

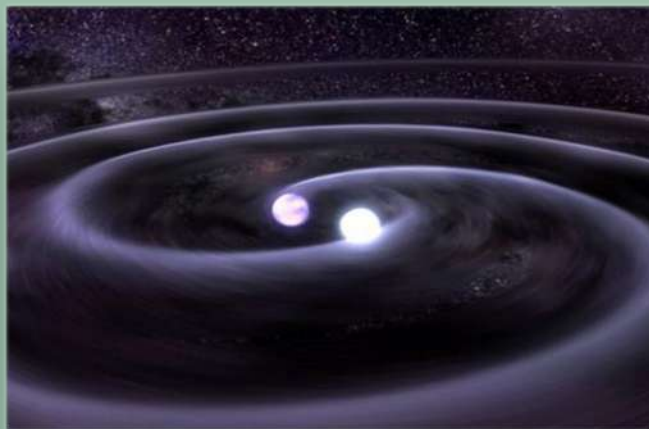
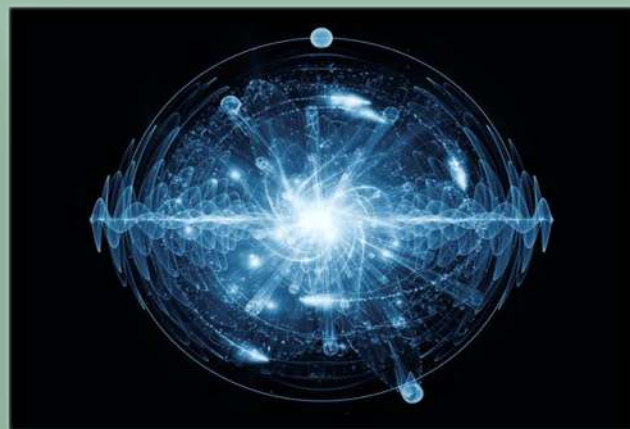


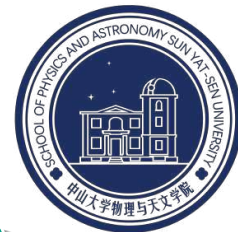
$0\nu\beta\beta$ 实验中子诱发本底反应 的高精度测量研究

安振东

中山大学物理与天文学院

“无中微子双贝塔衰变”研讨会，中山大学，珠海2021.05.19-23





1

宇宙中元素的起源、s-/r-过程

2

$0\nu\beta\beta$ 实验中子诱发本底反应： ^{76}Ge 为例

3

$^{74,76}\text{Ge}$ 同位素链中子俘获截面研究现状

4

CSNS开展Ge、Mo等(n, γ)实验的初步想法

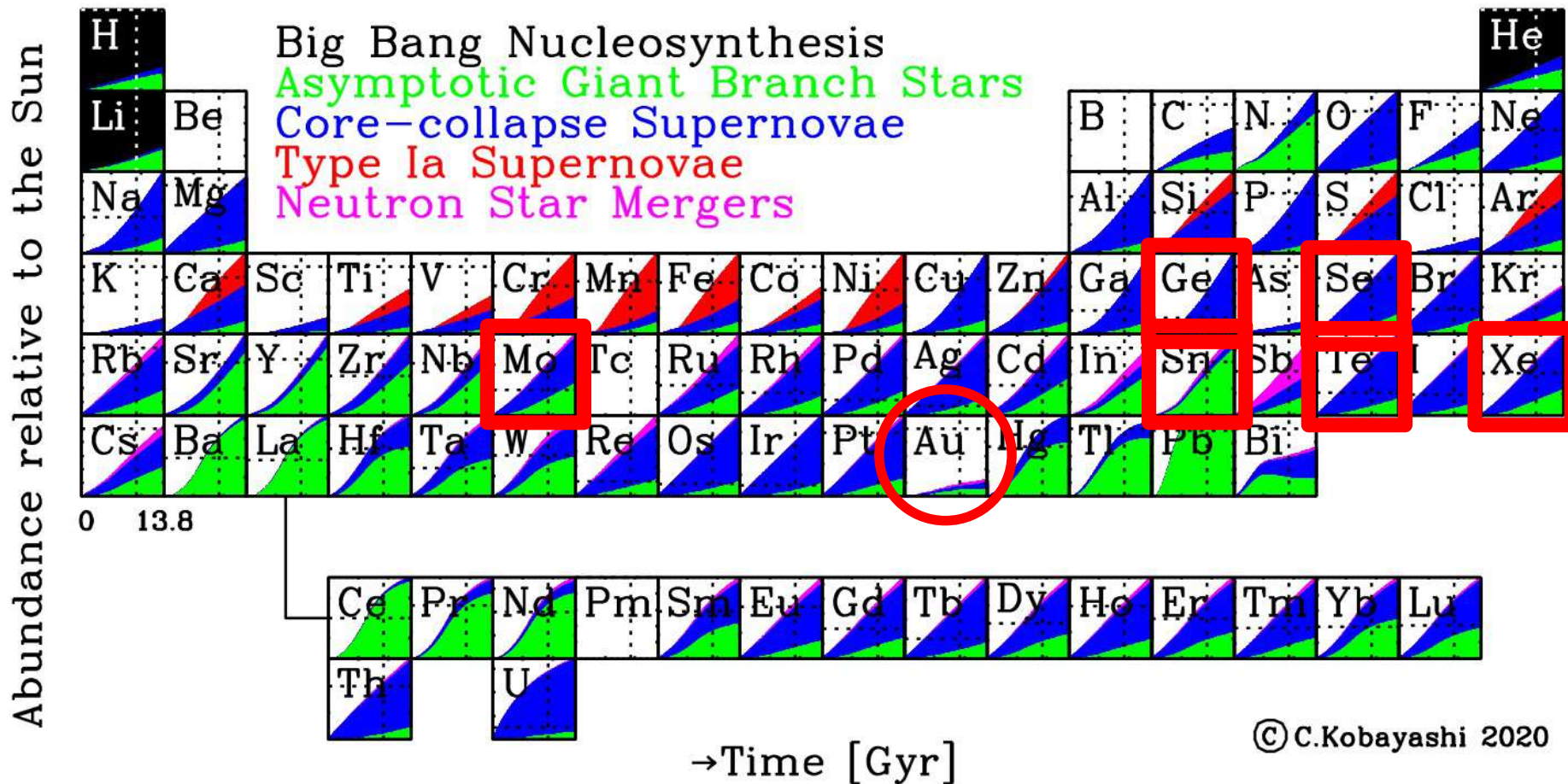
5

小结及未来的合作等

宇宙中元素的起源



GW170817双中子星并合产生约300培地球重量的黄金！

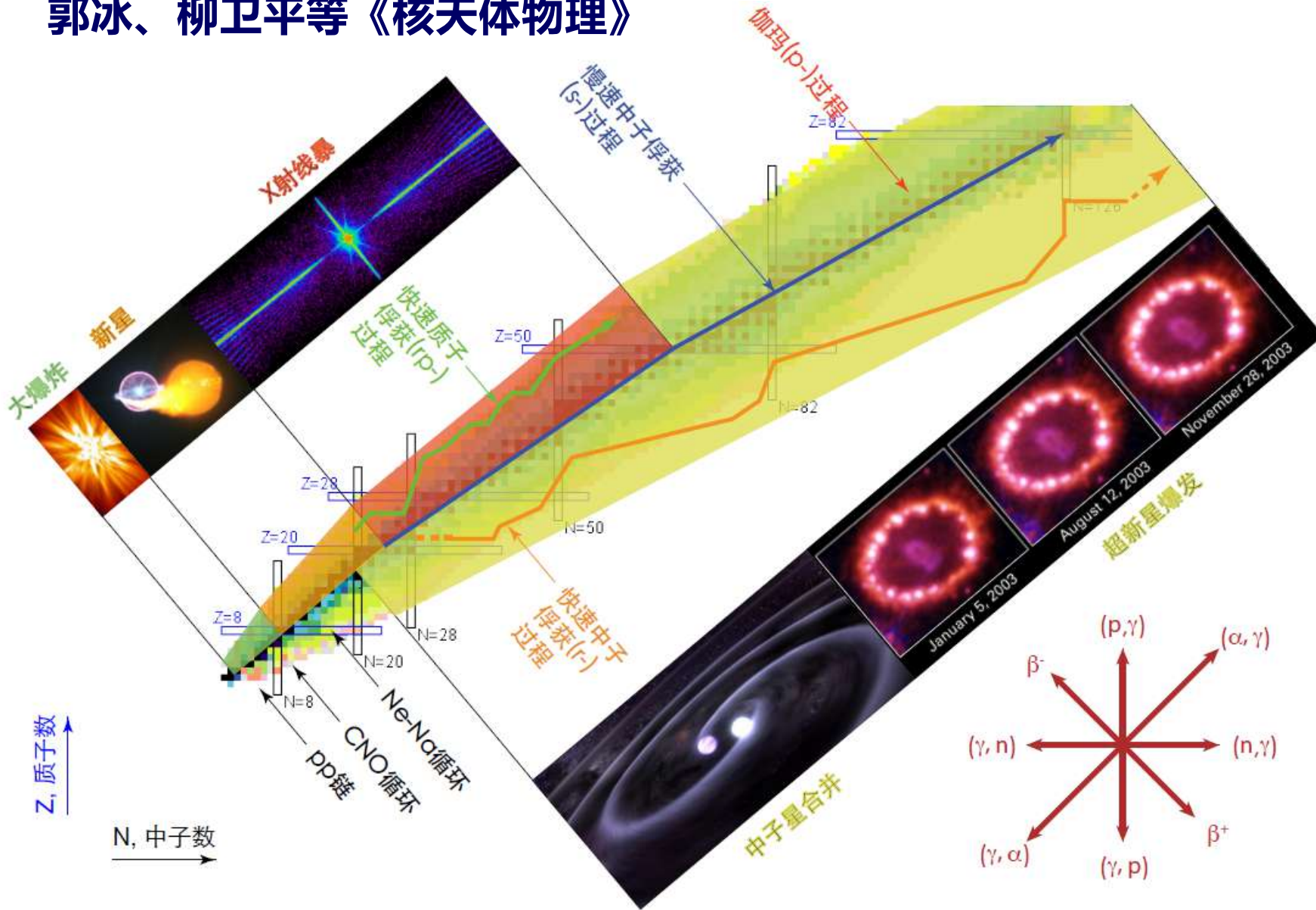


The Astrophysical Journal 900 (2020) 179

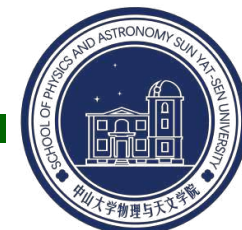
天体演化主要核过程



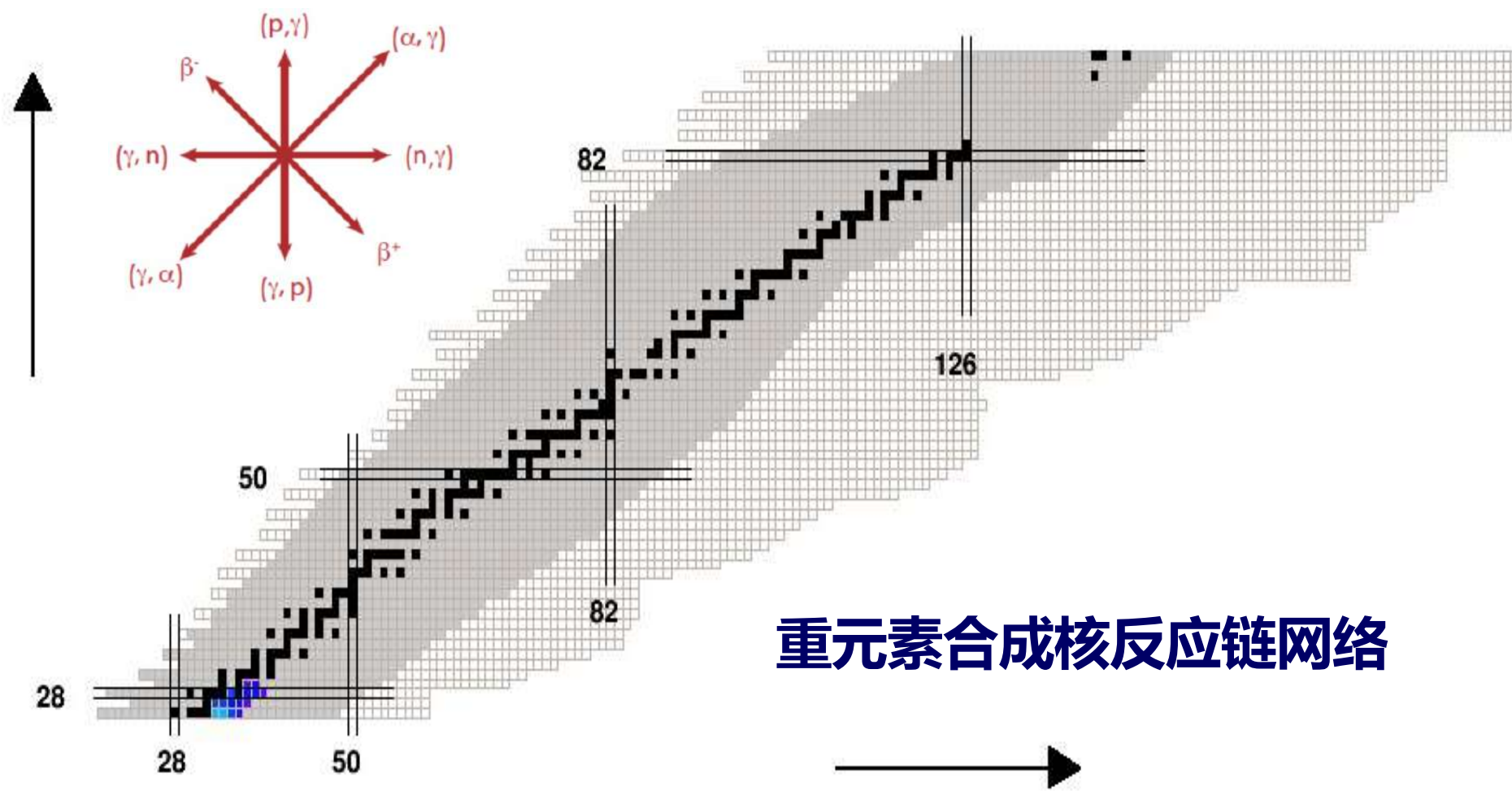
郭冰、柳卫平等《核天体物理》



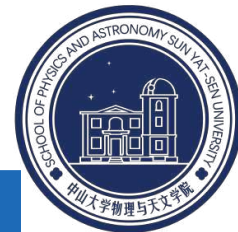
天体模型预言的不确定性的主要来源



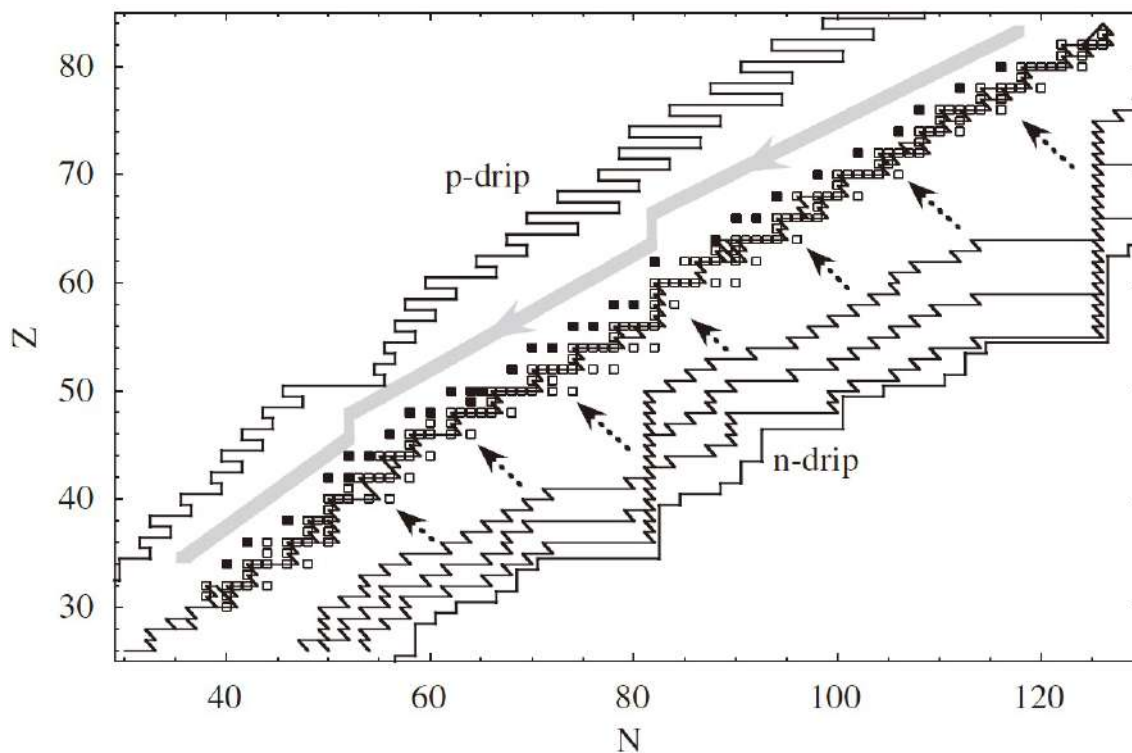
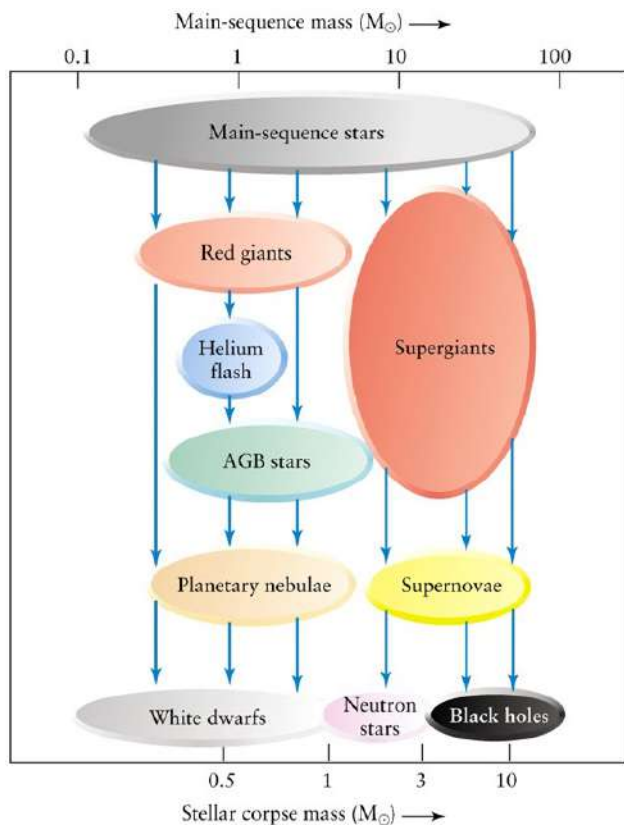
1、俘获反应率； 2、 β 衰变率； 3、同位素质量



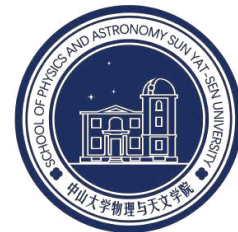
S-过程：主S-过程和弱S-过程



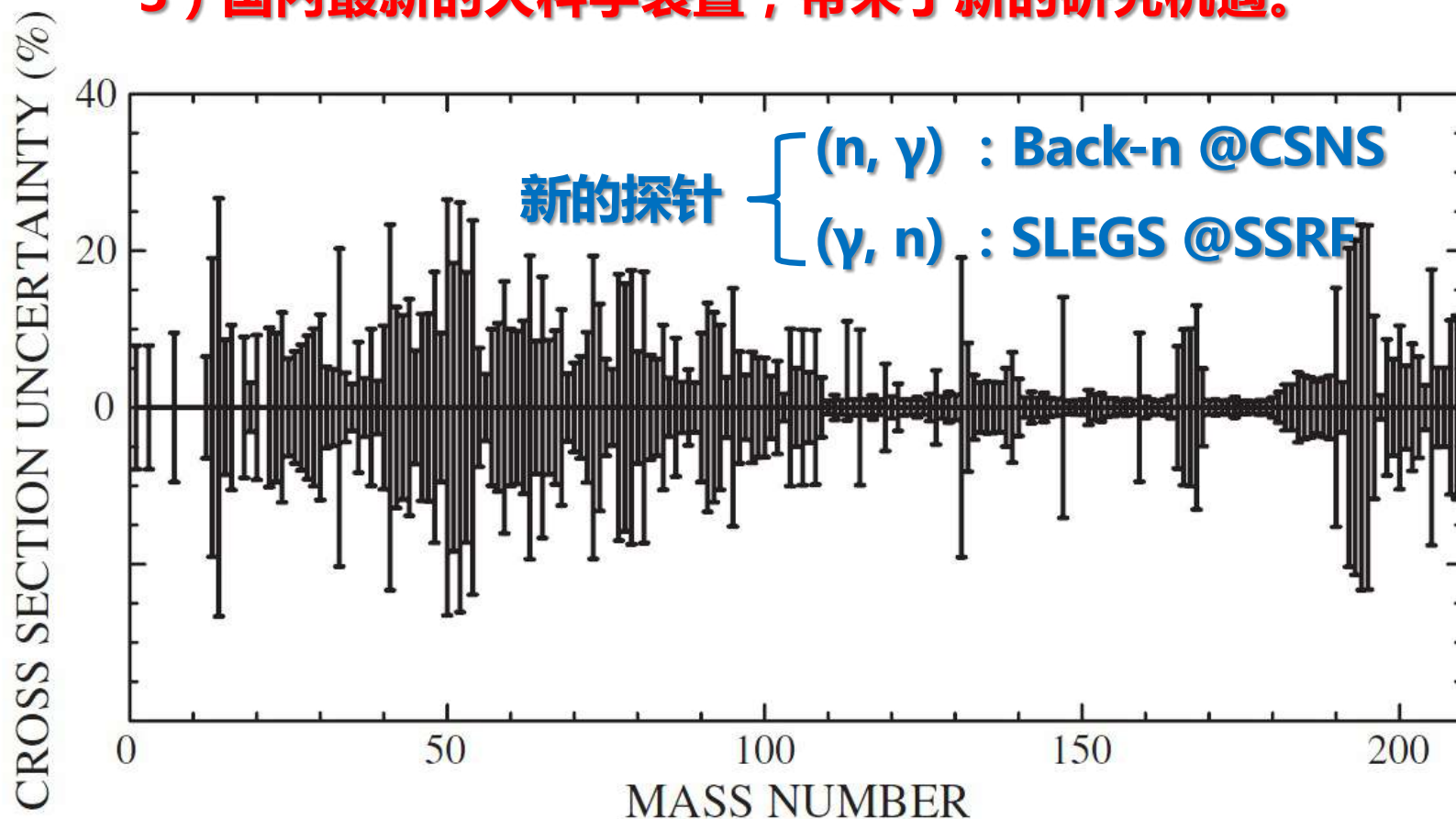
	主S-过程	弱S-过程)
恒星质量	$1.3M_{\odot} \leq M \leq 8M_{\odot}$	$\geq 8M_{\odot}$
演化阶段	恒星的渐进巨星分支阶段	恒星氦核心和碳燃烧壳层
反应产物	质量数 $A \geq 90$	$60 \leq A \leq 90$ Fe至Sr同位素



S-过程反应截面的研究现状

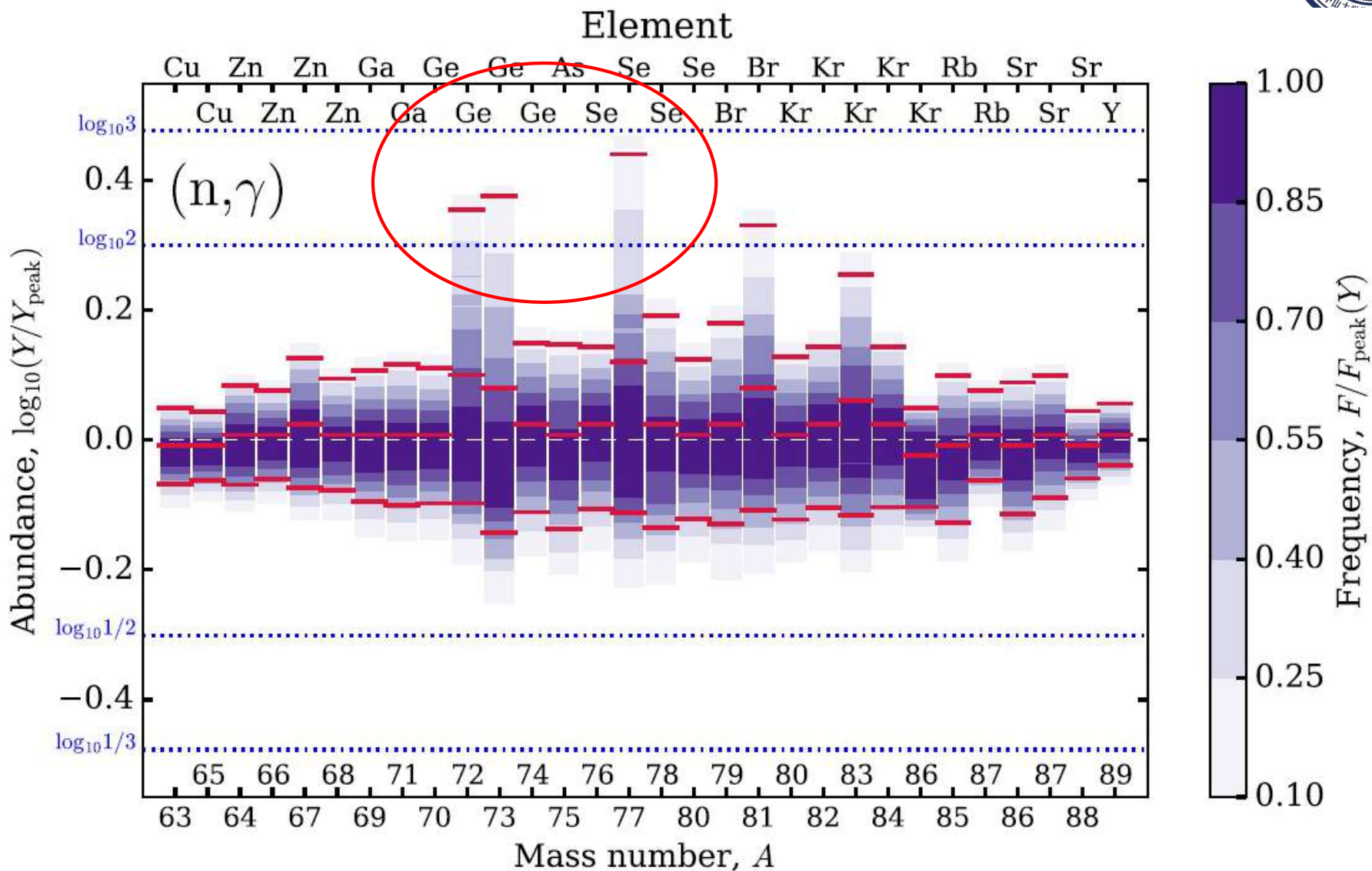
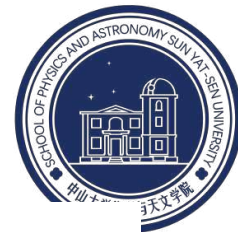


- 1) s-过程，实验数据、理论模型之间差别仍然比较大。
- 2) 实验数据误差较大，s过程模型计算要求的精度5%。
- 3) 国内最新的大科学装置，带来了新的研究机遇。



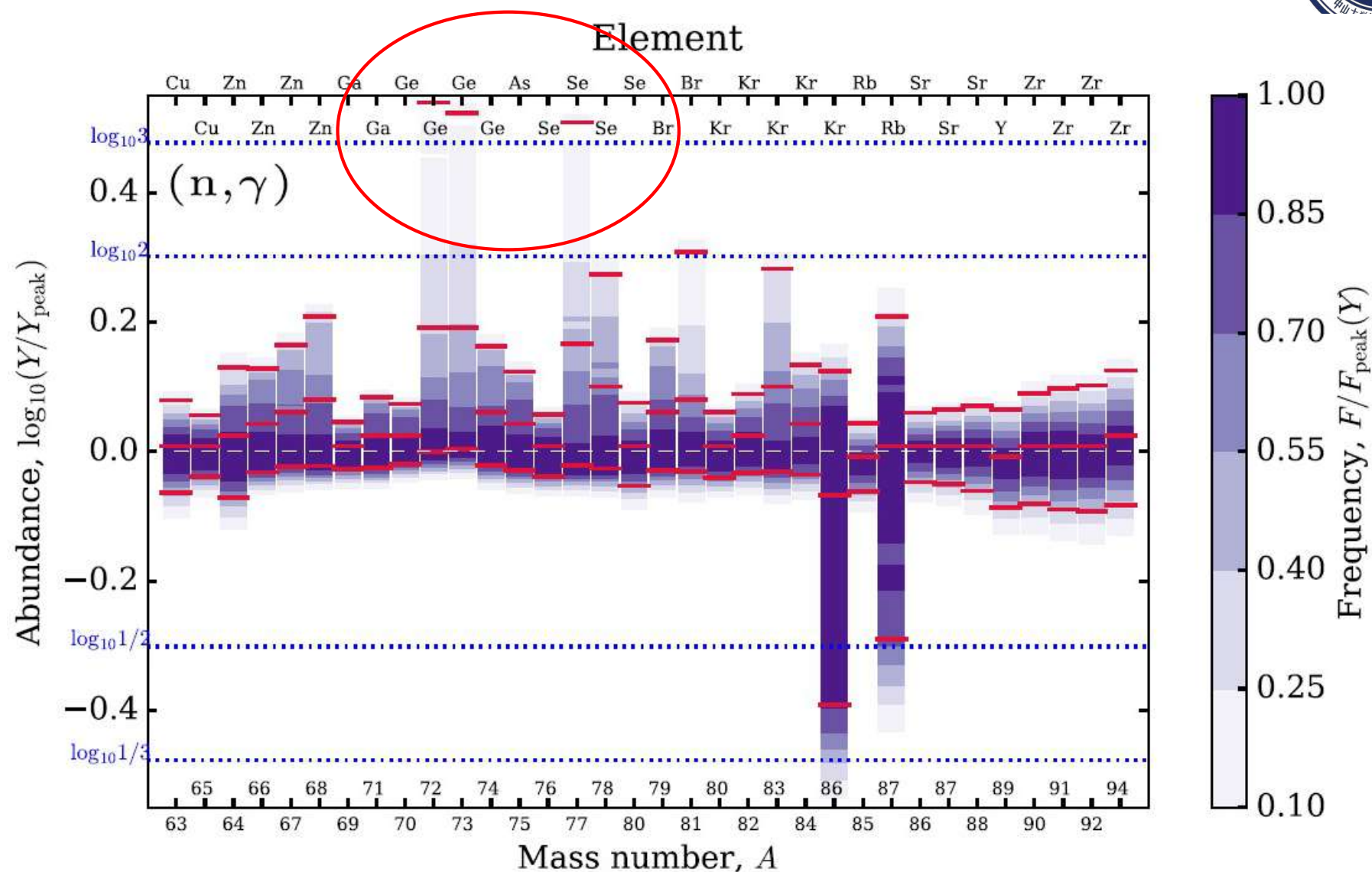
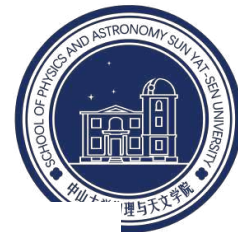
Kappeler et al, Rev. Mod. Phys. 83, 157 (2011).

弱S-过程：Ge、Se理论和观测的差别



N. Nishimura et al 2017

增强型弱S-过程：Ge、Se理论和观测的差别



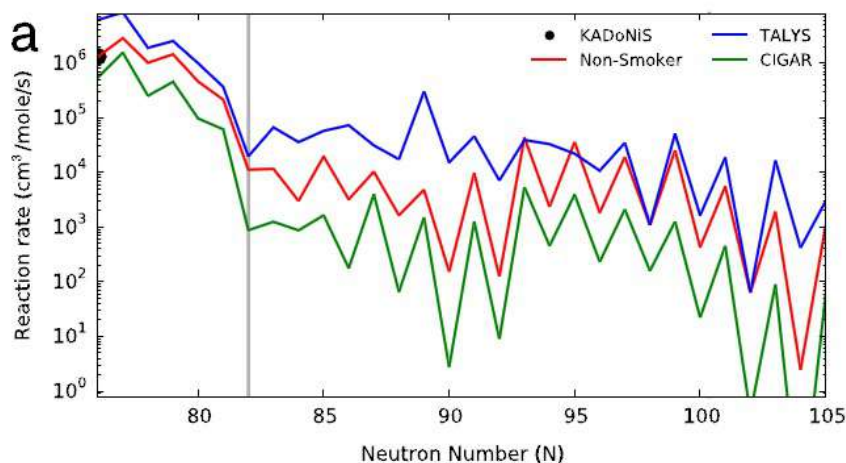
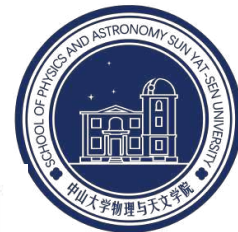
N. Nishimura et al 2017

重元素起源 (r-过程) 的天体模型

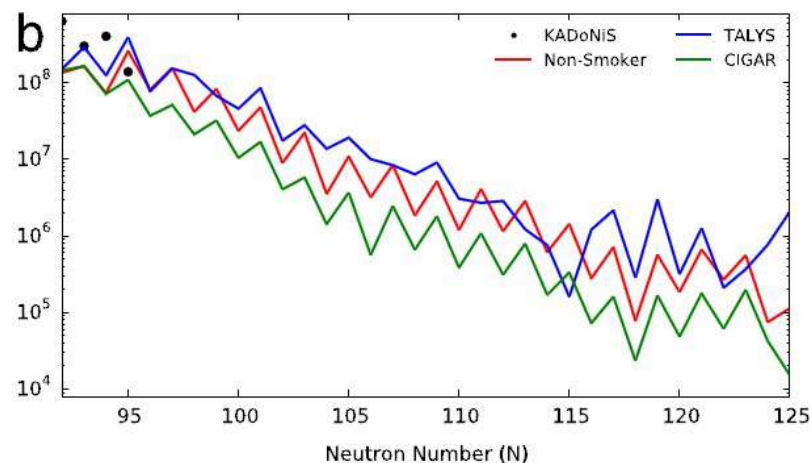


恒星质 M_{\odot}	相关的天体事件	核合成环境	反应机制
$\approx 8-20 M_{\odot}$	SN : 核心塌缩型超新星	中子星星风	α , vp-过程 r-过程
$\approx 8-10 M_{\odot}$	低质量(O-Ne-Mg) SN	O-Ne-Mg核心表层	r-过程
$\approx 25-100 M_{\odot}$	高质量 (Fe) SN	黑洞吸积盘的星风	r-过程
$\geq 8 M_{\odot}$ (双星)	中子星并合	黑洞吸积盘的星风	r-过程
$\geq 8 M_{\odot}$ (双星)	中子星并合	冷中子抛射物	r-过程
$\approx 11-16 M_{\odot}$; $49-75 M_{\odot}$	$[\text{Fe}/\text{H}] \leq -3$ SN	氦壳层	r-过程
$\approx 11-100 M_{\odot}$	$[\text{Fe}/\text{H}] > -3$ SN	氦壳层	i-过程

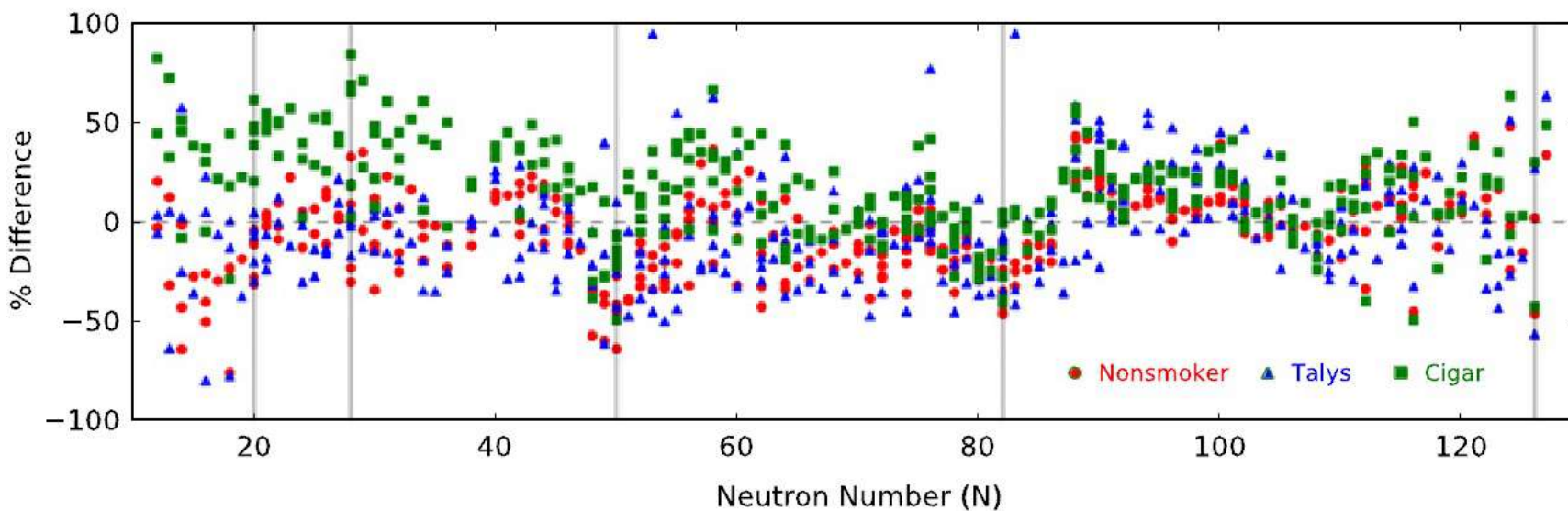
r-过程研究现状：实验数据极少，理论差别巨大



(a) Sn isotopes ($Z = 50$)

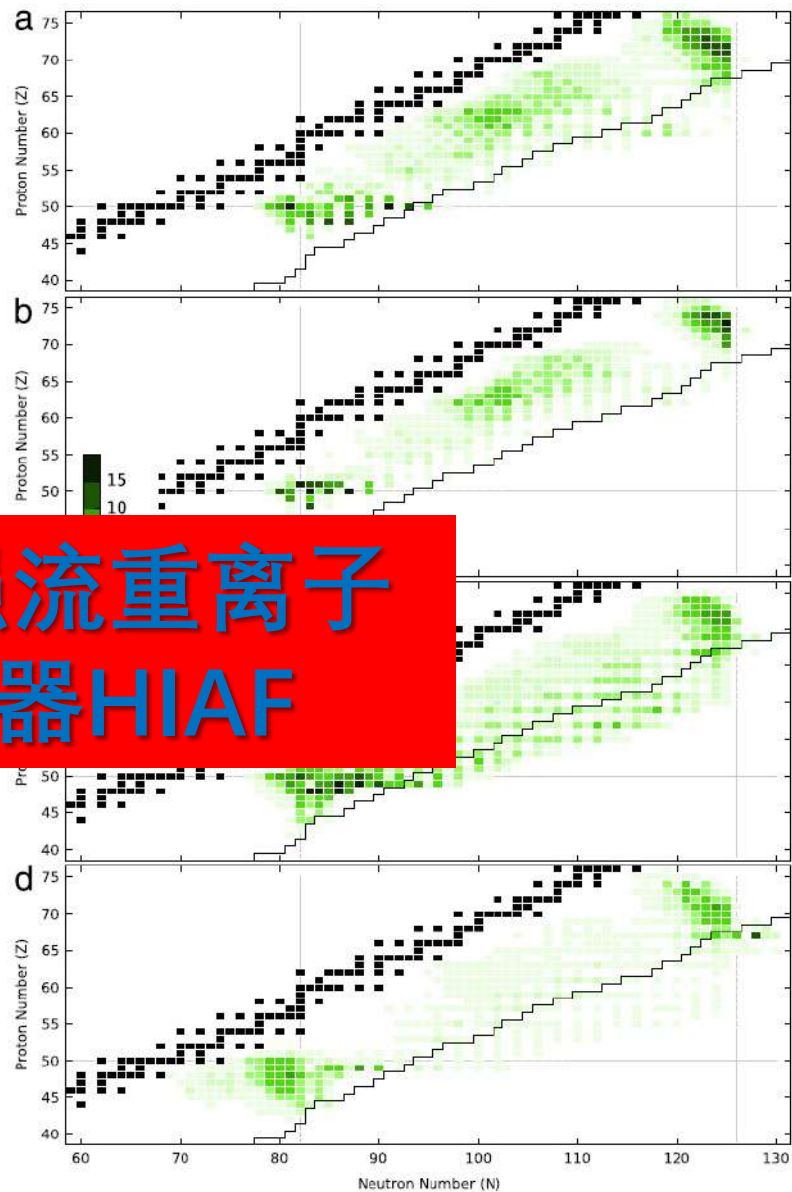
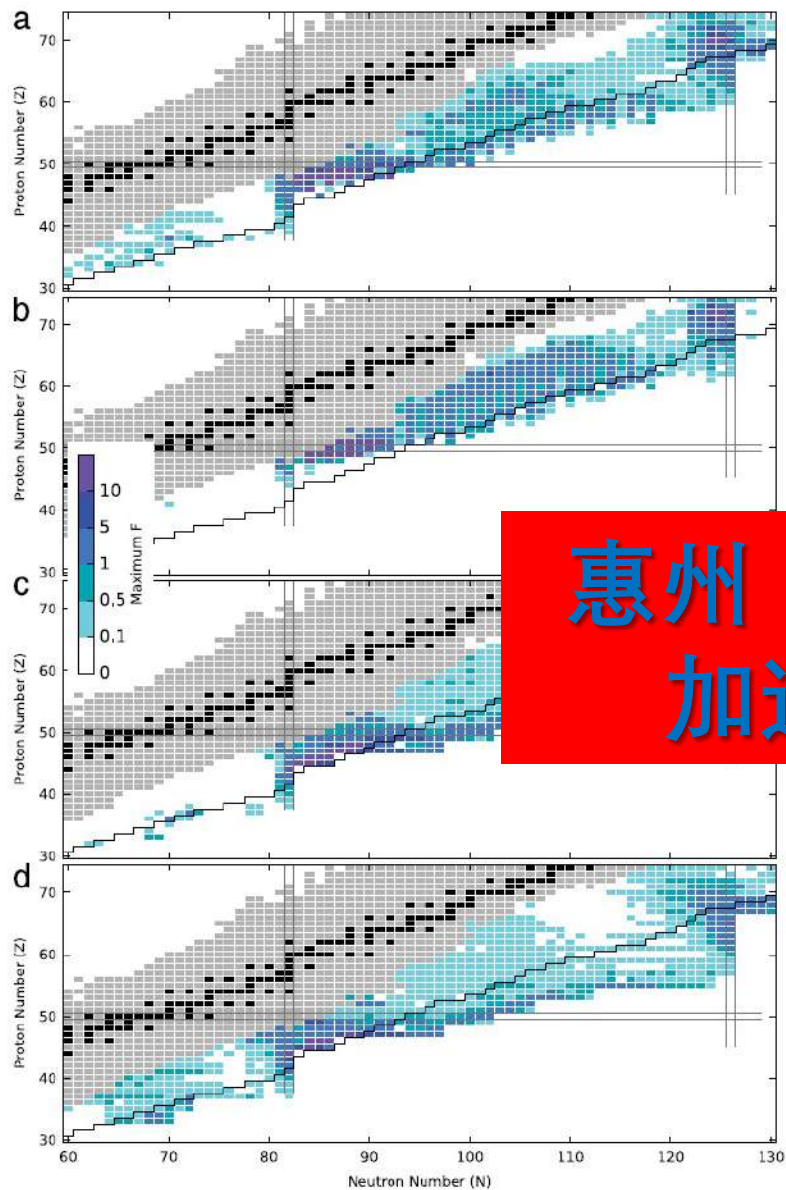


(b) Eu isotopes ($Z = 63$)



Mumpower et al, Prog. Part. Nucl. Phys. 86, 86 (2016).

r-过程：需着重研究的同位素和俘获反应

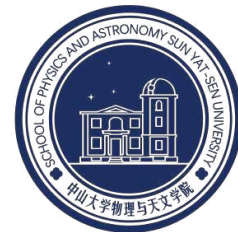


惠州 强流重离子
加速器HIAF

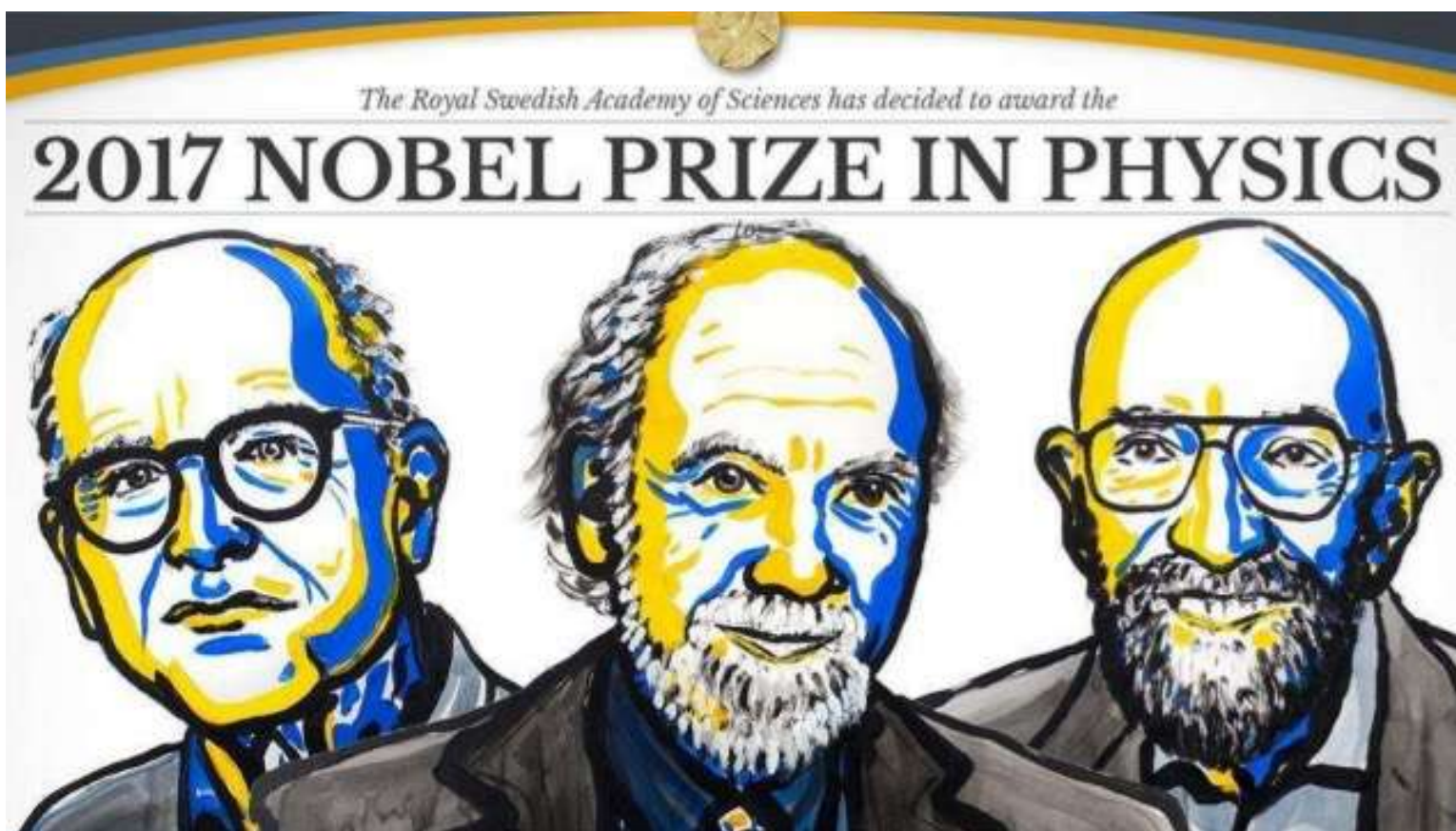
需要着重研究的核及中子俘获截面

(a) low entropy hot wind, (b) high entropy hot wind, (c) cold wind and (d) neutron star merger

引力波百年终获诺贝尔物理学奖

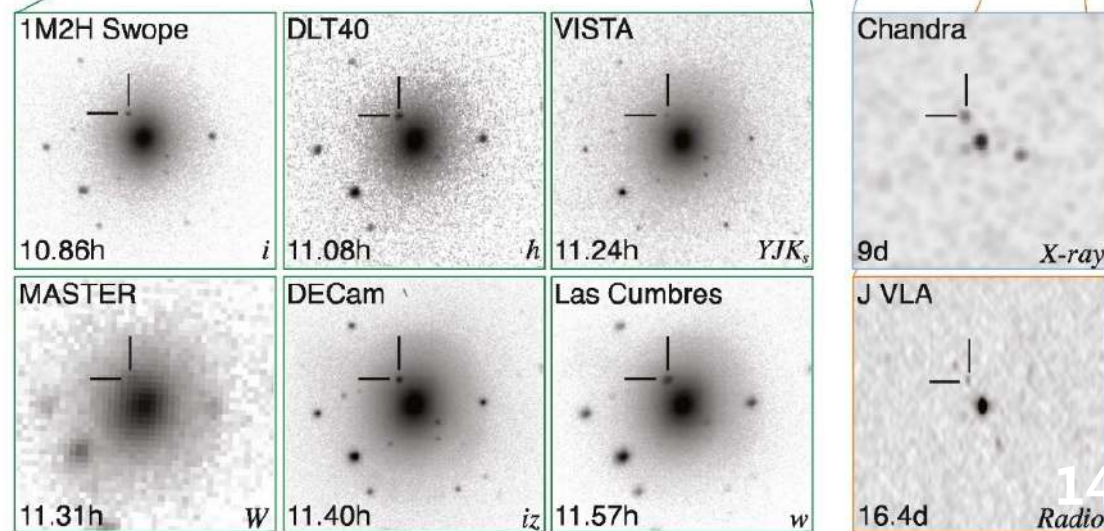
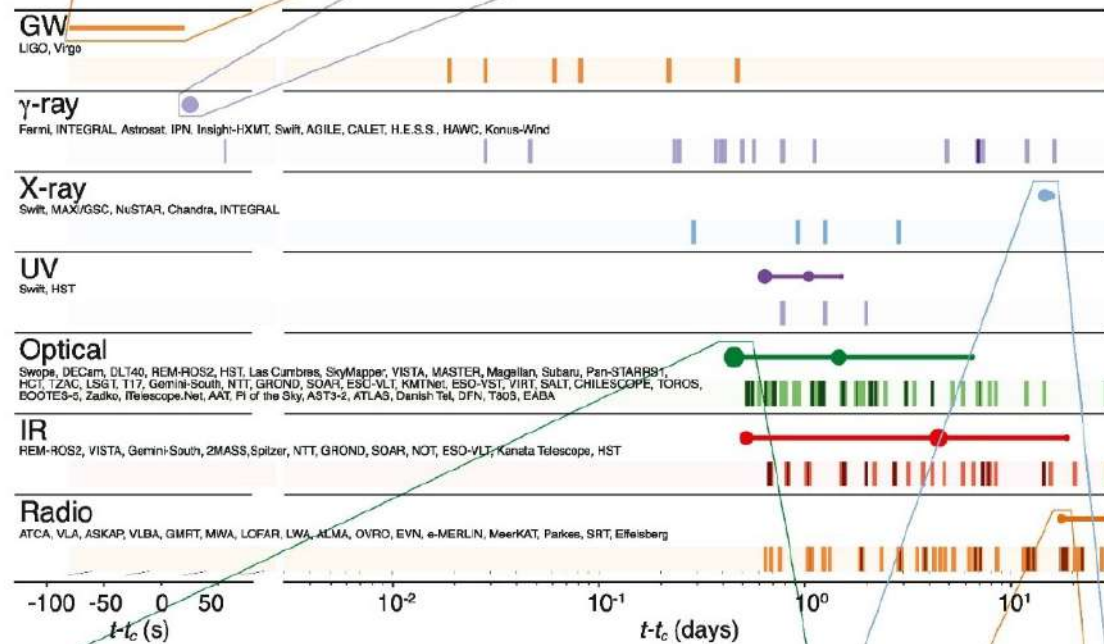
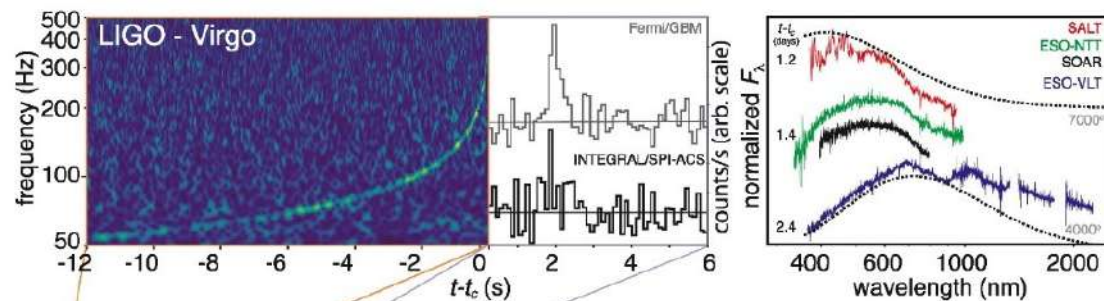
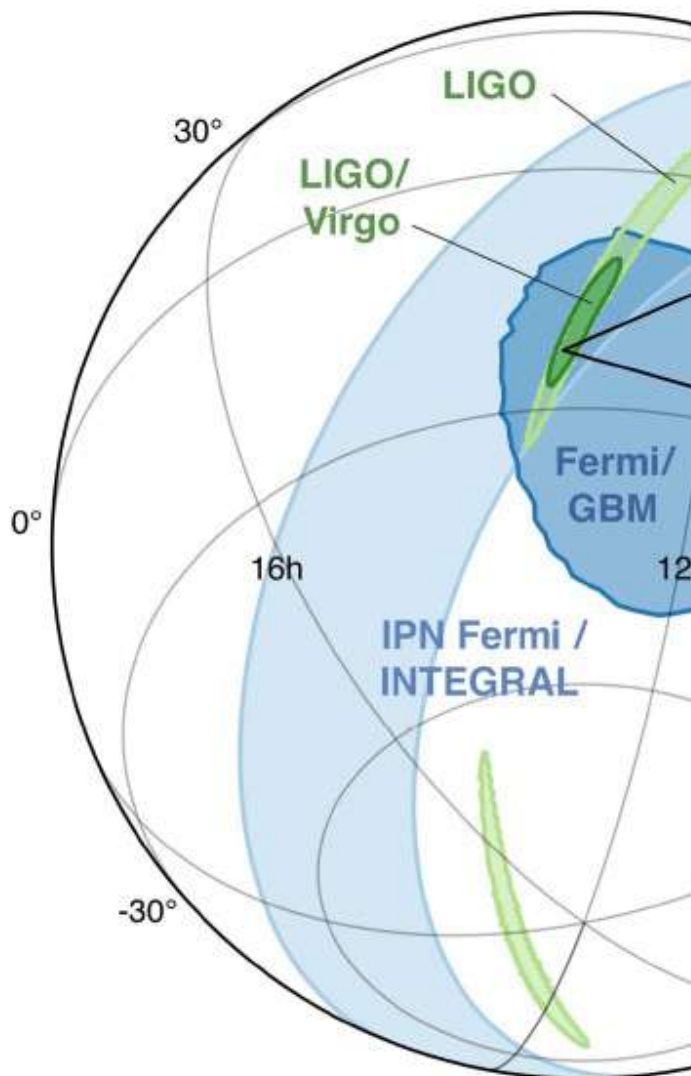


- ❖ 1915年，爱因斯坦在广义相对论的基础上提出了引力波的存在，并预言强引力场事件可产生引力波，比如黑洞合并、超新星爆发等。
- ❖ 2015年9月14日，LIGO引力波探测器首次探测到黑洞并合引力波。
- ❖ 2015年7月，中山大学启动天琴空间引力波探测计划，校长罗俊院士带队。



中子星并合引力波的

2017年10月16日晚10点LIGO两场新



四个天文发现：GW170817（引力波），GRI

中子星并合观测Sr锶元素丰度

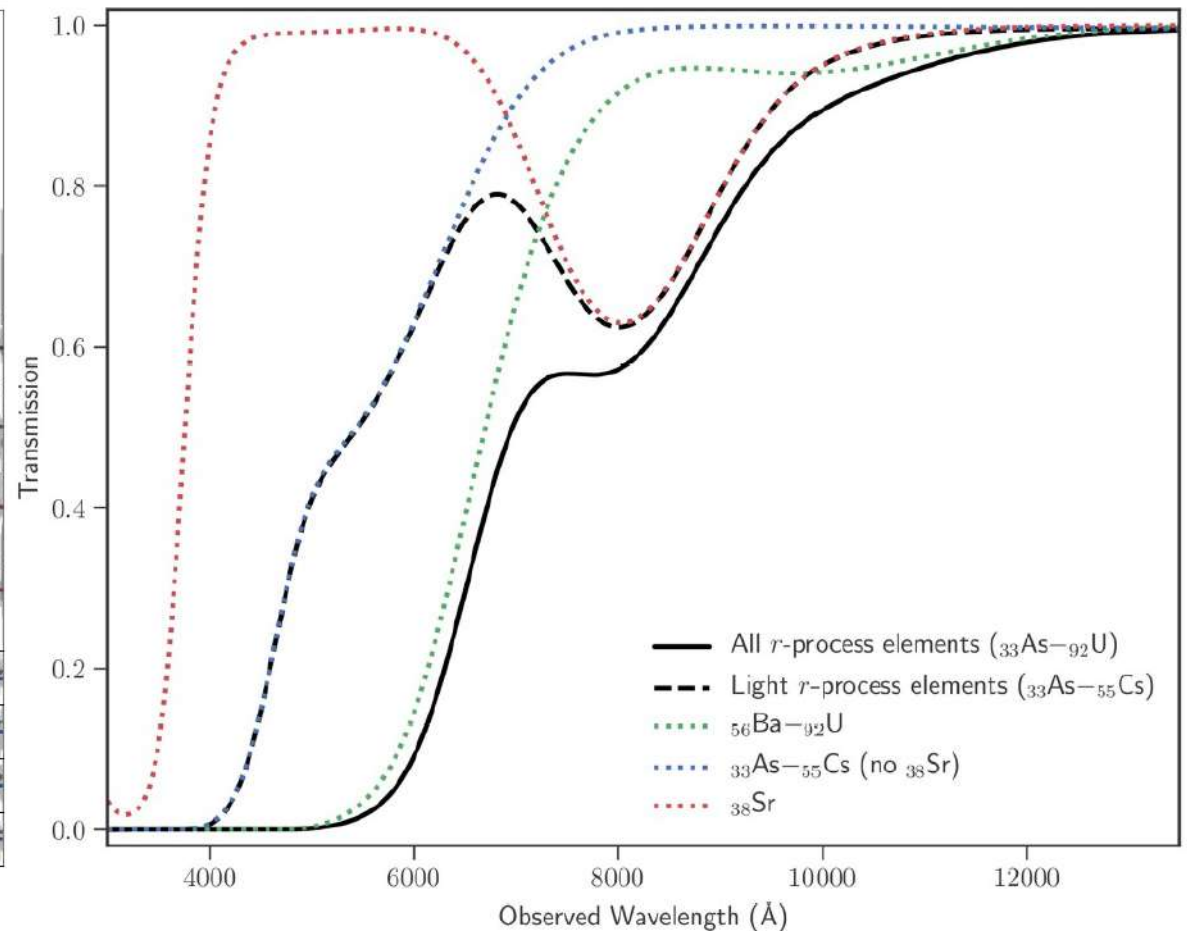
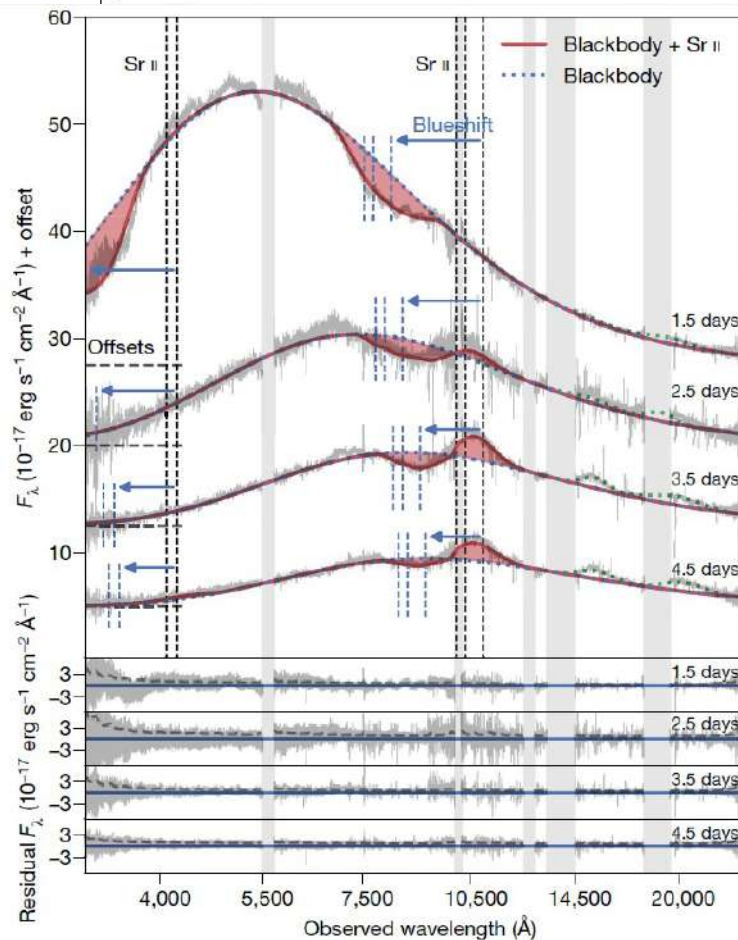


Article

Identification of strontium in the merger of two neutron stars

Sr 锶元素

Nature | Vol 574 | 24 OCTOBER 2019 | 497



天文观测中的Ba、Eu等元素丰度

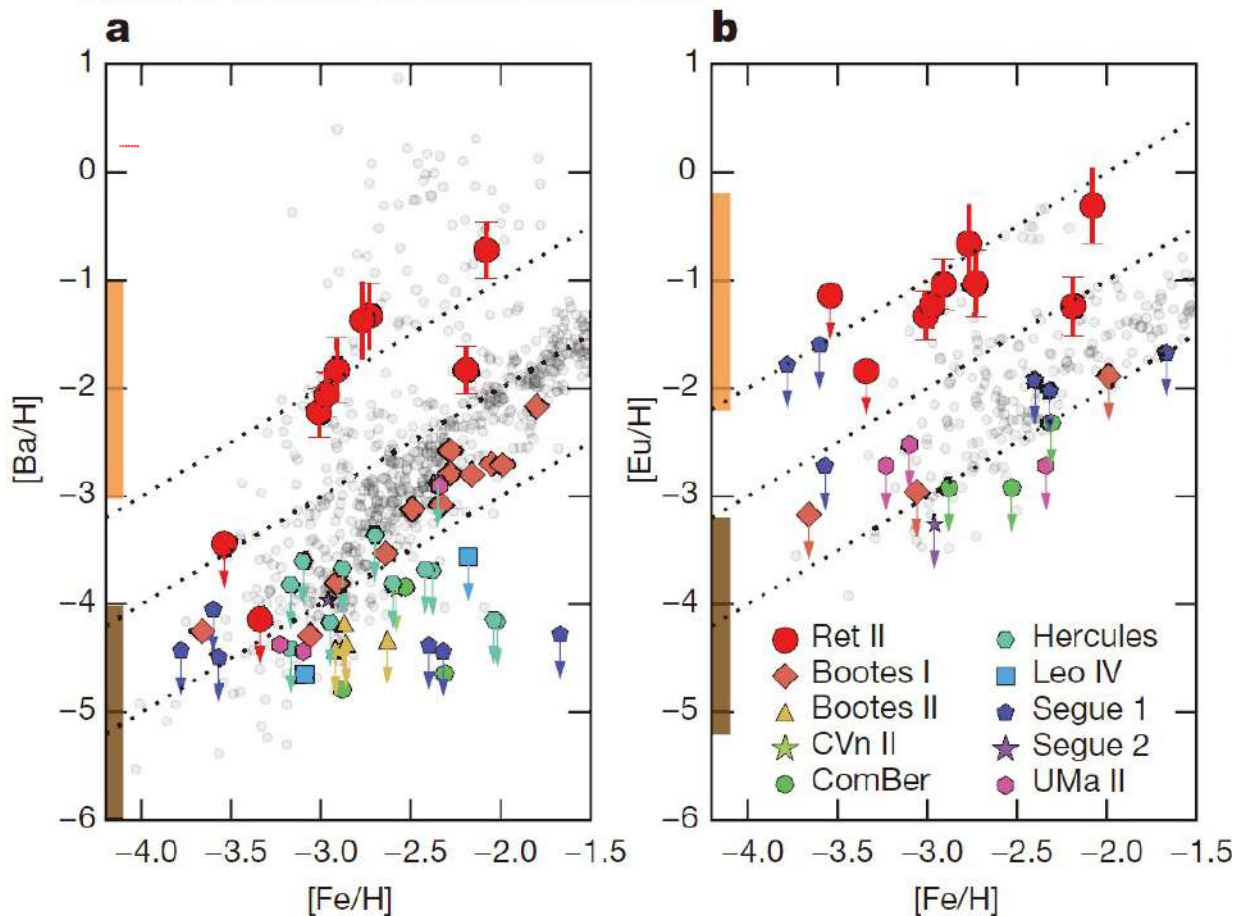


LETTER

doi:10.1038/nature17425

R-process enrichment from a single event in an ancient dwarf galaxy

Alexander P. Ji^{1,2}, Anna Frebel^{1,2}, Anirudh Chiti¹ & Joshua D. Simon³



❖ **Nature** : Reticulum II

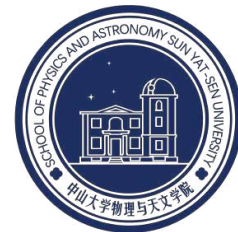
星系9颗星精细光谱；

❖ r-过程中Ba、Eu元素丰度，远高于普通核心坍缩超新星的r-过程的观测值；

❖ 可能源于中子星并合中r-过程理论预言的元素丰度。

APJ 738(2011) L32

Nature 531 (2016) 610



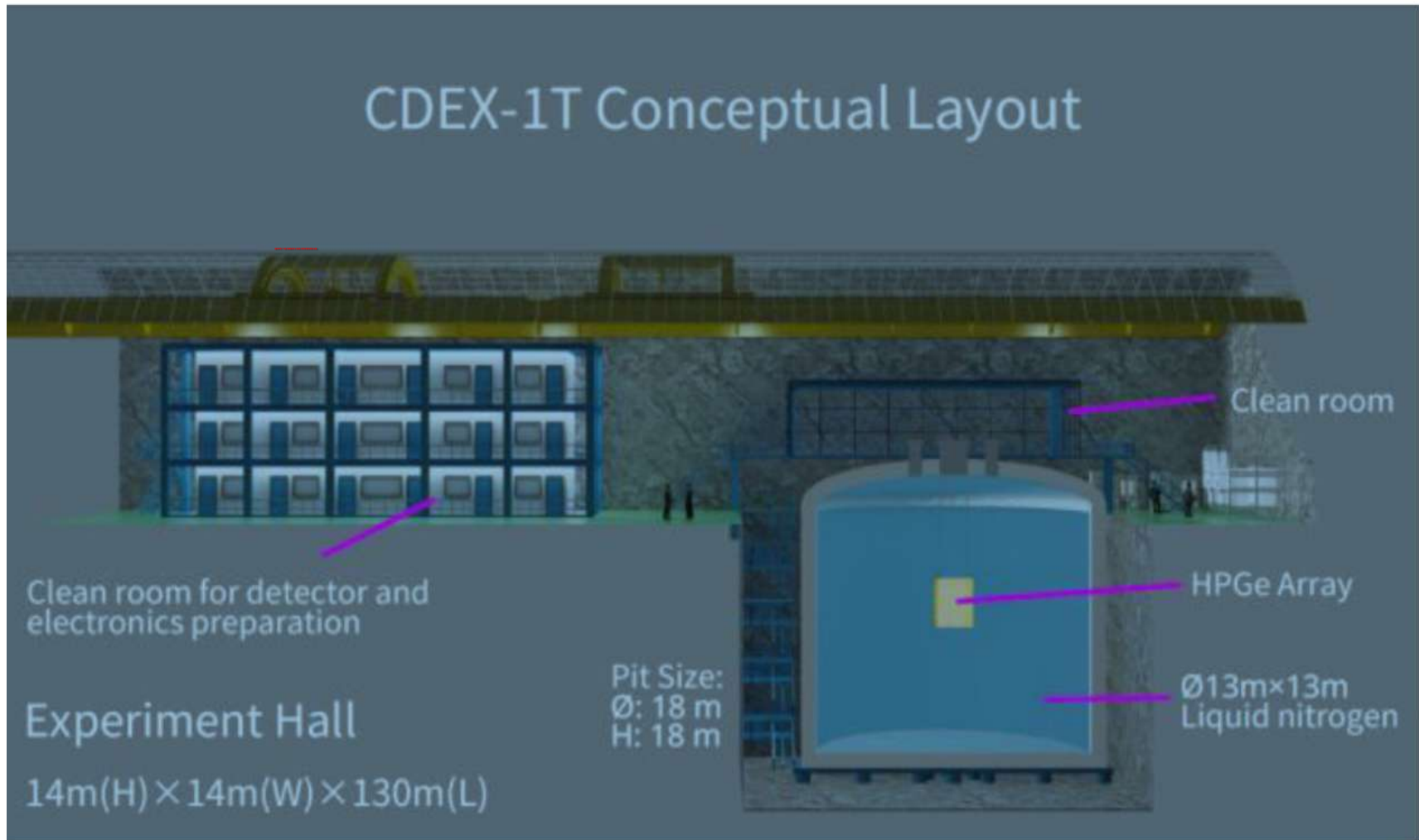
2

$0\nu\beta\beta$ 实验中子诱发本底反应： ^{76}Ge 为例

中国暗物质实验CDEX@CJPL-II



- ❖ 一项尖端技术：HPGe
- ❖ 两个前沿物理：DM（暗物质）+ $0\nu\beta\beta$ （无中微子双贝塔）



^{76}Ge 无中微子双贝塔衰变- $0\nu\beta\beta$



GERDA

The GERmanium Detector Array
for the search of neutrinoless double beta decay in Ge-76
at the Laboratori Nazionali del Gran Sasso (LNGS)

The GERmanium Detector Array

Science 365 (2019)1445

Phys. Rev. Lett. 120 (2018) 132503

Nature 544 (2017) 47



MAJORANA

A search for neutrinoless double-beta decay of germanium-76

The MAJORANA DEMONSTRATOR

Phys. Rev. Lett. 120 (2018) 132502

Phys. Rev. Lett. 120 (2018) 211804

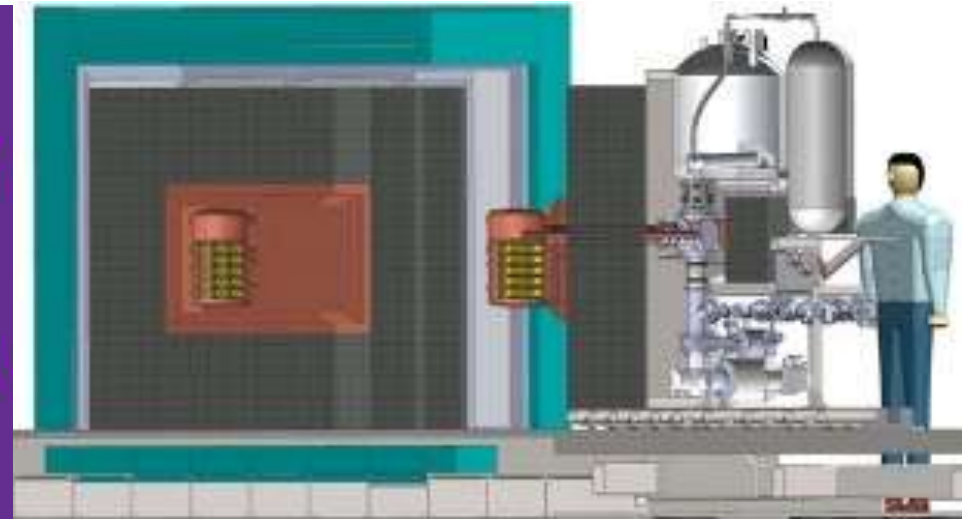
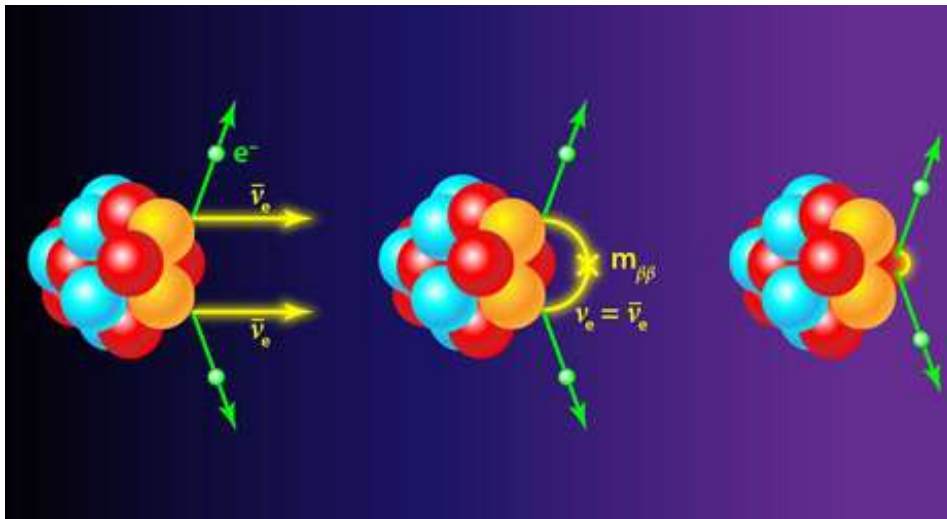
LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless $\beta\beta$ Decay

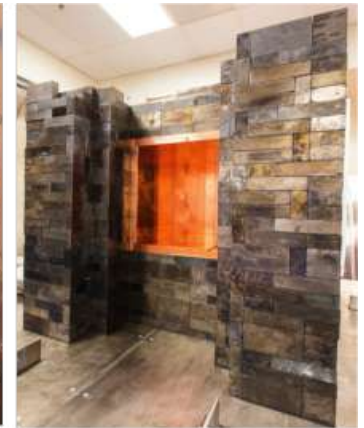
The LEGEND Collaboration

GERDA and Majorana

Accurately predict the neutron-induced internal background



Majorana



PPC HPGe Detector

Low-Mass Mount

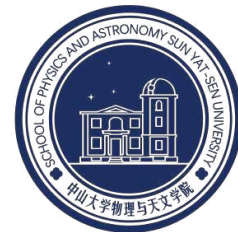
String

7-String Array

Cryostat

Shield

^{76}Ge 无中微子双贝塔衰变本底的主要来源



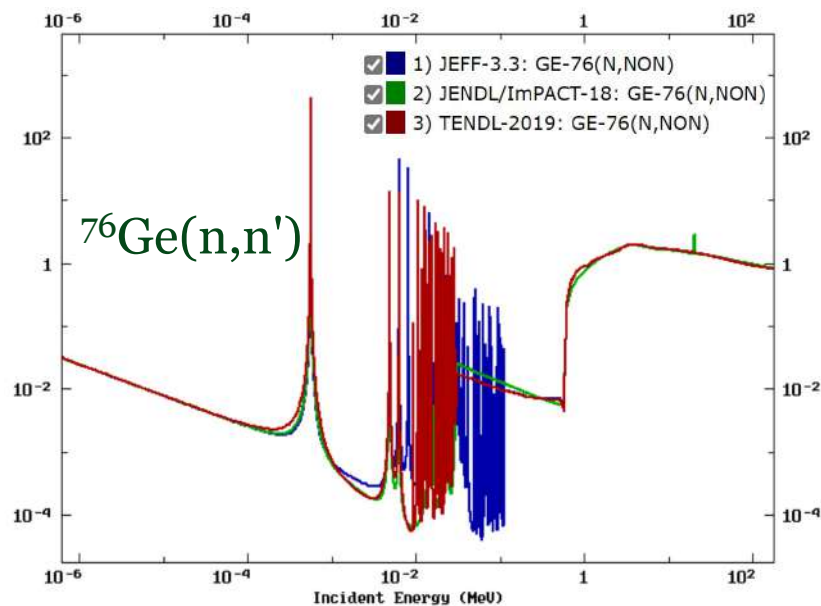
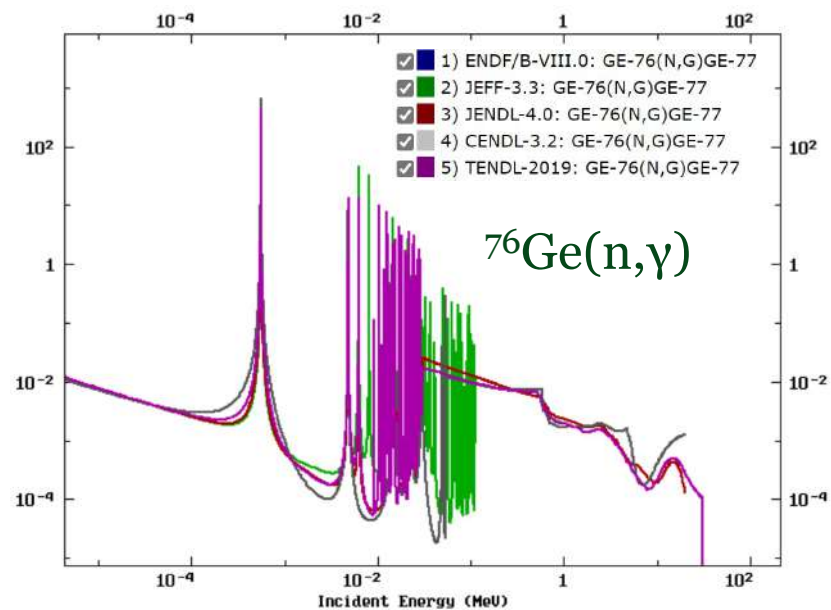
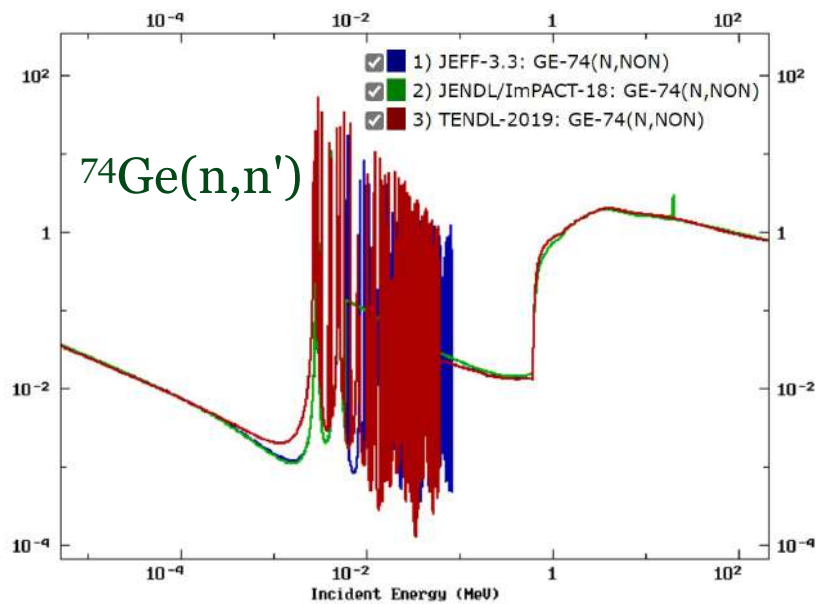
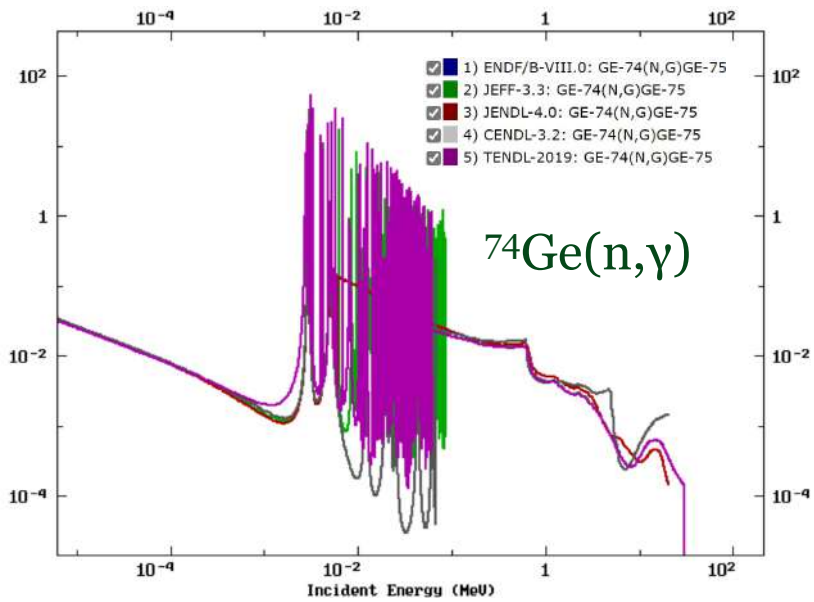
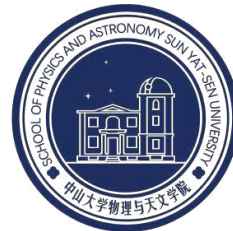
❖ $0\nu\beta\beta$ 实验中子本底的主要来源 (^{76}Ge 为例)

- 铜构件和高纯锗在地面制造过程中因宇宙线中 μ 子、中子和质子产生的宇生核素；
- 环境中原生的放射性核素产生的 γ 或中子，例如U，Th衰变产生的中子；
- μ 子在探测器和屏蔽材料中产生的中子等。

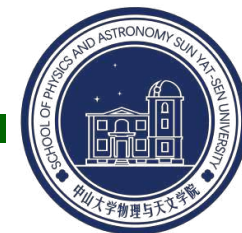
Background contribution	Rate
Majorana装置各部分对本底的贡献	c/(ROI t yr)
Electroformed Cu	0.23
OFHC Cu shielding	0.29
Pb Shielding	0.63
Cables and internal connectors	<0.38
Front Ends	0.6
U/Th within the Ge	<0.07
Plastics + Other	0.39
^{68}Ge , ^{60}Co within the $^{\text{enr}}\text{Ge}$	0.07
^{60}Co within the Cu	0.09
External γ rays, (alpha,n) reactions	0.1
Rn and surface α emission	0.05
Ge, Cu, Pb (n,n' γ) reactions	0.21
Ge(n,n') reactions	0.17
Ge(n, γ)	0.13
Direct μ passage	0.03
ν Induced background	<0.01
Total	<3.5

**Majorana
Demonstrator
本底构成**

$^{74,76}\text{Ge}(n,\gamma)$ & (n,n') 反应的现有评价数据测量

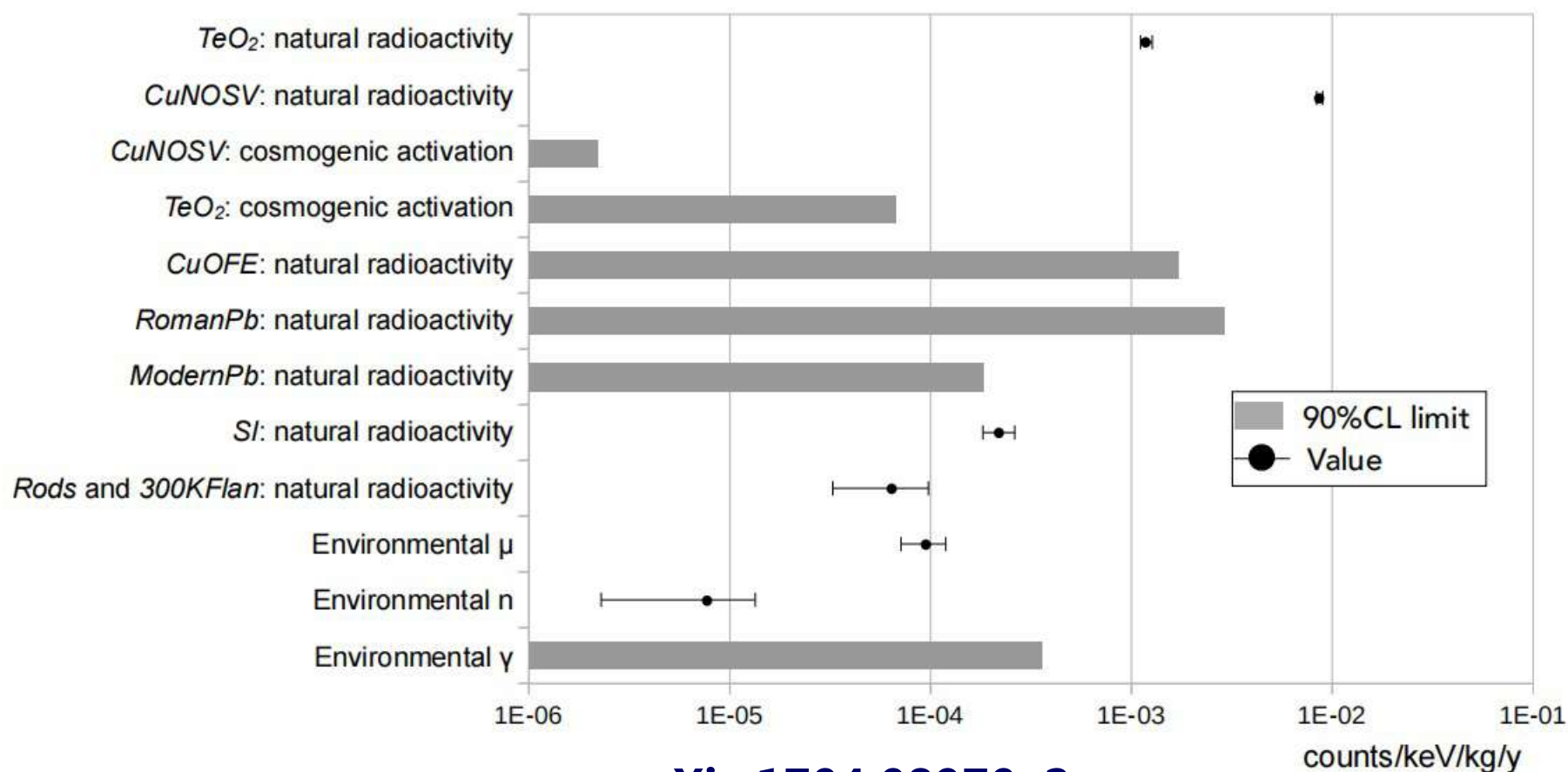


^{130}Te 无中微子双贝塔衰变本底的主要来源



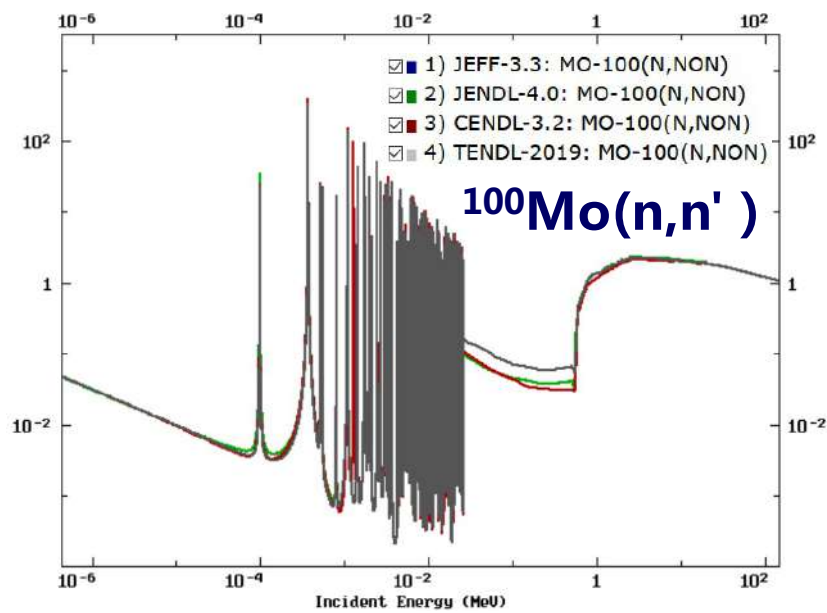
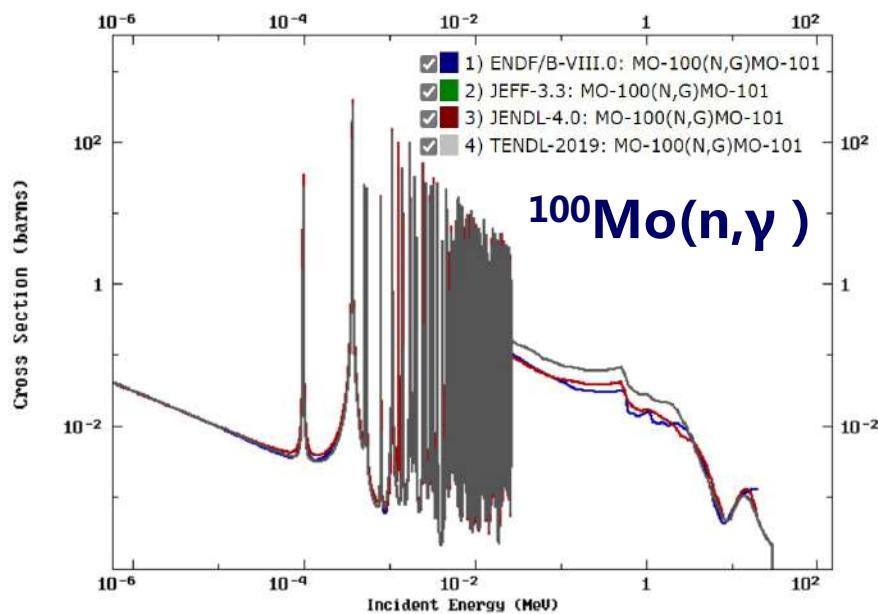
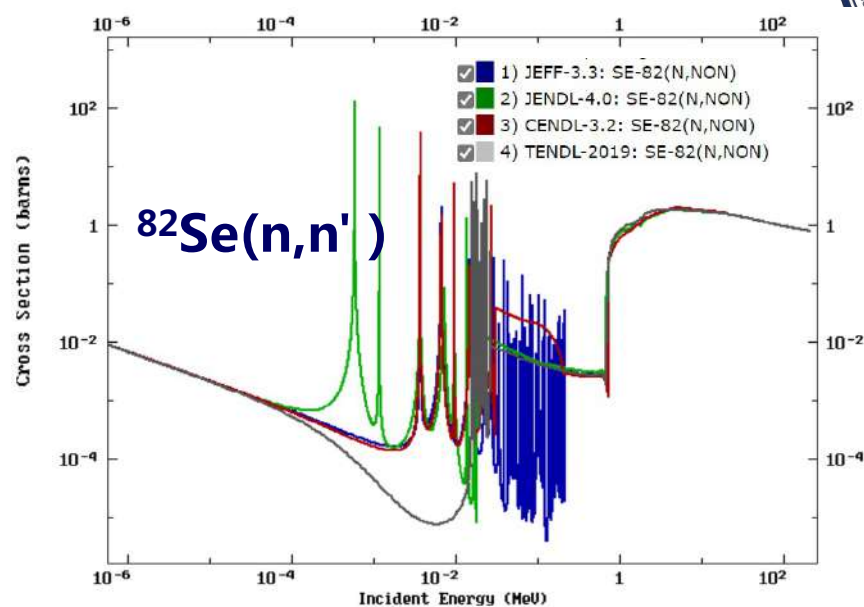
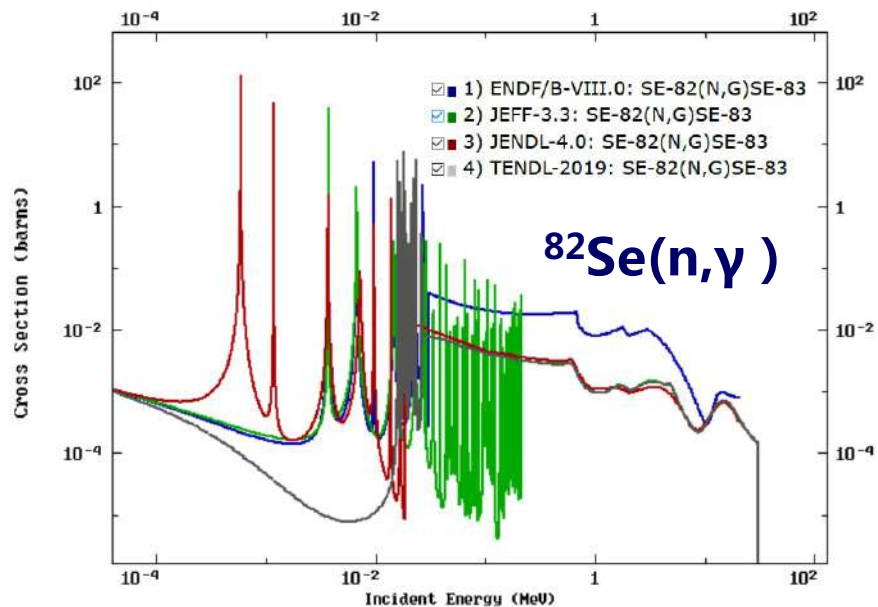
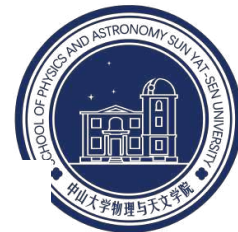
- ❖ CUORE实验本底的主要来源 (^{130}Te 为例)
- ❖ Cosmogenically-produced radioactive isotopes (e.g.

^{60}Co caused by Fast nucleon interactions in copper and tellurium);

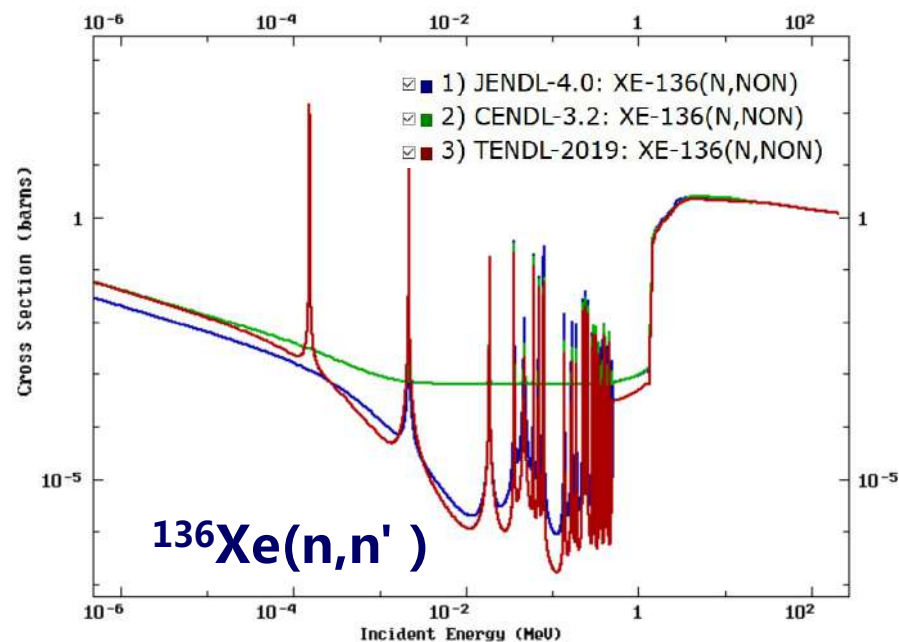
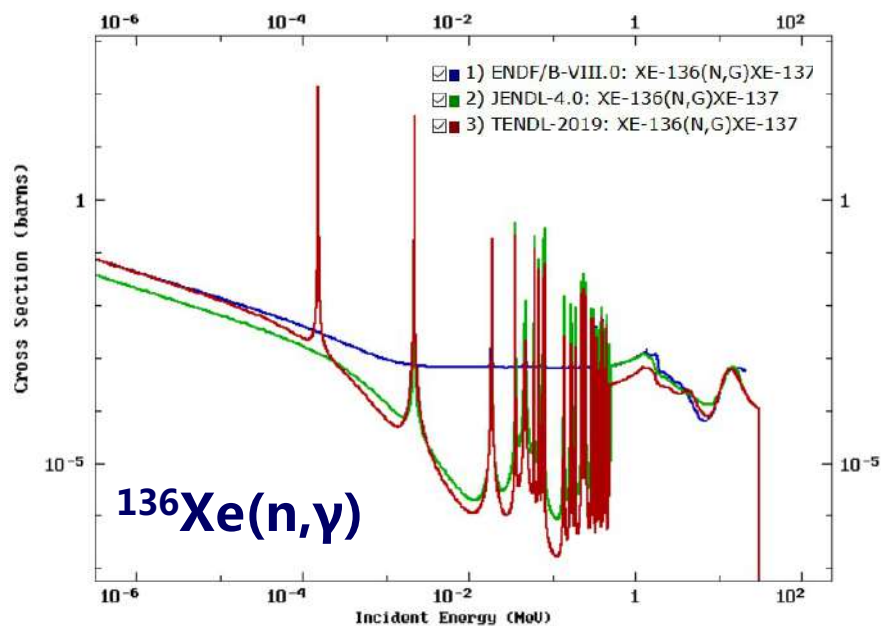
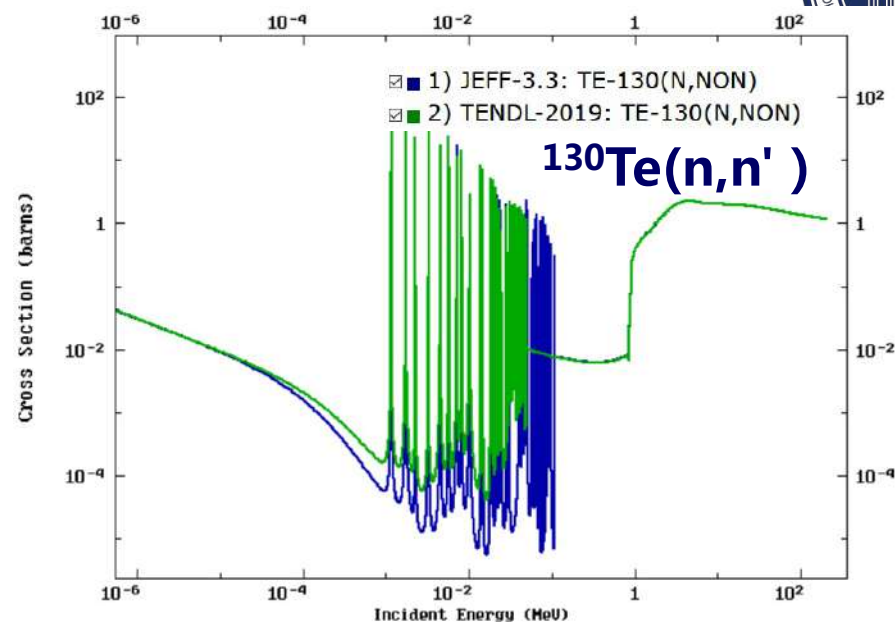
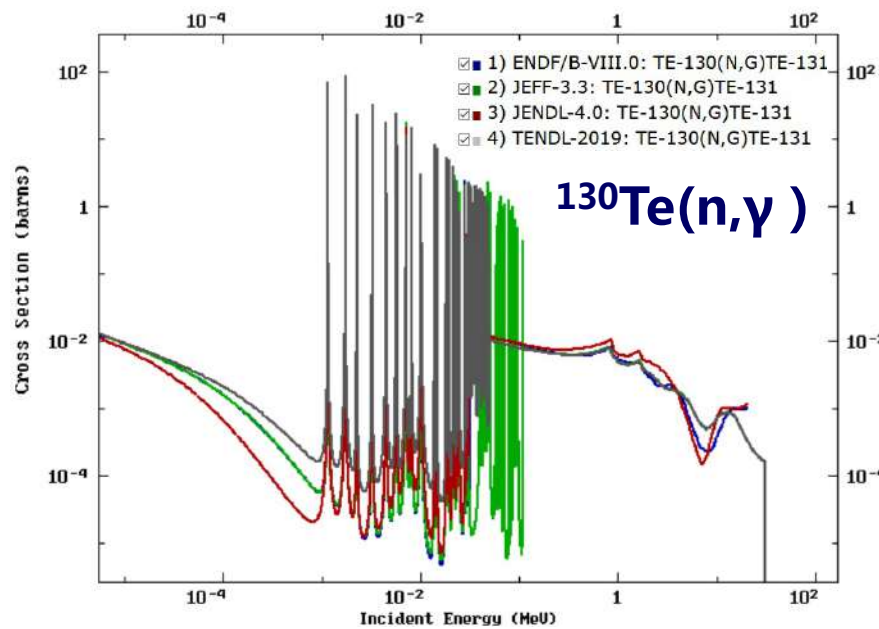
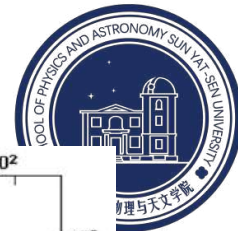


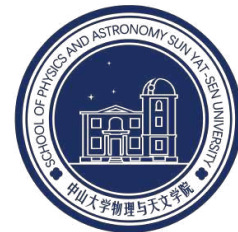
arXiv:1704.08970v2

^{82}Se 、 $^{100}\text{Mo}(n,\gamma)\&(n,n')$ 反应的现有评价数据



^{130}Te , $^{136}\text{Xe}(n,\gamma)$ & (n,n') 反应的现有评价数据





3

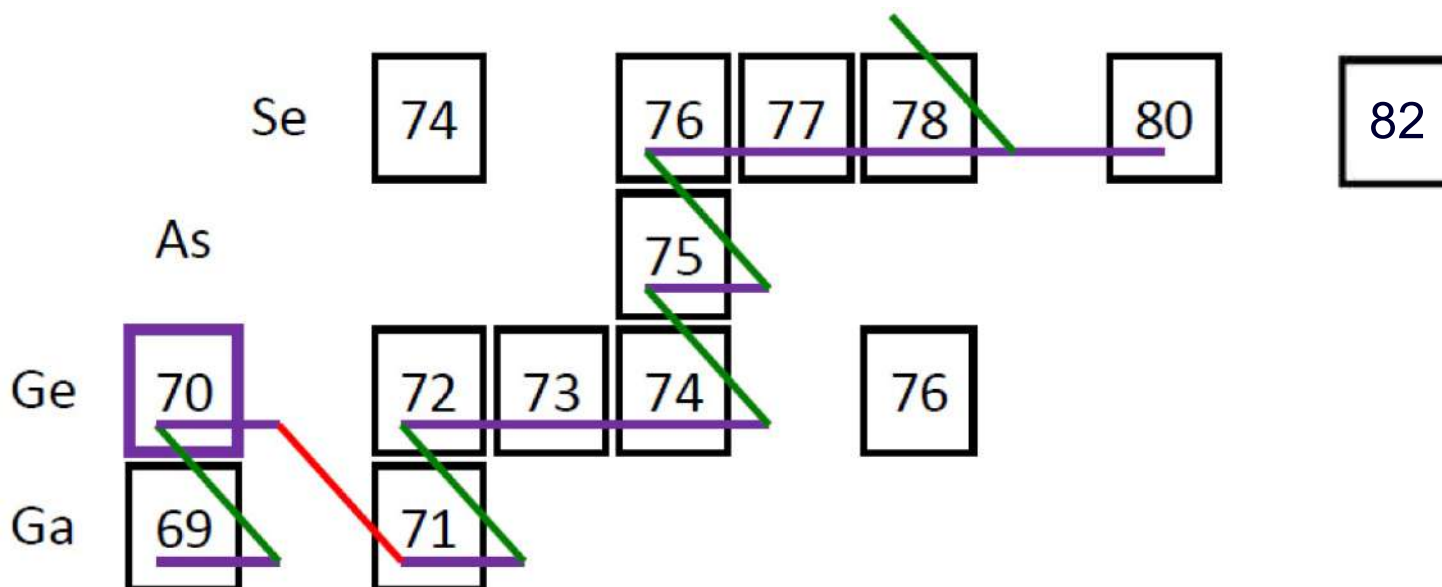
$^{74,76}\text{Ge}$ 同位素链中子俘获截面研究现状

Ge、Se元素的s-/r-过程



❖ Ge同位素的s-/r-过程

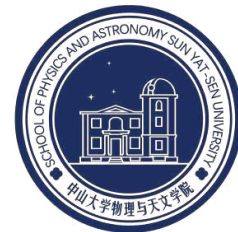
- 70,72,73,74Ge为s-过程产生、76Ge为r-过程产生



❖ 测量方法，主要有中子活化法和瞬发 γ 射线法

- 前者方法成熟、技术简单及数据精度高等特点。但受核半衰期长短的影响，不能在连续能区上实验。
- 瞬发 γ 射线法可以成功的避开中子活化法的缺点，但是技术复杂，影响精度的因素较多。

Ge, Se, Mo, Te, Xe的同位素及天然丰度



Ge70	Ge71 11.43 d 1/2- *	Ge72	Ge73	Ge74	Ge75 82.78 m 1/2- *	Ge76
0+		0+	9/2+ *	0+		0+
21.23	EC	27.66	7.73	35.94	β^-	7.44

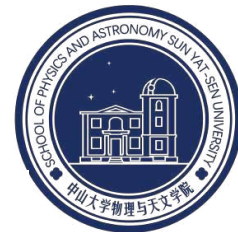
Se74	Se75 119.779 d 5/2+ *	Se76	Se77	Se78	Se79 1.13E6 y 7/2+ *	Se80	Se81 18.45 m 1/2- *	Se82 1.08E+20 y 0+
0+		0+	1/2- *	0+		0+	1/2- *	$\beta-\beta^-$
0.89	EC	9.36	7.63	23.78	β^-	49.61	β^-	8.73

Mo92	Mo93 4.0E+3 y 5/2+ *	Mo94	Mo95	Mo96	Mo97	Mo98	Mo99 65.94 h 1/2+ *	Mo100 1.2E19 y 0+
0+		0+	5/2+ *	0+	5/2+ *	0+	1/2+ *	$\beta-\beta^-$
14.84	EC	9.25	15.92	16.68	9.55	24.13	β^-	9.63

Te120	Te121 16.78 d 1/2+ *	Te122	Te123 1E+13 y 1/2+ *	Te124	Te125	Te126	Te127 9.35 h 3/2+ *	Te128 2.2E24 y 0+	Te129 69.6 m 3/2+ *	Te130 7.9E20 y 0+
0+		0+	EC	0+	1/2+ *	0+		0+	3/2+ *	β^-
0.096	EC	2.603	0.908	4.816	7.139	18.95	β^-	$\beta-\beta^-$ 31.69	β^-	33.80

Xe124 1.6E+14 y 0+	Xe125 16.9 h (1/2)+ *	Xe126	Xe127 36.4 d 1/2+ *	Xe128	Xe129	Xe130	Xe131	Xe132	Xe133 5.243 d 3/2+ *	Xe134	Xe135 9.14 h 3/2+ *	Xe136 2.36E21 y 0+
ECEC		0+		0+	1/2+ *	0+	3/2+ *	0+		0+	3/2+ *	0+
0.10	EC	0.09	EC	1.91	26.4	4.1	21.2	26.9	β^-	10.4	β^-	8.9

$^{74,76}\text{Ge}$ 国内外实验测量工作-中子活化法



PHYSICAL REVIEW C **79**, 065802 (2009)

Neutron capture cross sections of ^{74}Ge , ^{76}Ge , and ^{75}As at 25 keV

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(Received 7 January 2009; revised manuscript received 21 April 2009; published 25 June 2009)

The neutron capture cross sections of ^{74}Ge , ^{76}Ge , and ^{75}As have been measured at the Karlsruhe Van de Graaff accelerator by means of the activation technique. The neutron source reaction $^7\text{Li}(p, n)^7\text{Be}$ was used for simulating a thermal energy distribution for $kT = 25$ keV to determine the astrophysically relevant stellar cross sections directly. Based on an extended series of activations, consistent results could be obtained, corresponding to Maxwellian average cross sections at $kT = 30$ keV of 37.6 ± 3.9 mb for ^{74}Ge , 21.5 ± 1.8 mb for ^{76}Ge , and 362 ± 19 mb for ^{75}As . These results are more accurate than previous data and are, therefore, important for resolving previous discrepancies. By extrapolation Maxwellian averaged cross sections were derived for thermal energies from 5 to 100 keV. The implications of these results for the s -process abundances in massive stars and for the background conditions in double β decay experiments are discussed.

$^{74,76}\text{Ge}$ 国内外实验测量工作-中子活化法



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Physics Letters B

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Measurement of the neutron-capture cross section of ^{76}Ge and ^{74}Ge below 15 MeV and its relevance to $0\nu\beta\beta$ decay searches of ^{76}Ge



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ARTICLE INFO

Article history:

Received 1 September 2014

Received in revised form 2 December 2014

Accepted 3 December 2014

Available online 9 December 2014

Editor: D.F. Geesaman

Keywords:

Neutron radiative capture

Neutron induced background

Neutrino detectors

Double-beta decay detectors

Dark matter detectors

ABSTRACT

The neutron radiative-capture cross section of ^{76}Ge was measured between 0.4 and 14.8 MeV using the activation technique. Germanium samples with the isotopic abundance of $\sim 86\%$ ^{76}Ge and $\sim 14\%$ ^{74}Ge used in the $0\nu\beta\beta$ searches by the GERDA and Majorana Collaborations were irradiated with monoenergetic neutrons produced at eleven energies via the $^3\text{H}(p, n)^3\text{He}$, $^2\text{H}(d, n)^3\text{He}$ and $^3\text{H}(d, n)^4\text{He}$ reactions. Previously, data existed only at thermal energies and at 14 MeV. As a by-product, capture cross-section data were also obtained for ^{74}Ge at neutron energies below 8 MeV. Indium and gold foils were irradiated simultaneously for neutron fluence determination. High-resolution γ -ray spectroscopy was used to determine the γ -ray activity of the daughter nuclei of interest. For the ^{76}Ge total capture cross section the present data are in good agreement with the TENDL-2013 model calculations and the ENDF/B-VII.1 evaluations, while for the $^{74}\text{Ge}(n, \gamma)^{75}\text{Ge}$ reaction, the present data are about a factor of two larger than predicted. It was found that the $^{74}\text{Ge}(n, \gamma)^{75}\text{Ge}$ yield in the High-Purity Germanium (HPGe) detectors used by the GERDA and Majorana Collaborations is only about a factor of two smaller than the $^{76}\text{Ge}(n, \gamma)^{77}\text{Ge}$ yield due to the larger cross section of the former reaction.

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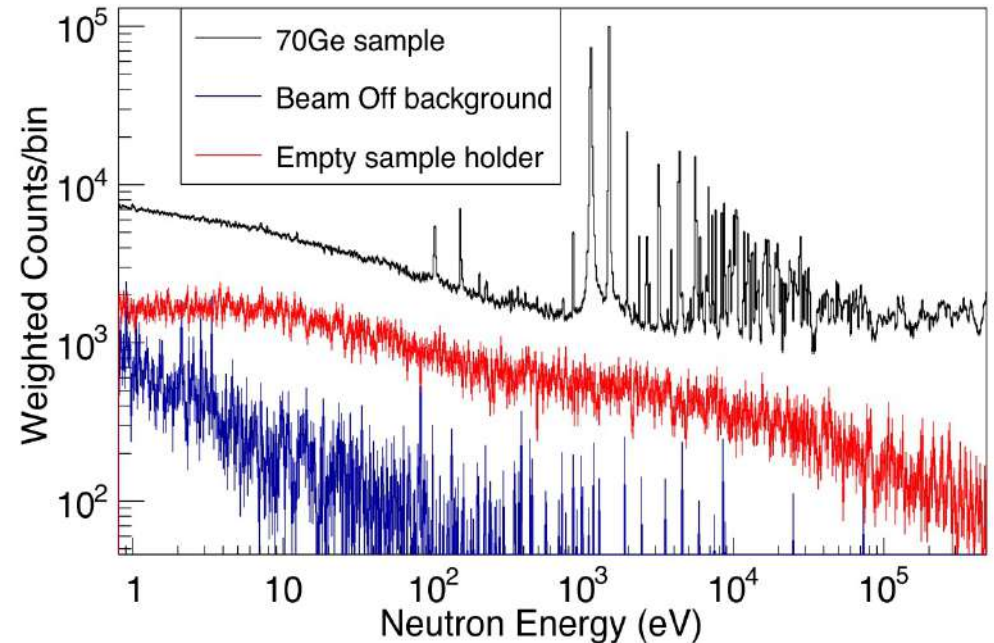
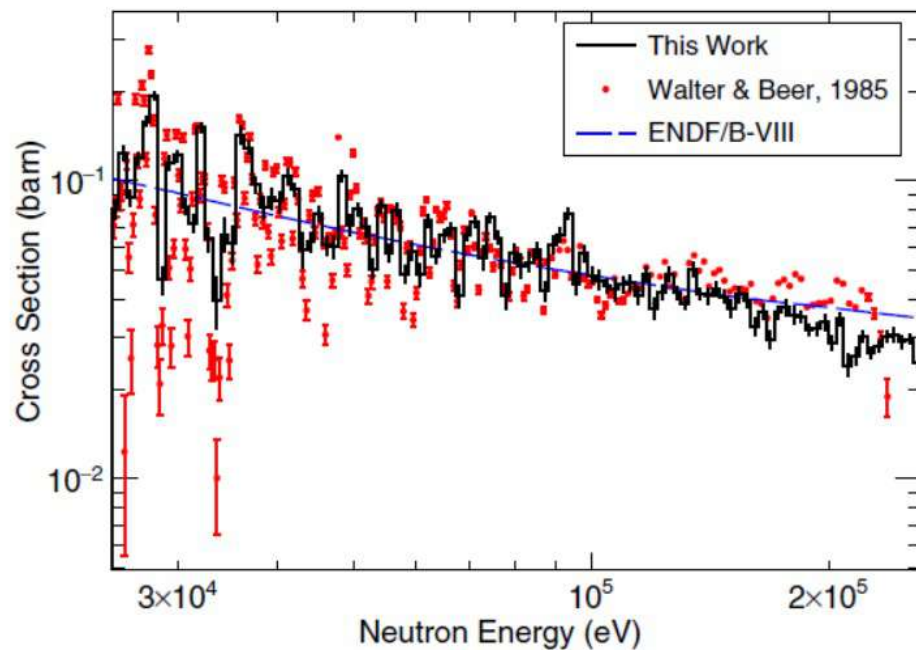
^{70}Ge 实验测量工作-瞬发 γ 射线法



PHYSICAL REVIEW C **100**, 045804 (2019)

Measurement of the $^{70}\text{Ge}(n, \gamma)$ cross section up to 300 keV at the CERN n_TOF facility

A. Gawlik,¹ C. Lederer-Woods,^{2,*} J. Andrzejewski,¹ U. Battino,² P. Ferreira,³ F. Gunsing,^{4,5} S. Heinitz,⁶ M. Krtička,⁷
C. Massimi,^{8,9} F. Mingrone,⁸ J. Perkowski,¹ R. Reifarth,¹⁰ A. Tattersall,² S. Valenta,⁷ C. Weiss,^{5,11} O. Aberle,⁵ L. Audouin,¹²



^{73}Ge 实验测量工作-瞬发 γ 射线法



Physics Letters B 790 (2019) 458–465



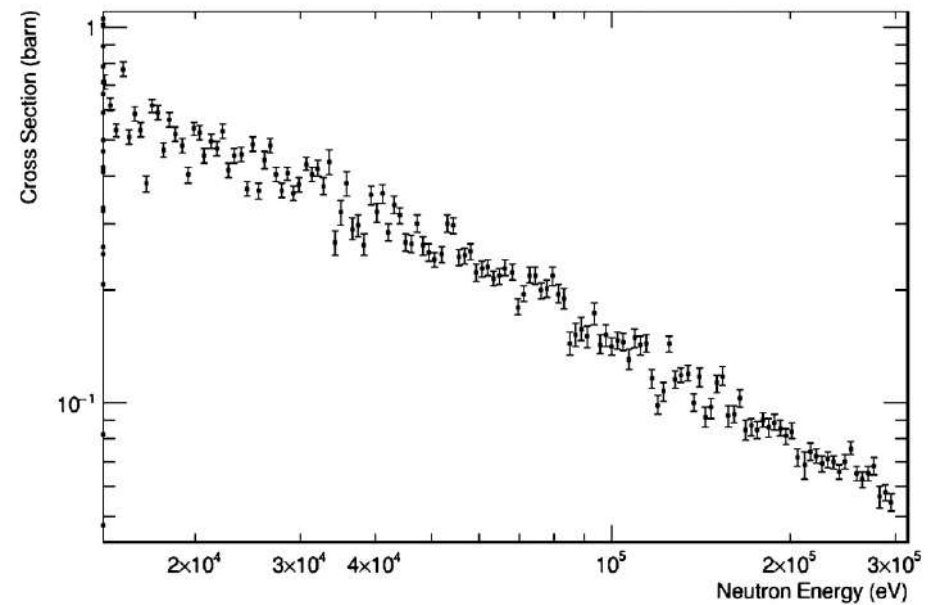
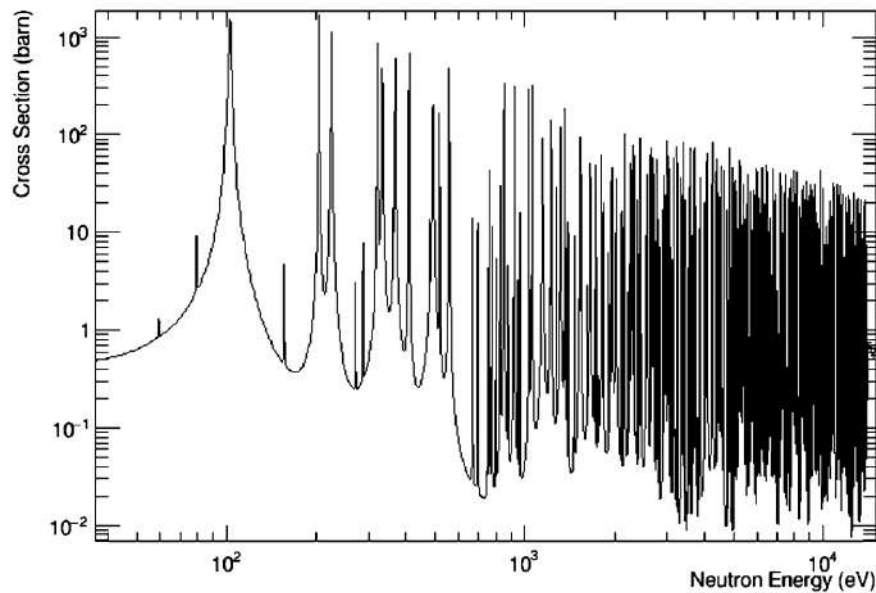
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Physics Letters B

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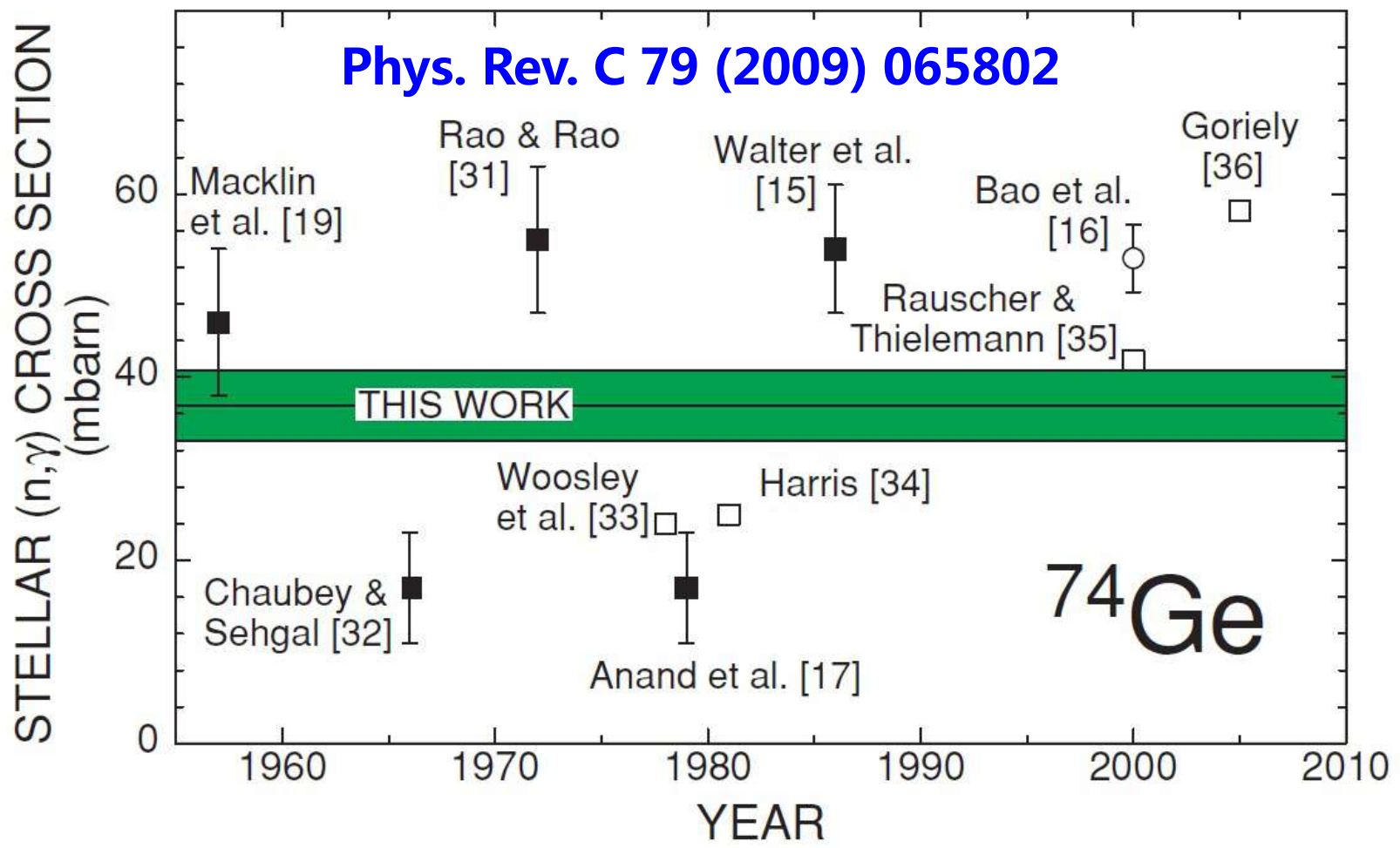
Measurement of $^{73}\text{Ge}(n, \gamma)$ cross sections and implications for stellar nucleosynthesis





s-过程：天体物理30keV截面差别极大

❖ 以 $^{74}\text{Ge}(n, \gamma)$ 反应为例，已有的实验和理论给出的截面差别很大。

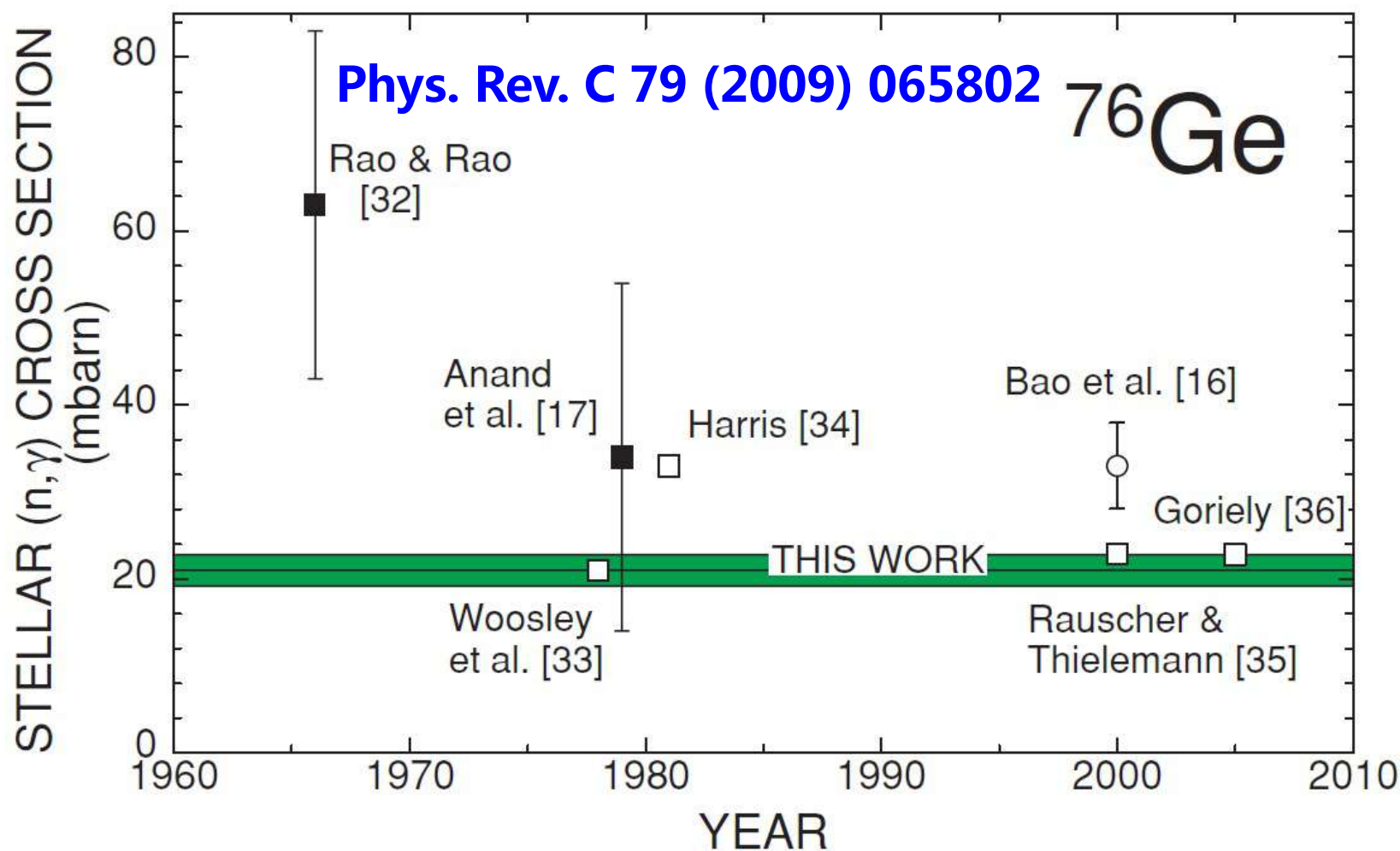


实心点实验值，空心点理论值

r-过程：天体物理30keV截面差别极大



❖ 以 $^{76}\text{Ge}(n, \gamma)$ 反应为例，已有的实验和理论给出的截面差别很大。

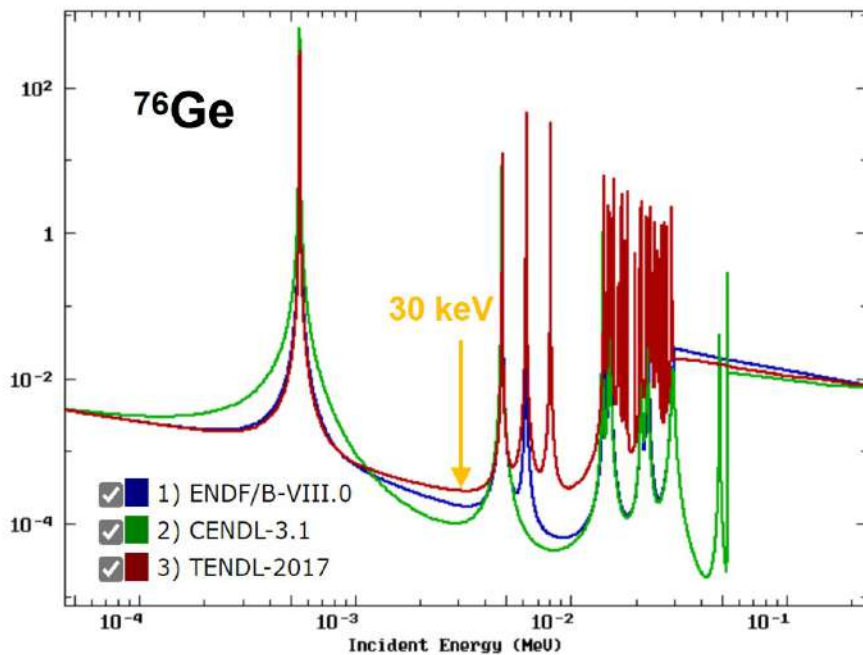
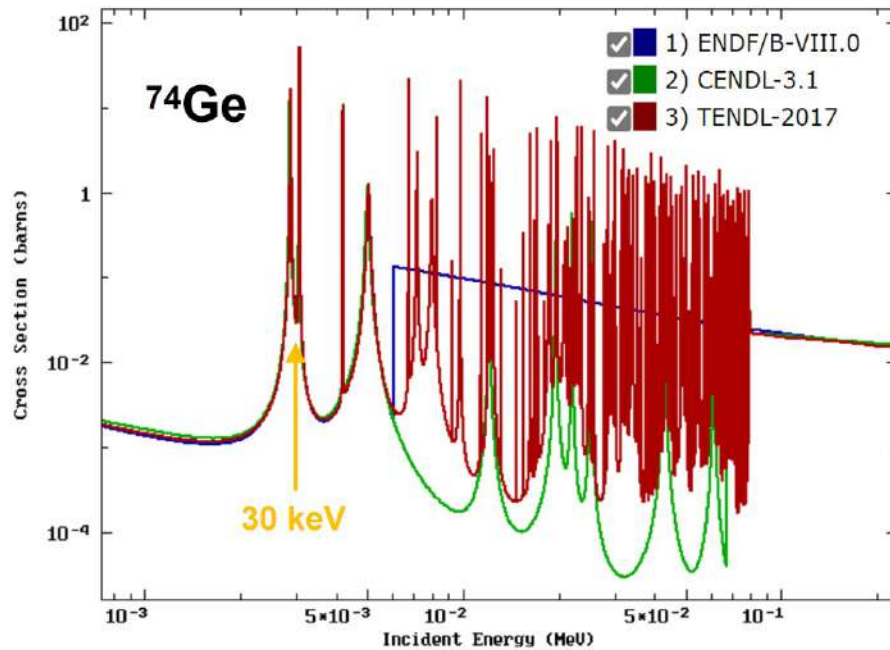


实心点实验值，空心点理论值

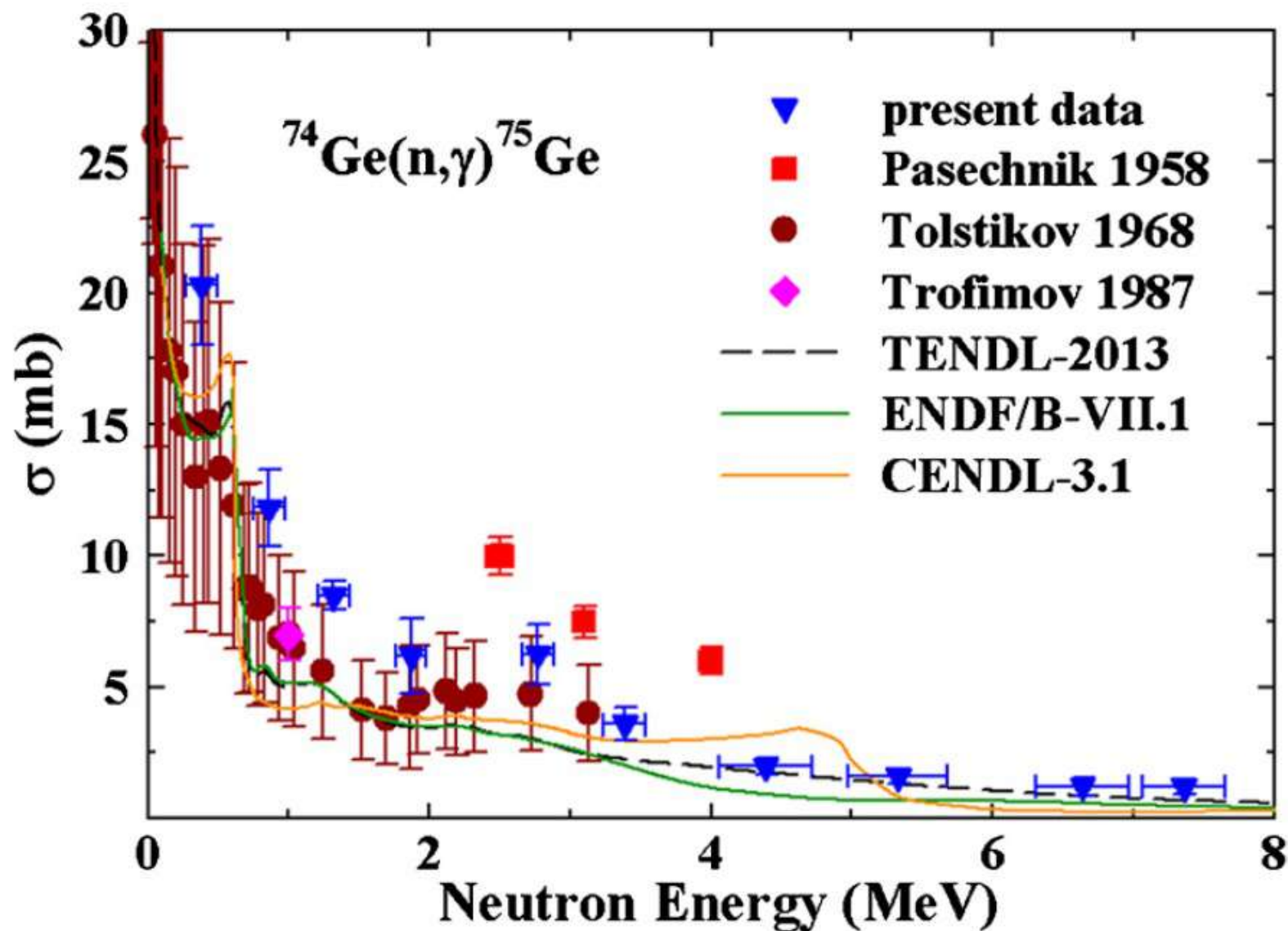
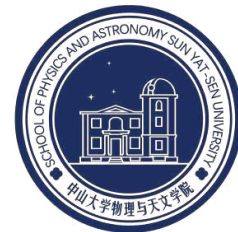


s-过程：天体物理30keV截面差别极大

- ❖ 30keV能区附近的截面明显受到附近共振结构的影响，其前后两个共振峰的形状直接影响着天体物理关注能区的测量值；
- ❖ ^{76}Ge 目前已有的共振截面ENDF/B-VIII.0、CENDL-3.1和TENDL-2013三个数据库推荐值明显存在差异。且与中中子活化法的实验值小了1-2个数量级。
- ❖ 迫切需要在白光中子源上开展新的实验研究，来澄清相关差异的原因。

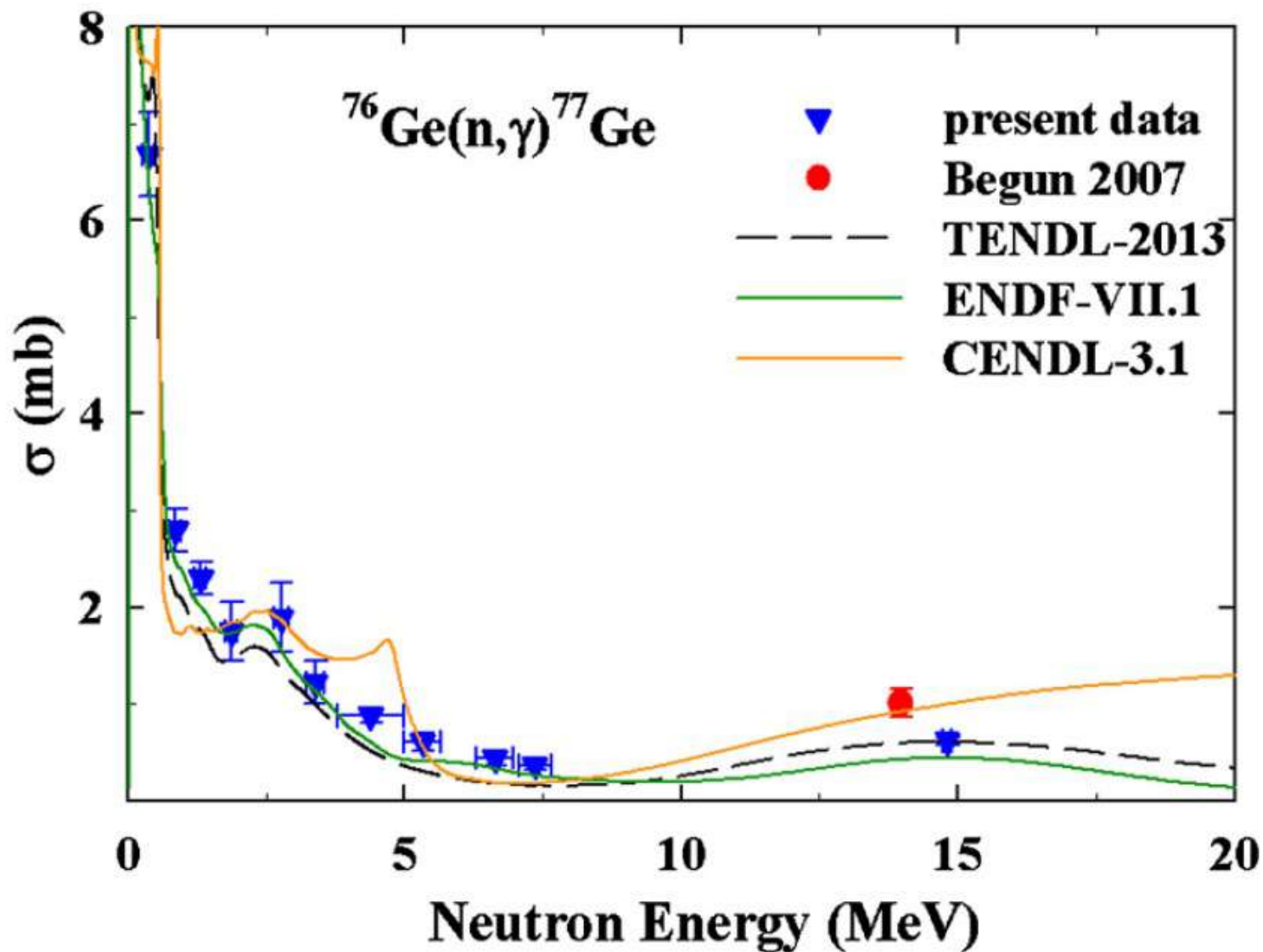
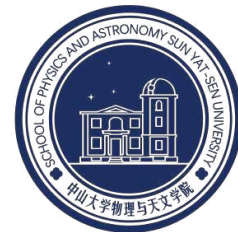


$^{74}\text{Ge}(n, \gamma)$ 反应 MeV 能区 实验与理论现状



Megha Bhike et al 2015

$^{76}\text{Ge}(n, \gamma)^{77}\text{Ge}$ 反应 MeV 能区 实验与理论现状



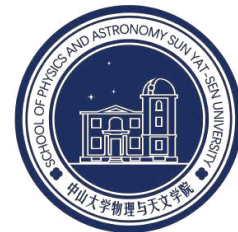
Megha Bhike et al 2015



4

CSNS开展Ge、Mo等(n, γ)实验的初步想法

CSNS : 反角白光中子源Back-n的优势



❖ CSNS : 100/500 kW, 1.6 GeV

▪ 打靶可产生非常强的脉冲中子，世界4大散裂中子源之一。

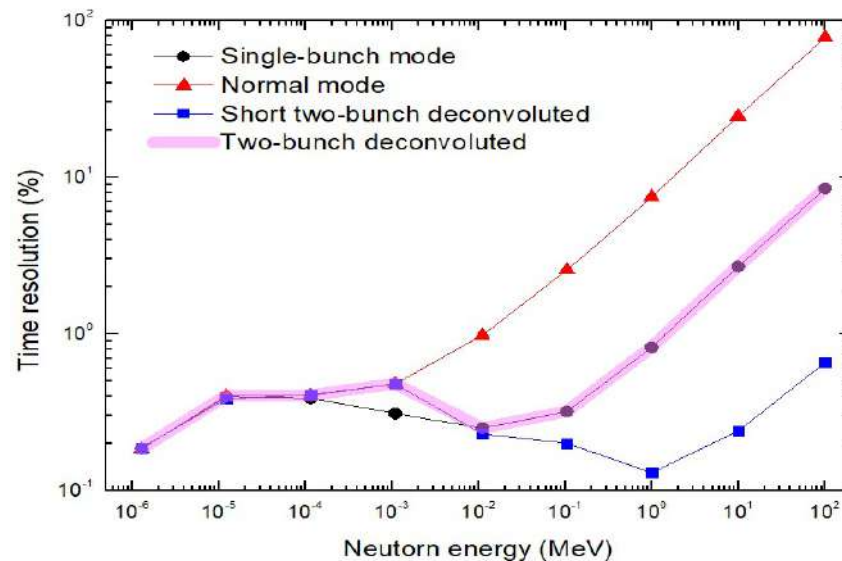
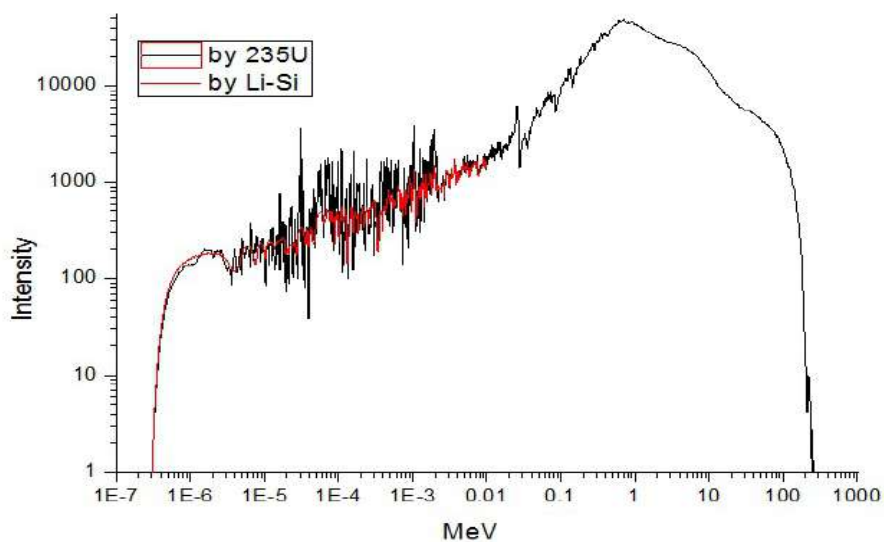
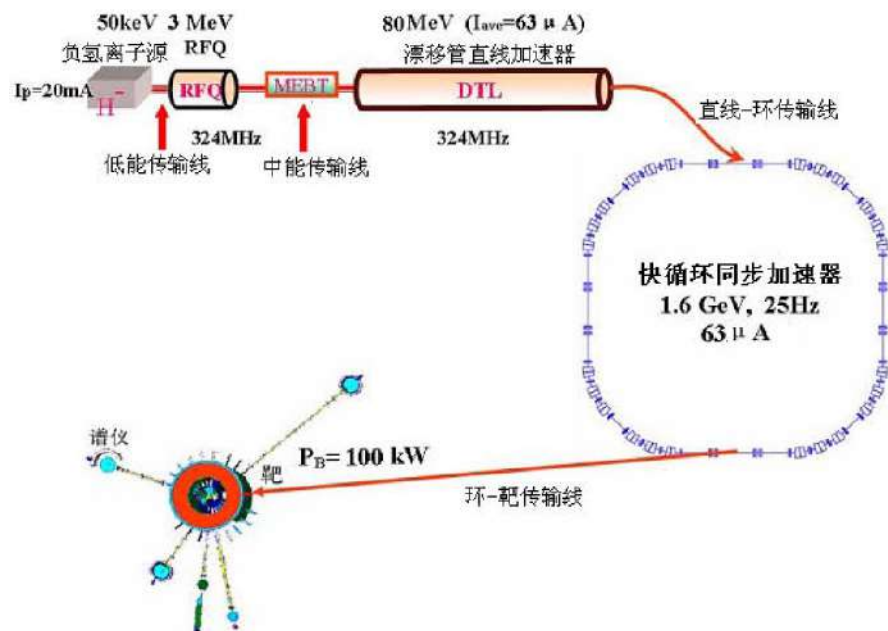
❖ Back-n, 沿质子束打靶通道反流的中子束

▪ 很好的能谱结构和时间结构

▪ 流强世界上最高, 10^7 n/cm²/s at 50 m

❖ 供束时间充分

▪ 每年大于4500小时



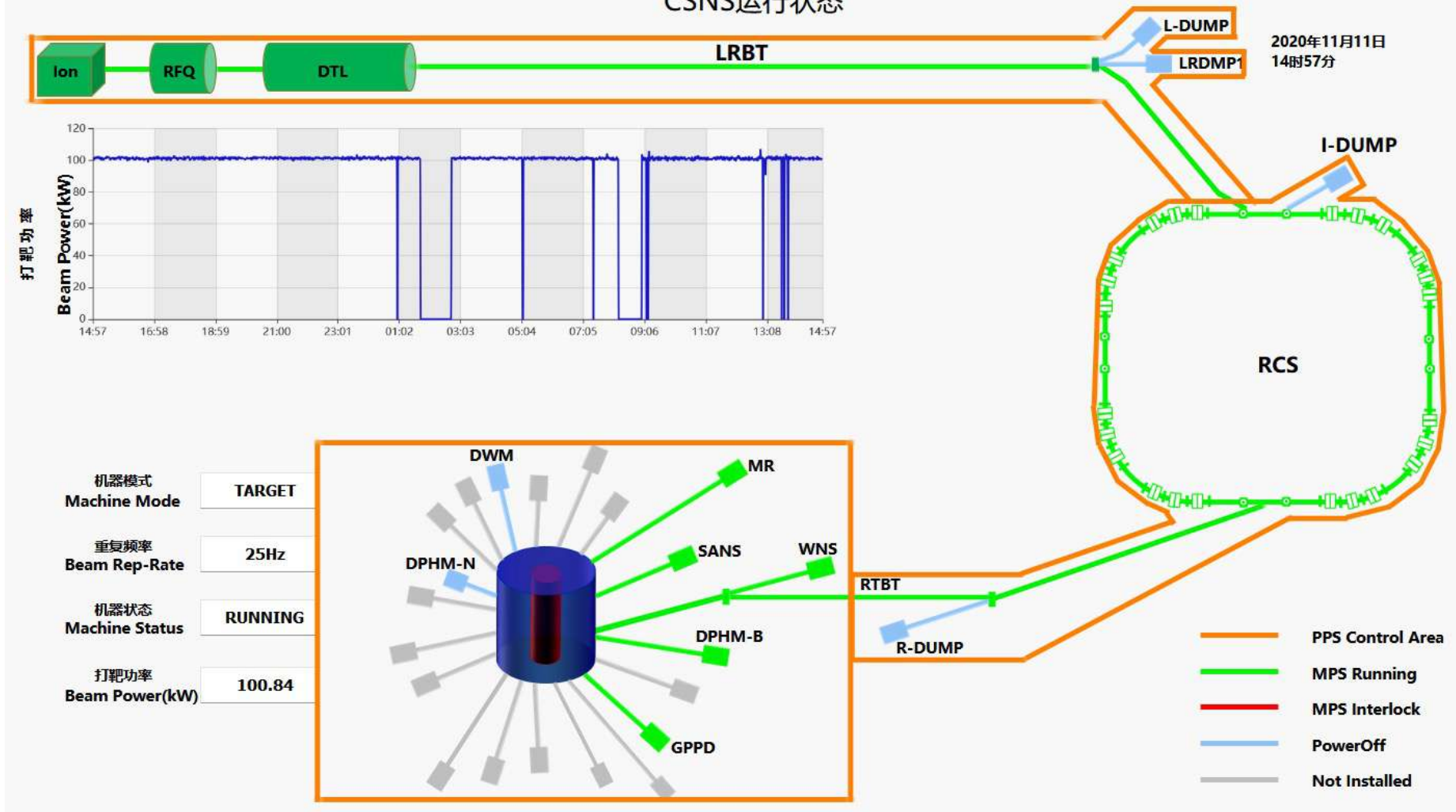
Back-n@CSNS : 核数据测量平台



CSNS运行状态



CSNS运行状态



Back-n与国际主流白光中子源的比较



Back-n: 在靶上的中子注量率最高

已开展的核数据测量实验



❖ Neutron capture

- C6D6: ^{169}Tm , ^{57}Fe , $^{\text{nat}}\text{Se}$, ^{89}Y , $^{\text{nat}}\text{Er}/^{162}\text{Er}$, ^{232}Th , ^{238}U , ^{93}Nb , **Cu**, **Lu**
- GTAF-II: ^{169}Tm

❖ Total cross-section

- ^{12}C , ^{27}Al , **^9Be** , **^7Li**

截止2020年7月

❖ Fission cross-section

- ^{235}U , ^{238}U , ^{236}U , ^{232}Th , **^{239}Pu**

❖ Light charged particle emission

- LPDA: $^6\text{Li}(n, x)$, $^{10}\text{B}(n, x)$, $(n-p)$, **^{63}Ni** , $(n-d)$, **^{17}O**
- TPC样机: **^{12}C** , **^{14}N**

❖ Inelastic cross-section (in-beam gamma)

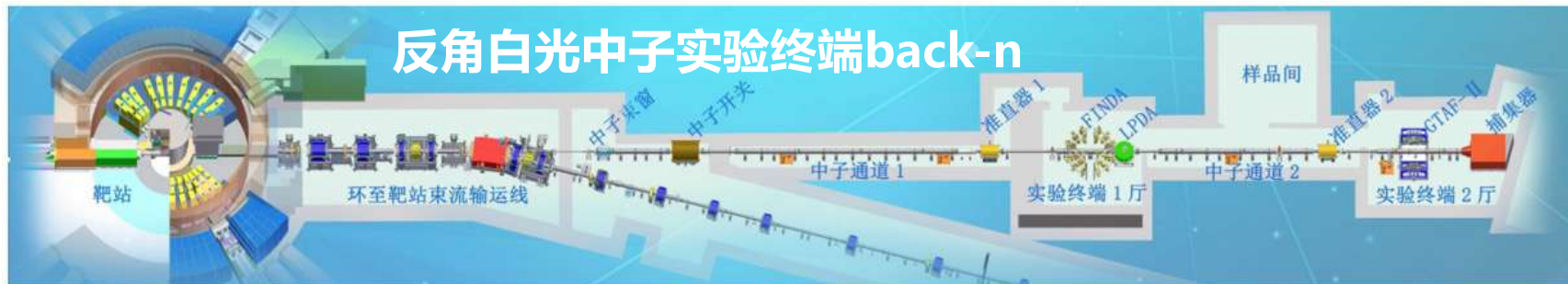
- $^{56}\text{Fe}(n, n')$, **Mo**, **^{16}O** , **Ru**, **Lu**, **Mo**, **Ti**

已在Back-n完成两次（160h+180h）实验工作

❖ 已在反角白光中子实验终端完成两次（160h+180h）实验测量工作

- 2020年10月完成 $^{151,153}\text{Eu}(n,\gamma)$ 实验，国自然（大科学装置联合基金）资助
- 2021年4月完成 $^{113,115}\text{In}$ 、 $^{185,187}\text{Re}$ 及 $^{181}\text{Ta}(n,\gamma)$ 实验，目前正在处理实验数据

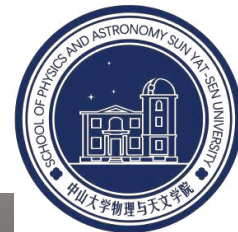
❖ ^{76}Ge 实验为例：最好富集样品， $\phi 40\text{mm} \times 1.0\text{mm}$ ，约10-20g



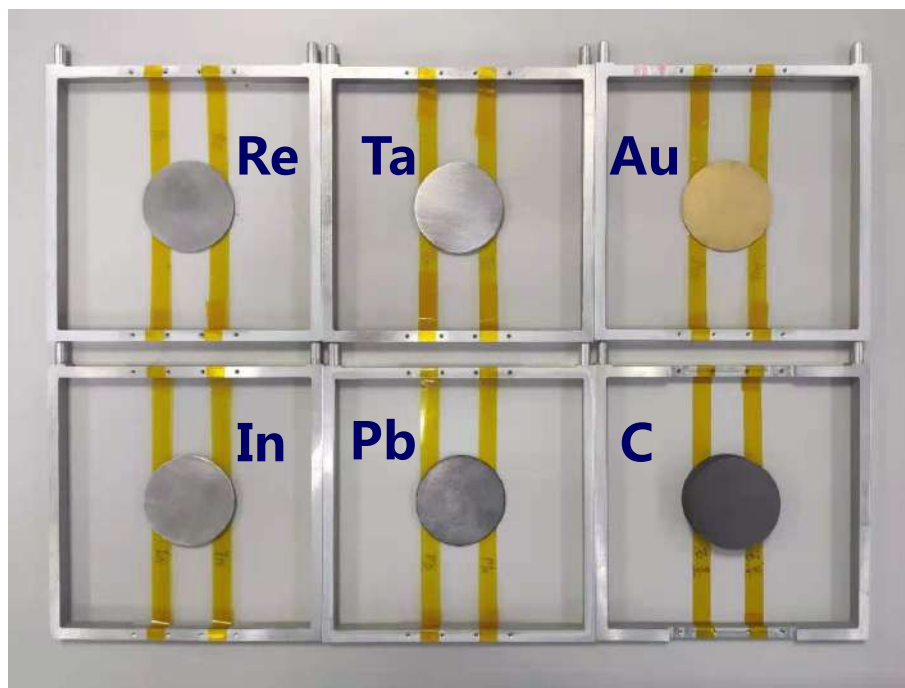
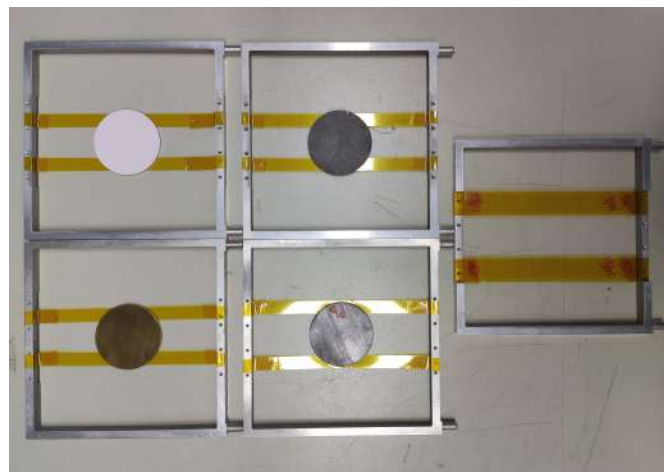
实验厅2中的C6D6探测器



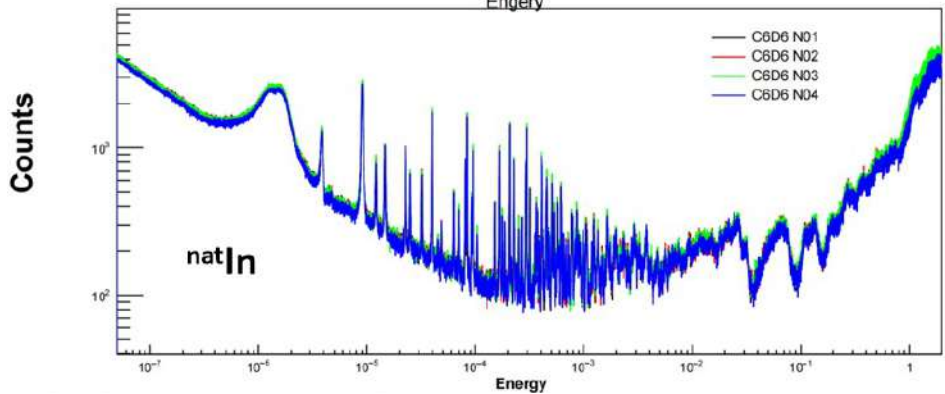
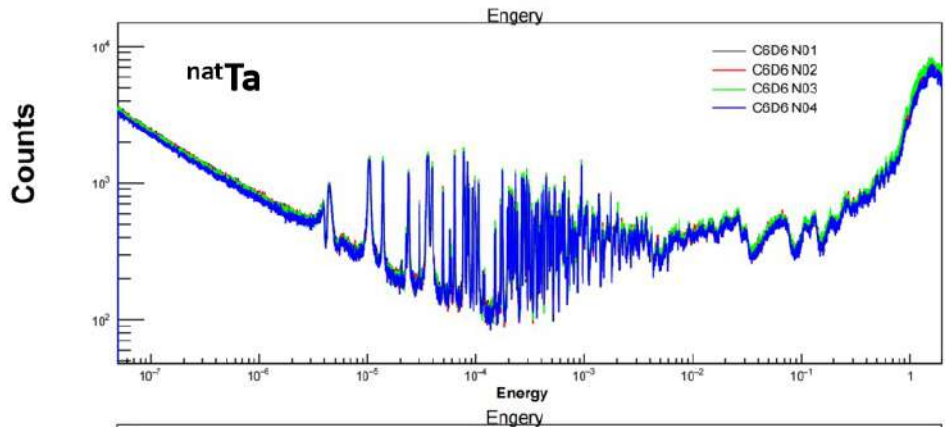
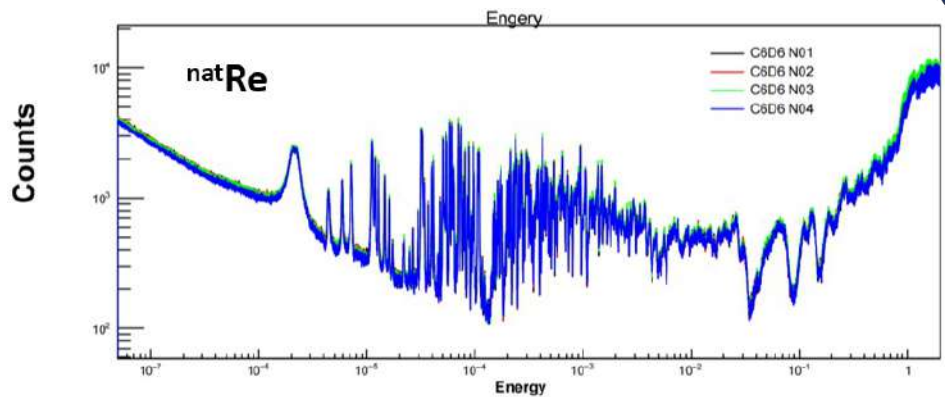
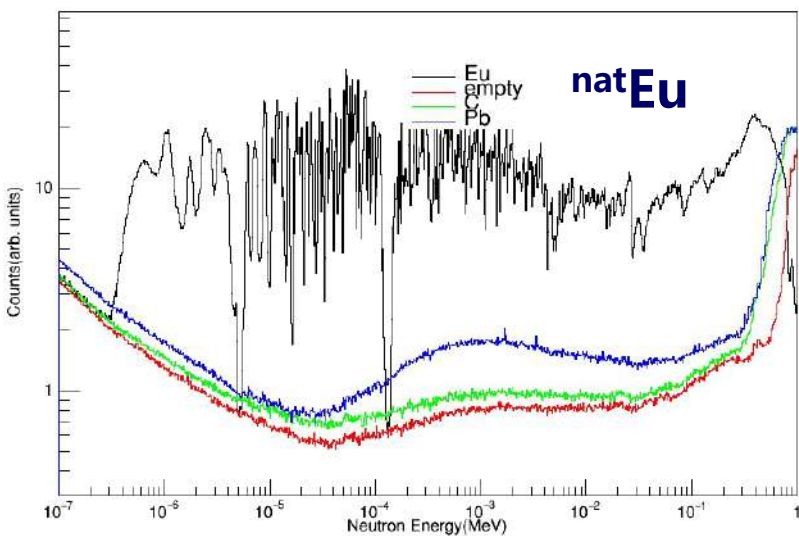
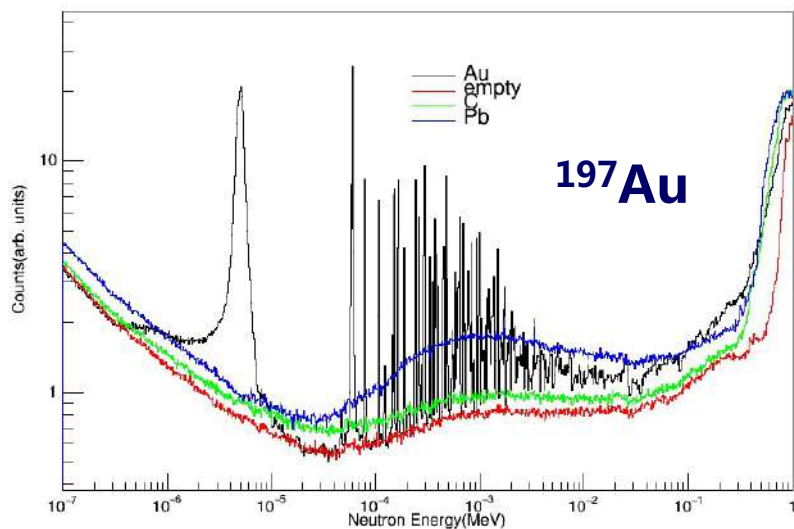
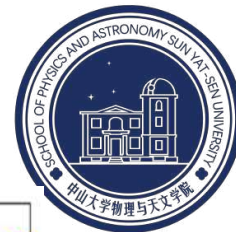
实验方案、测量：实验样品



- ❖ natEu_2O_3 靶1个， $\varphi 40\text{mm} \times 2\text{mm}$ ；
- ❖ ^{197}Au 靶1个， $\varphi 40\text{mm} \times 0.1\text{mm}$ ；
- ❖ natC 靶1个， $\varphi 40\text{mm} \times 0.1\text{mm}$ ；
- ❖ natPb 靶1个， $\varphi 40\text{mm} \times 0.53\text{mm}$ ；

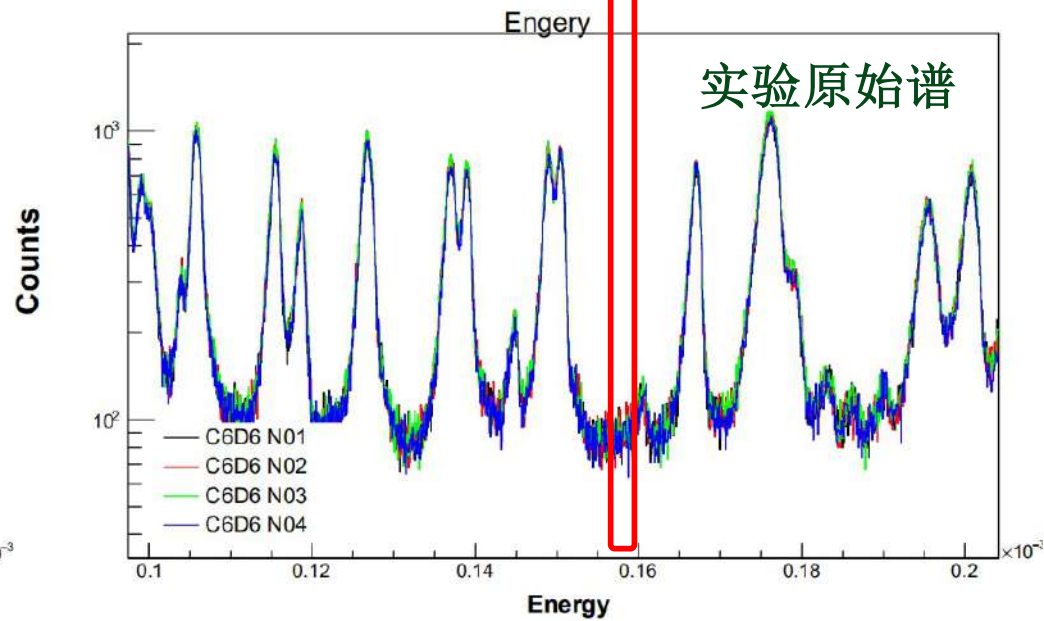
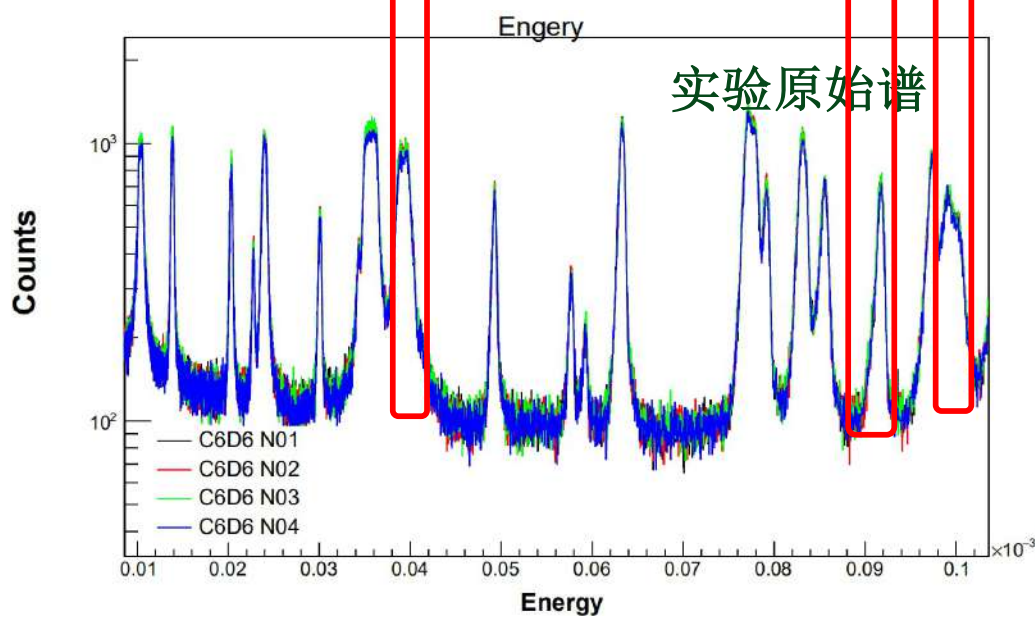
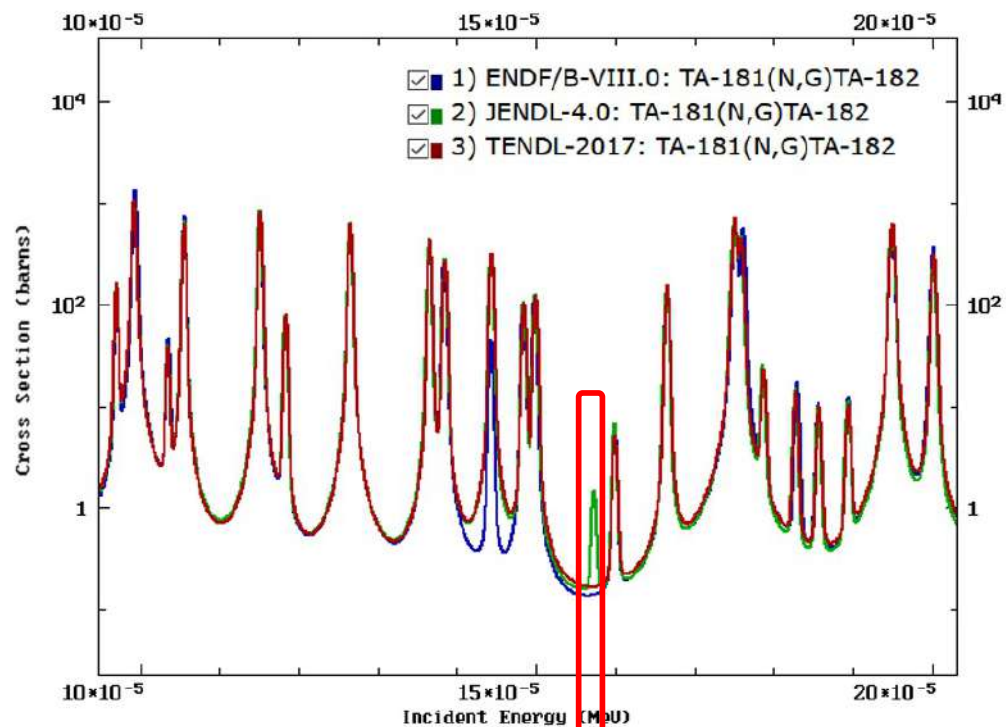
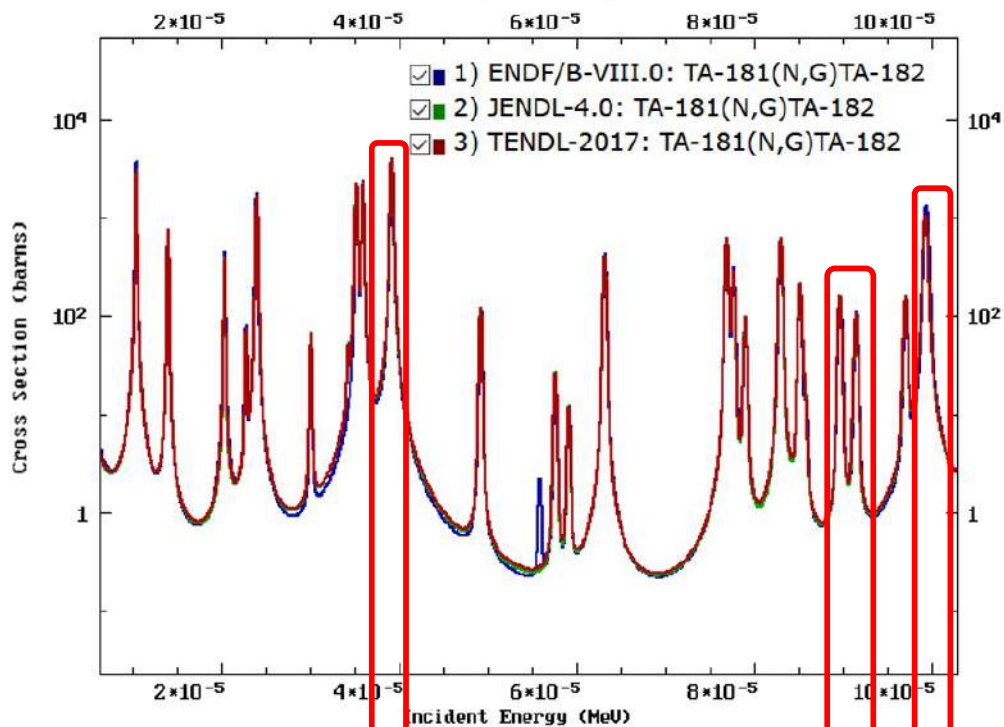


已完成的两次实验 ^{197}Au 、 natEu 、 natRe 、 natTa 、 natIn 原始谱



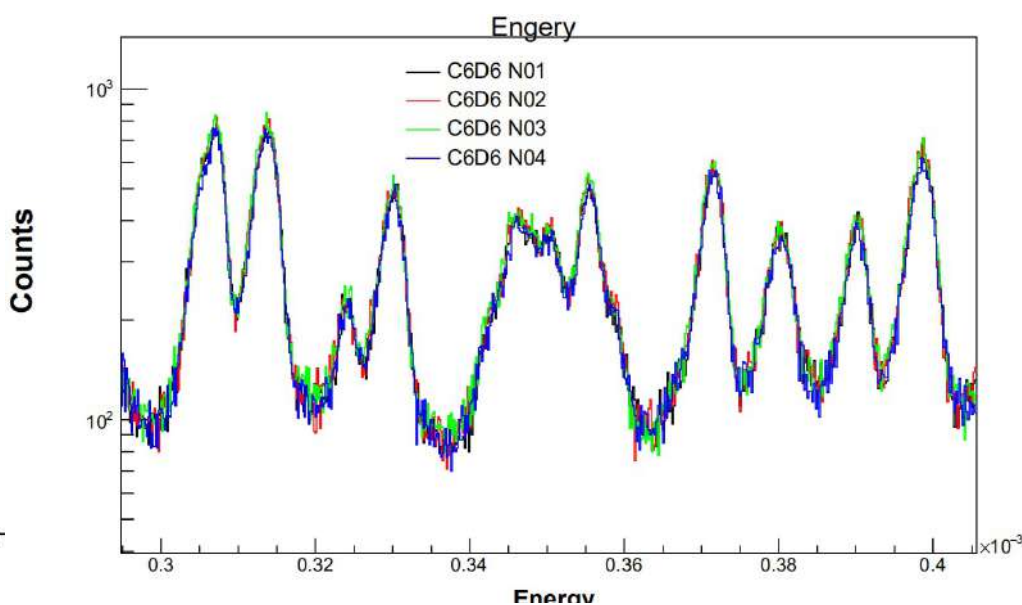
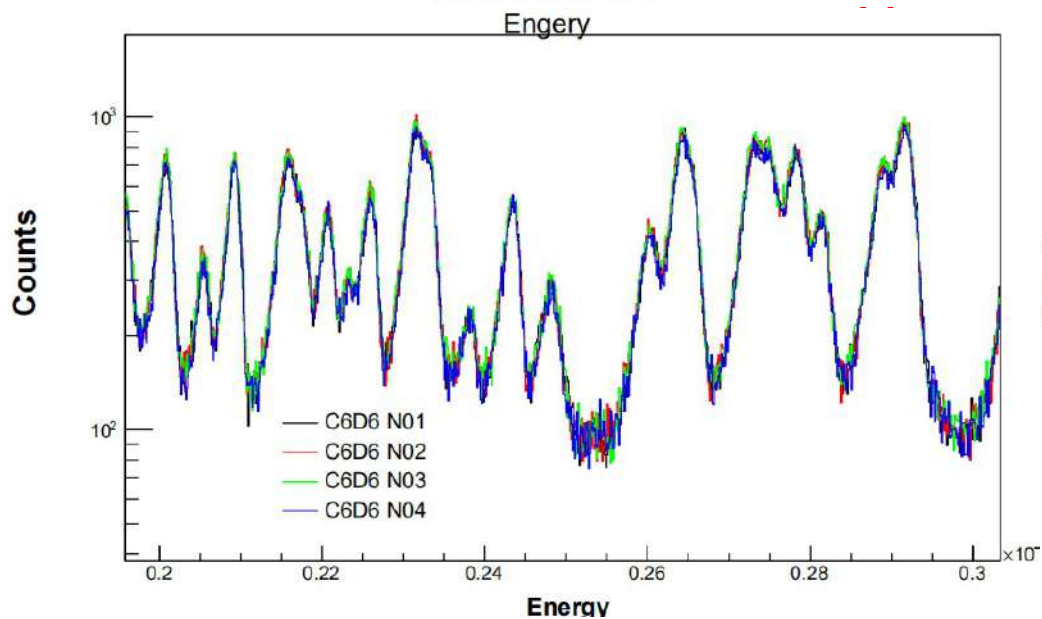
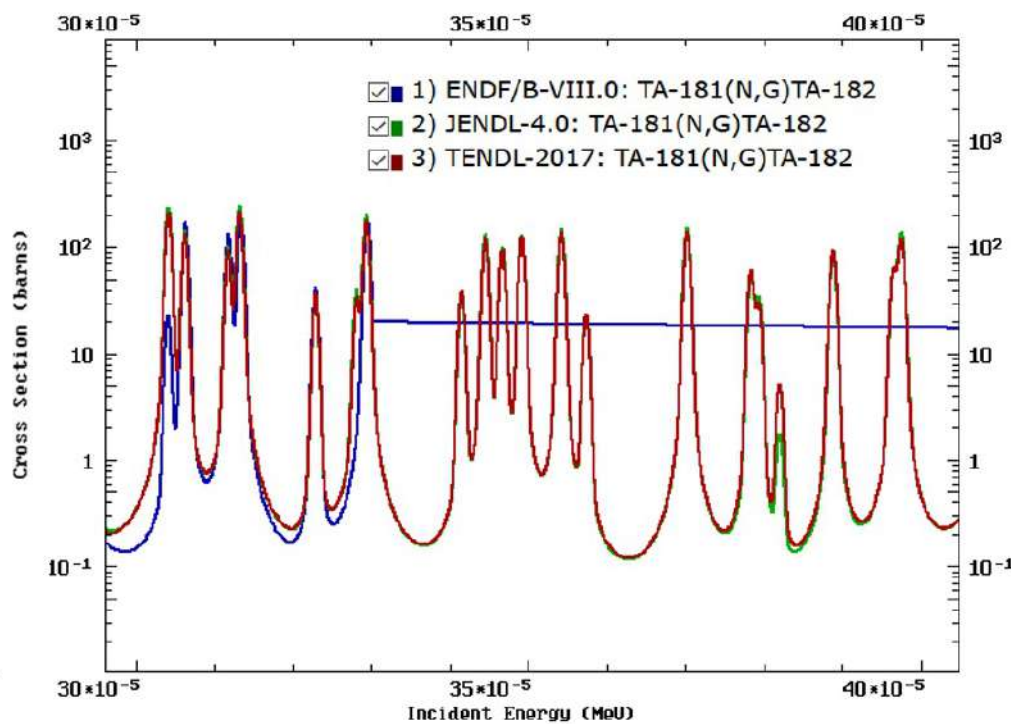
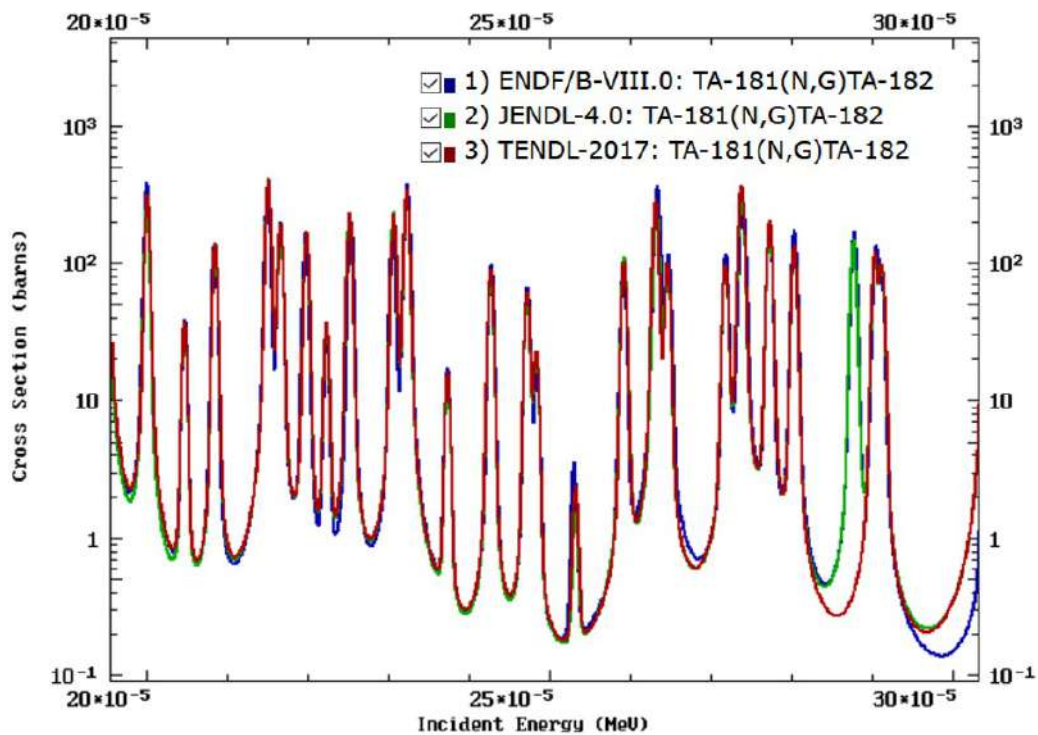
181Ta评价数据: 10-100eV

181Ta评价数据: 100-200eV

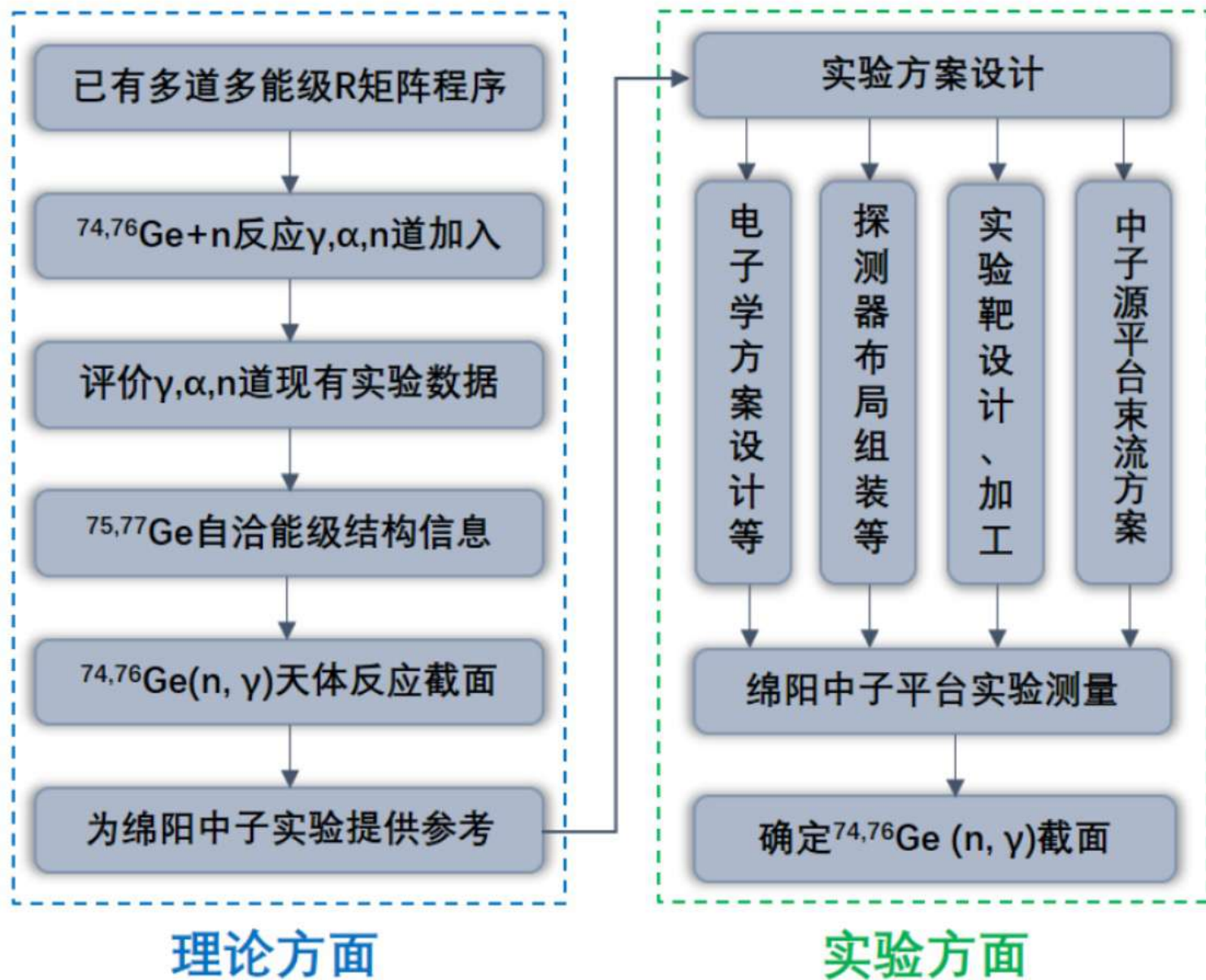
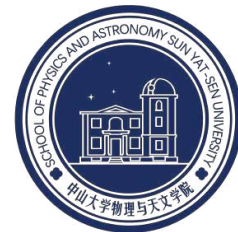


^{181}Ta 评价数据: 200-300eV

^{181}Ta 评价数据: 300-400eV



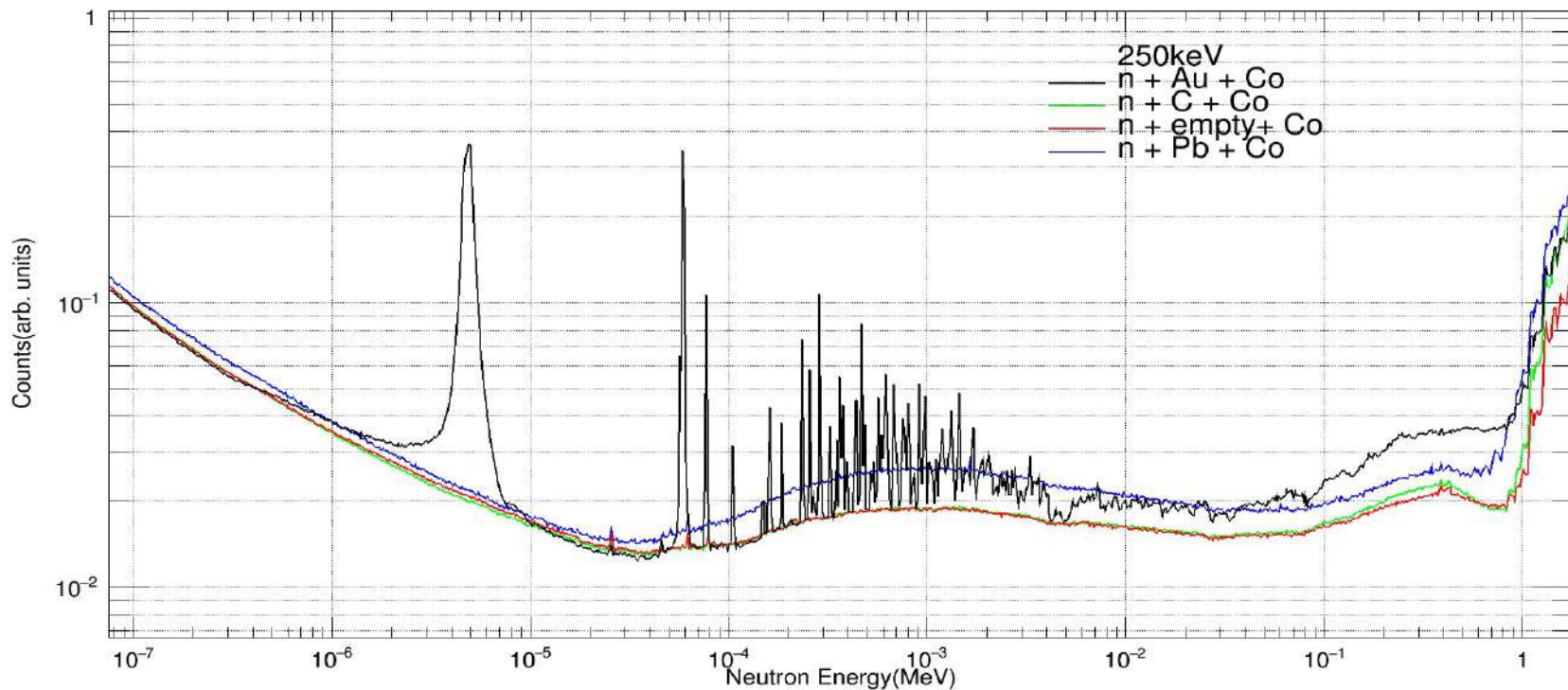
基于Back-n@CSNS^{74,76}Ge+n实验



本底分析与扣除



- ❖ 实验中测量了无束流环境本底、有束流空靶、碳靶，Pb靶本底谱。
 - 无束流环境伽马本底（位于极低能部分，对截面影响很小）
 - 环境散射中子引起的伽马本底（有束流空靶，☑）
 - 实验靶散射的中子引起的伽马本底（有束流碳靶，☑）
 - 在束伽马本底，主要影响80eV-100keV部分本底（有束流铅靶，☑）

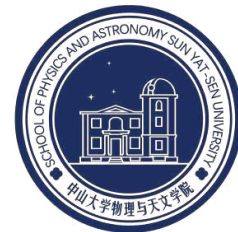


实验样品（靶）的设计



样品	尺寸	备注	质量
^{74}Ge	直径40 mm , 厚度1.0mm	实验样品	10-20g
^{76}Ge	直径40 mm , 厚度1.0mm	实验样品	10-20g
natGe	直径40 mm , 厚度1.0 mm	实验样品	
^{197}Au	直径40 mm , 厚度0.5 mm	标准样品	
natC	直径40 mm , 厚度2.0 mm	散射中子本底测量	
natPb	直径40 mm , 厚度1.0 mm	在束 γ 本底测量	
^{100}Mo	直径40 mm , 厚度1.0 mm	钼酸锂实验样品	10-15g
^{130}Te	直径40 mm , 厚度1.0 mm	TeO_2 实验样品	10-20g
^{136}Xe	直径40 mm , 厚度1.0 mm	液氙	

北大4.5MV静电加速器：中子活化法

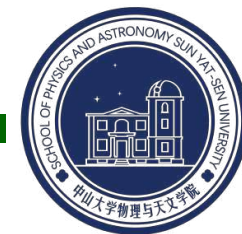


❖ 4.5MV静电加速器中子源

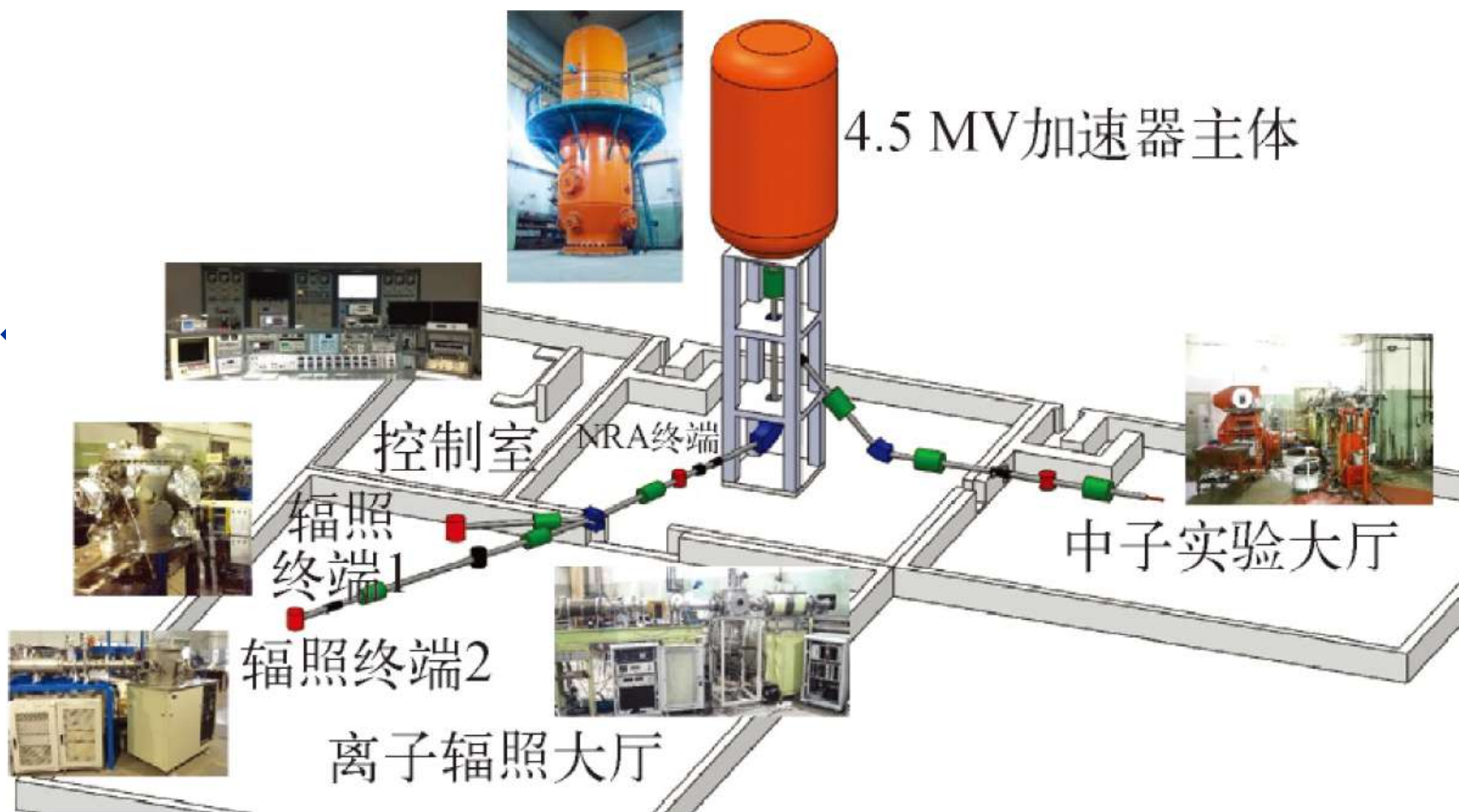
- 上世纪80年代 陈佳洱院士主持建造
- 1991年投入运行，1994年正式通过鉴定验收
- 端电压：3.8MV
- 能量稳定度：1kV
- 加速的离子：p, d, ^4He
- 束流强度：10mA 直流 / (脉冲束)
- 配有宽敞的中子实验大厅(20x12x10 m³)
- 中子本底很弱，适合于核反应数据测量



北京大学：4.5MV静电加速器



- ❖ 通过(p,n) (d,n)反应可产生准单能中子
 - 薄LiF靶： ${}^7\text{Li}(p,n){}^7\text{Be}$ ，keV 能区中子



九院高压倍加器PD-300：中子活化法

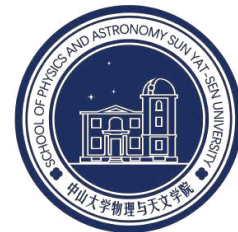


□ PD-300中子发生器

- 俄罗斯引进，2006年投入使用



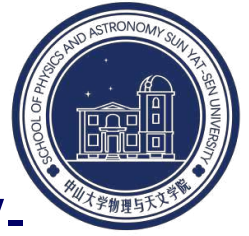
九院高压倍加器PD-300：中子活化法



- ❖ 该装置使用以来，已经在中子-核相互作用截面的精确测量研究方面取得了非常好的成果。其在开展的核天体物理学领域的恒星演化和超新星研究相关反应方面也有优势。
- ❖ 以河西学院罗均华教授为代表的众多研究学者，在PD-300装置完成的部分截面测量工作参见下表。

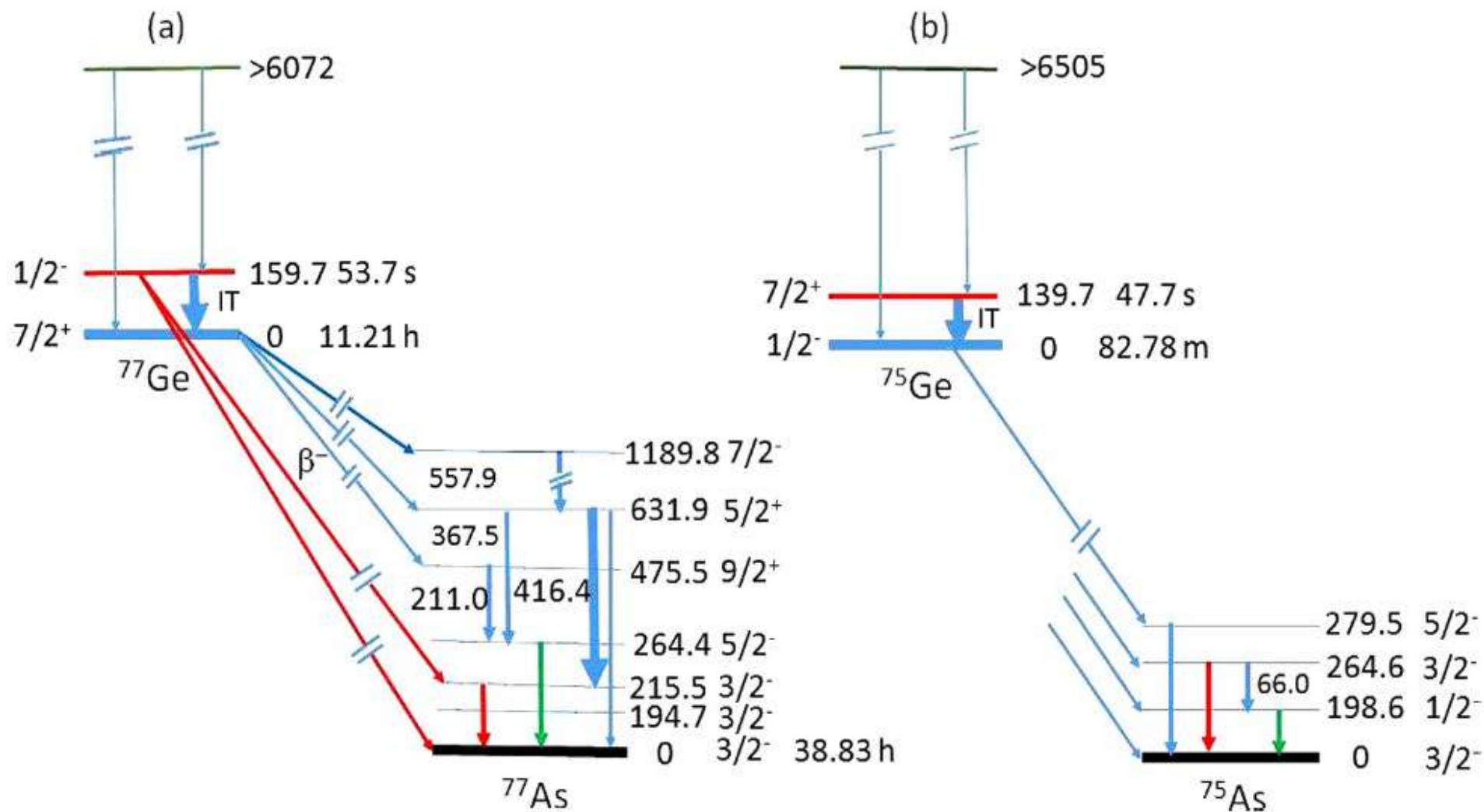
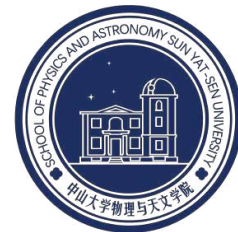
Nucleus	Reaction	Ref
^{76}Ge	(n, 2n)	European Physical Journal A 54 (2018) 67
^{110}Pd	(n, 2n)	Journal of Radio analytical and Nuclear Chemistry 316 (2018) 733
$^{151,153}\text{Eu}$	(n, 2n)	Radiation Physics and Chemistry 148 (2018) 43 Physical Review C 96 (2017) 044617
$^{113,115}\text{In}$	(n, 2n)	Nuclear Science and Engineering 188 (2017)198
$^{132,134}\text{Ba}$	(n, 2n)	Radiochim Acta 105 (2017) 779
^{151}Eu	(n, α)	Journal of Radioanalytical and Nuclear Chemistry 311 (2017) 349
^{89}Y	(n, α)	Nuclear Science and Engineering 184 (2016) 254
^{141}Pr	(n, γ)	Journal of Radioanalytical and Nuclear Chemistry 293 (2012) 261
^{71}Ga	(n, γ)	Nuclear Science and Engineering 172 (2012) 122

小结及未来的合作等



- ❖ **瞬发 γ 射线法**：基于CSNS白光中子源Ge\Mo\Te\Xe(n, γ) 截面10 eV-1MeV测量研究，特别是s-/r过程关注的30keV处截面的直接测量。
- ❖ **中子活化法**：基于北京大学4.5MV静电加速器中子源、九院PD-300高压倍加器，可以精确开展MeV能区Ge\Mo\Te\Xe(n, γ) 截面的测量工作。
- ❖ CSNS实验目前需要富集的实验样品：Ge同位素询价，1g约6000美金，实验成本过高；清华大学GeO₂粉末？钼酸锂样品？TeO₂样品？
- ❖ 最终为国际上正在开展的0 $\nu\beta\beta$ 实验、以及未来锦屏深地实验室0 $\nu\beta\beta$ 实验研究，提供高精确本底反应数据。
- ❖ 未来可开展，基于CSNS白光中子源back-n溴化镧探测器、TPC等Ge\Mo\Te\Xe的(n, n'), (n, n' γ)及(n, x)反应截面测量工作。
- ❖ “大科学装置前沿研究”重点专项：无中微子双贝塔衰变和太阳中微子实验关键技术研究！

74, 76Ge(n, γ)反应机制



$^{76}\text{Ge}(n, \gamma)$ 反应实验研究难点



- ❖ $^{75,77}\text{Ge}$ 激发态退激发会产生总能量分别超过6505keV和6072keV的 γ 射线。
- ❖ ^{77}Ge 基态 $7/2^+$ ， ^{75}Ge 基态 $1/2^-$ 半衰期分别为11.2h和82.8m。
- ❖ ^{77}Ge 的同质异能态到基态的跃迁 $1/2^- \rightarrow 7/2^+$ ，和 ^{75}Ge 的同质异能到基态的跃迁态 $7/2^+ \rightarrow 1/2^-$ 的半衰期分别为53.7s和47.7s，与 $^{74,76}\text{Ge}$ 基态半衰期在数量级内可比。
- ❖ ^{77}Ge 位于159.7keV的同质异能态 $1/2^-$ ，其 β -衰变具有相当大的分支比(19%)。因此，为了获得总俘获截面，除了考虑 ^{77}Ge 的基态 β -衰减外，还必须考虑其同质异能态对 ^{77}As 的衰减。
- ❖ 由于159.7keV态的半衰期仅为53.7s，在MeV能量范围内，由于缺乏足够强的单能中子源，在实验上测量其衰变具有很大的挑战。
- ❖ ^{75}Ge 位于139.7keV的同质异能态的 β -衰变分支比仅为0.030%，因此在后续工作中将被忽略。