高流强重离子加速器装置
(*High Intensity Heavy-ion Accelerator Facility*：HIAF)
上的核物理研究

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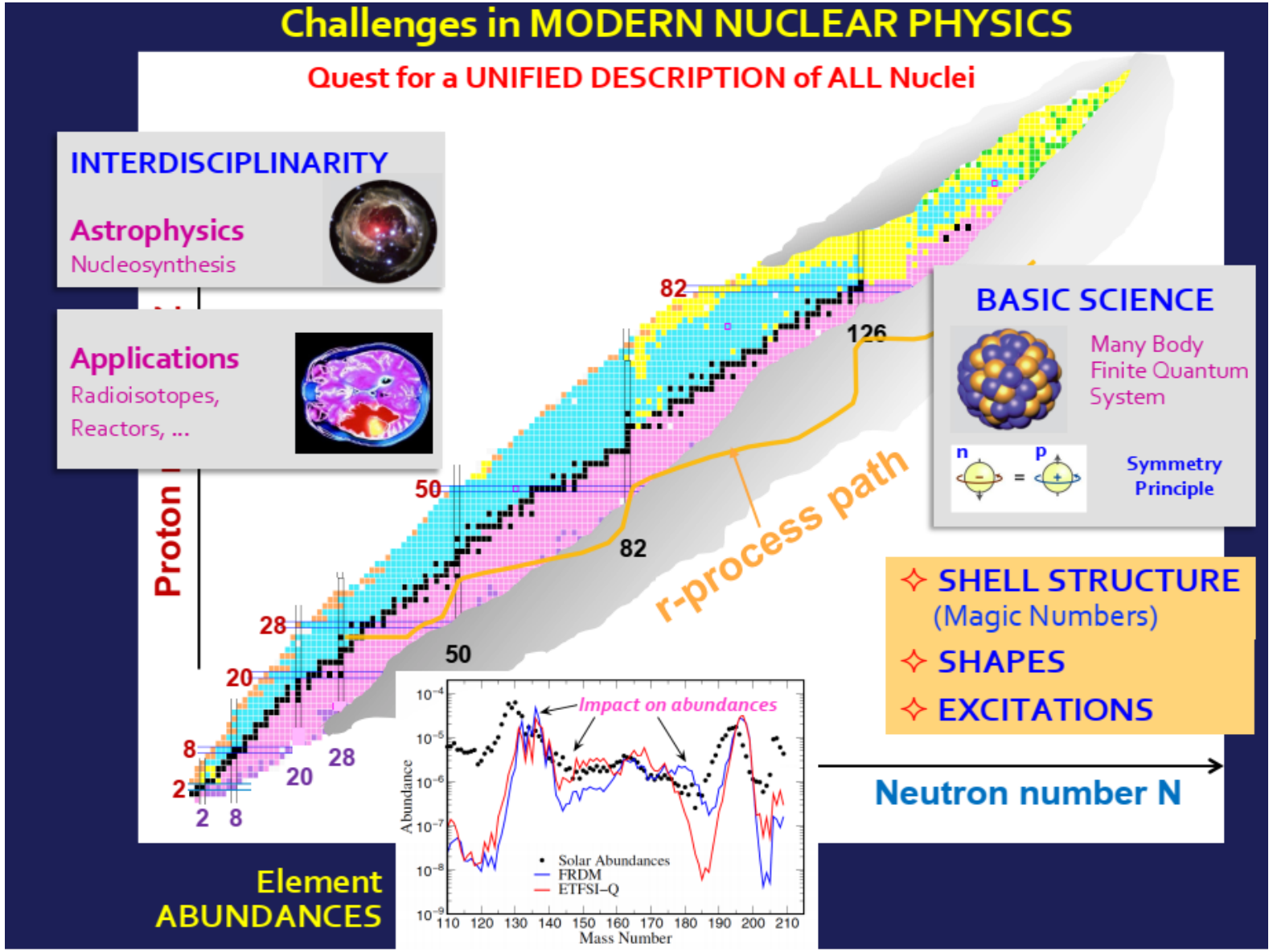
- HIAF简介
- HIAF上计划开展的核物理研究工作
- HIAF建设进展
- 总结



- 研究目标
  - 核力的本质，原子核的统一描述
  - 原子核的存在极限
  - 化学元素的起源
  - QCD相结构与低温高密核物质的性质
  - ……

- 手段

  探索未知领域
  更强的重离子束流
  领先的探测装置

需要建设新一代的高流强重离子加速器装置

HIAF简介

IMP 中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

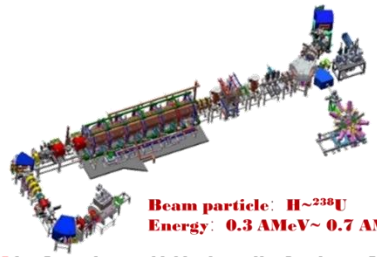
IMP 现有实验设施

SSC: H~238U up to ~100 AMeV

SFC: H~238U up to ~10 AMeV

Proton: 1.5 MeV~25 MeV
H~Ke: 1.33 AMeV~6 AMeV

CAFe: Chinese ADS Accelerator Front-end

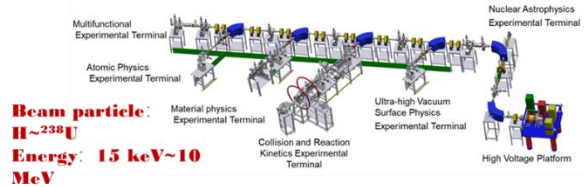


Beam particle: H~238U
Energy: 0.3 AMeV~ 0.7 AMeV

LEAF: Low Energy intense-highly-charged ion Accelerator Facility

Beam particle: H He N O Ar Fe ...
Energy: 500 eV~40 keV

EBIS: super low energy heavy ion experiment platform



Beam particle: H~238U
Energy: 15 keV~10 MeV

320 kV Highly Charged Ion Beam Platform

重离子核物理及加速器驱动先进核能研究基地型研究所

1 核物理基础及交叉前沿研究 — 基础前沿
新元素合成及原子核存在极限、核物质相结构、高电荷态原子结构

2 面向国家重大需求的离子束应用研究 — 交叉应用
先进离子治疗技术、同位素靶向药物研发、辐照育种、功能材料研究及应用、航天元器件单粒子效应地面模拟、电子加速器技术

3 加速器驱动的先进核能研究 — 先进核能
ADS燃烧器、乏燃料再生、核能材料研究、重离子驱动的高能量密度物理研究

4 先进离子加速器物理与技术 — 支撑
离子束制备与精确操控技术：高流强、高功率、高品质

HIAF简介

2010 提交*HIAF*项目建议书

May, 2011 *HIAF*进入“十二五”候选项目名单（共16项）

December, 2015 建设地点最终确定，*HIAF*项目得到政府批准立项

April, 2017 *HIAF*项目可研报告获批

2018 12月23号，HIAF建设正式启动

强流重离子加速器装置（HIAF）

国际上脉冲束流强度最高的重离子加速器装置

“十二五”国家重大科技基础设施

定位于重离子物理及应用研究

科学目标：

1）认识原子核中的有效相互作用

2）理解宇宙中从铁到铀重元素的来源

3）研究高能量密度物理性质

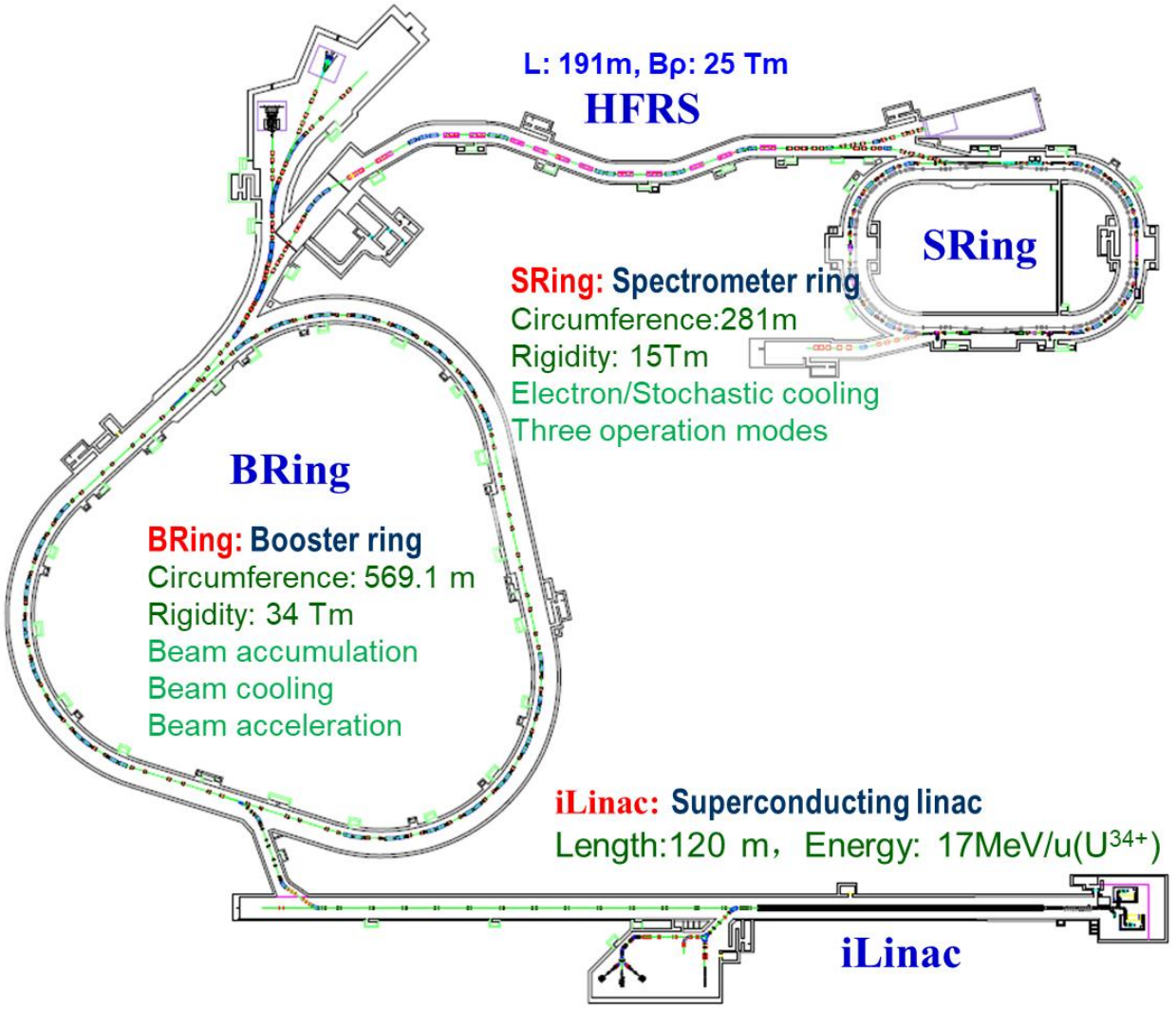
4）空间辐射环境地面模拟

5）……

国家投资16.7亿元
预计建设时间7年！

■坐落地点: 广东省惠州市黄埠镇

HIAF简介



■ HIAF 主要参数

	SECR	iLinac	BRing	HFRS	SRing
Length / circumference (m)	---	114	569	192	277
Final energy of U (MeV/u)	0.014 (U^{35+})	17 (U^{35+})	835 (U^{35+})	800 (U^{92+})	800 (U^{92+})
Max. magnetic rigidity (Tm)	---	---	34	25	15
Max. beam intensity of U	50 pμA (U^{35+})	28 pμA (U^{35+})	2×10^{11}ppp (U^{35+})	-------	10^{10}ppp (U^{92+})
Operation mode	DC	CW or pulse	fast ramping (12T/s, 3Hz)	Momentum-resolution 1100	DC, deceleration
Emittance or Acceptance (H/V, π·mm·mrad, dp/p)		5 / 5	200/100, 0.5%	±30mrad(H)/±15 mrad(V), ±2%	40/40, 1.5% (normal mode)

HIAF 目标

提供最高流强的重离子束流

AGS booster	BNL	5×10^{9}	Au^{31+}	
LEIR	CERN	1×10^{9}	Pb^{54+}	
SIS18	**GSI**	**1.5×10^{11}**	**U^{28+}**	**2.7 Hz**
SIS100	GSI	6×10^{11}	U^{28+}	<1 Hz
NICA	JINR	4×10^{9}	Au^{32+}	
HIAF	**IMP**	**2×10^{11}**	**U^{35+}**	**3-10 Hz**

面临的技术挑战：

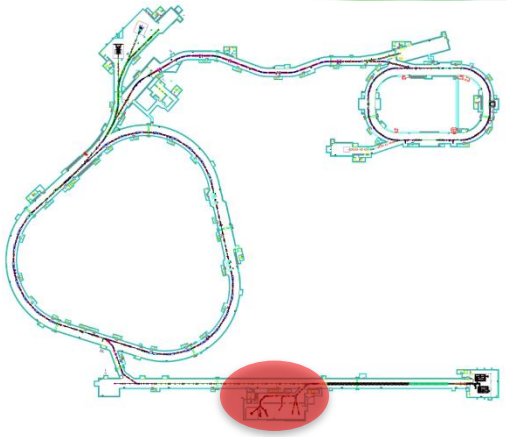
- 第4th 代ECR离子源，超导直线加速器；
- 新的束流注入方法以提高注入效率，突破空间电荷极限；
- 快的循环速度(12T/s)以减小电离束流损失和动态真空效应；

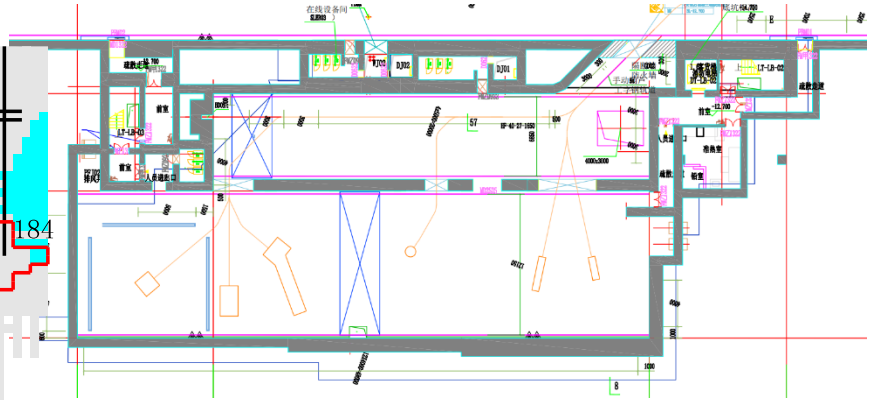
HIAF上计划开展的核物理研究

主要目标（核物理）

- 探索核图中迄今未知的领域
- 发现奇异的核特性，并认识其背后的物理原理
- 理解宇宙中化学元素的起源
- 描述核物质的QCD相图

低能实验终端





- 熔合蒸发反应
- 多核子转移反应

Products of fusion reactions

Products of MNT reactions

Observed nuclei
Predicted nuclei
Stable nuclei
Bf < 5 MeV
Known masses

- To synthesize new isotopes
- To measure nuclear masses and lifetimes
- To build the decay schemes
- To map out the drip lines
- To root the decay chains of the SHN
- To build a bridge to the island of SHN
- To simulate the *rp* and *r* processes
- To study the evolution of shell structure

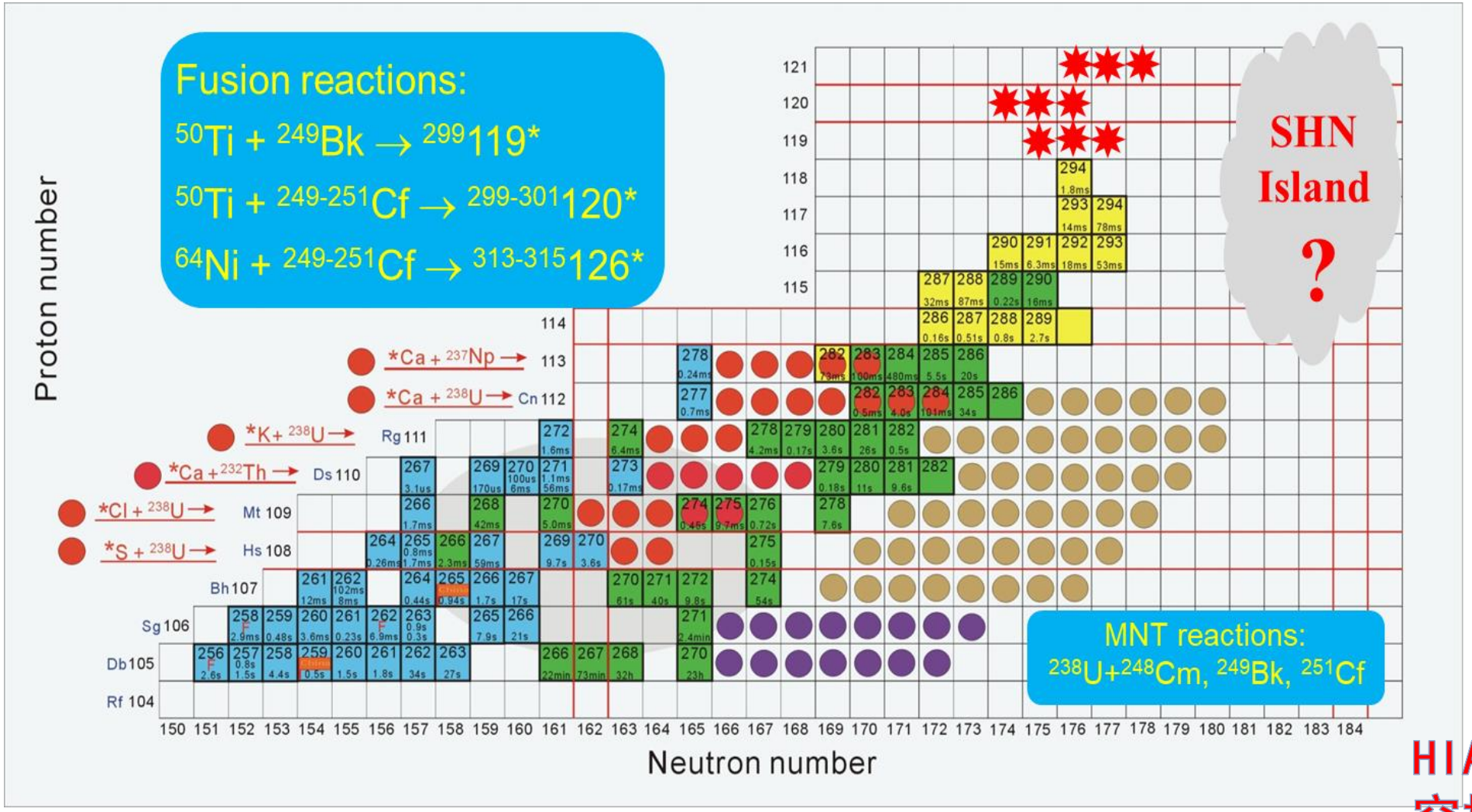
离子种类	能量 (MeV/u)	流强 (pμA)
H_2^+	48	10
$^{18}O^{6+}$	36	10
$^{78}Kr^{19+}$	30	10
$^{209}Bi^{31+}$	30	10
$^{238}U^{34+}$	17	10

The low-energy intense beams will enable producing very n-deficient nuclei by fusion reactions and particularly heavy and super-heavy n-rich nuclei by multi-nucleon transfer reactions

低能实验终端

Is there a limit, in terms of proton and mass numbers, to the existence of nuclei?

Unprecedented opportunities for the synthesis of new isotopes and structure studies



科学目标

新元素和新核素合成：

- 合成120-126号新元素
- 研究超重元素化学性质
- 合成新超重核素
- 。。。。。。

探索超重核“稳定岛”：

- 发展直接鉴别技术和方法
- 重核间的多核子转移机制
- 合成丰中子超重核素
- 。。。。。。

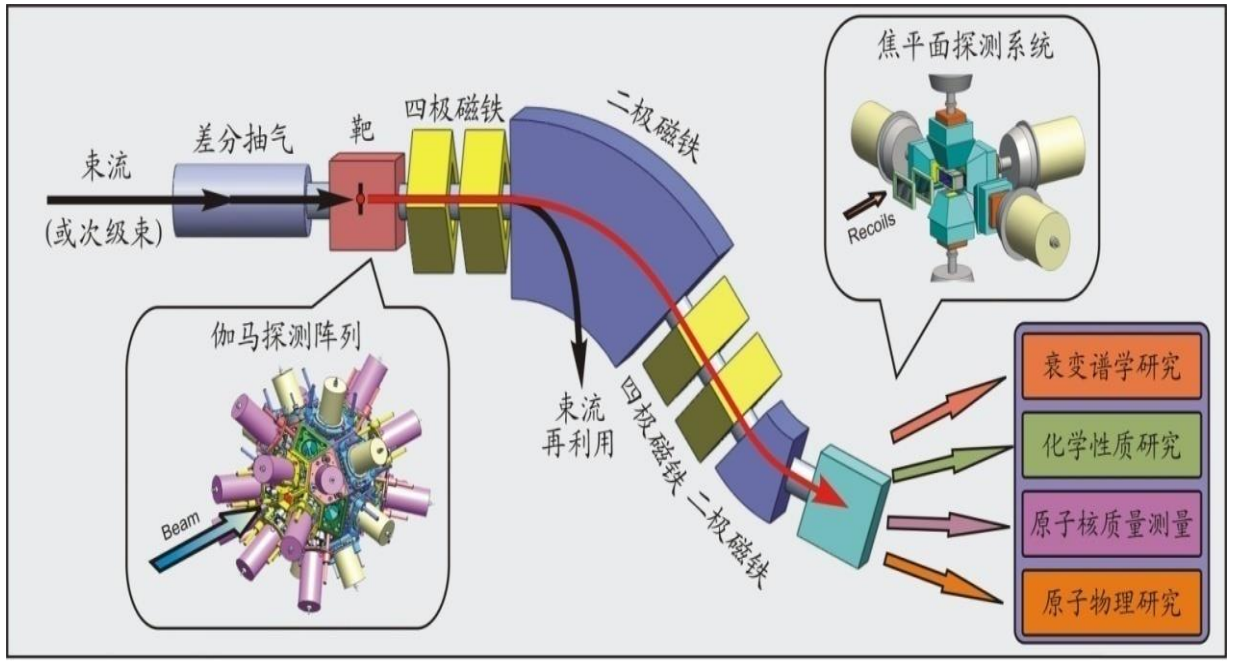
超重核素性质研究：

- 超重核素质量和寿命测量
- 寻找新的K-isomers
- 超重核素中单粒子态的信息
- 。。。。。。

HIAF可以为新元素的研究提供最好的实验条件

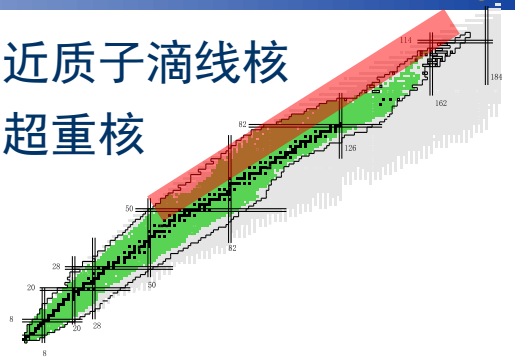
低能实验终端

低能核结构谱仪–充气反冲核分离器



近质子滴线核

超重核



谱仪性能:

- 分离传输效率>50%
- 1.0 MeV的 γ 射线：
  探测效率~10%
  能量分辨~2.0 keV
- 10.0 MeV的 α 粒子：
  探测效率~80%
  能量分辨~1.0%

超导直线加速器能够提供国际上最强的中低能重离子束流

重离子熔合蒸发反应

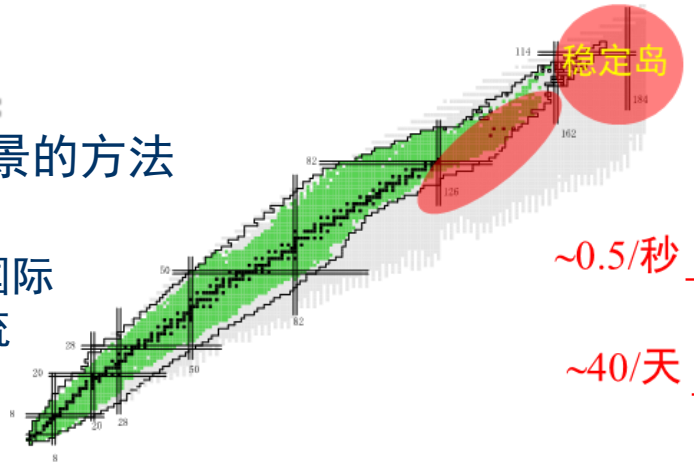
合成超重新元素（核素）、质子滴线核素；超重元素化学性质研究；
探索产生超重核的反应机制；建立远离稳定线原子核在束和衰变纲图

低能实验终端

Separation and Identification of Products from Multi Nucleon Transfer(MNT) *Reactions*

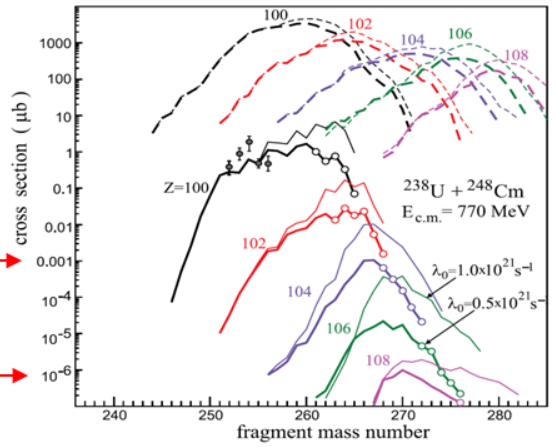
重核间多核子转移反应：
产生丰中子重核最有前景的方法

超导直线加速器能够提供国际上最强的中低能重离子束流

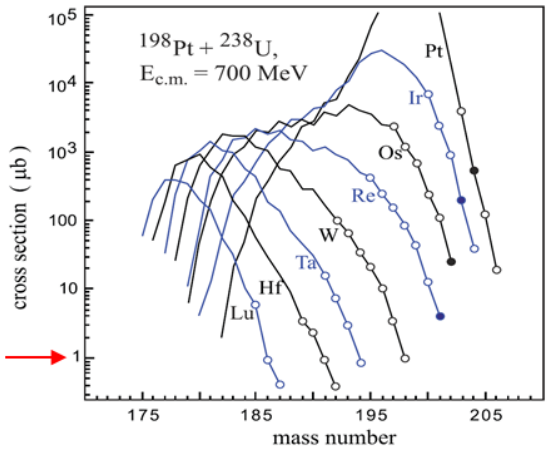


~0.5/秒

~40/天

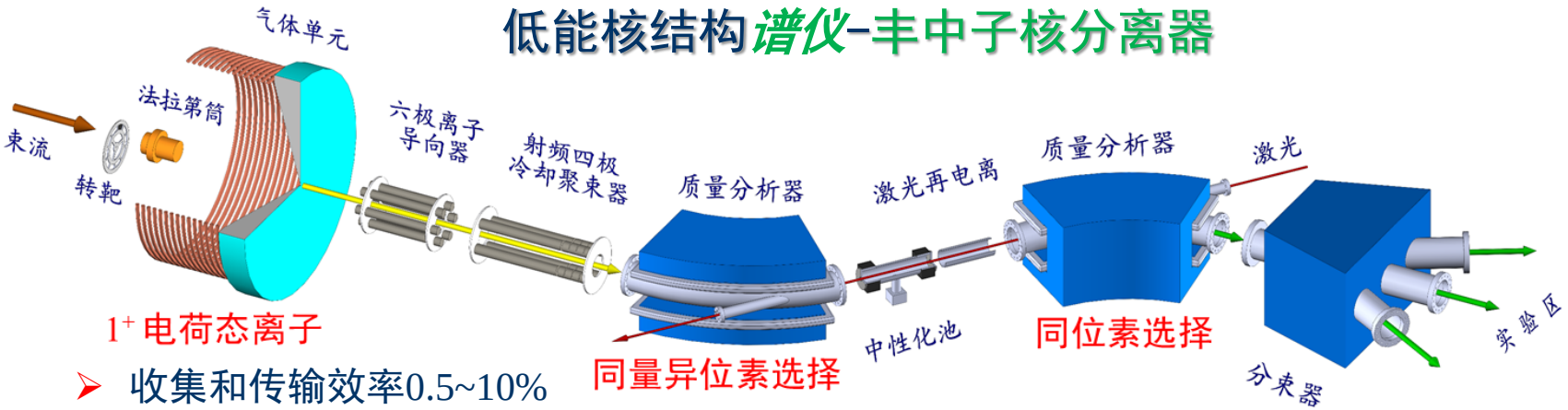


~500/秒



将形成在国际上独具特色、极具竞争力的丰中子重核素和超重核素合成及其衰变性质研究、超重元素化学性质研究、超重原子结构研究综合实验平台

低能核结构*谱仪*–丰中子核分离器

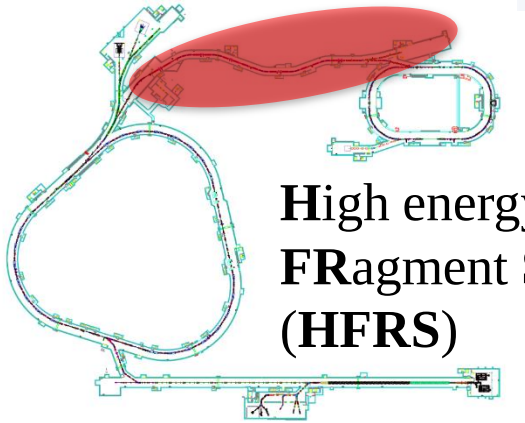


- 收集和传输效率0.5~10%
- 质量数、电荷数鉴别

- **原子核衰变测量装置：** 研究原子核衰变性质和结构
- **多反射飞行时间谱仪：** 精确测量原子核质量
- **彭宁离子阱：** 精确测量原子核质量
- **共线激光谱仪：** 测量原子核电荷分布半径等
- **气相和液相热色谱仪：** 研究超重元素化学性质

产生和制备低能、高品质、脉冲化丰中子重核和超重核束流

放射性束线

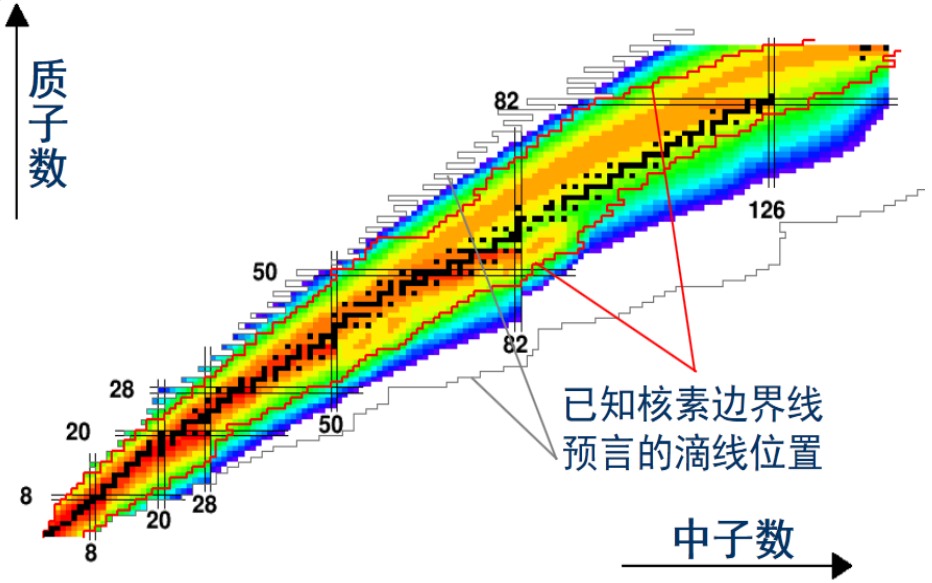


High energy **FR**agment **S**eparator (**HFRS**)

To explore the hitherto unknown territories and find new phenomena

- 原子核存在的极限是什么（特别是对丰中子核）？
- 远离稳定线的核物质有什么新的形态?
- 在极丰中子区域量子能级是如何演变的?
- 远离稳定线的集体运动有什么新的形式?
- 奇特核中动力学对称性是如何体现的（特别是沿着N=Z线）？
- …

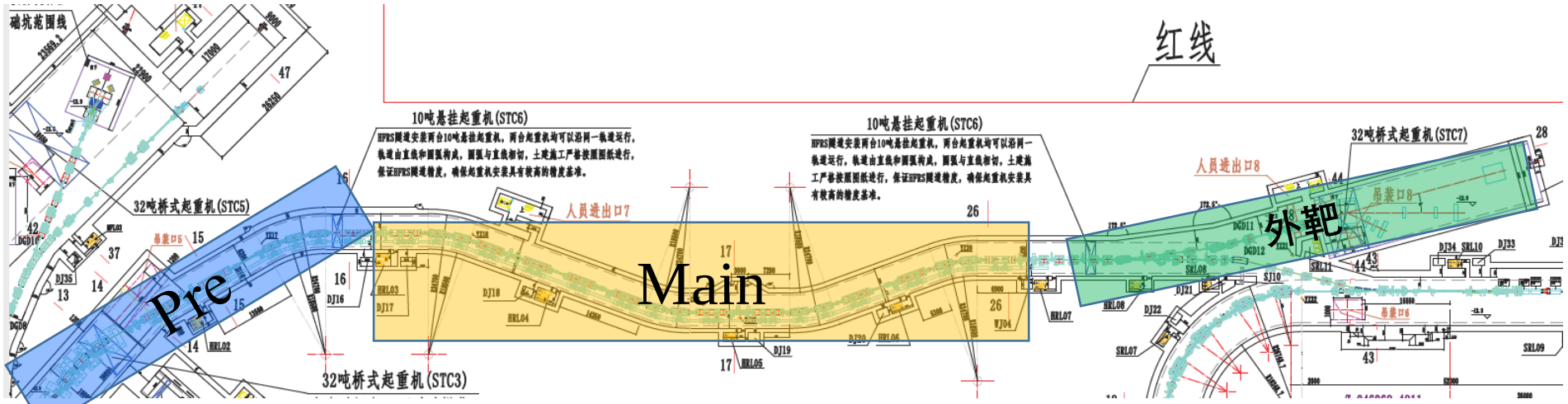
- 通过弹核碎裂及重核的飞行中裂变产生RIBs
- Pre/Main结构：去除强流主束、具备多种工作模式
- 超导磁铁：更大接收度，更高磁刚度，拓展研究领域



研究目标：数千种不稳定核素

- 发现新核素
- 有效相互作用中的张量力
- 单粒子态和集体态性质
- 传统幻数演化、寻找新幻数
- 晕结构、巨晕结构、核分子态
- 原子核电荷和物质分布
- 非束缚态的结构和性质
- ……

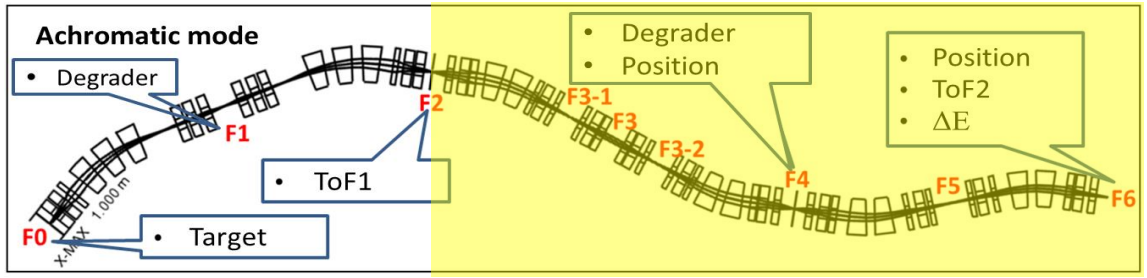
放射性束线



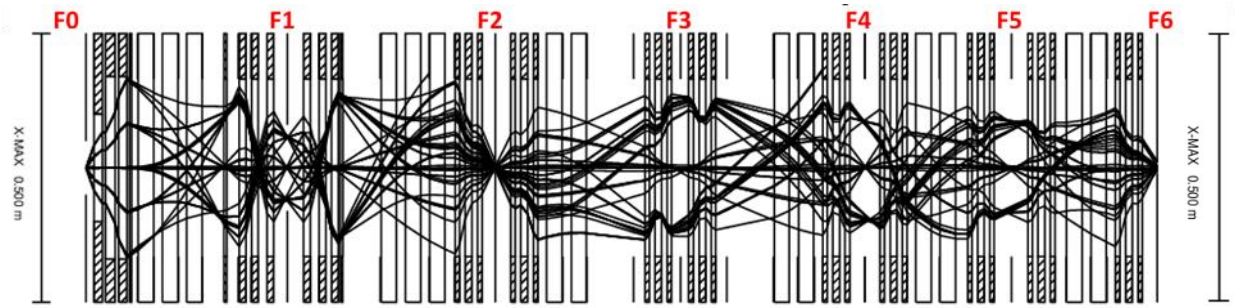
	长度 (m)	角接收度 (mrad)	动量接收度 (%)	分辨本领	最大磁刚度 (Tm)
HFRS NIM.B 469(2020),1	191.8	±30 (X); ±15 (Y)	±2.0	850/1100 (ΔX=±1mm)	25
SuperFRS NIM.B 204(2003),71	182.2	±40 (X); ±20 (Y)	±2.5	750/1500 (ΔX=±1mm)	20
BigRIPS Prog.Theor.EXP.Phys.2012,03C003	78.2	±40 (X); ±50 (Y)	±3	1260/3420 (ΔX=±1mm)	9.5
ARIS NIM.B 317(2013)349	86.8	±40 (X); ±40 (Y)	±5	1720/3000 (ΔX=±1mm)	8

放射性束线

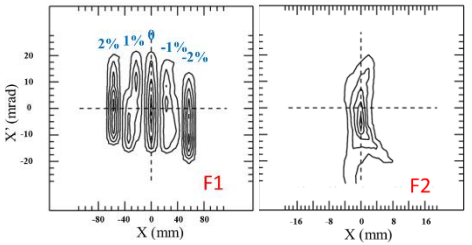
Achromatic mode



F2->F6: 117m

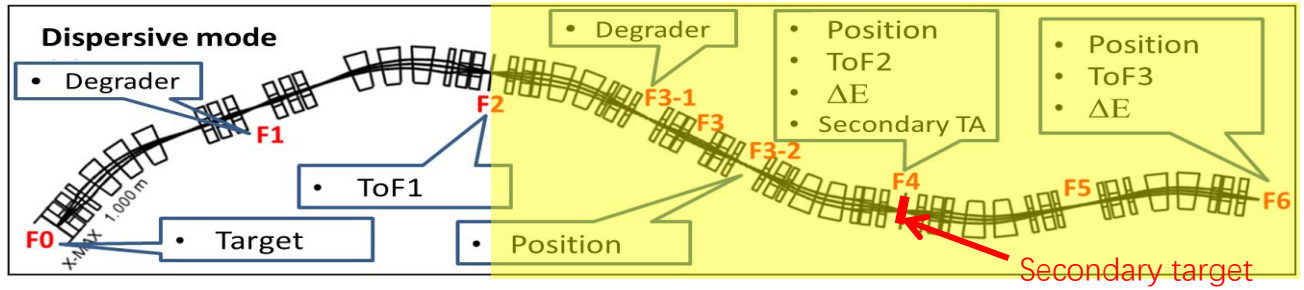


ΔX=±1mm
ΔX'=±30mrad
ΔY=±1.5mm
ΔY'=±25mrad
ΔP/P=±2%

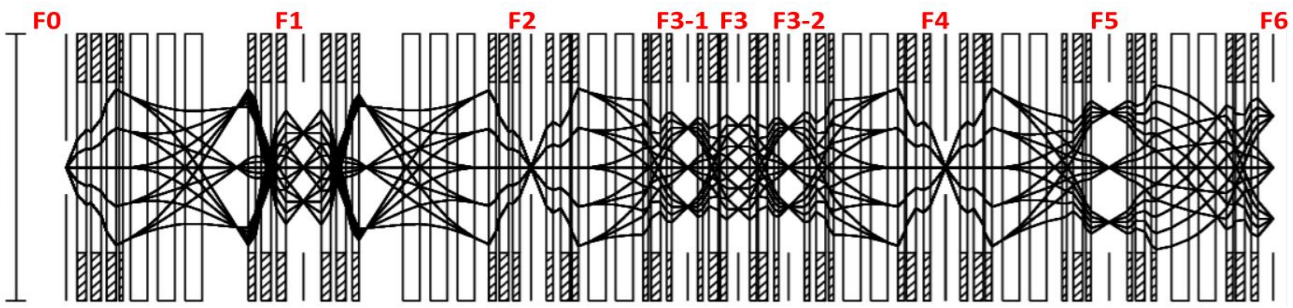


分辨本领	最大磁刚度 (Tm)
F1:850; F4:1100	25

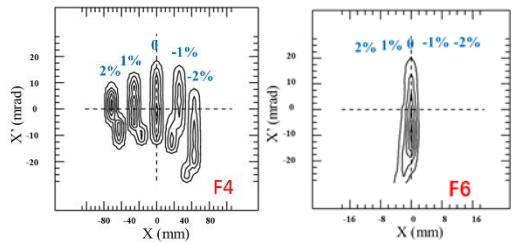
Dispersive mode



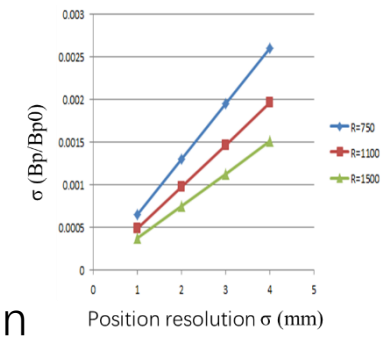
F2->F4: 65m F4->F6: 53m



Fragment Separator + Zero Degree Spectrometer



分辨本领	最大磁刚度 (Tm)
F1:850; F3-1:700	25
F6:1000	25

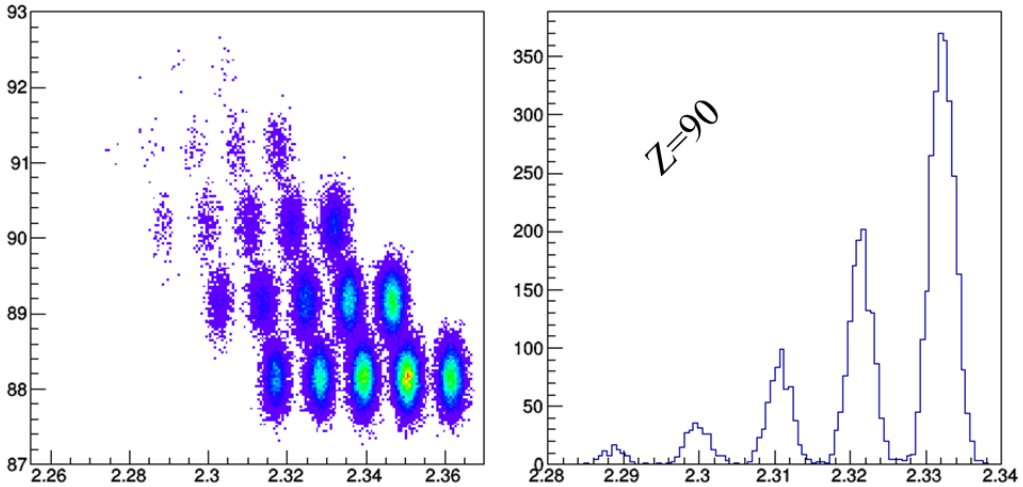


Detectors aided high mass resolution

放射性束线

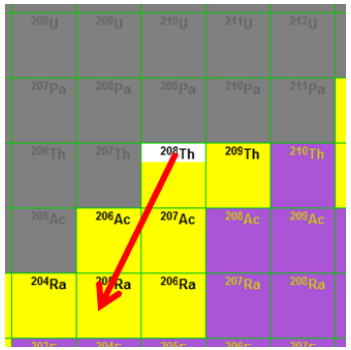
Achromatic mode

^{238}U@800AMeV+^{12}C -> ^{208}Th
Bρ=10.66Tm

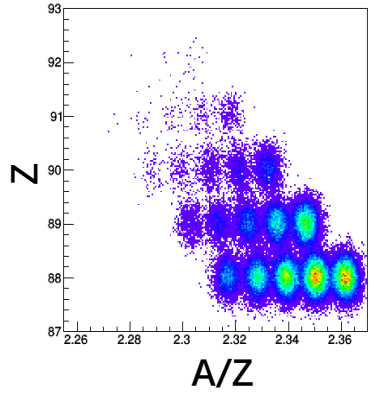


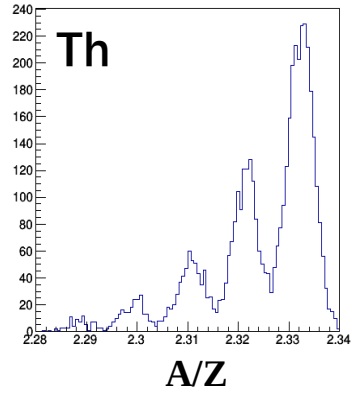
Dispersive mode

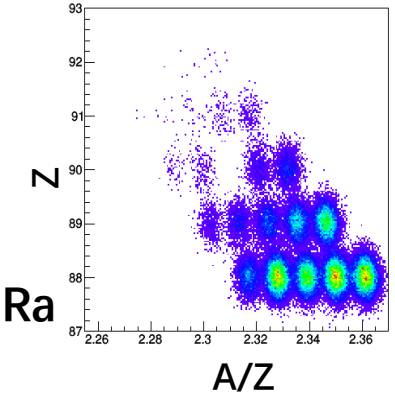
F0 – F4:
^{238}U+^{12}C-> ^{208}Th
800AMeV
Bρ=10.66Tm

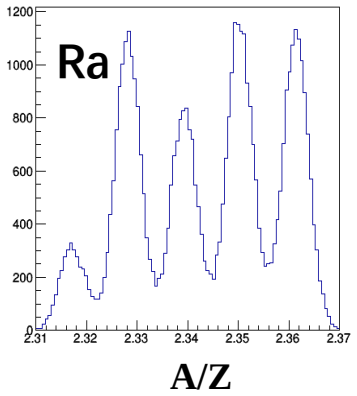


F4 – F6:
^{208}Th+^{12}C -> ^{205}Ra
Bρ=10.22Tm









- ✓ Time resolution (σ) : 50ps
- ✓ Position resolution (σ) : 1.0mm
- ✓ Energy resolution (σ) : 0.5%

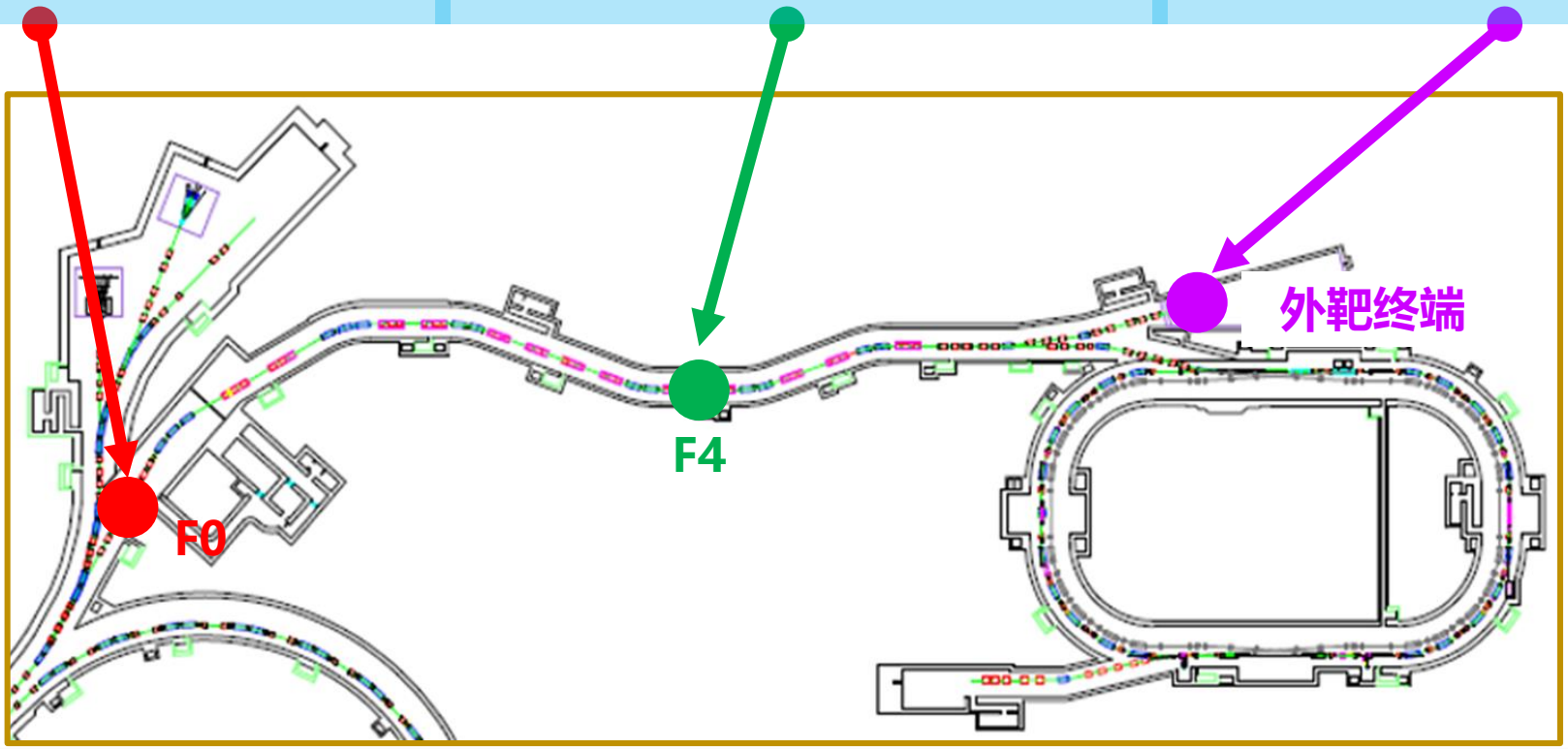
放射性束线

F0初级靶实验

F4次级靶实验

外靶终端实验

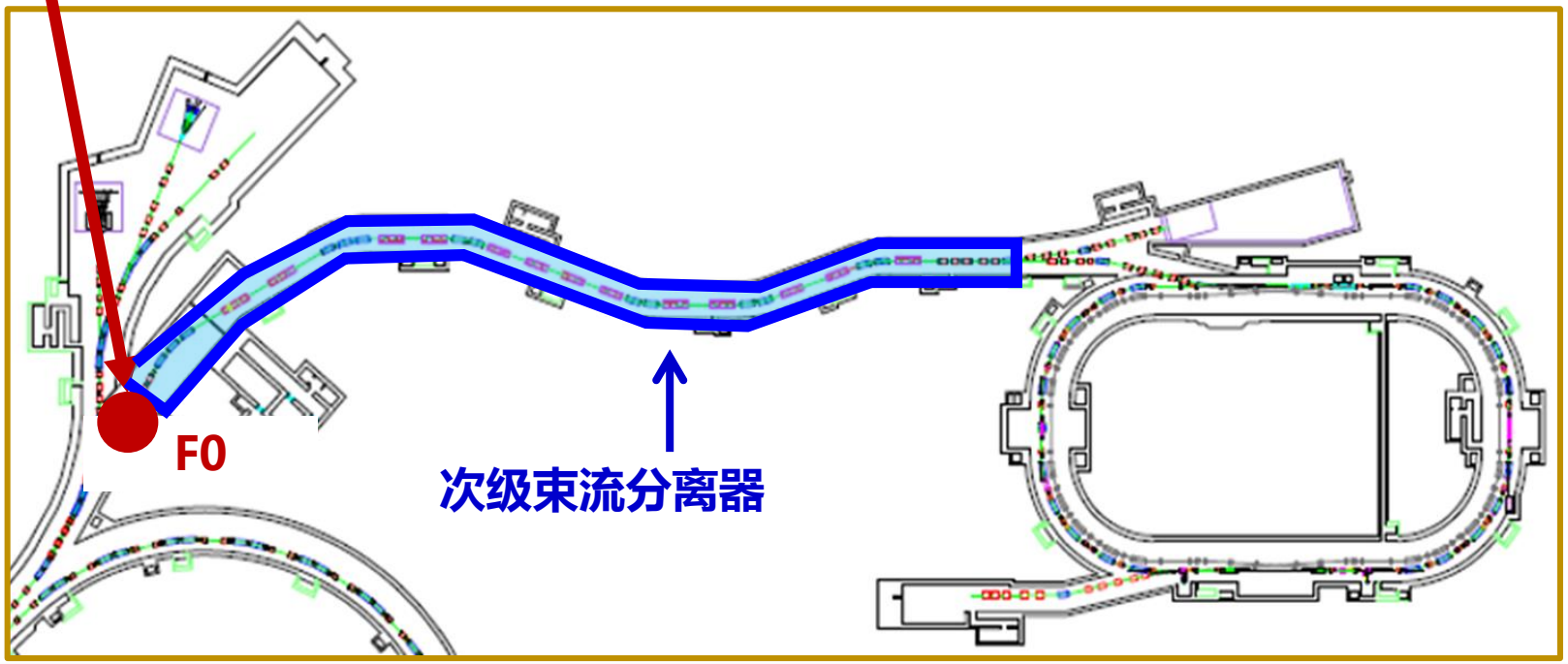
HFRS上可开展物理实验的区域



放射性束线

基于HFRS的碎片分离束线功能，结合束线探测器可开展的实验研究：

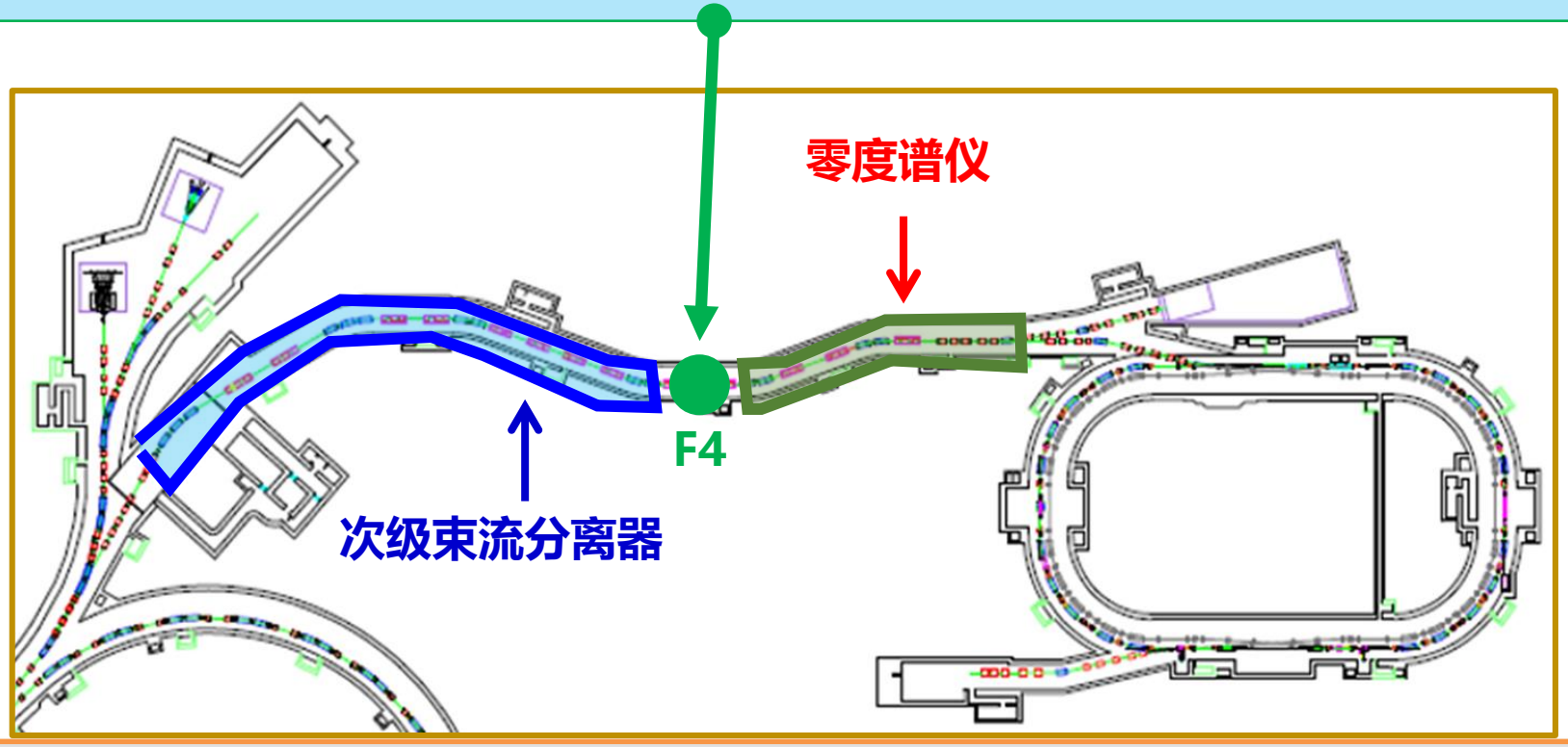
- RIB production mechanism
- Discovery of new isotope
- Mass measurement of extremely short-lived nuclei
- Mechanism of fission/spallation
- ……



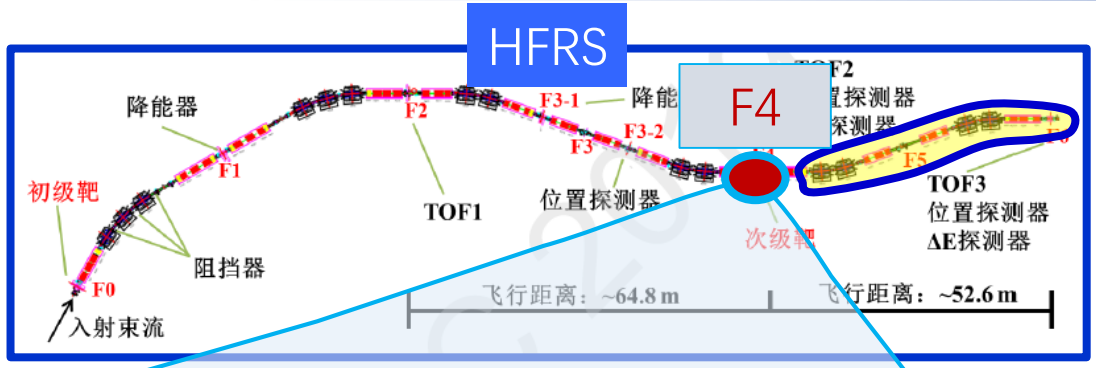
放射性束线

利用HFRS的F0-F4部分作为碎片分离束线及F4-F6作为零度谱仪，
结合新建造的探测装置，可开展多种类型的物理实验：

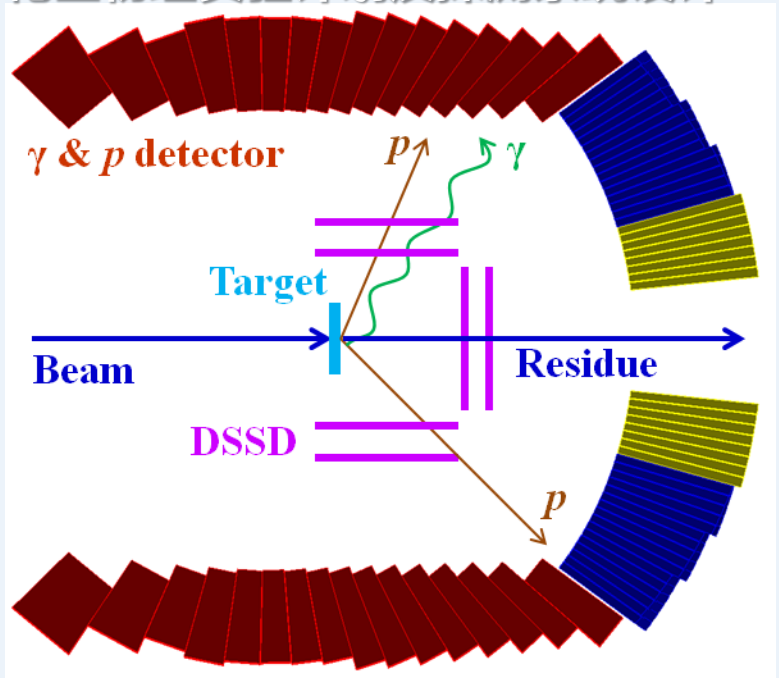
- Interaction cross section → nuclear radii and matter distribution, halo and skin structures
- Knockout/Quasifree knockout → single-particle structures, unbound states/nuclei, clusters
- Charge change/exchange → Gamow-Teller strength, spin-dipole resonance, neutron skins
- ……



放射性束线



F4靶区物理实验计划及探测系统设计



F4靶区探测系统构型

- New magic numbers
- Shell evolution
- Shape coexistence
- halos
- ……

② F4-F6谱仪：类弹产物测量

- Interaction cross section/Fragmentation cross section
- Knockout (inclusive cross section + momentum distr.)
- Charge exchange

……

② CsI阵列：在束γ谱测量

- Spectroscopy of nuclei at limits → E(2^+), E(4^+), …
- Knockout (exclusive cross section + momentum distr.)
- Inelastic/Coulomb excitation→ B(E2)

……

② CsI阵列+DSSD阵列：轻带电粒子ΔE, E, 径迹

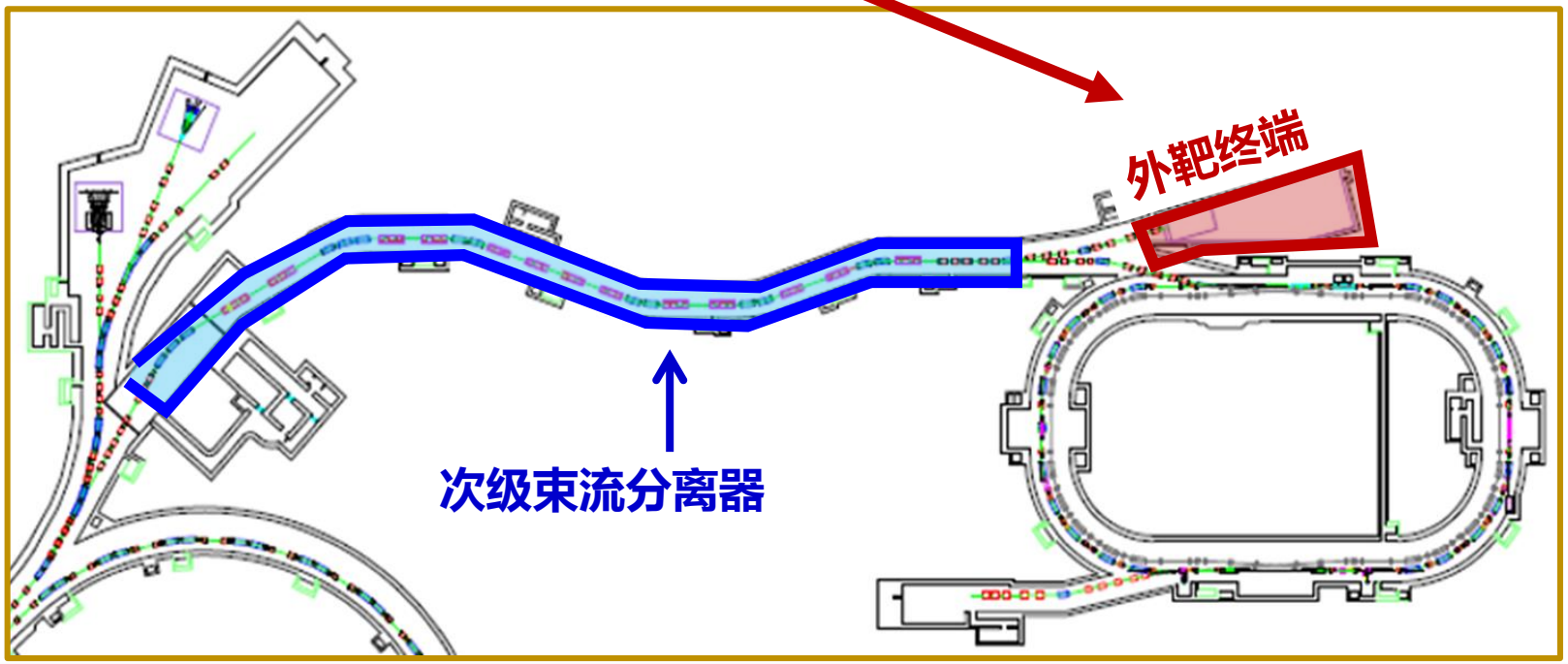
- Quasi-free scattering
- Missing mass → unbound states
- Reaction mechanism of knockout/quasi-free/…

……

放射性束线

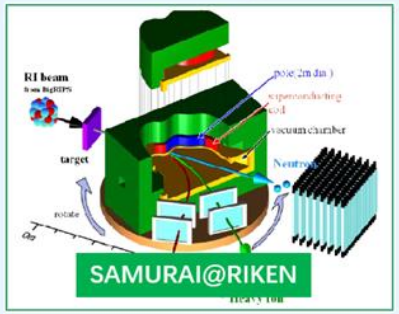
外靶终端区域预留空间充足（面积~400 m^2），
将来可建造多种实验装置、开展多种类型的物理实验

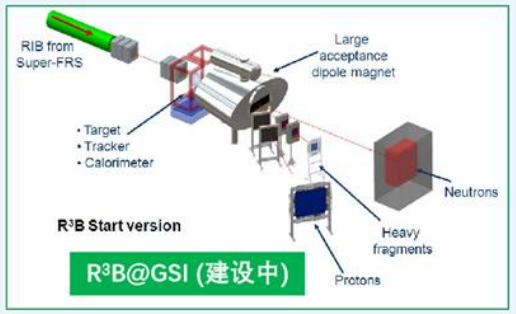
大接收度谱仪装置 （高能放射性束反应实验）	束流慢化+低能实验装置 （低能放射性束反应实验）	束流阻停+衰变实验装置 （衰变实验）

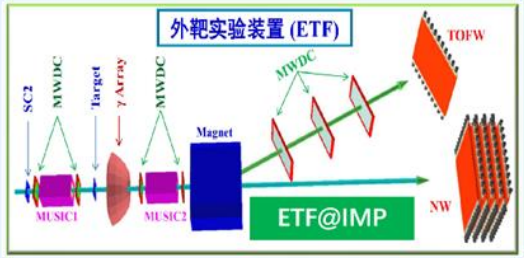


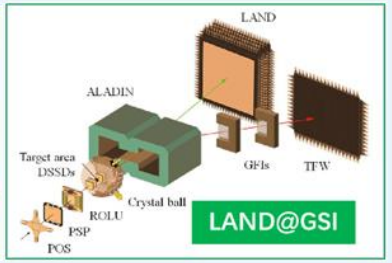
放射性束线

大接收度磁谱仪









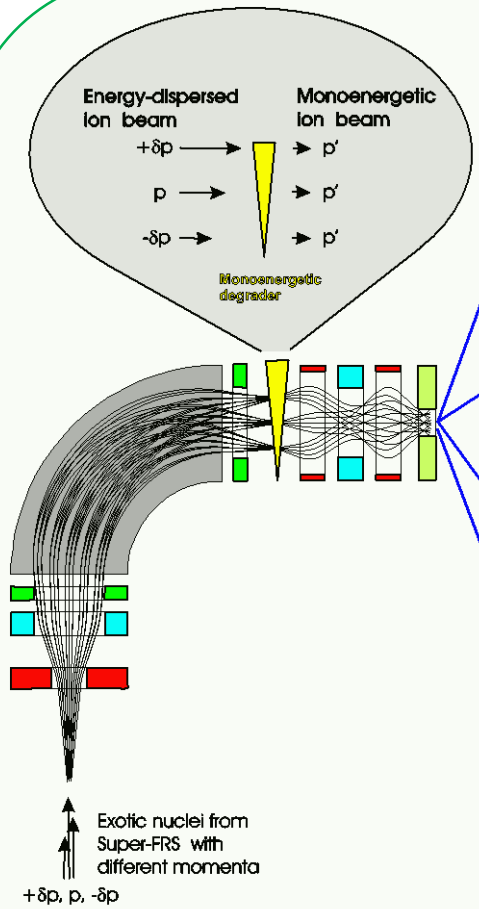
实验探测及物理研究主要目标：

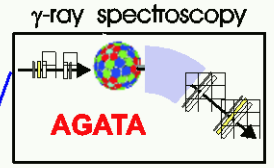
全粒子测量（运动学完全测量）

Invariant Mass Measurement
Missing Mass Measurement

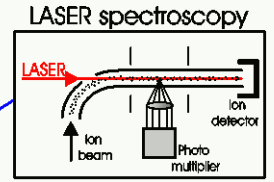
Nuclear structure and dynamics of unbound states/nuclei

放射性束的慢化和阻停

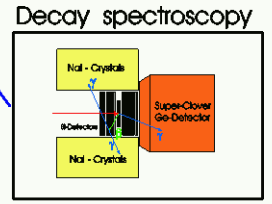




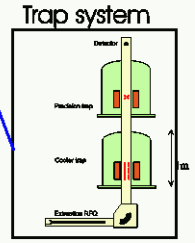
in-beam γ-ray spectroscopy with AGATA



LASER spectroscopy moments, radii



α, β, γ -decay spectroscopy isomers, very exotic nuclei



in-trap ex-periments precision mass mesurements

LEB@NuSTAR，FAIR

放射性束线

原子核结构和动力学

质量和寿命的系统性测量

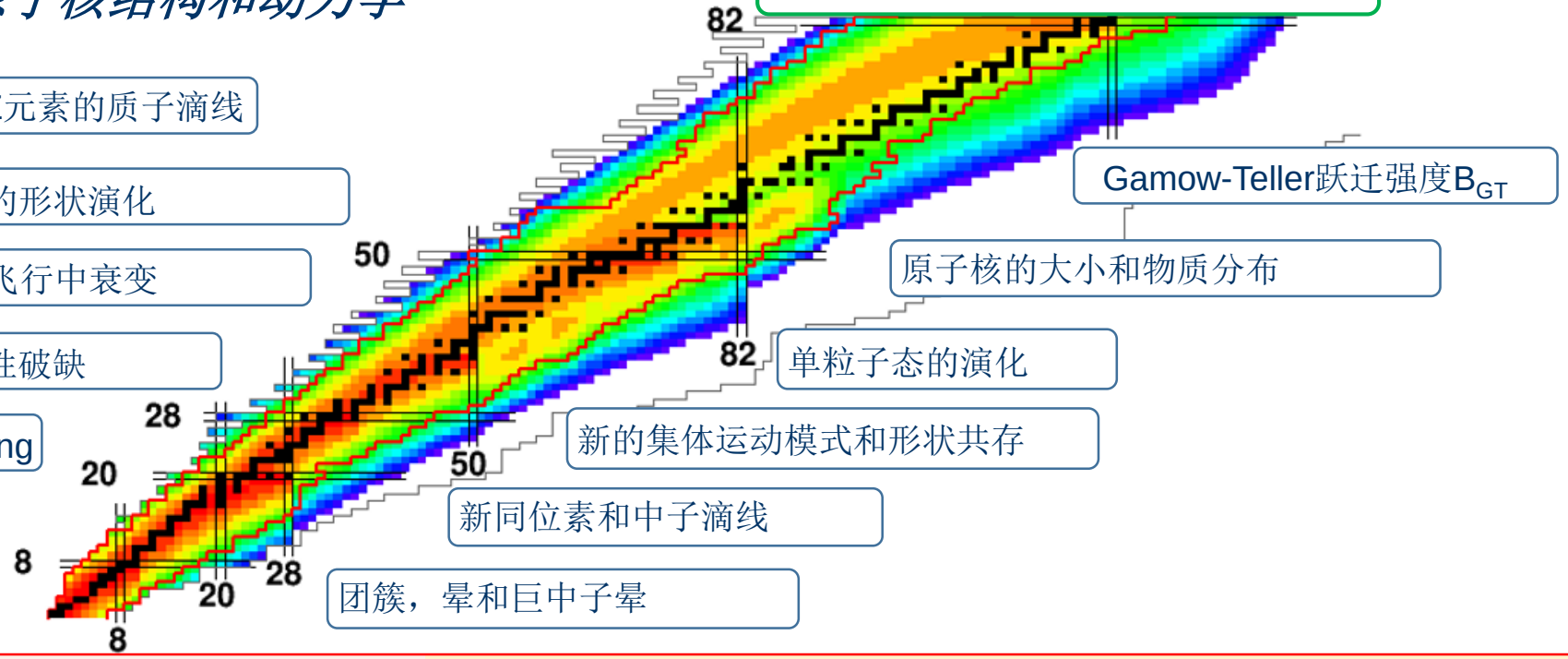
偶Z元素的质子滴线

沿着*N=Z*线的形状演化

非束缚核的飞行中衰变

同位旋对称性破缺

新的*np* pairing



Gamow-Teller跃迁强度B_{GT}

原子核的大小和物质分布

单粒子态的演化

新的集体运动模式和形状共存

新同位素和中子滴线

团簇，晕和巨中子晕

Experimental methods

- interaction cross section/elastic scattering →
- knockout/quasi-free knockout →
- electromagnetic excitation →
- charge-exchange reactions →
- fission →
- spallation →
- fragmentation/cascade fragmentation →
- slowed/stopped beam experiment →

Physics goals

nuclear radii and matter distribution, halo and skin structures
single-particle structures, unbound states/nuclei, clusters
B(E2), pigmy/giant resonance, astrophysical S factor
Gamow-Teller strength, spin-dipole resonance, neutron skins
shell structure, dynamical properties
reaction mechanism, applications (waste transmutation, ...)
new isotope, mass of very exotic nuclei, γ-ray spectroscopy, equation of state
low energy experiment, β delayed γ, p, n, … emission, isomer decay, proton decay

放射性束线

Nucleon distributions or radii

Total interaction cross sections

Elastic proton scattering

Proton distributions or radii

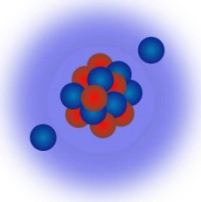
Isotope shifts

Electron scattering

μ atom

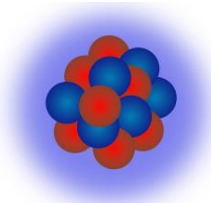
Charge changing cross sections

Halo



- Halos in heavier nuclides
- Giant neutron halos with > two neutrons
- Deformed halos
- Coupling of continuum and discrete states

Neutron distributions or radii



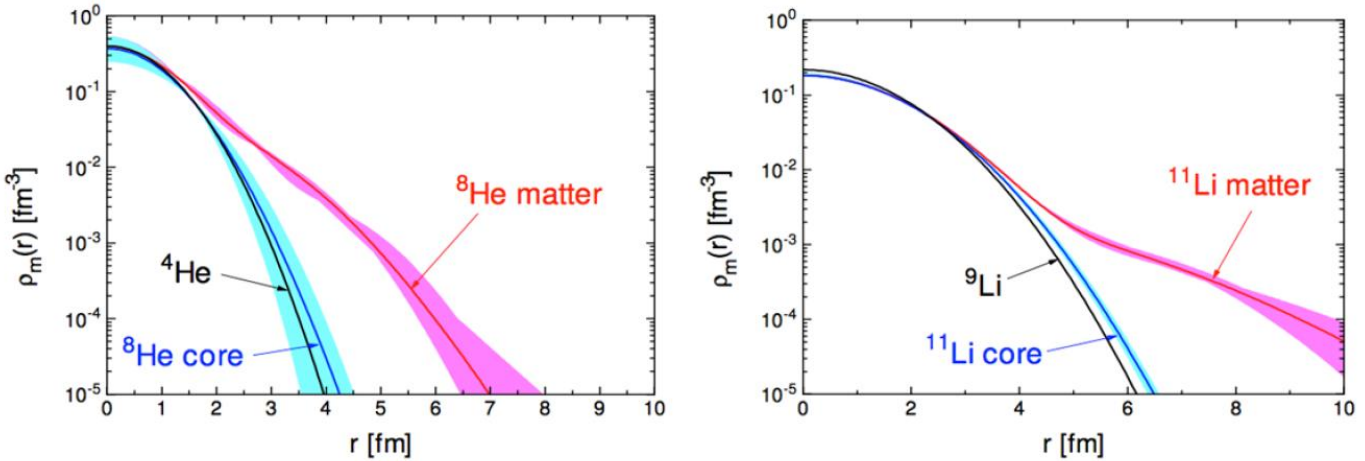
Skin

- Nuclear size evolution of n-rich nuclides
- New shell closures in n-rich regions
- Constrains on nuclear theories
- EOS for cold asymmetric nuclear matter

Measurements of nuclear matter and/or charge radii provide the most original evidences for neutron and proton halos, neutron skins, and new magic numbers

Proton scattering or light particle scattering with low-momentum transfer provides crucial information on nuclear matter distribution and incompressibility of nuclide

Pilot IKAR experiments performed at FRS.



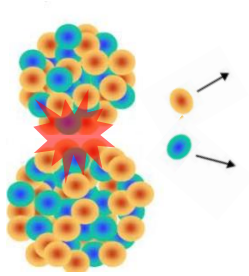
In inverse kinematic reactions using an active target, precisely measure the angular distribution in a broad angular region including the first diffraction minimum

In the center-of-mass frame, proton wavelength of ~ 1 fm at an incident energy of 500 MeV/u

- Measurements of the nucleon density distribution by elastic proton scattering
- Study of the *N/Z* ratio dependence of the saturation density; the nuclear density near the maximum of $r^2\rho(r)$ sensitive to the saturation density of nuclear matter

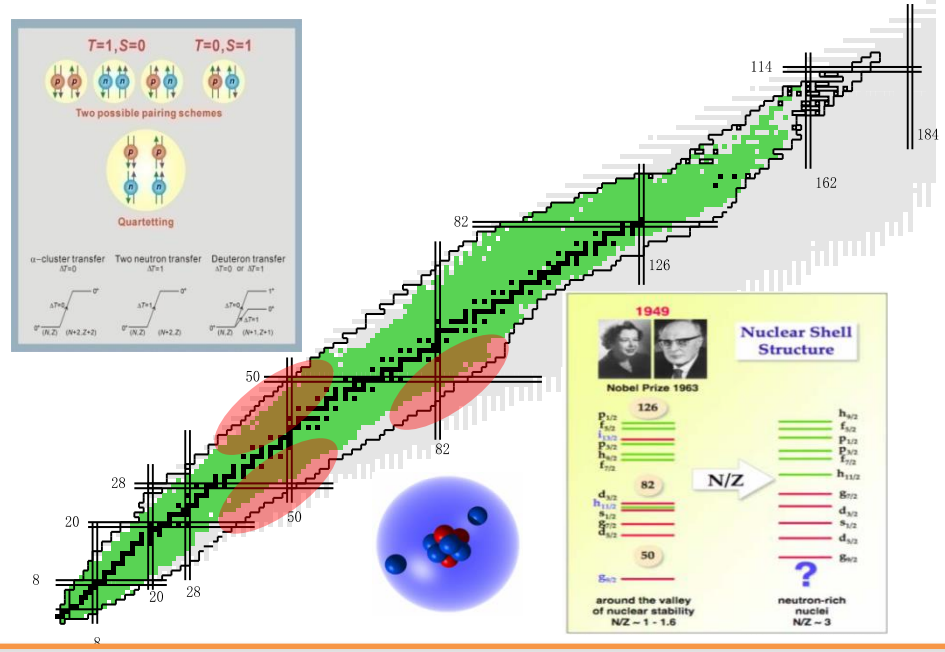
放射性束线

In order to understand the properties of nuclides far away from the stability, it is crucial to precisely locate the position of single particle states near the Fermi surface, and to investigate the degree to which their wave functions reflect pure single-particle motion



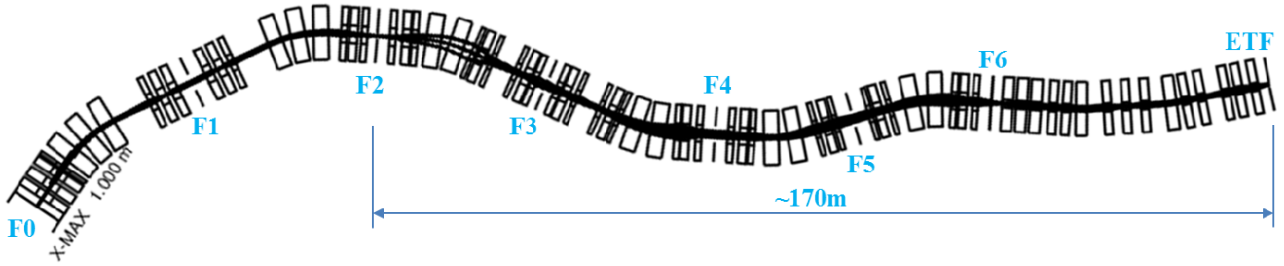
The momentum distributions of fragments following one- or two-nucleon removal is the spectroscopic method well established, that gives knowledge on the wave function of the initial nucleons

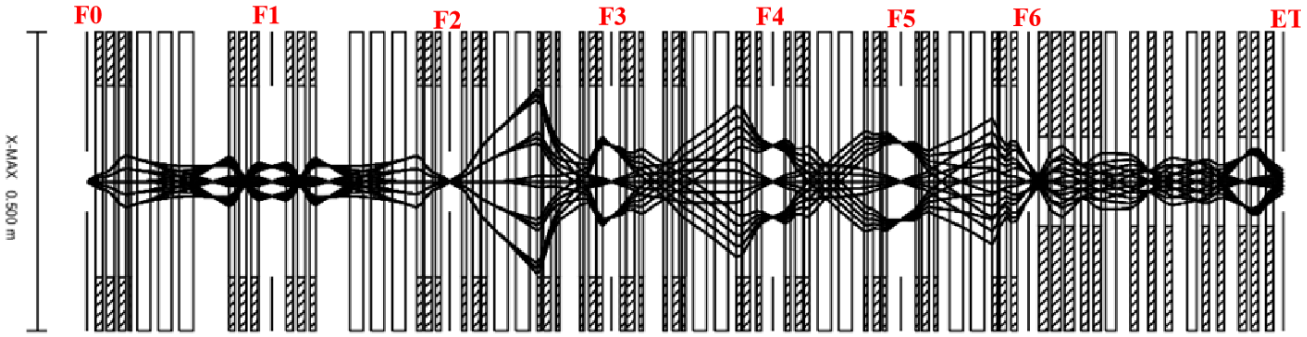
Can use very low intensity beam (~10 /s)!



Systematic study along isotopic and/or isotonic chains:

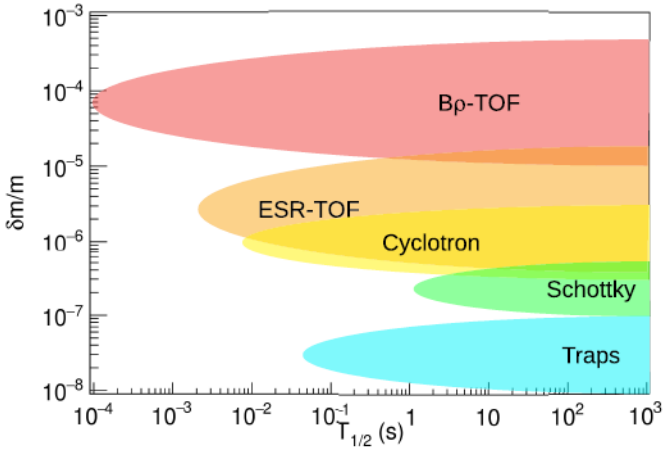
- Evolution of single particle states?
- Robustness of the shell closures?
- *T*=0, *S*=1 proton-neutron pairing?
- Coupling to the continuum?
- Heavier Halos and giant halos?
- ……





角接收度 (mrad)	动量接收度 (%)	分辨本领 (ΔX=±1mm)	最大磁刚度 (Tm)
±5 (X); ±15 (Y)	±0.5	F1:850; F4:5000	15

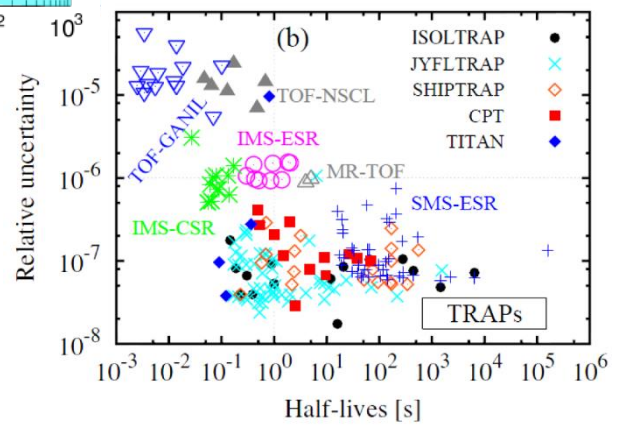
飞行时间法测量原子核质量(Bρ-TOF mass measurment)



International Journal of Modern Physics E 28(04), 1930005 (2019)

2003年-2016年间首次测量质量的原子核

EPJ Web of Conferences 109, 04008 (2016)

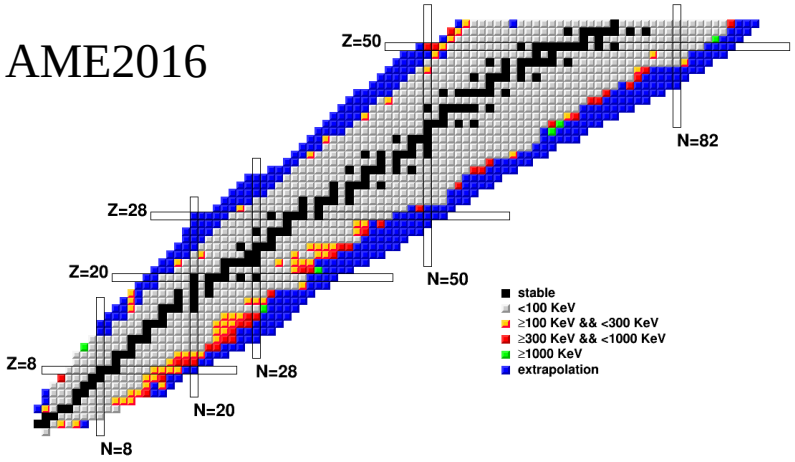


$$\left(\frac{\sigma_{m_0}}{m_0}\right)^2=\left(\gamma^2\frac{\sigma_\beta}{\beta}\right)^2+\left(\frac{\sigma_P}{P}\right)^2=\left[1-\left(\frac{L}{ct}\right)^2\right]^{-2}\left(\frac{\sigma_t^2}{t^2}+\frac{\sigma_L^2}{L^2}\right)+\frac{\sigma_P^2}{P^2}$$

	E (MeV/u)	v (cm/ns)	L (m)	tof (ns)	σtof (ns)	σtof/tof	D (mm)	σR (mm)	σR/D	σm/m
SPEG	100	12.8761	82	636.8388	0.085	1.33E-04	10000	1	1.00E-04	1.92E-04
S800	100	12.8761	59	458.2133	0.08	1.75E-04	11000	0.25	2.27E-05	2.15E-04
SHARAQ	300	19.6094	105	535.4575	0.017	3.17E-05	14760	0.127	8.60E-06	5.62E-05
HFRS	400	21.4216	170	793.5915	0.03	3.78E-05	12000	0.3	2.50E-05	8.12E-05

放射性束线

AME2016



σ_m/m=8.12e-5，则对A=100

若统计单个事件σ_m~±3.8MeV；

统计50000事件：σ_m~34KeV；

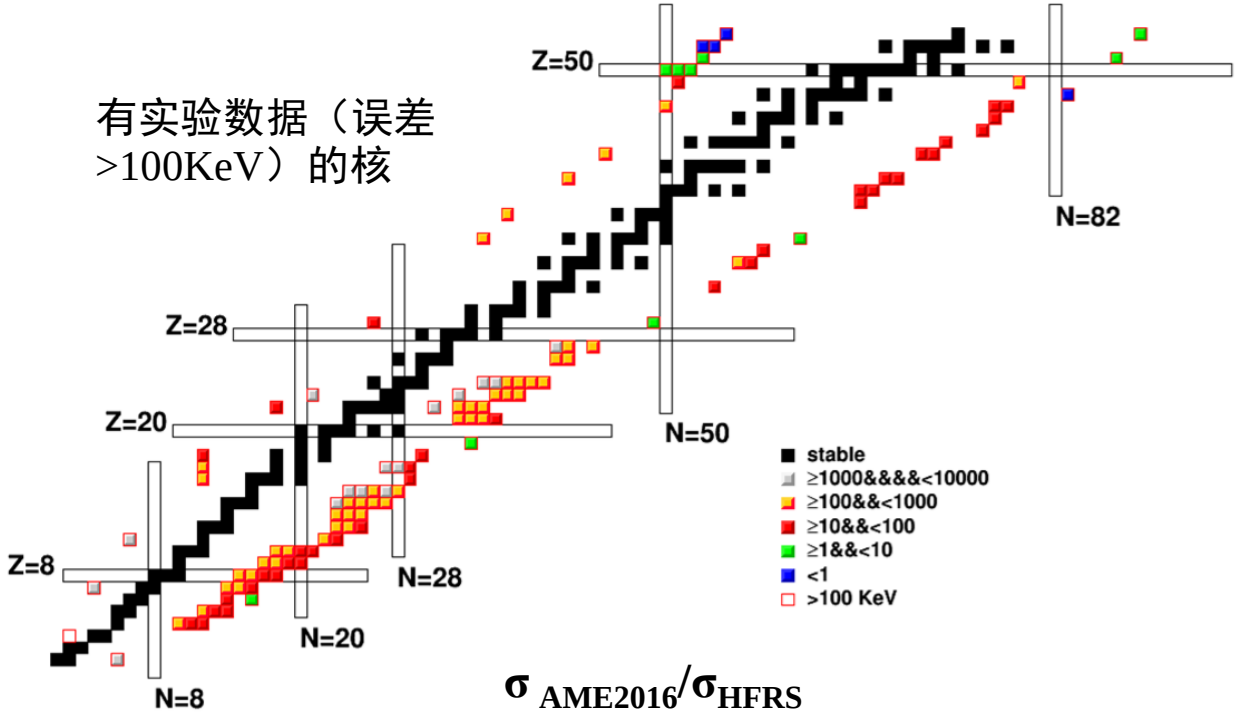
统计500事件： σ_m~340KeV；

统计5000事件：σ_m~107 KeV

统计50事件： σ_m~1074 KeV

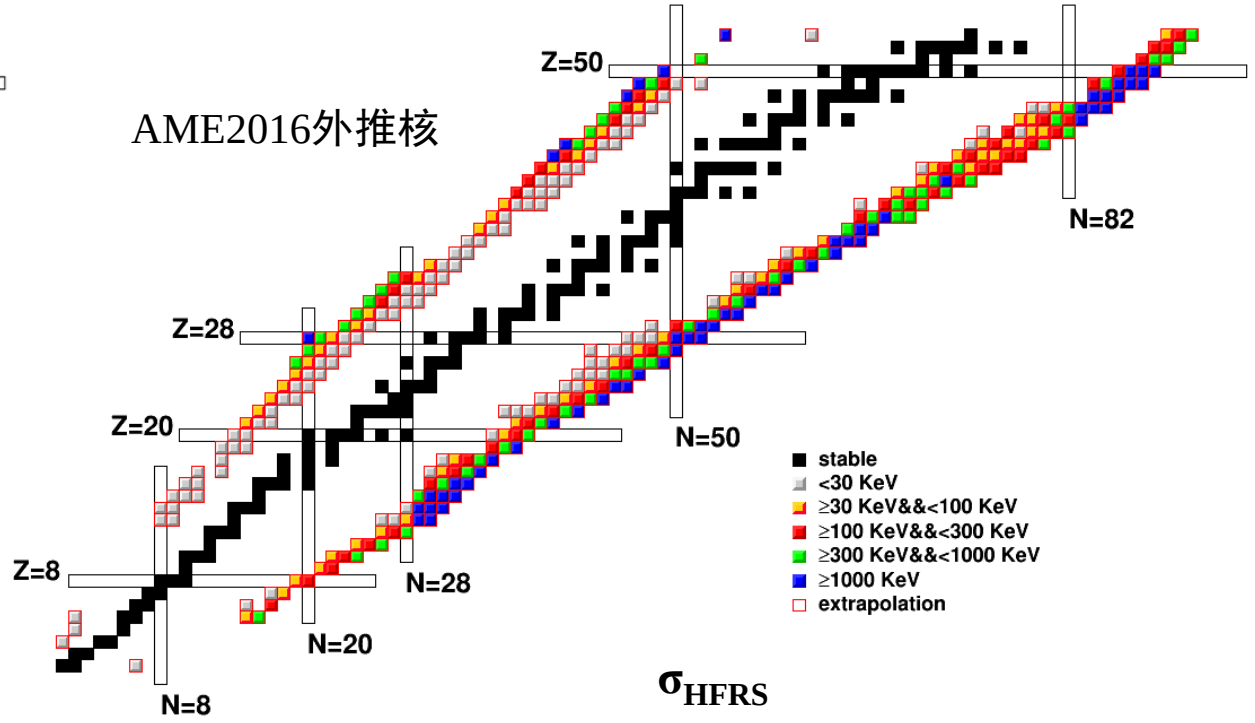
周期13秒，实验时间2天

有实验数据（误差>100KeV）的核



$\sigma_{AME2016}/\sigma_{HFRS}$

AME2016外推核



σ_{HFRS}

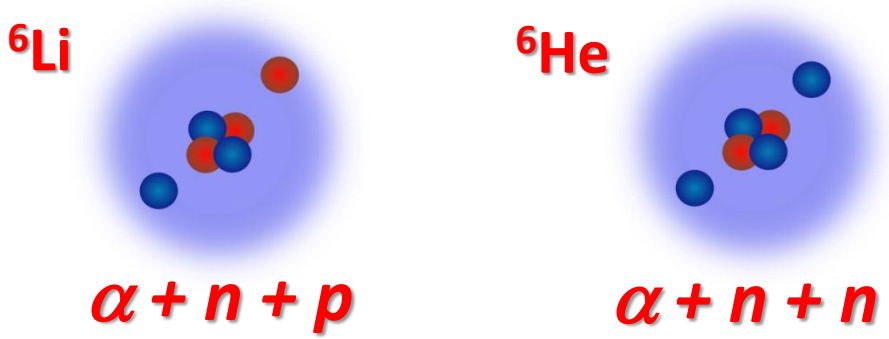
The tensor forces are essential to bind nucleons together in light nuclides, but they are not treated explicitly in models such as mean field models and shell models

The pion interaction:

$$\vec{\sigma}_1 \cdot \vec{q}\vec{\sigma}_2 \cdot \vec{q} = \frac{1}{3}q^2 S_{12}(\hat{q}) + \frac{1}{3}\vec{\sigma}_1 \cdot \vec{\sigma}_2 q^2$$

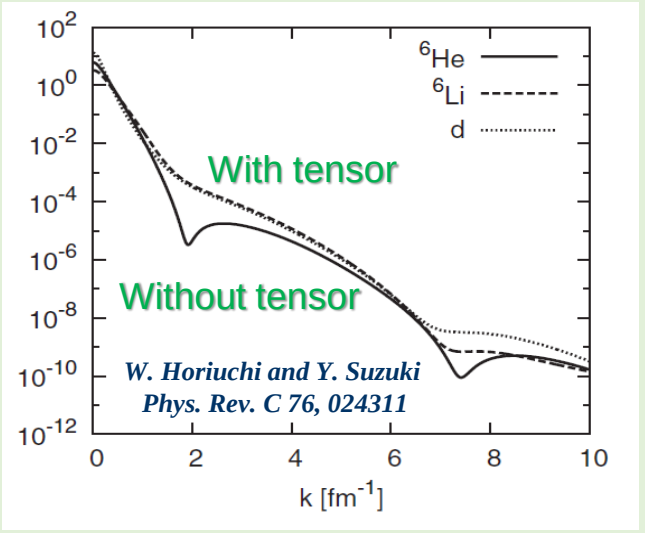
The tensor force is as important as the central forces!

In a three-body model

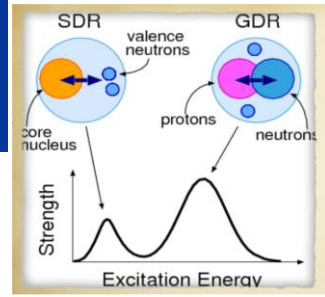


The tensor force leads to a strong correlation between a *np* pair and high-momentum nucleons in nuclei. While the high-momentum nucleon is picked up by a particle, the correlated nucleon may be emitted and measured using (*p*, *pd*), (*p*, *nd*), and (*d*, *pt*) reactions

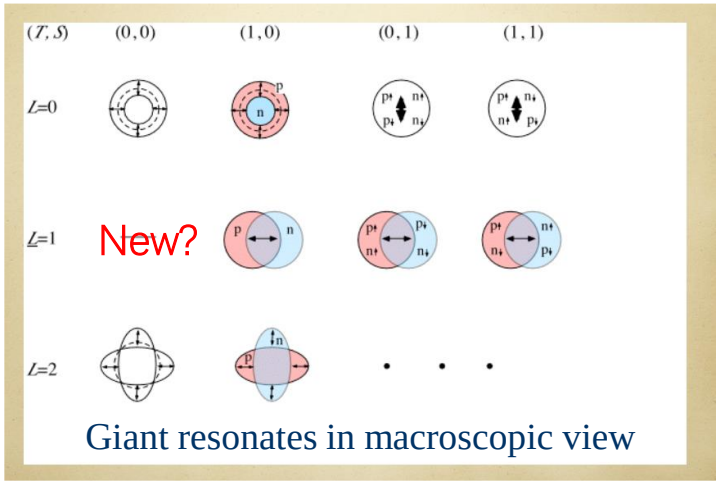
Proposed by I.Tanihata and S.Terashima



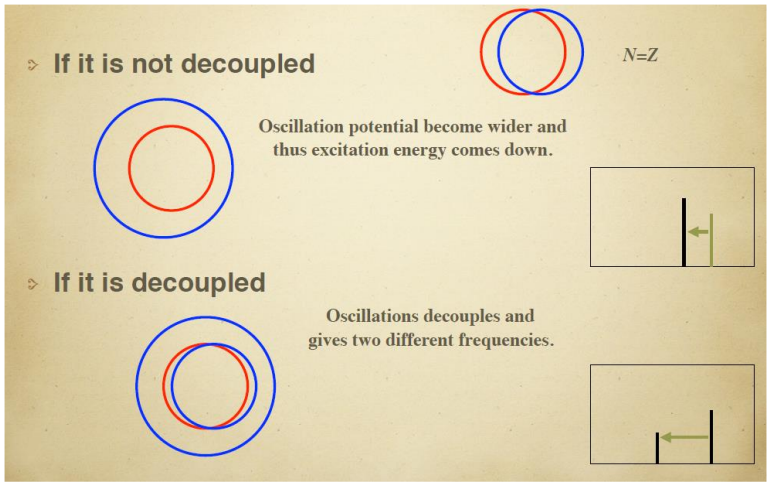
The momentum distribution of relative motion of the two nucleons in ^{6}Li and ^{6}He, reflecting the effect of tensor forces



Radioactive beams of energy higher than 1-2A GeV provide new opportunities to study **giant resonances** in asymmetric nuclei including a new mode (isoscalar E1)



Giant resonates in macroscopic view

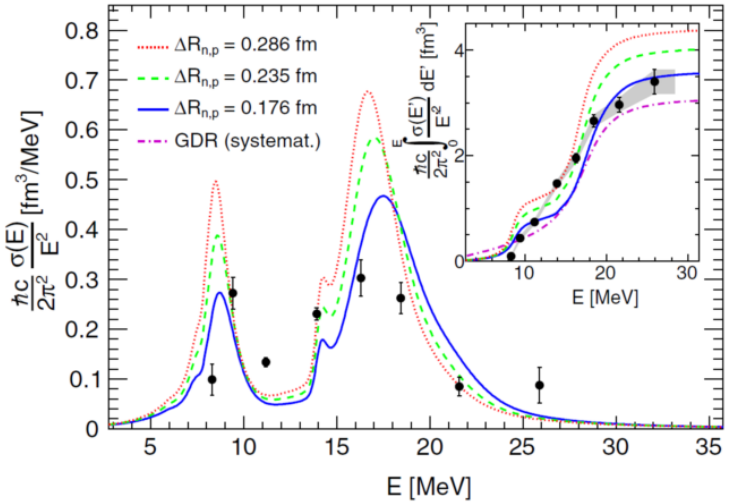


Is a neutron skin decoupled from the core?

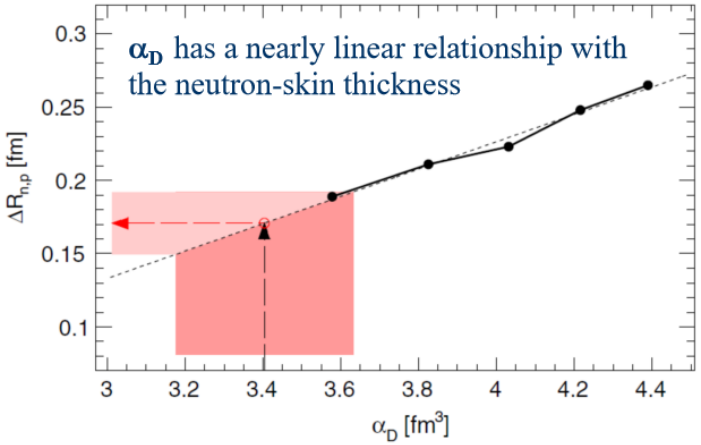
Giant dipole resonance of n-rich nuclei: a precise determination of neutron skins

- The low-lying E1 strength (PDR) in n-rich nuclei constrains the neutron-skin thickness
- The α_D is a robust and less model dependent observable to extract neutron-skin thickness

The electric dipole polarizability: $\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma(E)}{E^2}dE,$



Inverse energy-weighted dipole strength for ^{68}Ni. Inset: Experimental dipole polarizability

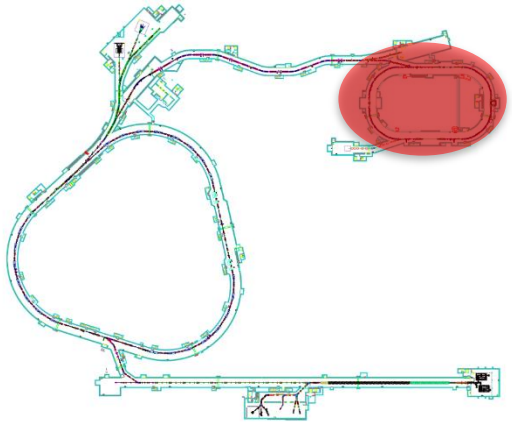


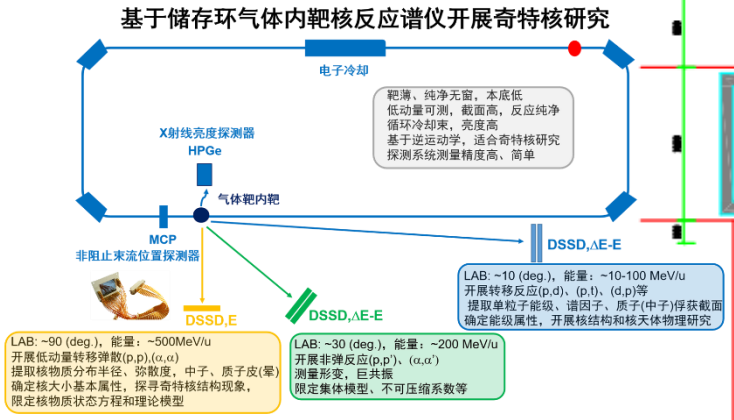
Correlation between neutron-skin thickness and dipole polarizability in ^{68}Ni

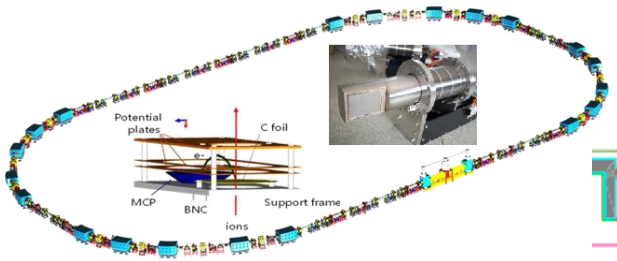
D. Rossi et al. PRL 111, 242503 (2013)

A systematic change of neutron skin thicknesses provides sensitive constraints on the EOS

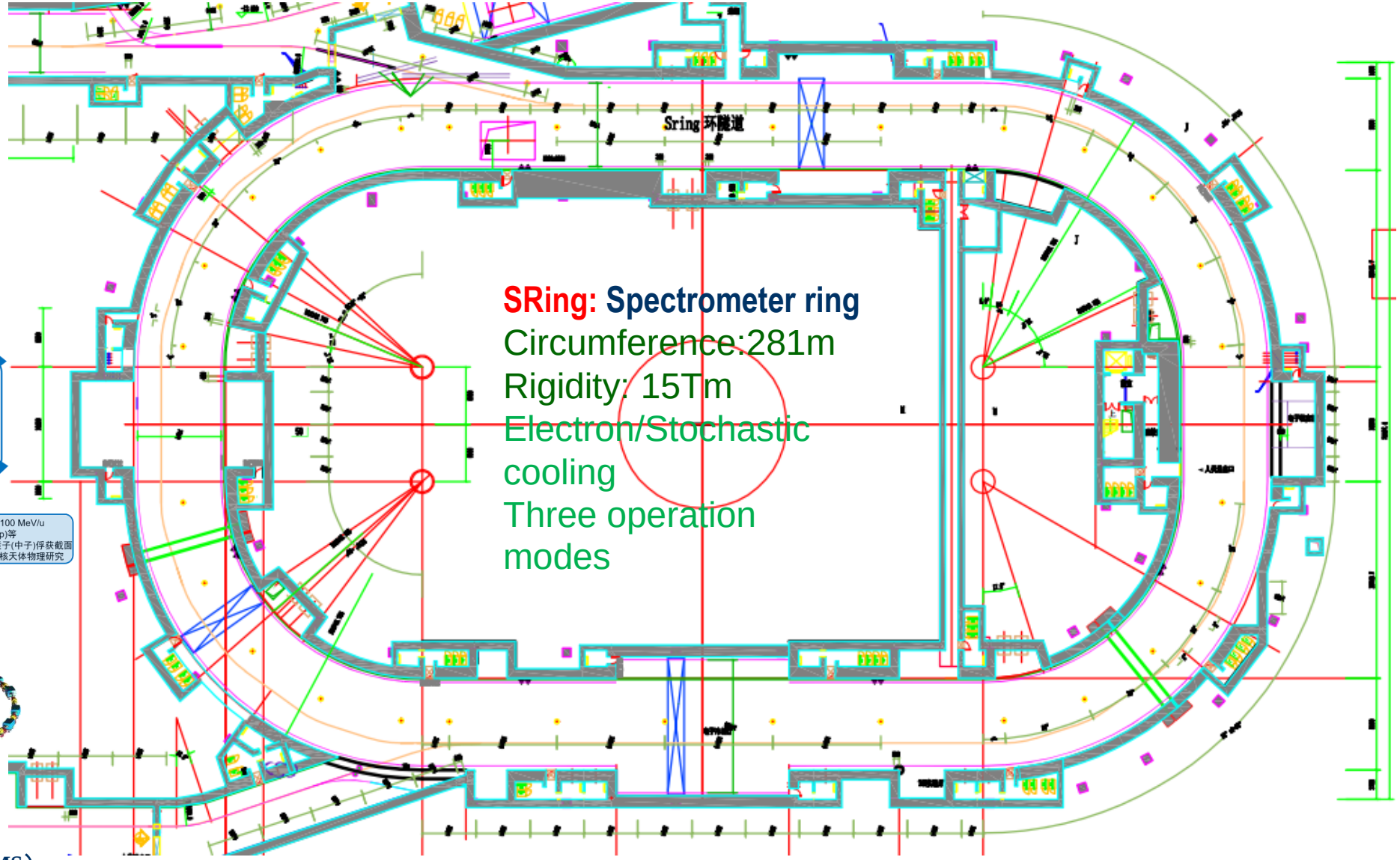
SRing







等时性质谱仪（IMS）和Schottky 质谱仪（SMS）



SRing: Spectrometer ring

Circumference:281m

Rigidity: 15Tm

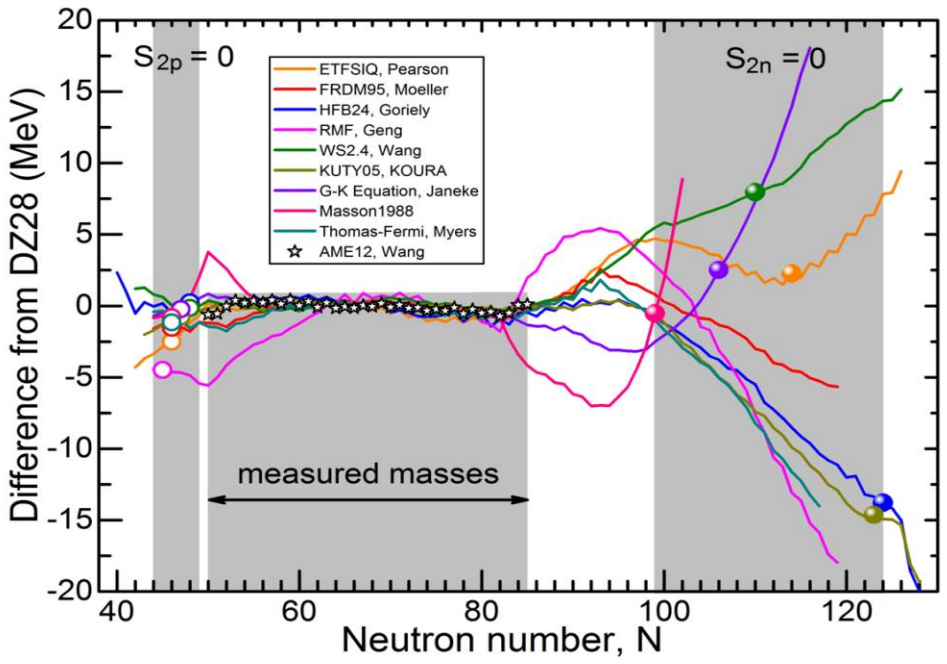
Electron/Stochastic cooling

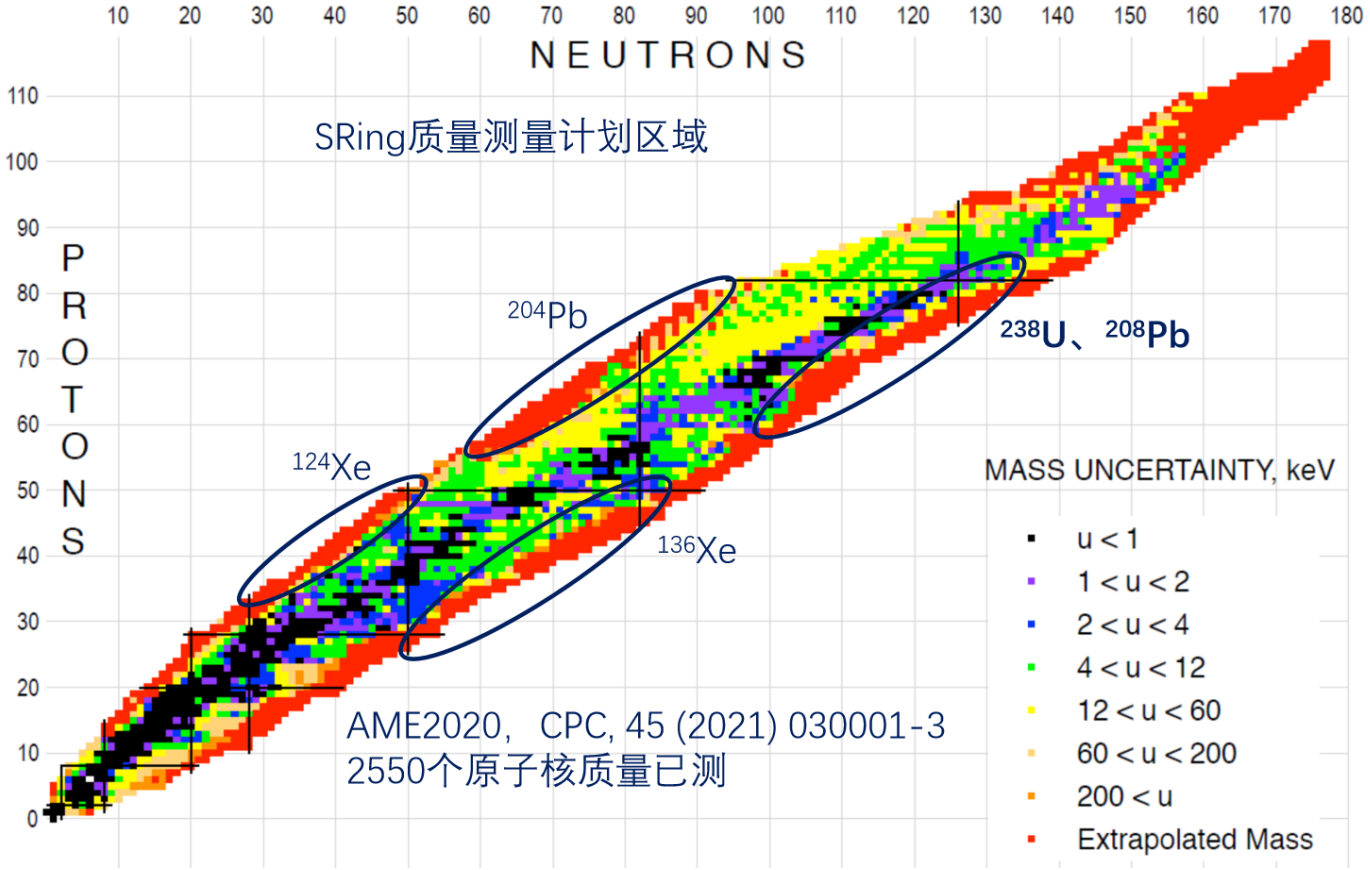
Three operation modes

等时性质谱仪（IMS）和Schottky 质谱仪（SMS）

物理目标：

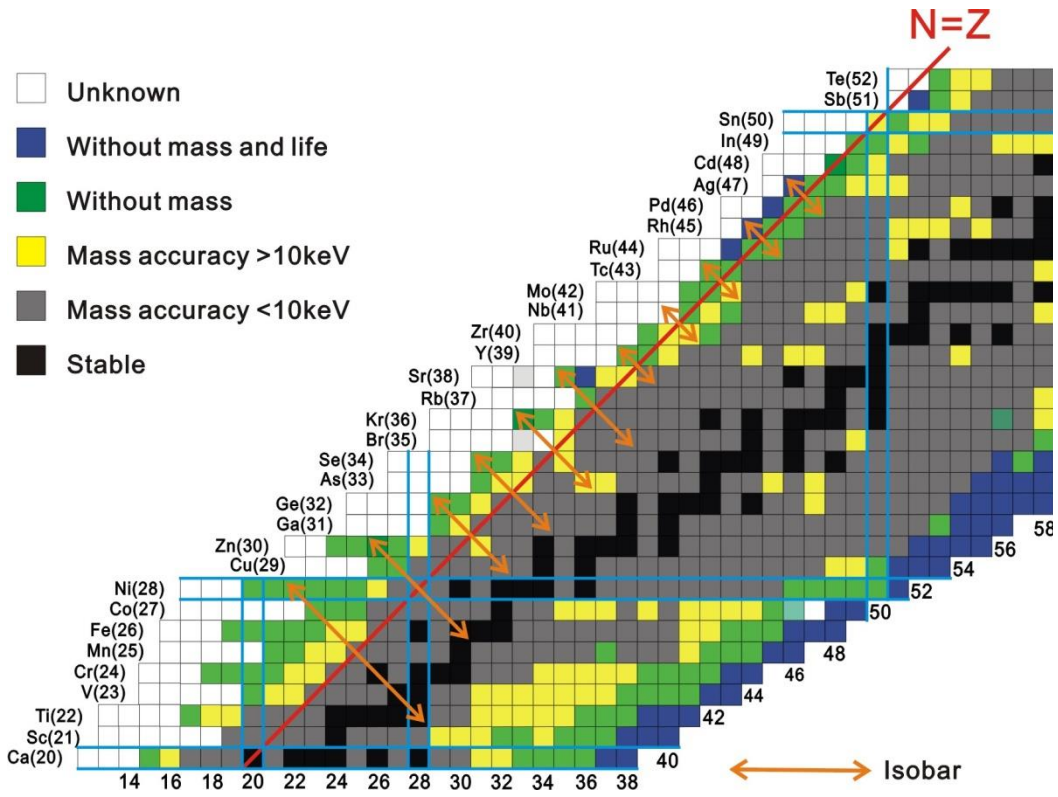
- 确定质子、中子滴线位置
- 研究幻数演化、发现新幻数
- 寻找高电荷态离子奇异衰变
- 模拟天体环境中核过程



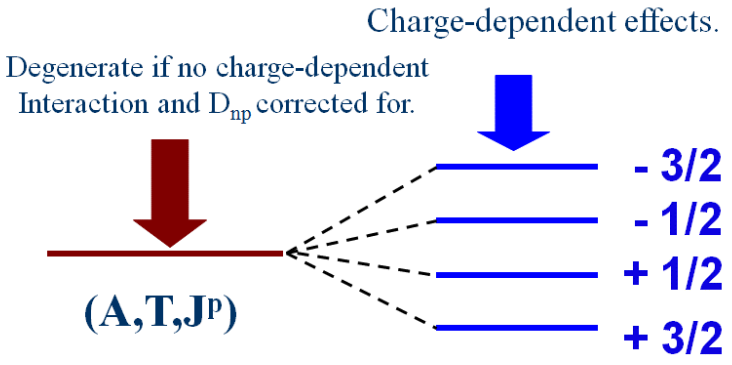


精确测量远离稳定线原子核的质量、寿命，寻找高电荷态离子的奇异衰变

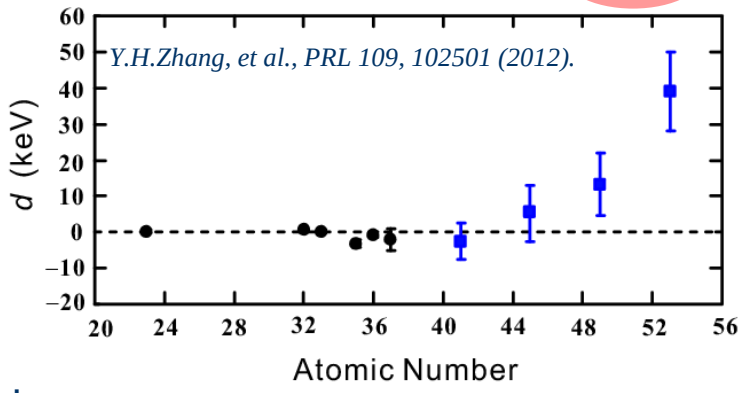
Physics along the N=Z line



Test the Isospin Multiplet Mass Equation

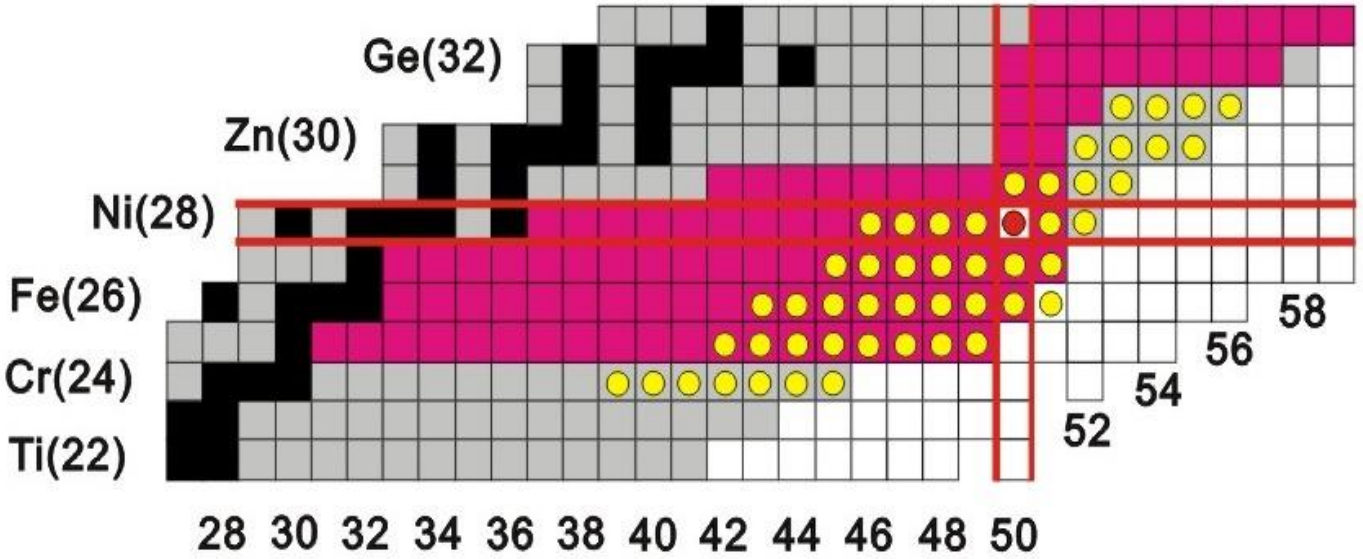


$$M(T,A,T_3) = a(T,A,) + b(T,A)T_3 + c(T,A)T_3^2 + d(T,A)T_3^3$$



- Understanding of the *rp* process path and end point.
- Shape evolution for the nuclei along the *N=Z* line.
- Study of the isospin symmetry breaking and its mechanisms.
- Search for the new form of *n-p* pairing.
- Precision tests of the shell model around ^{100}Sn.

Mass Measurements of N-rich Nuclides around ^{78}Ni



Production: Fragmentation of Projectile ^{86}Kr Using the HFRS.

Measurement: The Isochronous Mass Spectrometer with Double ToF Detectors.

Systematically measure nuclear masses with a precision of ~ 50keV, and deduce one-neutron and two-neutron separation energies.

Study the evolution of the *N*=50 shell closure and Simulate the r-process.

Understanding of the solar pp neutrinos

LOREX project: ^{205}Tl in lorandite at Allchar mine is used for long-time detection of solar pp neutrinos with the by far lowest threshold of neutrino energy of 52 keV.

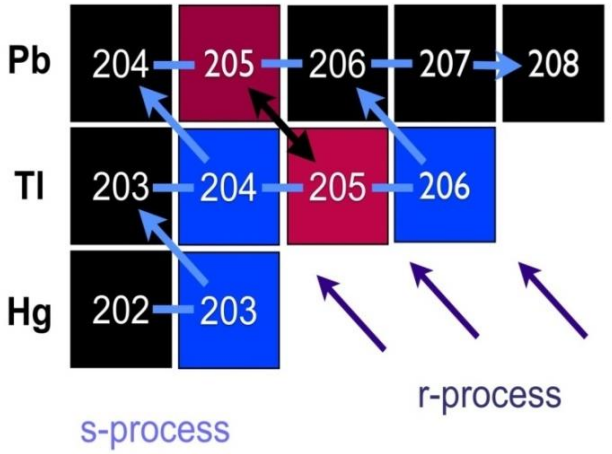
The neutrino caputure cross section σ_{ve} can be deduced from the half-life of bound-state β decay of $^{205}Tl^{81+}$.

LOREX: $^{205}\mathrm{Tl} + \nu_e \rightarrow {}^{205}\mathrm{Pb}^* + e^- \Longrightarrow <\Phi_{\nu_e} \cdot \sigma_{\nu_e}>$

Share common M_{if}

β_b decay: $^{205}\mathrm{Tl}^{81+} \rightarrow {}^{205}\mathrm{Pb}^* + e^- + \tilde{\nu}_e \Rightarrow \sigma_{\nu_e}$

Understanding of the abundance of ^{205}Pb



$$N(^{205}Pb)/N(^{204}Pb) = P(^{205}Pb)/P(^{204}Pb) \times T(^{205}Pb)/T_G$$

$\sim 10^{-3}$	~ 1	$\sim 2.5 \cdot 10^{-3}$
in inter-stellar media	s-production ratio	lifetime raio of the Galaxy

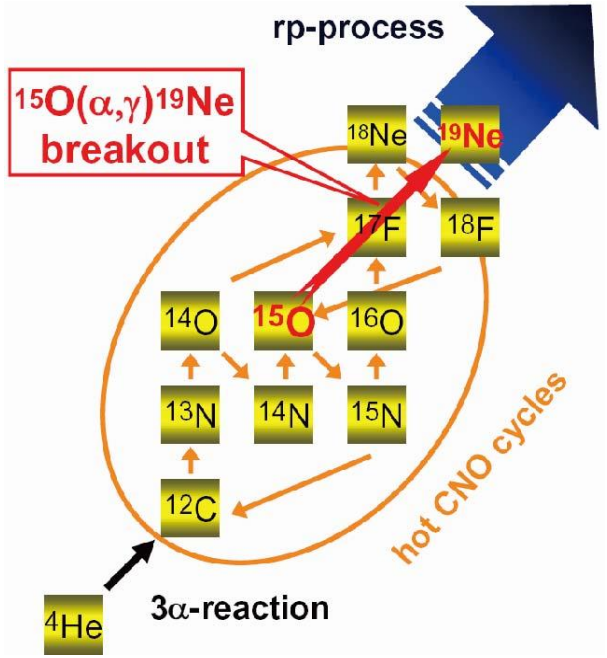
In the s-process enviroment:

^{205}Pb is strongly reduced by free electron capture.

The mean lifetime of ^{205}Tl is determinde by $\lambda_{\beta b}$ of bare ^{205}Tl.

Is ^{205}Pb counter-balanced by the β_b decay of bare ^{205}Tl?

通过^{20}Ne(p, d)^{19}Ne研究alpha衰变分支比



突破CNO循环的关键反应

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **67**, 012801(R) (2003)

α-decay branching ratios of near-threshold states in ^{19}Ne and the astrophysical rate of ^{15}O$(\alpha,\gamma)^{19}$Ne

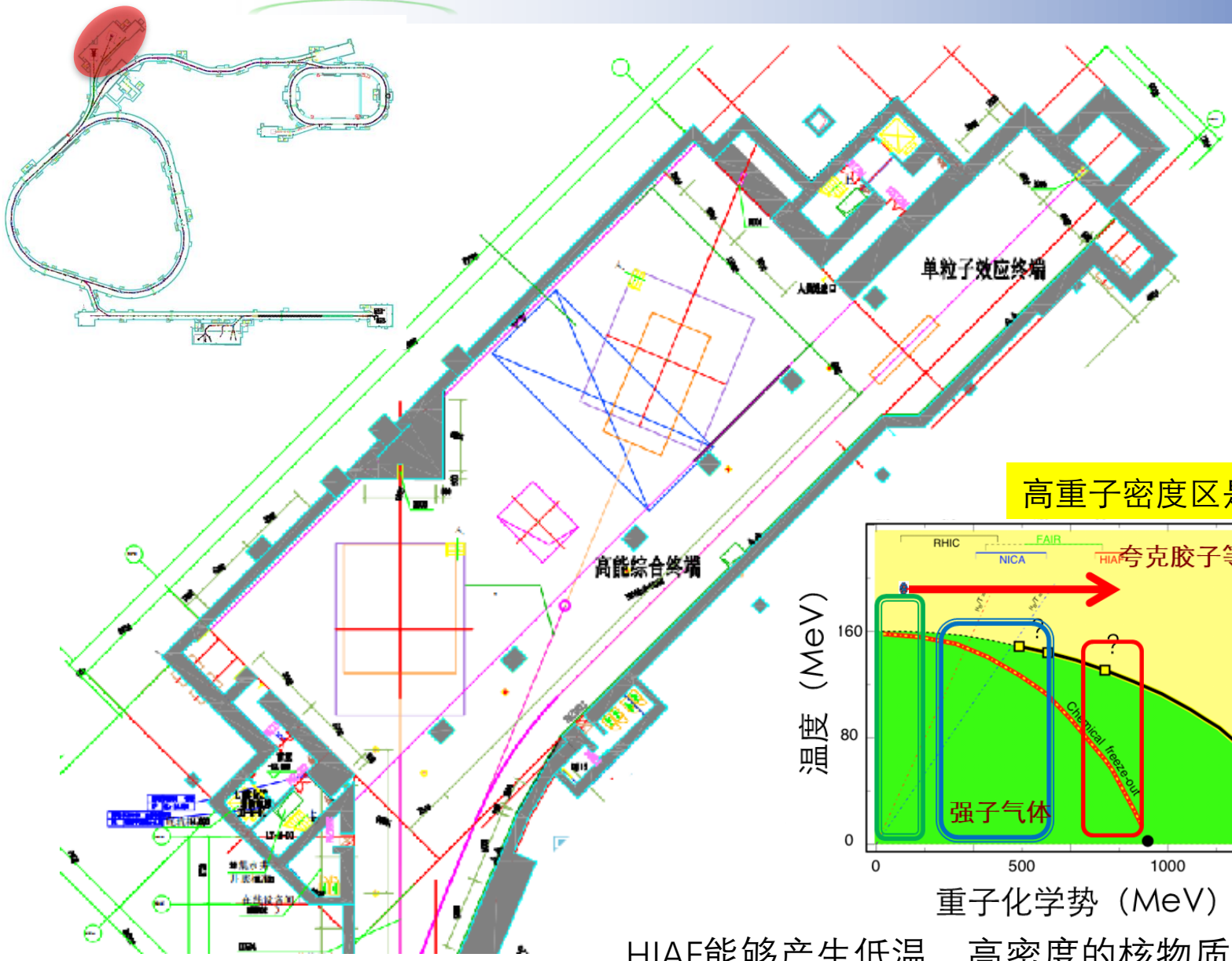
B. Davids,[1] A. M. van den Berg,[1] P. Dendooven,[1] F. Fleurot,[1,*] M. Hunyadi,[1] M. A. de Huu,[1] K. E. Rehm,[2] R. E. Segel,[3] R. H. Siemssen,[1] H. W. Wilschut,[1] H. J. Wörtche,[1] and A. H. Wuosmaa[2]
[1]*Kernfysisch Versneller Instituut, Zernikelaan 25, 9747 AA Groningen, The Netherlands*
[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439*
[3]*Department of Physics, Northwestern University, Evanston, Illinois 60208*
(Received 5 June 2002; published 21 January 2003)

TABLE I. Branching ratios $B_\alpha \equiv \Gamma_\alpha/\Gamma$ and decay widths. Upper limits are specified at the 90% confidence level.

E_x (MeV)	J^π	B_α (present work)	B_α (Ref. [10])	B_α (Ref. [19])	B_α (adopted)	Γ_γ (meV)	Ref.	Γ_α (meV)
4.033	$\frac{3}{2}^+$	$\leqslant 4.3\times10^{-4}$			$\leqslant 4.3\times10^{-4}$	12^{+9}_{-5}	[20]	$\leqslant 0.011$
4.379	$\frac{7}{2}^+$	$\leqslant 3.9\times10^{-3}$	0.044 ± 0.032		$\leqslant 3.9\times10^{-3}$	458 ± 92	[23]	$\leqslant 2.4$
4.549	$(\frac{1}{2},\frac{3}{2})^-$	0.16 ± 0.04	0.07 ± 0.03		0.10 ± 0.02	39^{+34}_{-15}	[18]	$4.4^{+4.0}_{-2.0}$
4.600	$(\frac{5}{2}^+)$	0.32 ± 0.04	0.25 ± 0.04	0.32 ± 0.03	0.30 ± 0.02	101 ± 55	[22]	43 ± 24
4.712	$(\frac{5}{2}^-)$	0.85 ± 0.04	0.82 ± 0.15		0.85 ± 0.04	43 ± 8	[18]	230 ± 80
5.092	$\frac{5}{2}^+$	0.90 ± 0.06	0.90 ± 0.09		0.90 ± 0.05	196 ± 39	[23]	1800 ± 1000

$T_9 < 0.6$ 时，主导反应率的4.03 MeV共振能级，尚无实验数据

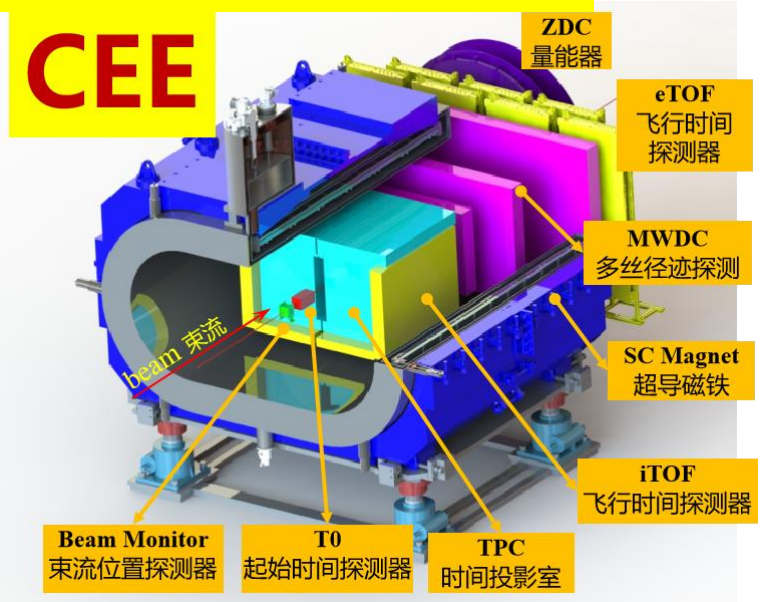
高能实验终端



离子种类	能量(GeV/u)	流强(ppp)
P	9.3	2.0×10^{12}
$^{18}O^{6+}$	2.6	4.0×10^{11}
$^{78}Kr^{19+}$	1.7	2.5×10^{11}
$^{209}Bi^{31+}$	0.85	1.0×10^{11}
$^{238}U^{35+}$	0.8	1.0×10^{11}
$^{238}U^{76+}$	2.45	4.0×10^{10}

高重子密度区是目前国际中高能核物理研究的大趋势

HIAF能够产生低温、高密度的核物质

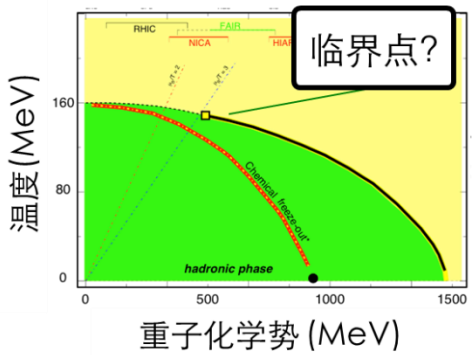


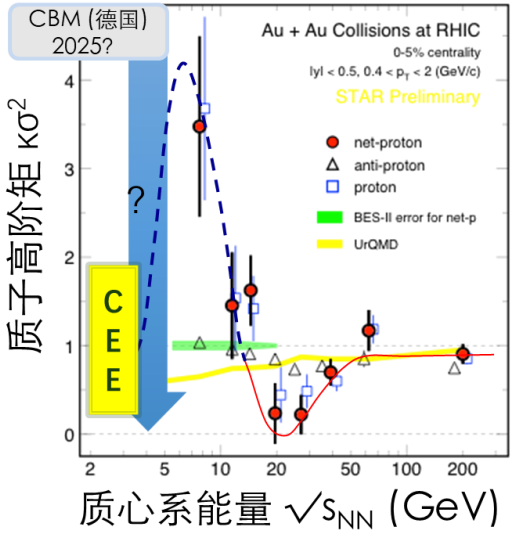
QCD相结构和对称能研究

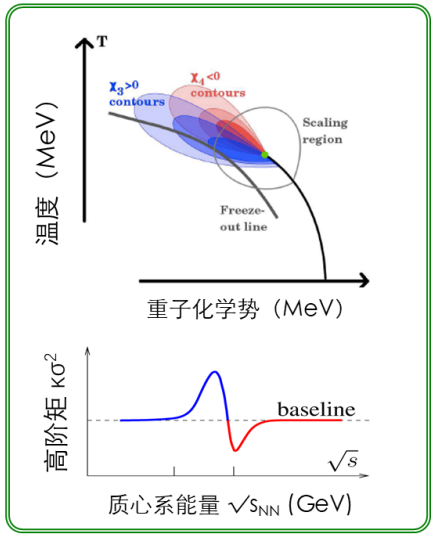
寻找QCD相变临界点

低温高密区QCD 相结构 (物质结构)

- 夸克禁闭
- 手征对称自发破缺
- 临界点、相边界 …

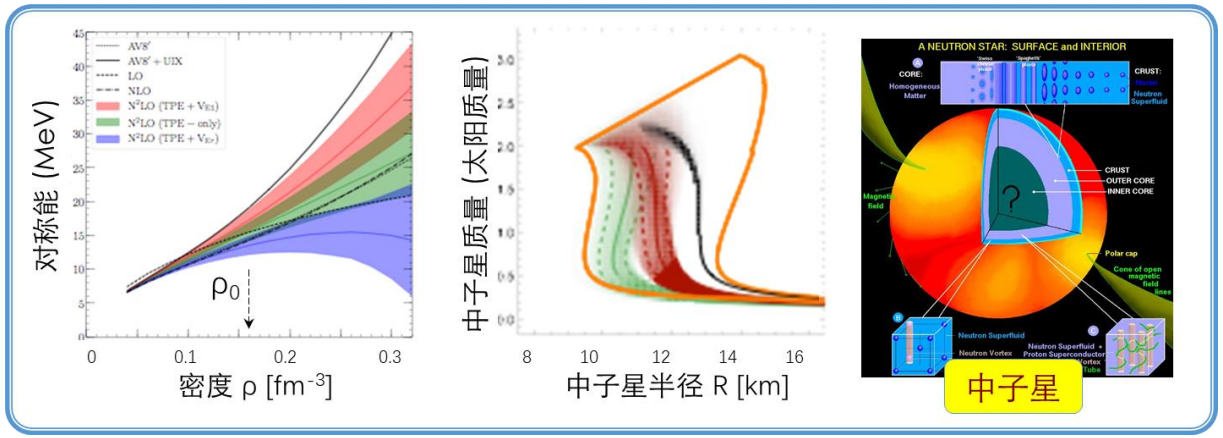


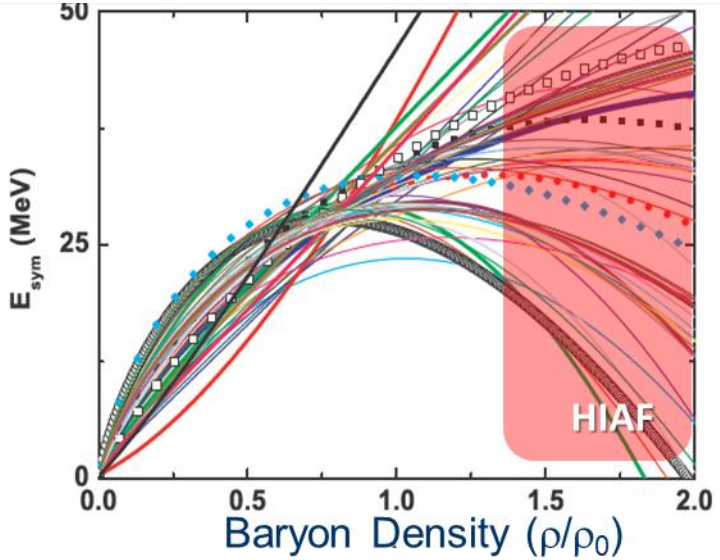




HIAF能区✚低温高密核物质测量谱仪(CEE)➔为确定QCD临界点提供绝佳机遇!

非对称核物质状态方程

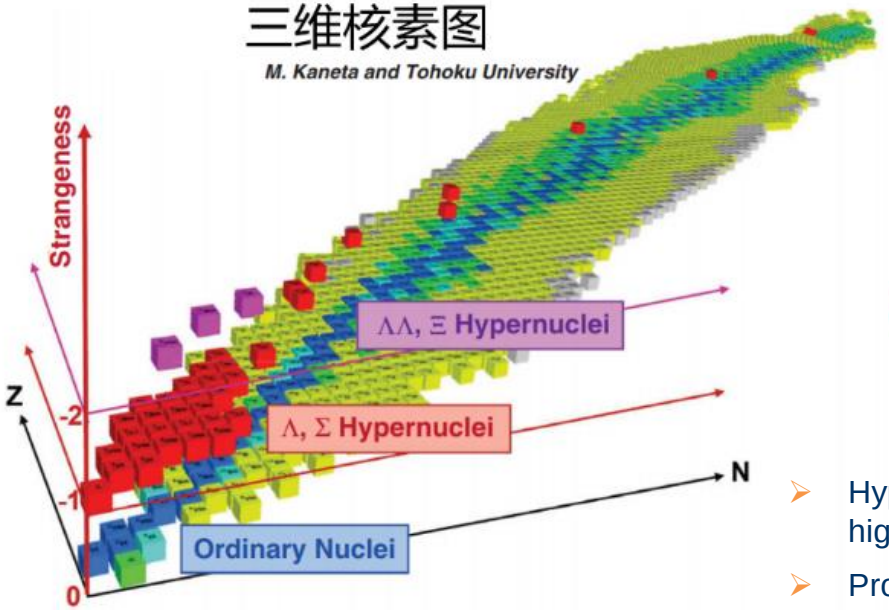


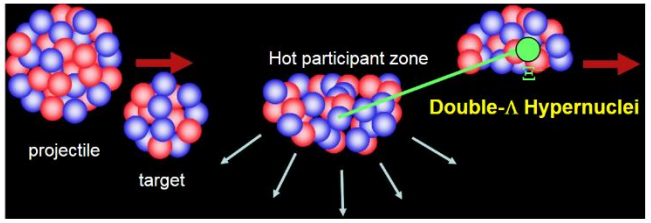


HIAF能区也是研究对称能$E_{sym}(\rho)$的理想能区

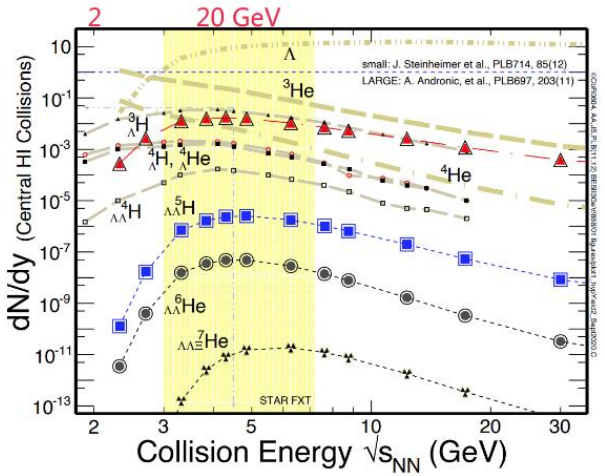
Hypernuclei with Double Strangeness

发现新的超核，特别是双奇异数超核；研究超核性质、超子-核子以及超子-超子相互作用。不仅对强相互作用物质性质的理解有重要意义，也为宇宙演化、中子星结构等问题的研究提供了重要的核物理输入。





- Hypernuclei are produced by coalescence of Λ in high-energy peripheral collisions
- Production of hypernuclei is expected to have large cross sections at high-energy (>1.2 AGeV)
- In high-energy (>3.75 AGeV) collisions, double-Λ hypernuclei can be produced!



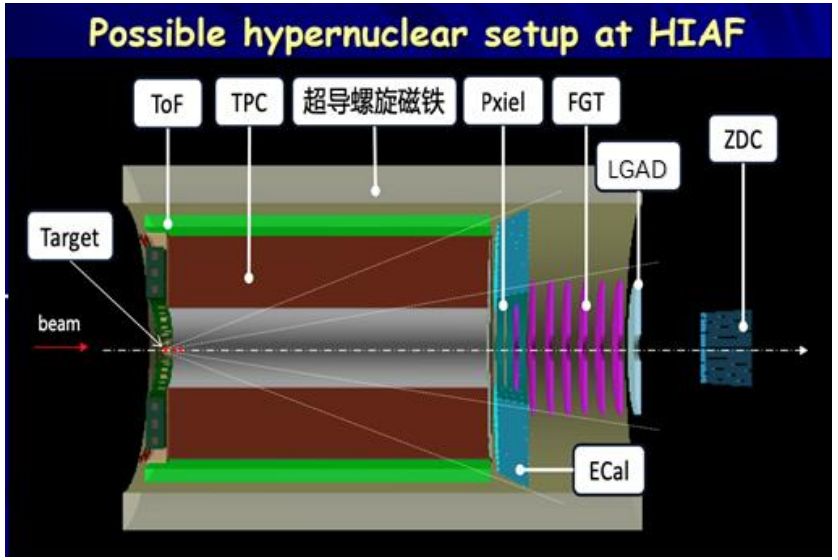
重离子碰撞中超核产额和碰撞质心系能量依赖关系

Decay of ΛΛ hypernuclei

- $n\Lambda\Lambda \rightarrow {}^{3}He + \pi^- + \pi^-$
- $nn\Lambda\Lambda \rightarrow {}^{4}He + \pi^- + \pi^-$
- ${}^{4}_{\Lambda\Lambda}H \rightarrow p + {}^{3}He + \pi^- + \pi^-$
- ${}^{5}_{\Lambda\Lambda}H \rightarrow p + {}^{4}He + \pi^- + \pi^-$
- ${}^{7}_{\Lambda\Lambda}He \rightarrow {}^{7}Be + \pi^- + \pi^-$
- ${}^{8}_{\Lambda\Lambda}He \rightarrow {}^{4}He + {}^{4}He + \pi^- + \pi^-$
- ${}^{10}_{\Lambda\Lambda}Li \rightarrow {}^{10}B + \pi^- + \pi^-$
- ${}^{11}_{\Lambda\Lambda}Li \rightarrow {}^{11}B + \pi^- + \pi^-$
- ${}^{11}_{\Lambda\Lambda}Be \rightarrow {}^{11}C + \pi^- + \pi^-$
- ${}^{12}_{\Lambda\Lambda}Be \rightarrow {}^{12}C + \pi^- + \pi^-$
- …

Production of ΛΛ hypernuclei

- $d + \Xi^- \rightarrow n\Lambda\Lambda$
- $t + \Xi^- \rightarrow nn\Lambda\Lambda$
- ${}^{3}He + \Xi^- \rightarrow {}^{4}_{\Lambda\Lambda}H$
- ${}^{4}He + \Xi^- \rightarrow {}^{5}_{\Lambda\Lambda}H$
- ${}^{6}Li + \Xi^- \rightarrow {}^{7}_{\Lambda\Lambda}He$
- ${}^{7}Li + \Xi^- \rightarrow {}^{8}_{\Lambda\Lambda}He$
- ${}^{9}Be + \Xi^- \rightarrow {}^{10}_{\Lambda\Lambda}Li$
- ${}^{10}Be + \Xi^- \rightarrow {}^{11}_{\Lambda\Lambda}Li$
- ${}^{10}B + \Xi^- \rightarrow {}^{11}_{\Lambda\Lambda}Be$
- ${}^{11}B + \Xi^- \rightarrow {}^{12}_{\Lambda\Lambda}Be$
- …



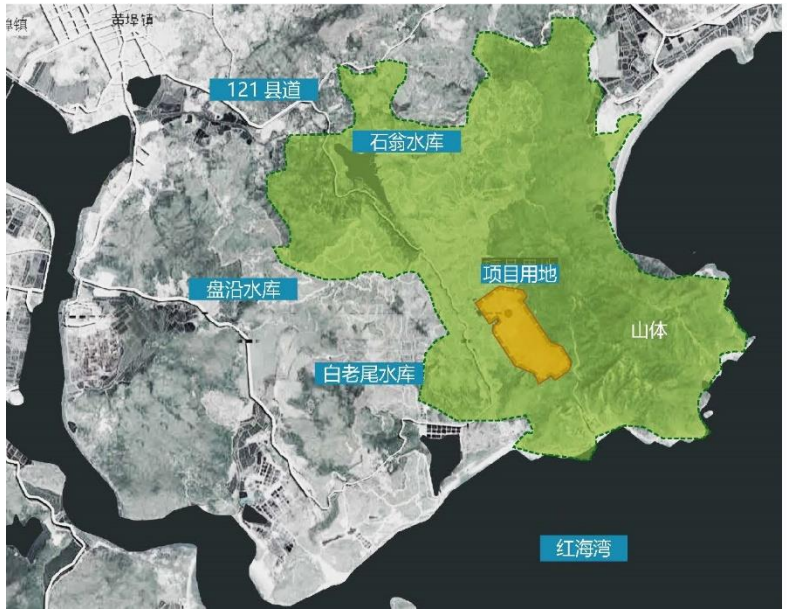
High energy & moderate intensity

Expected reconstructed rate

- $^{20}Ne + {}^{12}C$ at 4.25 A GeV
- Beam intensity: 10^7 /s

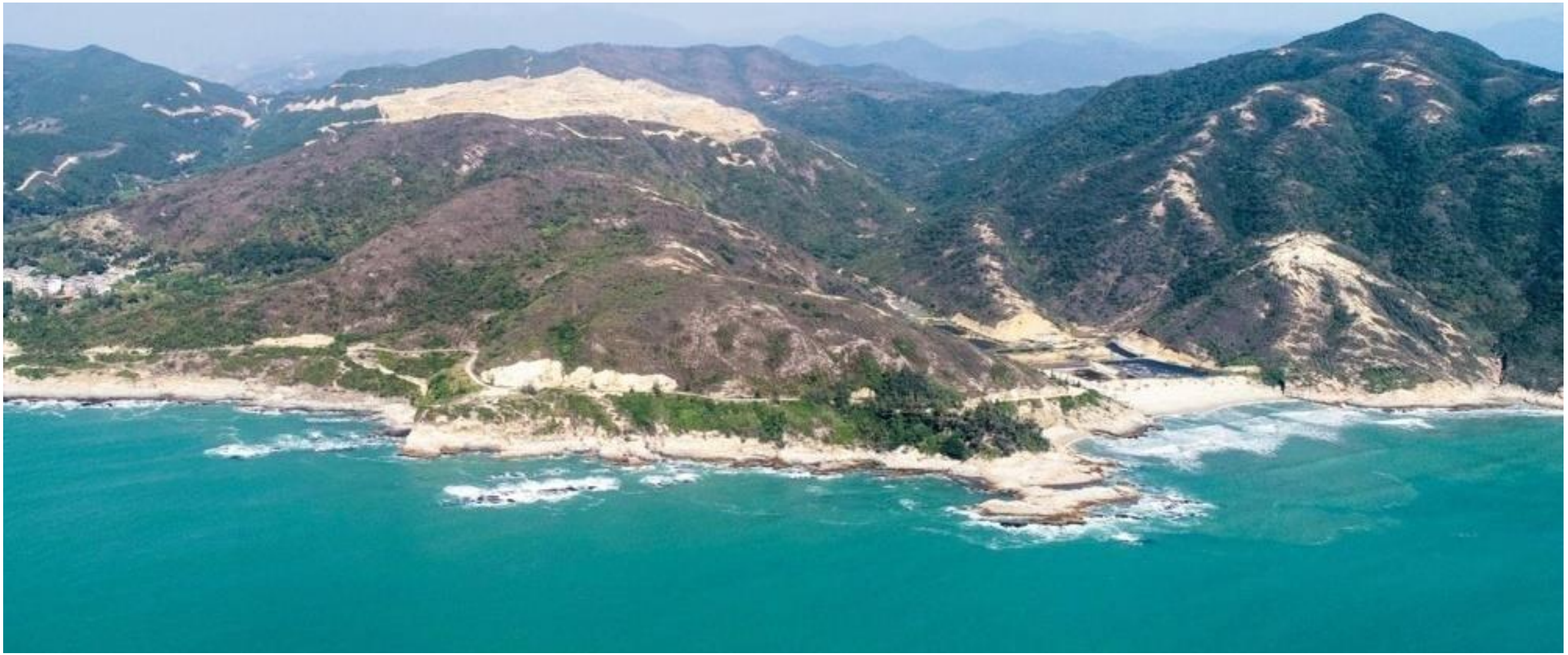
	Single-Λ hypernuclei	Double-Λ hypernuclei
per day	8×10^5	9×10^1
per week	6×10^6	6×10^2
per month	2×10^7	3×10^3

HIAF建设进展



The first phase covers an area of ~0.6 square kilometers (900 mu)
Total construction area ~ 125,000 square meters
another 2 square kilometers space is reserved for future development

- **Total budget is ~ 6.8 billion CNY**
- ~ 3.49 billion comes from the central government. 1.67 billion for HIAF and 1.82 billion for CiADS.
- 1.0 billion from The China National Nuclear Corporation (CNNC) for CiADS
- 2.35 billion from local government for infrastructure
- Partners for the CiADS project: CIAE, CGN, IHEP



Ground broke in August 2018

HIAF建设进展

HIAF建设进展

HIAF建设进展

- 土石工程，水电道路等配套设施建设已经完成；
- 土建工作正在进行中，部分隧道已封顶。

■ HIAF construction time schedule

2019	2020	2021	2022	2023	2024	2025	
Civil construction							Day One exp.
		Electric power, cooling water, compressed air, network, cryogenic, supporting system, etc.					
ECR design & fabrication		SECR installation and commissioning					
	Linac design & fabrication		iLinac installation and commissioning				
Prototypes of PS, RF cavity, chamber, magnets, etc.			fabrication	BRing installation & commissioning			
				HFRS & SRing installation & commissioning			
				Terminals installation			

- 2022年底SECR实现供束；
- 2024年底iLinac开始供束；
- 2025年4月Bring实现束流引出。

2025年中期具备开展物理实验的条件

研究所已落户粤港澳湾区

中国科学院近代物理研究所惠州研究部

地址：惠城区新桥北路1号

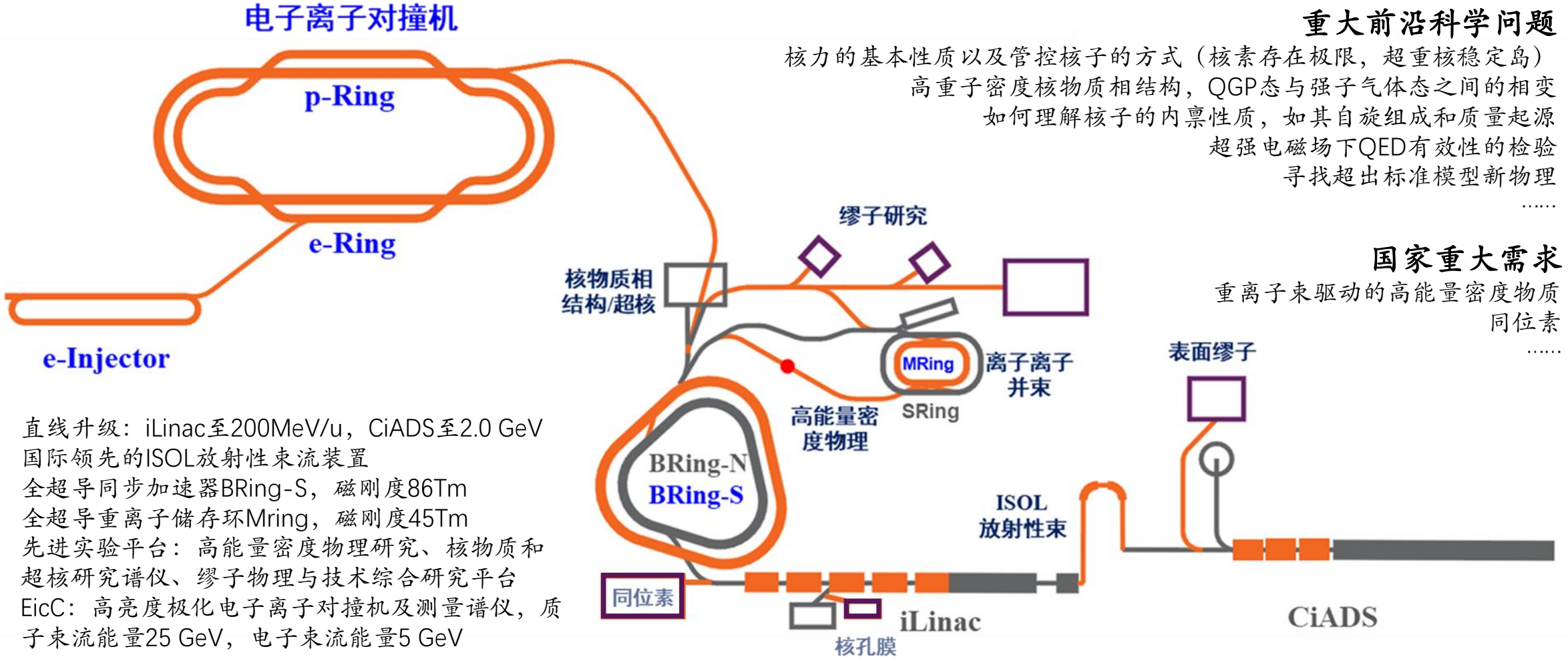
今年初已经投入使用

距离HIAF & CiADS
两装置园区约70公里

占地128亩，建筑面积5.2万平米

未来发展规划

惠州核科学研究中心



重大前沿科学问题

核力的基本性质以及管控核子的方式（核素存在极限，超重核稳定岛）
高重子密度核物质相结构，QGP态与强子气体态之间的相变
如何理解核子的内禀性质，如其自旋组成和质量起源
超强电磁场下QED有效性的检验
寻找超出标准模型新物理
……

国家重大需求

重离子束驱动的高能量密度物质
同位素
……

- 直线升级：iLinac至200MeV/u，CiADS至2.0 GeV
- 国际领先的ISOL放射性束流装置
- 全超导同步加速器BRing-S，磁刚度86Tm
- 全超导重离子储存环Mring，磁刚度45Tm
- 先进实验平台：高能量密度物理研究、核物质和超核研究谱仪、缪子物理与技术综合研究平台
- EicC：高亮度极化电子离子对撞机及测量谱仪，质子束流能量25 GeV，电子束流能量5 GeV

中国先进核物理研究装置

(China advanced NUclear physics research Facility, CNUF)

Summary and Outlook

- 国家重大科技基础设施-强流重离子加速器（HIAF）将为我国核物理基础和应用研究提供一流的束流条件。
- HIAF的建设工作已在惠州全面展开，目前项目进展顺利，预期将于2025年出束。
- HIAF上的物理研究工作期盼更多国内和国际合作者的加入，希望能在研究目标确立和相关探测设备研制等方面发挥更关键的作用。
- IMP希望能够进一步深化和粤港澳大湾区同行的交流与合作，共同促进我国核物理研究的未来发展!

谢谢