5cm 厚：2.5cm	8	0.6	8.8	36.5	~200

北大组在兰州的β延迟中子衰变实验



近几年北大组和MSU-NSCL组在N同位素β延迟衰变方面的研究形成友好竞争

PHYSICAL REVIEW C **72**, 064327 (2005)

β-decay of the neutron-rich nucleus ^{18}N

Z. H. Li, Y. L. Ye, H. Hua,* D. X. Jiang, Y. M. Zhang, F. R. Xu, Q. Y. Hu, G. L. Zhang,

北大组-^{18}N-2005年

PHYSICAL REVIEW C **74**, 024322 (2006)

β-delayed neutron decay of ^{19}N and ^{20}N

C. S. Sumithrarachchi,* D. W. Anthony, P. A. Lofy,† and D. J. Morrissey

MSU组-$^{19-20}$N-2006年

PHYSICAL REVIEW C **75**, 057302 (2007)

Observation of a new transition in the β-delayed neutron decay of ^{18}N

J. L. Lou,[1] Z. H. Li,[1,*] Y. L. Ye,[1] H. Hua,[1] D. X. Jiang,[1] L. H. Lv,[1] Z. Kong,[1] Y. M. Zhang,[1] F. R. Xu,[1] T. Zheng,[1] X. Q. Li,[1]

北大组-^{18}N-2007年

PHYSICAL REVIEW C **80**, 054315 (2009)

Experimental study of the β-delayed neutron decay of ^{21}N

Z. H. Li, J. L. Lou, Y. L. Ye,* H. Hua, D. X. Jiang, X. Q. Li, S. Q. Zhang, T. Zheng, Y. C. Ge, Z. Kong, L. H. Lv,

北大组-^{21}N-2009年

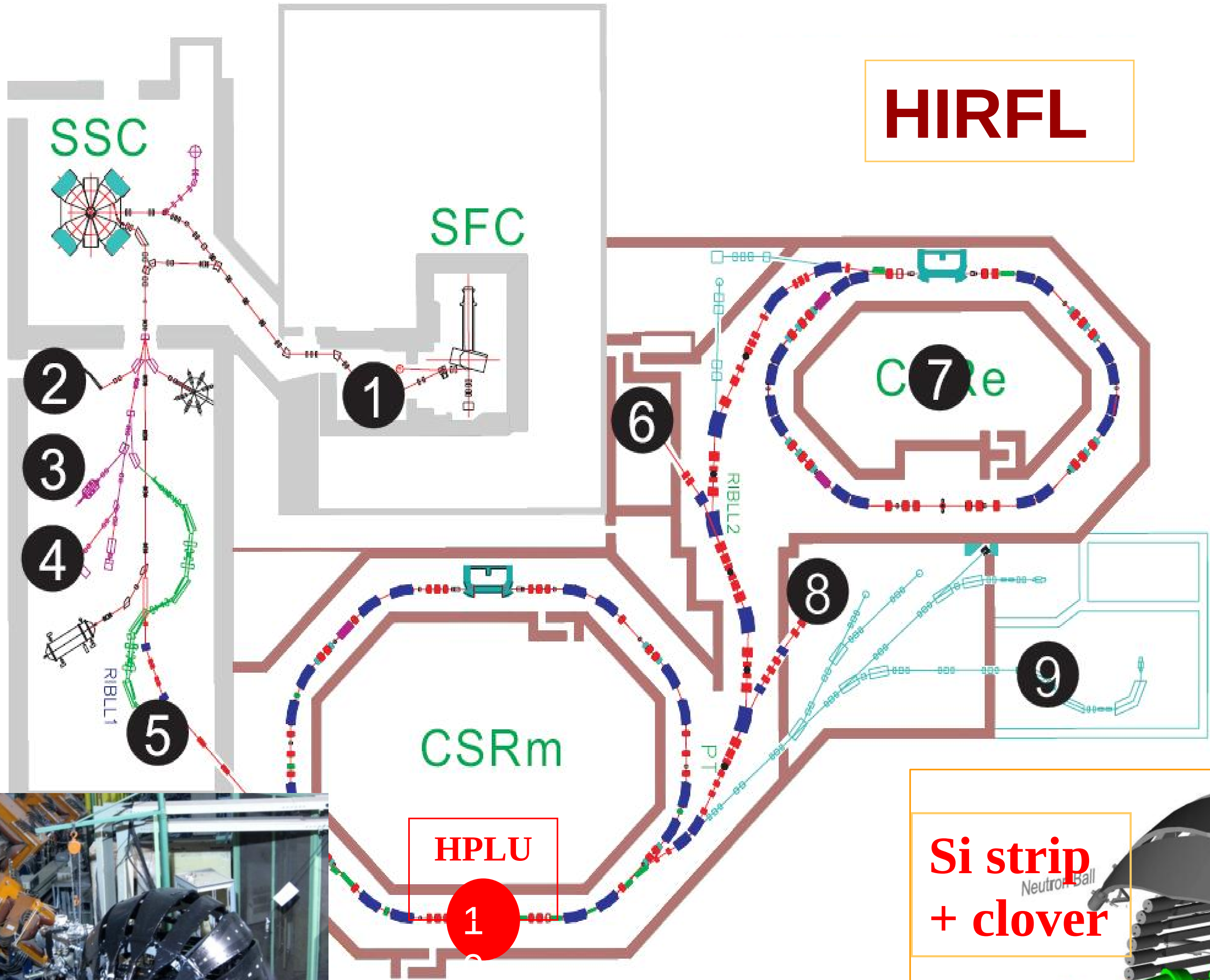
PHYSICAL REVIEW C **81**, 014302 (2010)

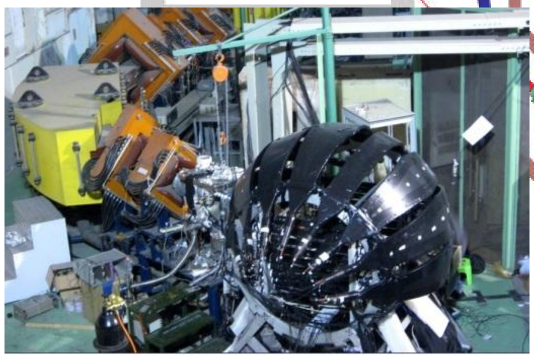
States in ^{22}O via β decay of ^{22}N

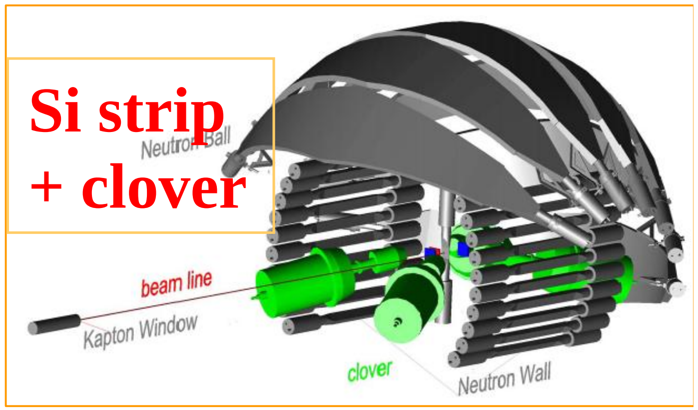
C. S. Sumithrarachchi,[1,2,*] D. J. Morrissey,[1,2] A. D. Davies,[1,3] D. A. Davies,[1,2]

MSU组-^{22}N-2010年

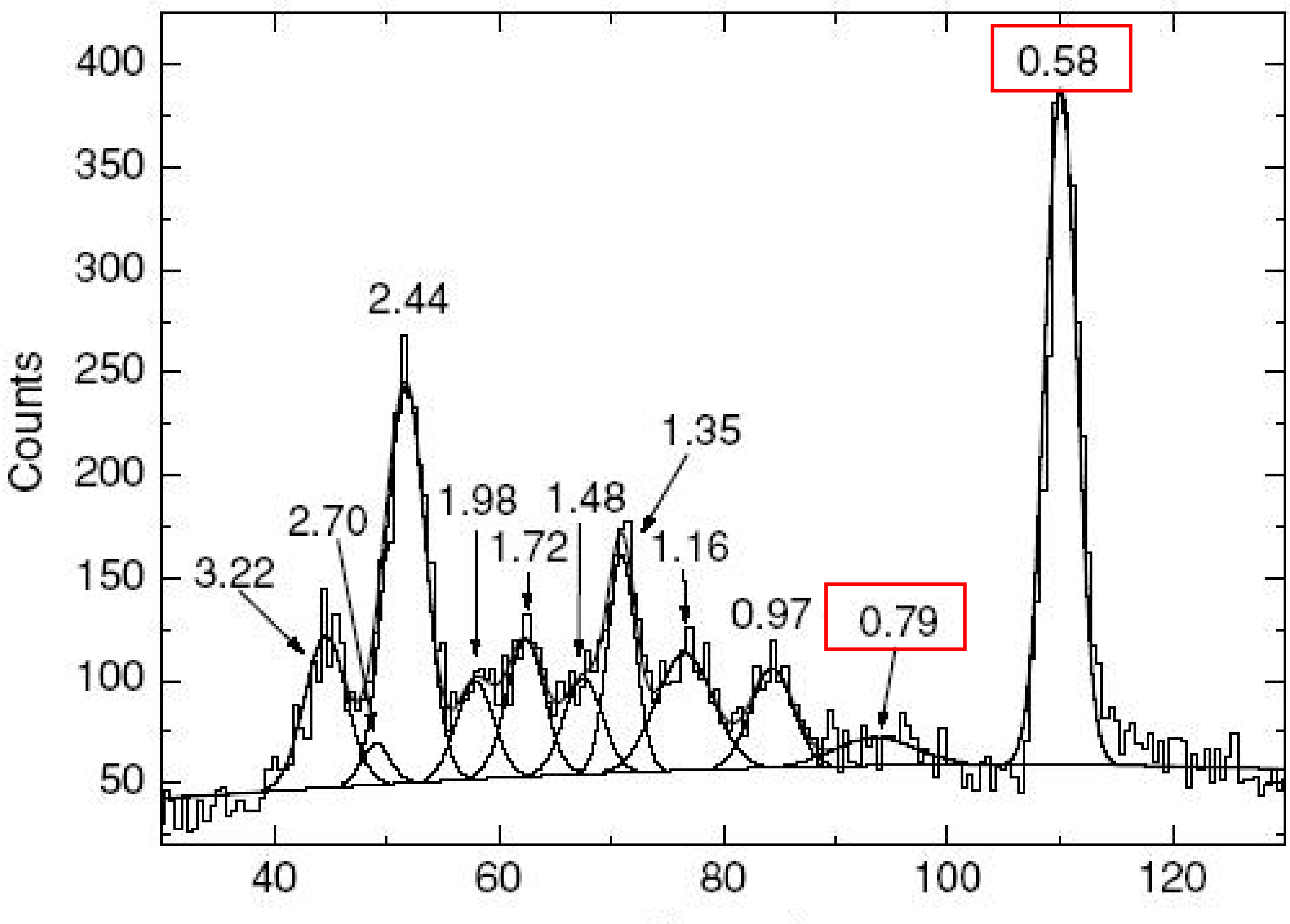
HIRFL


SSC
SFC
1
2
3
4
5
6
7
8
9
CSRe
RIBLL2
RIBLL1
CSRm
PT
HPLU
1



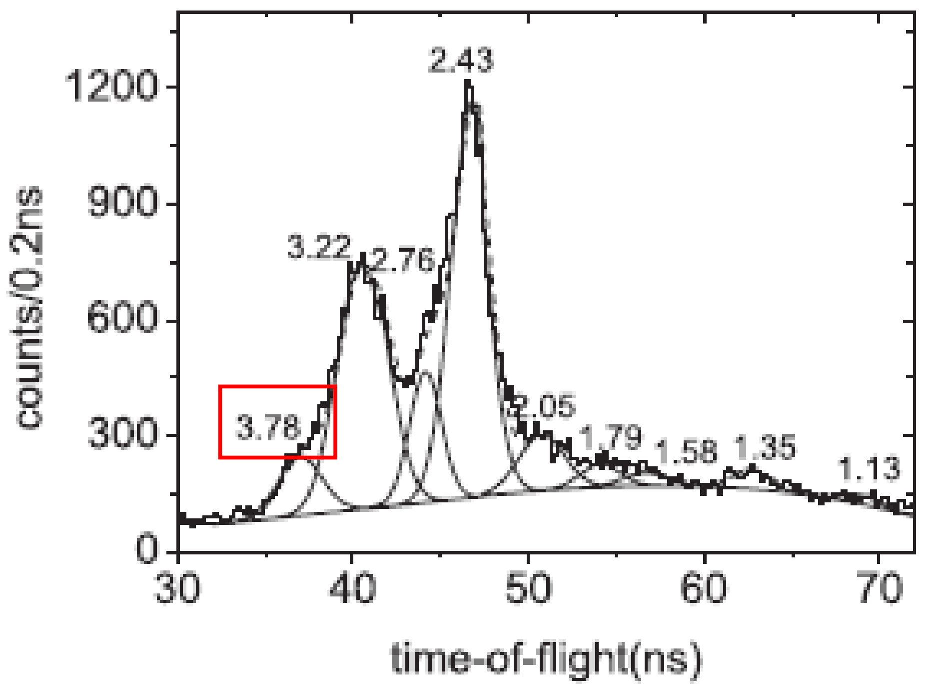

Si strip
+ clover
Neutron Ball
beam line
Kapton Window
clover
Neutron Wall

Neutron ToF spectrum for ^{18}N β-n measured by the Neutron wall



- Z.H. Li, Y.L. Ye, H. Hua, D.X. Jiang et al., Physical Review C72, 064327(2005)

Neutron ToF spectrum for ^{18}N β-n measured by the Neutron sphere



Phys. Rev. C75(2007)057302

Neutron & γ spectra for ^{21}N β-n- γ

Phys.Rev.C 80, 054315(2009)

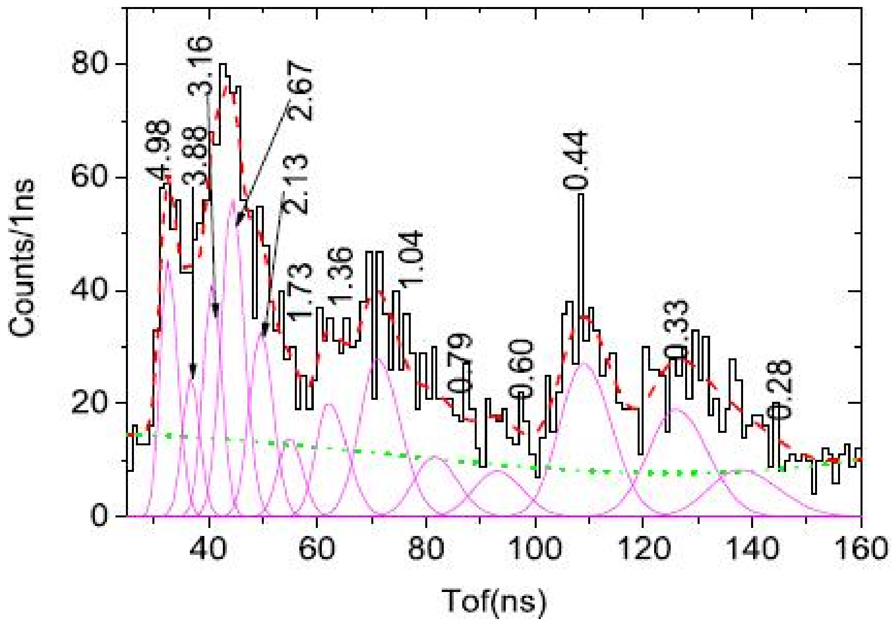


Fig.3 The time-of-flight spectrum measured by neutron neutron wall. The flight path of all neutron detectors were unified to 1 meter. The step vert solid line, the dash line, the dot line, and the solid line stand for original data, fitted data, background and fitted neutron peaks, respectively.

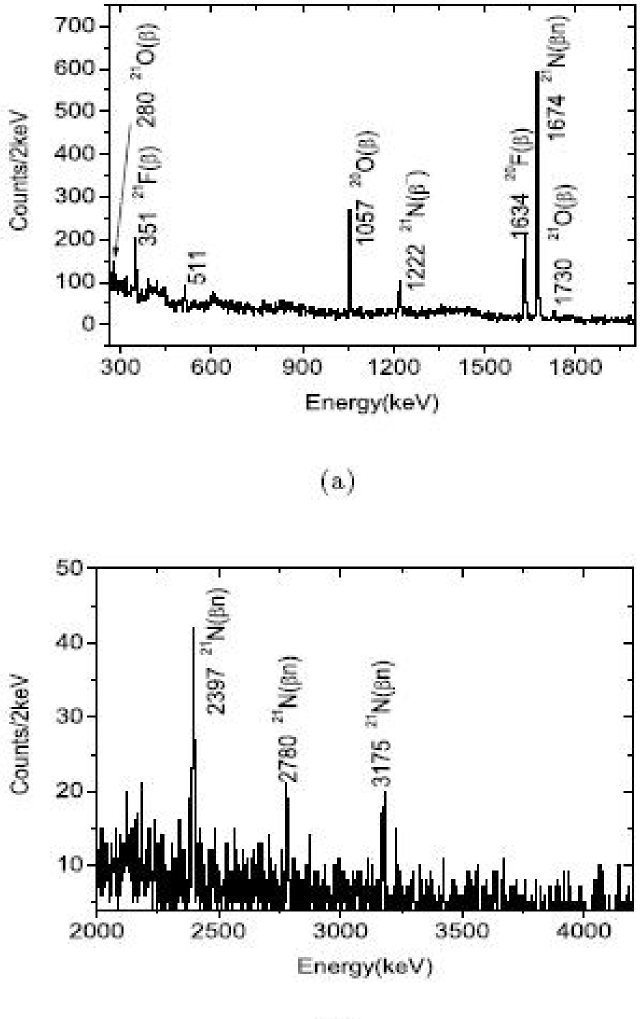
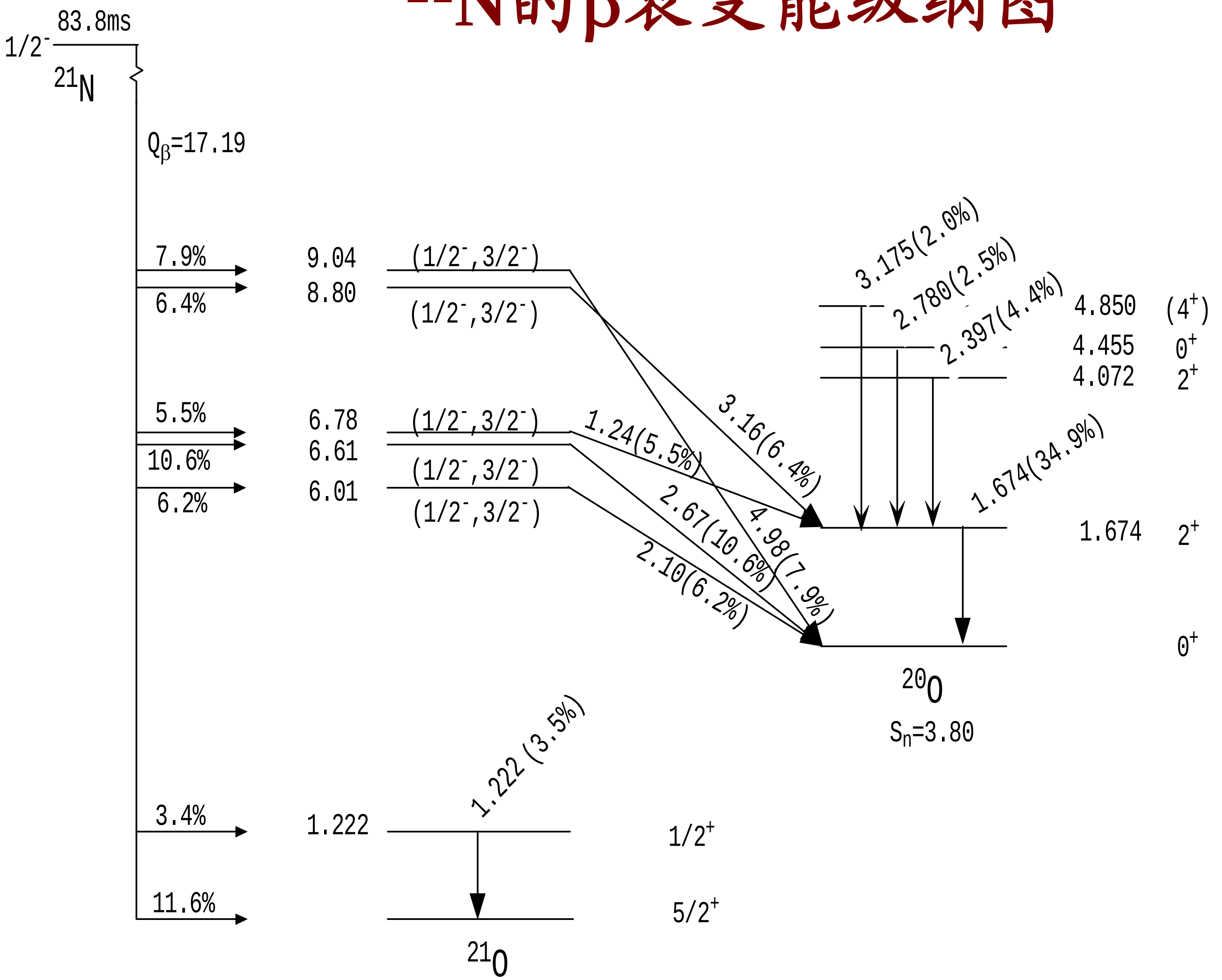


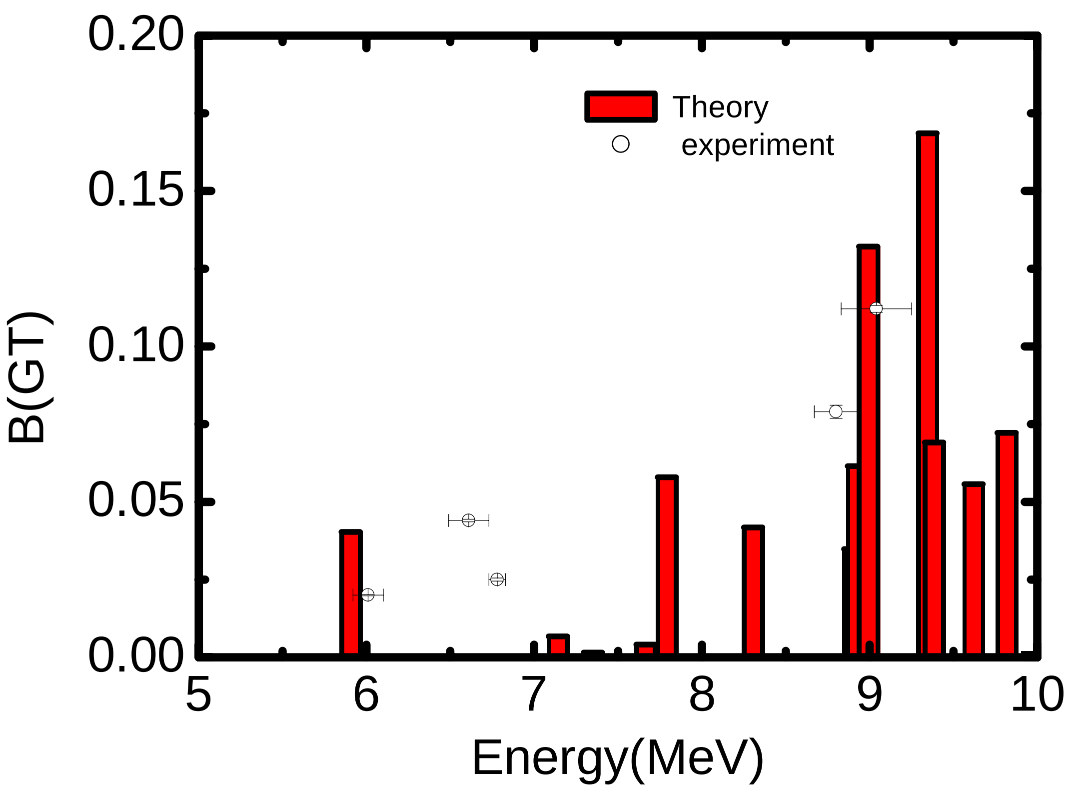
Fig.4 β-γ coincidence spectrum from the β-decay of ^{21}N, (a) is the low energy part and (b) is the high energy part, and all the energies are given in keV.

^{21}N的β衰变能级纲图



- J.L. Lou, Z.H. Li, Y.L. Ye, D.X. Jiang, et al., Chin. Phys. Lett 5,1992(2008)
- Z.H. Li, J.L. Lou, Y.L. Ye, H. Hua et al., Phys. Rev. C 正在审稿

^{21}N的理论计算与实验比较



B(GT)值的理论计算与实验结果的比较

2012年RMP(IF43.93)和RPP(IF14.72)重点引用北大组在HIRFL-RIBLL1上开展的^{21}N的β延迟衰变谱学测量工作

PHYSICAL REVIEW C **80**, 054315 (2009)

Experimental study of the β-delayed neutron decay of ^{21}N

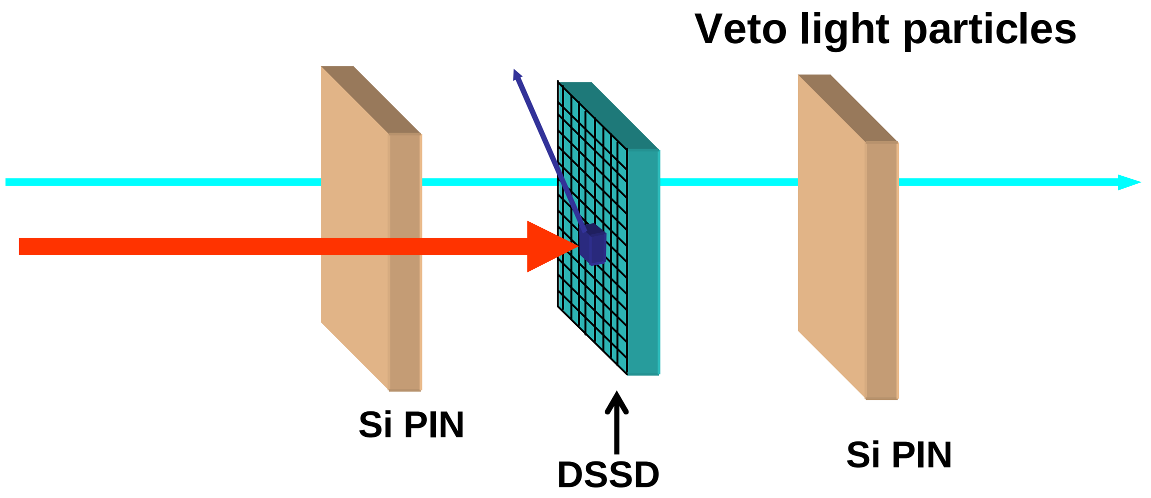
Z. H. Li, J. L. Lou, Y. L. Ye,* H. Hua, D. X. Jiang, X. Q. Li, S. Q. Zhang, T. Zheng, Y. C. Ge, Z. Kong, L. H. Lv, C. Li, F. Lu, F. Y. Fan, Z. Y. Li, Z. X. Cao, L. Y. Ma, and Q. Faisal

- 国际著名的综述刊物《**Reviews of Modern Physics**》（影响因子**43.93**）在**2012** 年**4** 月涉及非稳定核衰变的专题综述文章**“Radioactive decays at limits of nuclear stability”**中，引用了我们的代表作**1**，指出**“Analogous neutron-gamma experiments have already been performed, e.g., for 21N (Li et al., 2009)”**。
- 国际著名综述刊物《**Rep. Prog. Phys.**》（影响因子**14.72**）在**2012** 年**2** 月的综述文章**“Nuclear structure experiments along the neutron drip line”**中指出“The β-delayed neutron-emission technique has been used successfully to explore neutron unbound states in several experiments (see figure 2), **some of them being the first** to observe specific neutron-unbound states (e.g. 21,22O [77, 78])”.

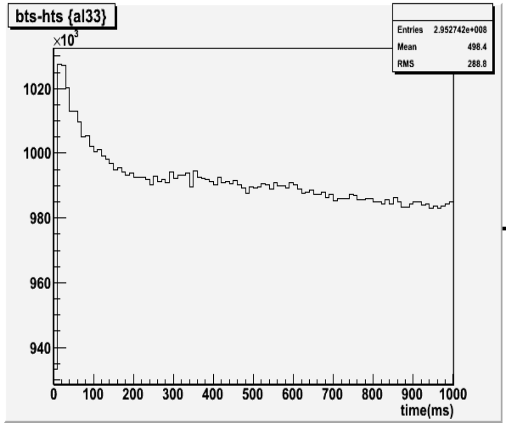
New: Continuous Beam mode

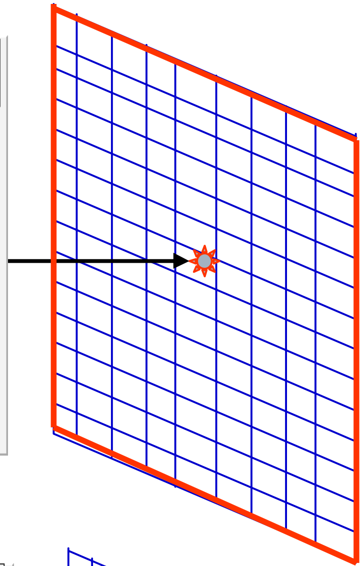
•**Implantation DSSD:**
x-y position (pixel), time

•**Decay DSSD:**
x-y position (pixel), time

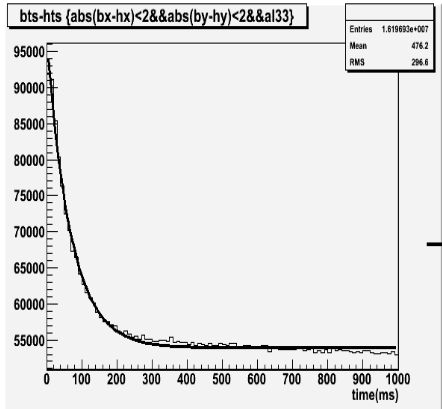


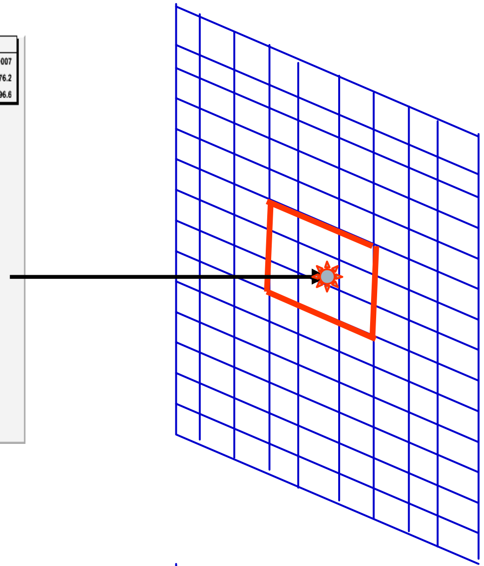
Experimental results



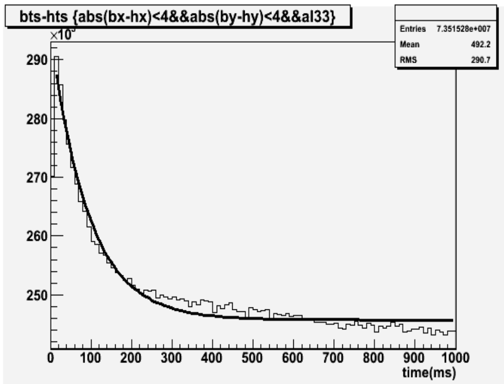


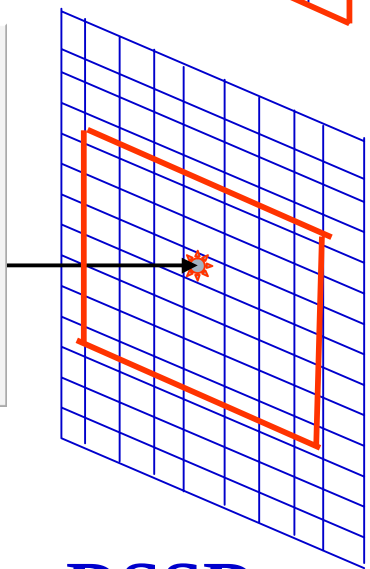
No pixel limitation



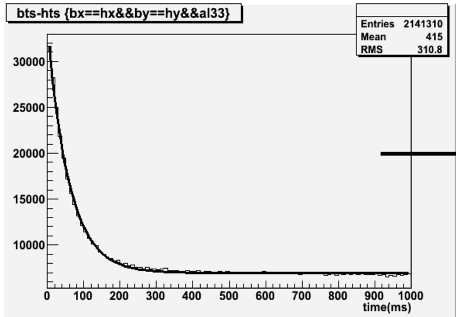


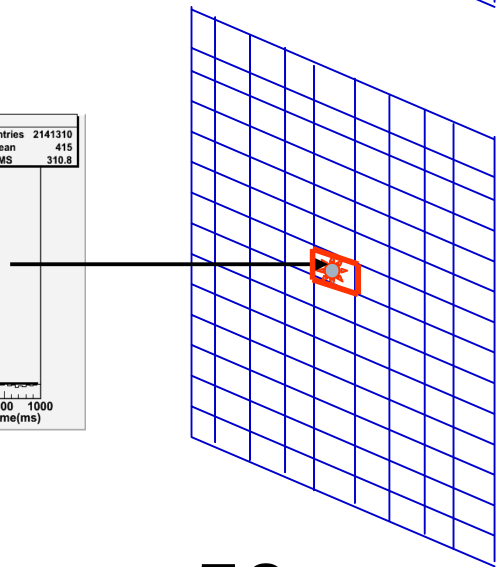
pixel <2





pixel <4



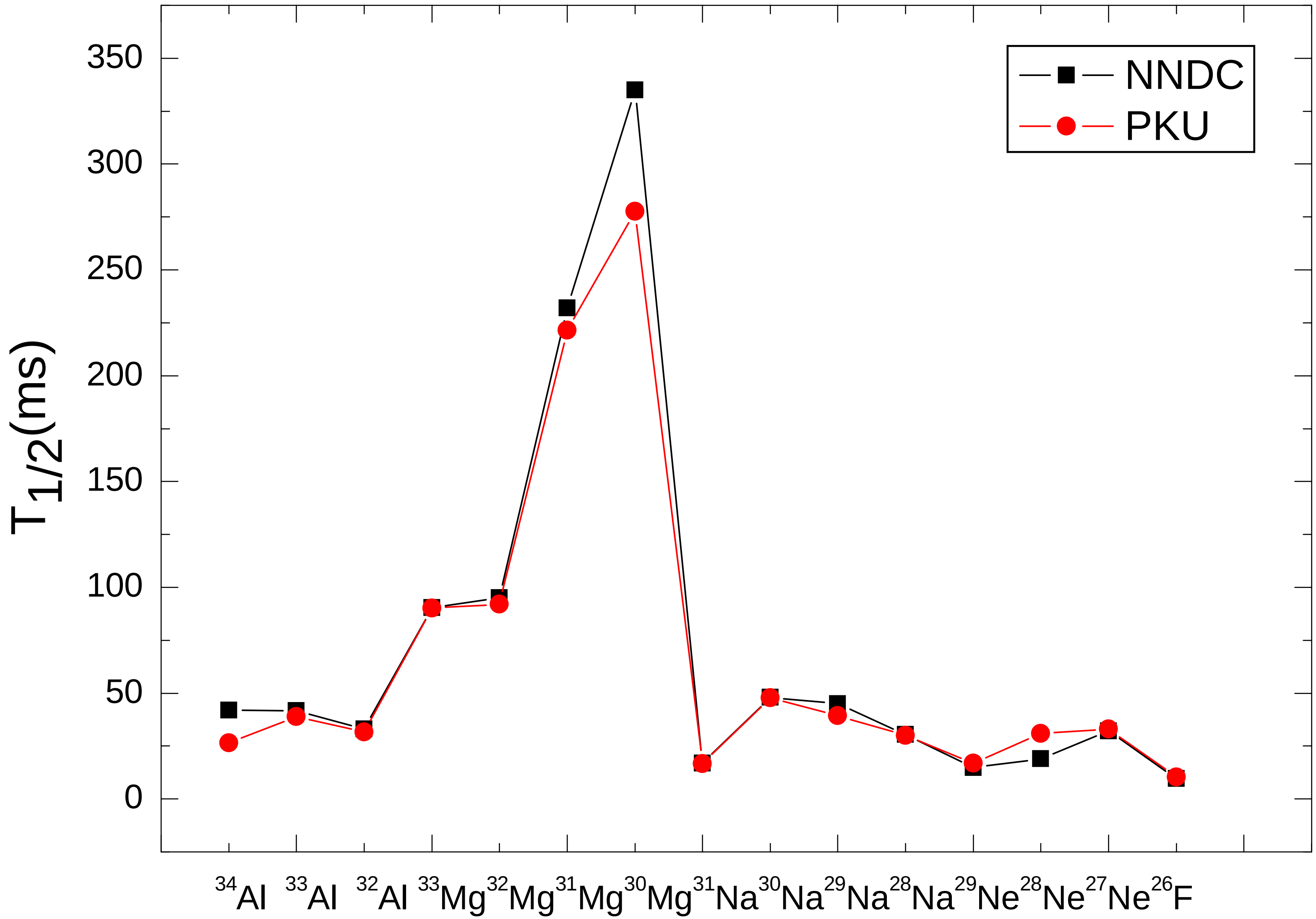


Same pixel

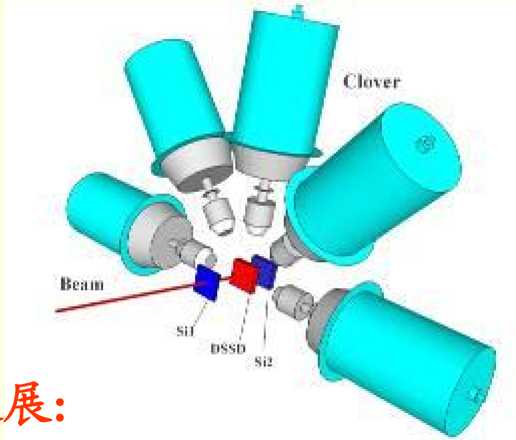
Space correlation

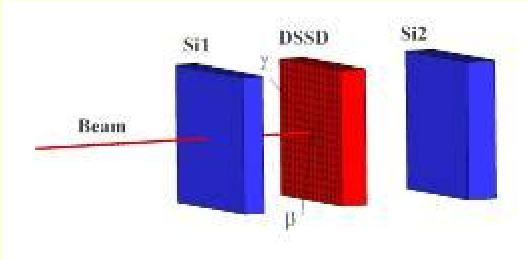
DSSD

连续束实验：同时测量一批核!



2012年北大组在《中国科学》发表的文章被封面介绍，报道了在HIRFL-RIBLL1开展的反转岛区原子核β衰变研究

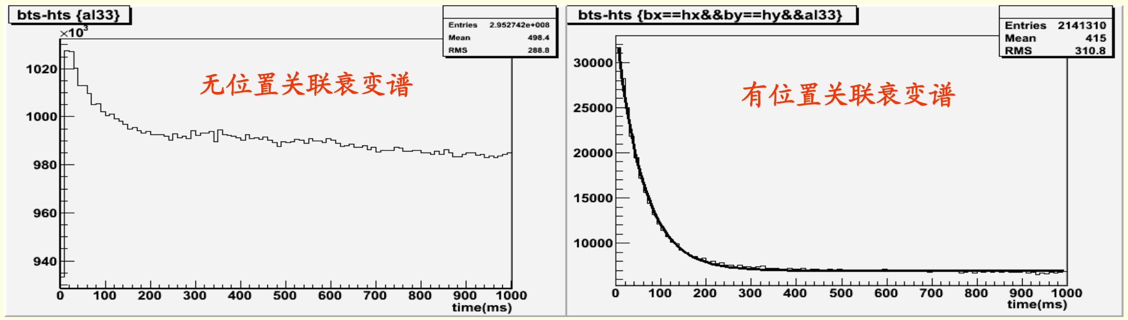


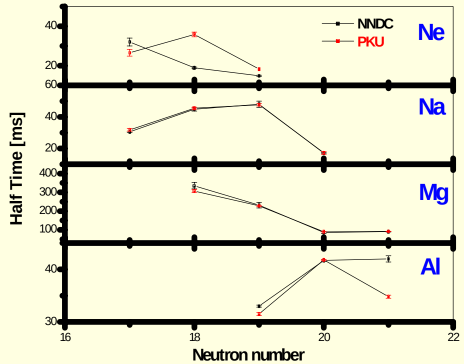


主要进展:

(1)针对远离稳定线束流流强很弱的特点，研制了一套工作在连续束模式的粒子注入和β探测装置。

(2)利用这套装置，在中科院近代物理研究所RIBLL上顺利开展了反转岛区丰中子核的衰变研究。在连续束模式下，一次实验同时测量了多个丰中子核β衰变的半衰期，实验结果与NNDC上发表的结果符合得很好。





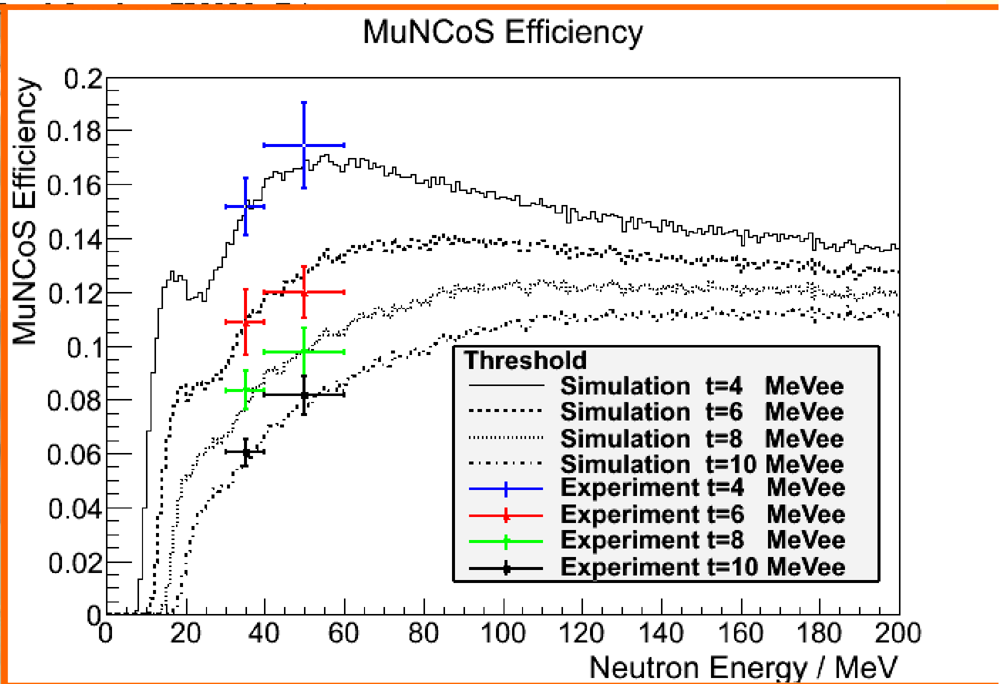
A new neutron spectrometer at Peking University - MuNCoS

Nuclear Instruments and Methods in Physics Research A 728 (2013) 47–52

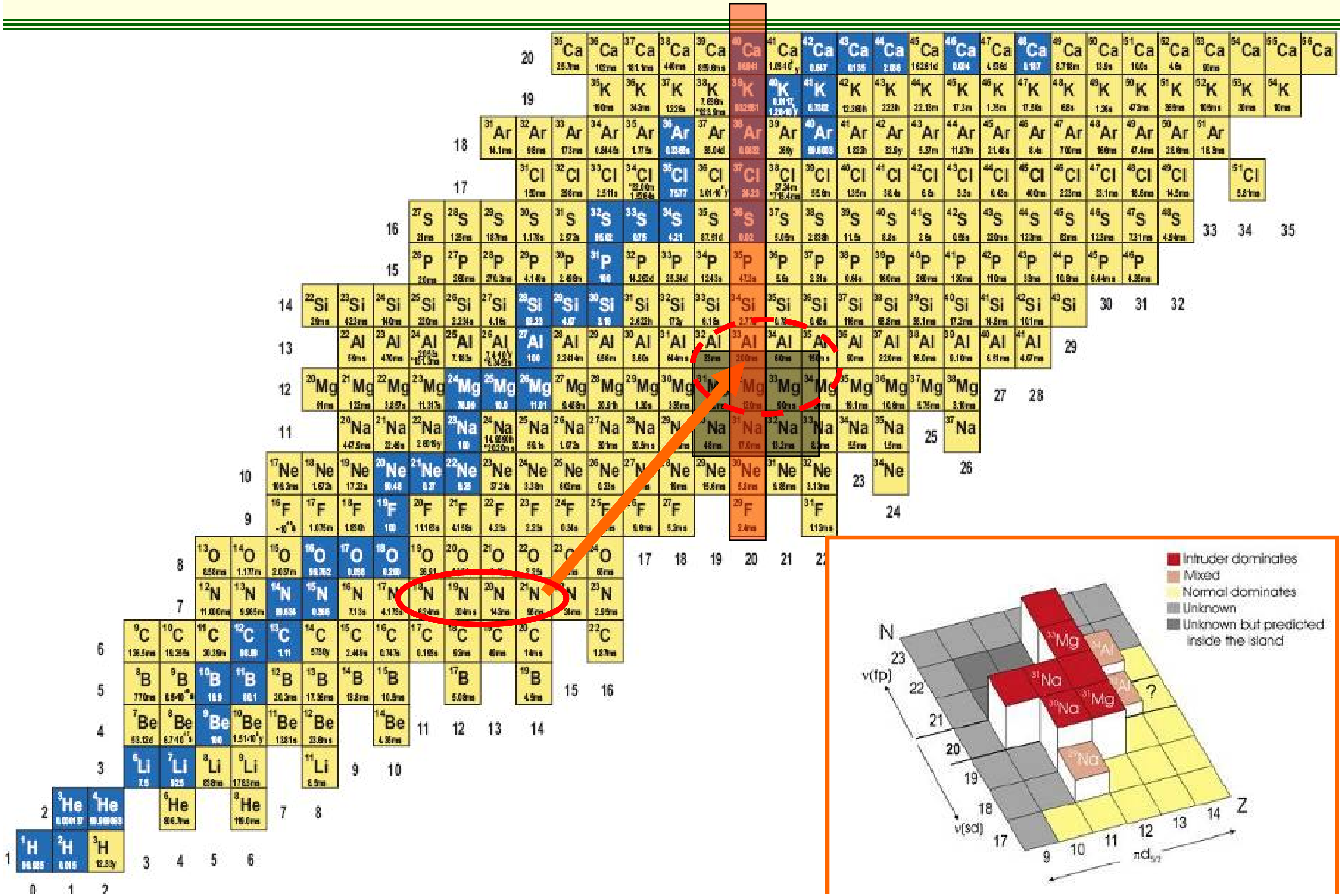
Construction and calibration of the multi-neutron correlation spectrometer at Peking University

H.B. You [a], Z.H. Yang [a], Y.L. Ye [a,*], Z.H. Li [a], Y.C. Ge [a], J.L. Lou [a], Q.T. Li [a], J. Xiao [a], R. Qiao [a], Z.Y. Tian [a], Y.L. Sun [a], H.N. Liu [a], J. Chen [a], J. Wu [a], B. Yang [a], K. Yang [a], J.S. Wang [b], Y.Y. Yang [b], P. Ma [b], J.B. Ma [b], S.L. Jin [b], J.L. Han [b]

[a] *School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*



正在开展$^{33-34}$Al-Mg的单粒子激发态结构研究



谢谢！