

通过质子衰变研究原子核 的镜像对称性破缺

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高能与低能核物理交叉学术研讨会，华东师范大学和复旦大学，2026年5月15-18日

报告提纲

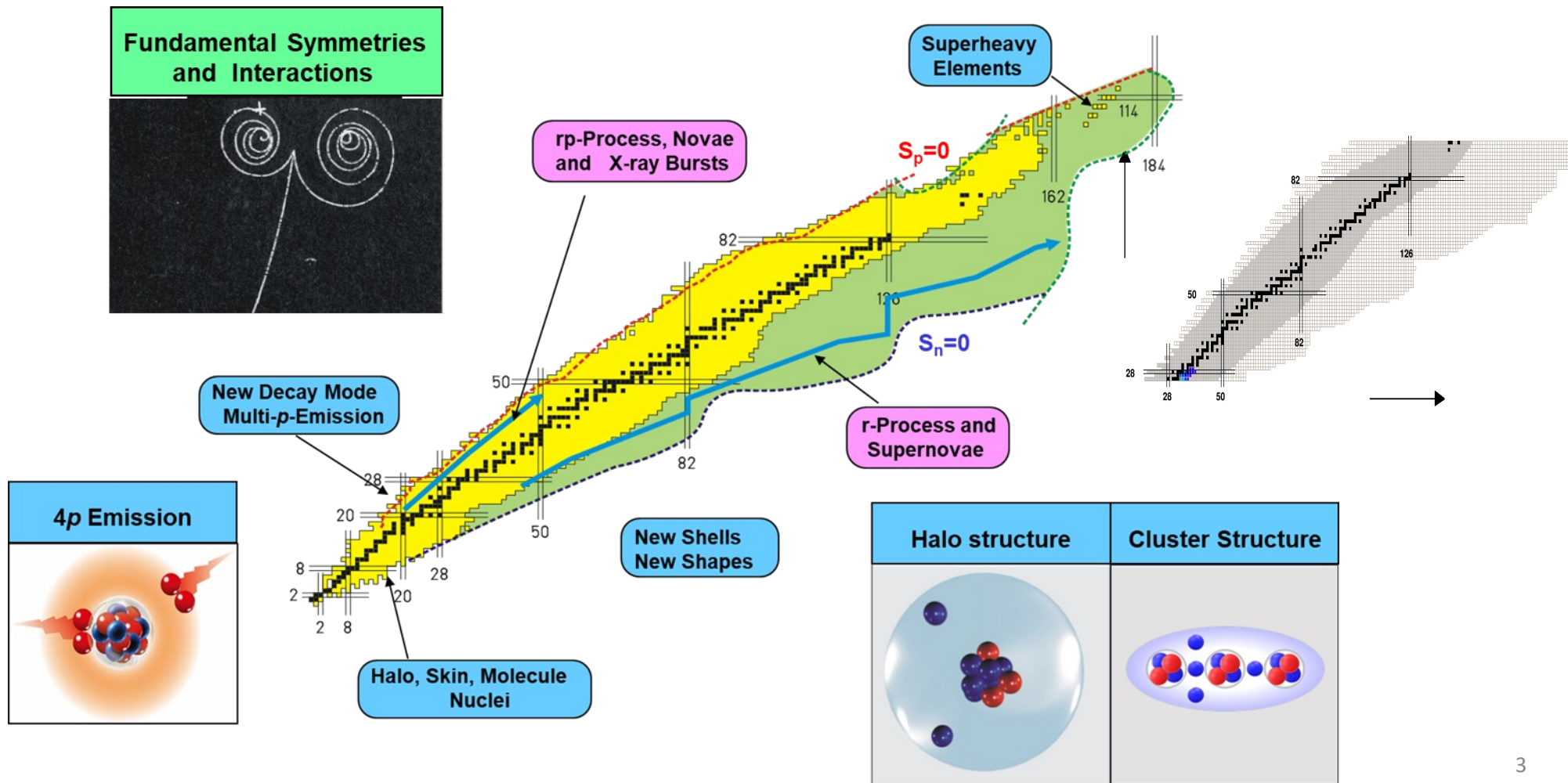
一、研究背景

二、研究工作

三、总结和展望

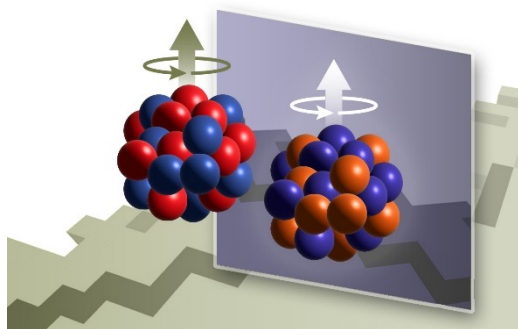
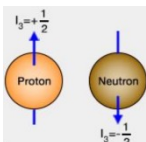
一、研究背景

远离 β 稳定线原子核新现象

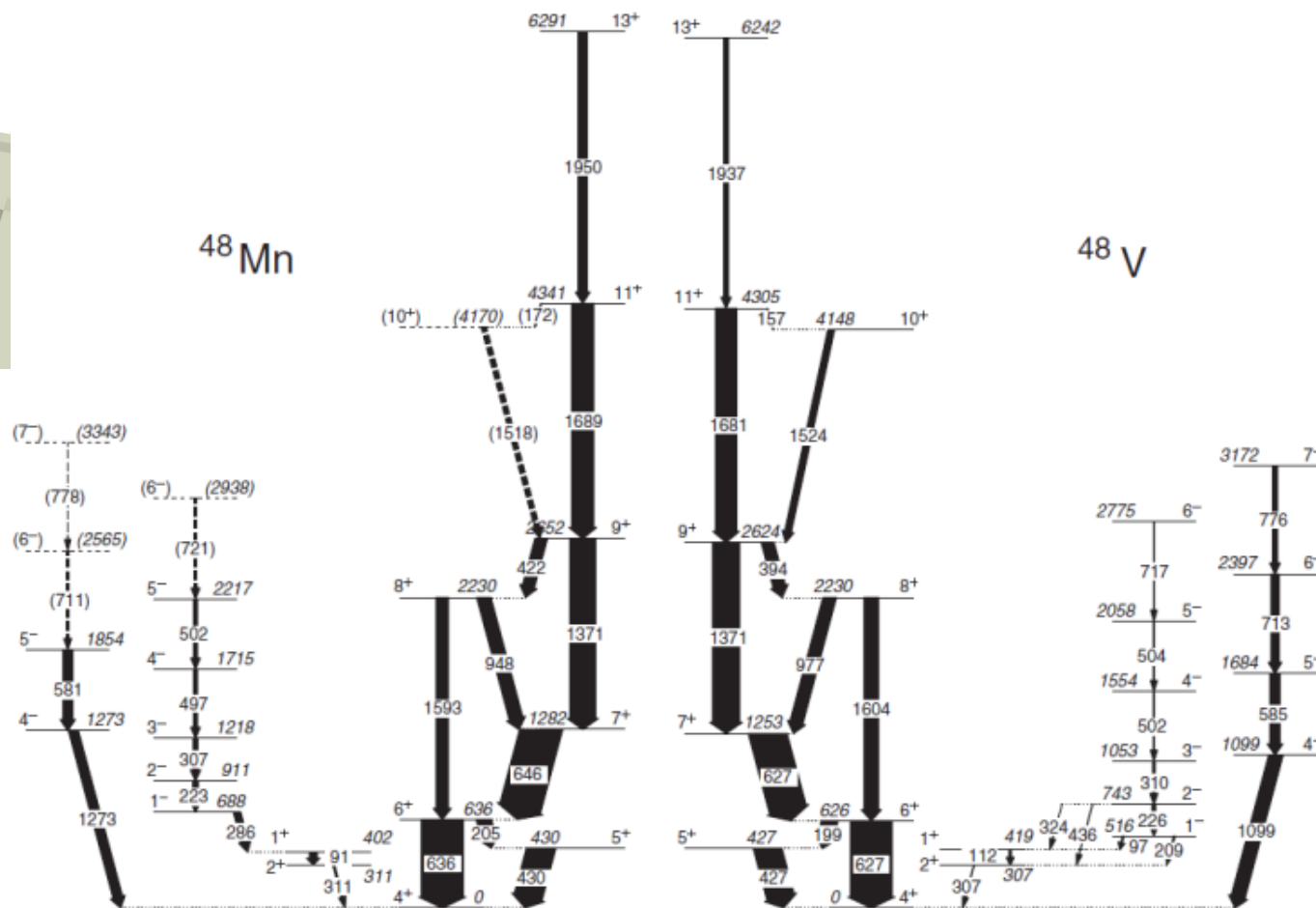


原子核镜像对称性

同位旋: 1932 Heisenberg-----Z. Phys. 77, 1(1932)



镜像核

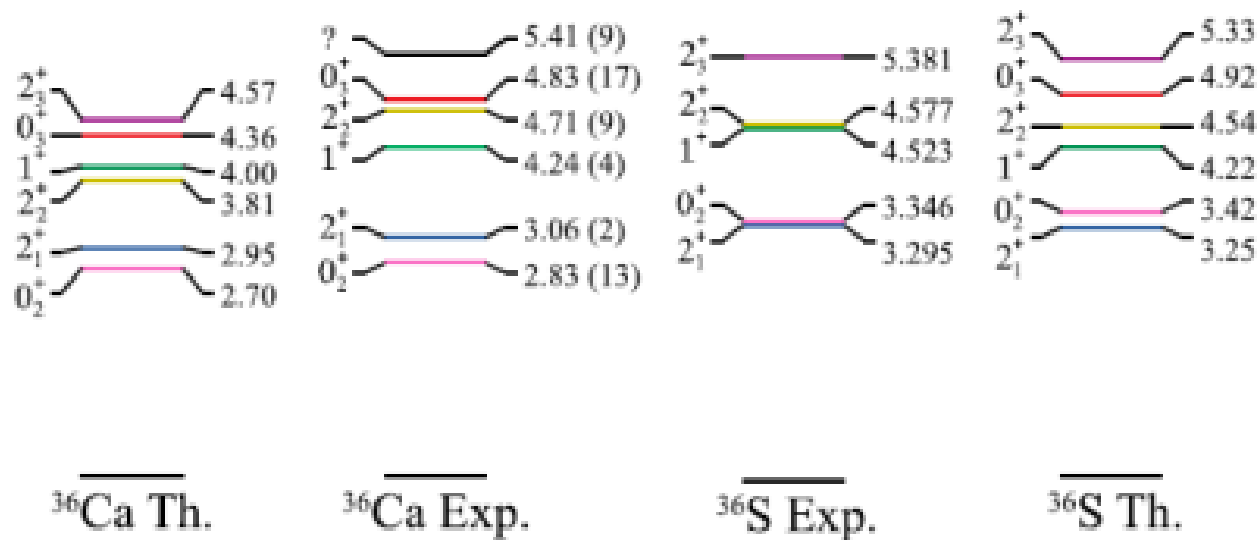
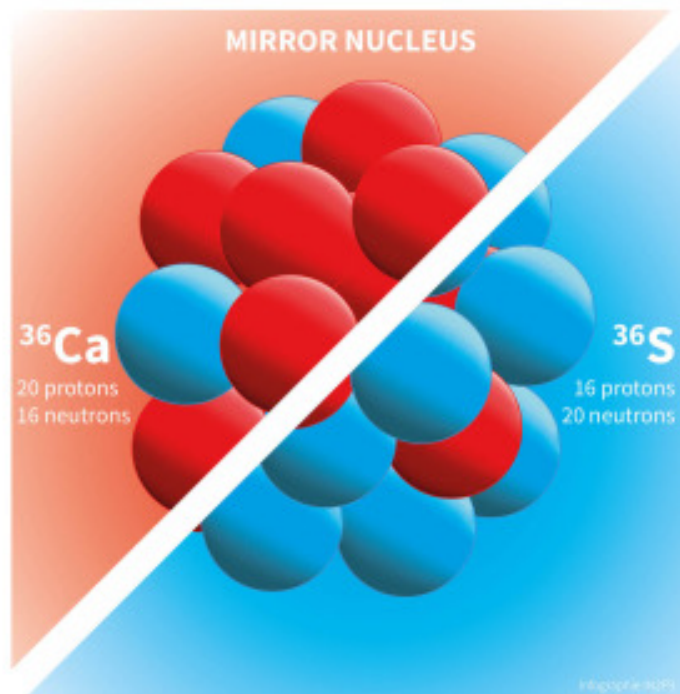


原子核镜像对称性破缺—能级

PHYSICAL REVIEW LETTERS 129, 122501 (2022)

Structure of ^{36}Ca under the Coulomb Magnifying Glass

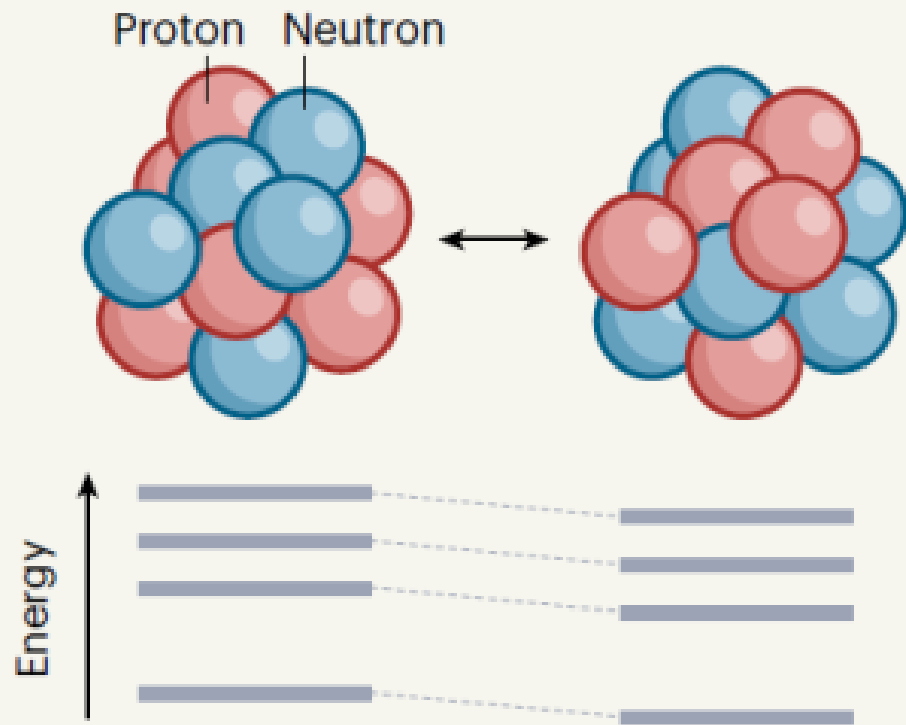
L. Lalanne^{1,2,*} O. Sorlin,^{2,†} A. Poves,³ M. Assié,¹ F. Hammache,¹ S. Koyama,^{4,2} D. Suzuki,⁵ F. Flavigny,⁶
V. Girard-Alcindor,² A. Lemasson,² A. Matta,⁶ T. Roger,² D. Beaumel,¹ Y. Blumenfeld,¹ B. A. Brown,⁷
F. De Oliveira Santos,² F. Delaunay,⁶ N. de Séréville,¹ S. Franchoo,¹ J. Gibelin,⁶ J. Guillot,¹ O. Kamalou,² N. Kitamura,⁸
V. Lapoux,⁹ B. Mauss,^{5,2} P. Morfouace,^{2,10} M. Niikura,⁴ J. Pancin,² T. Y. Saito,⁴ C. Stodel,² and J.-C. Thomas²



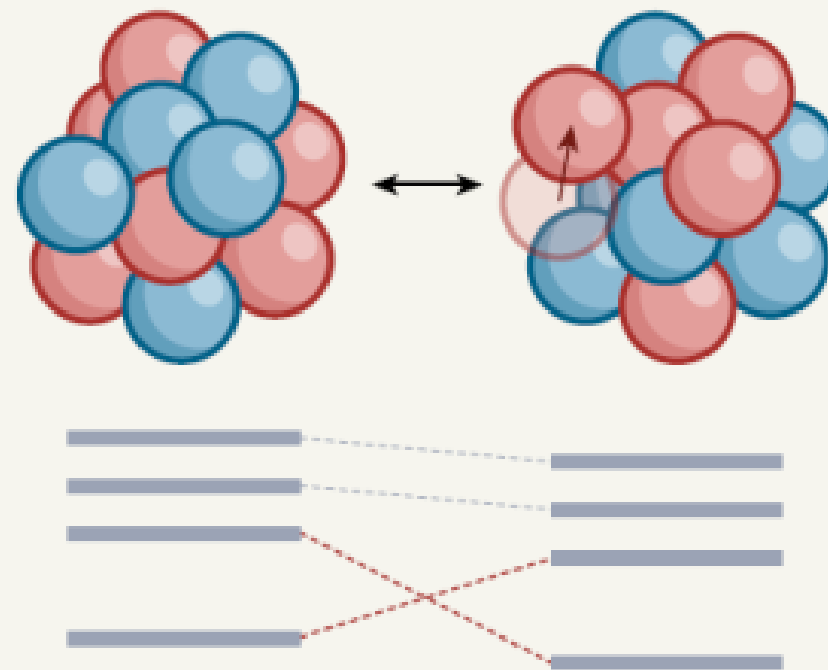
通过 (p, d) 和 (p, t) 转移反应研究了 ^{36}Ca 的结构，在 ^{36}Ca - ^{36}S 镜像核的激发态中观察到了较大的镜像能量差。

原子核基态镜像对称性破缺——能级

a Mirror symmetry

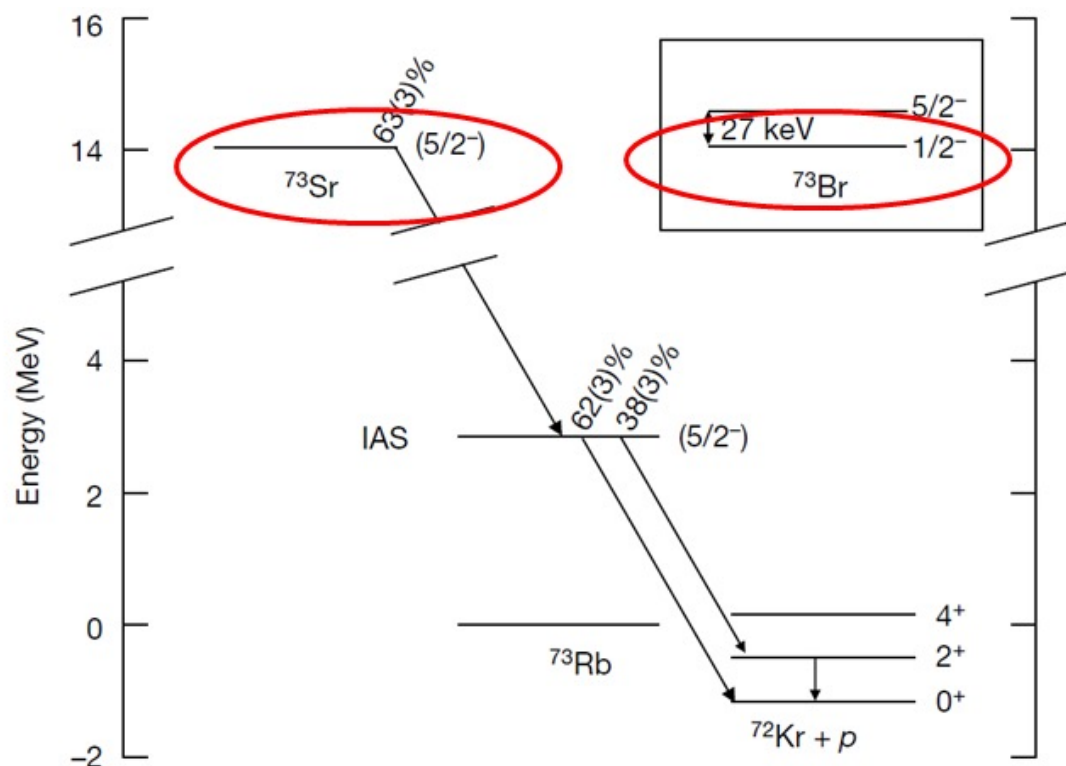


b Mirror symmetry broken

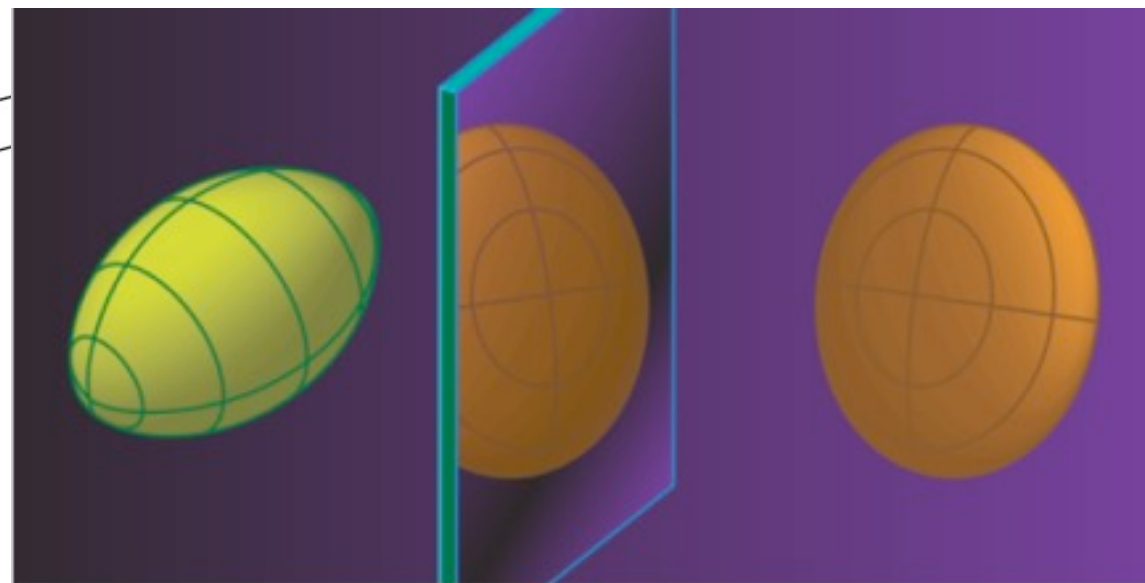


原子核基态镜像对称性破缺——能级

I. 形变引起(束缚-束缚镜像对)



镜像核不同的形变



^{73}Sr -- ^{73}Br 镜像对

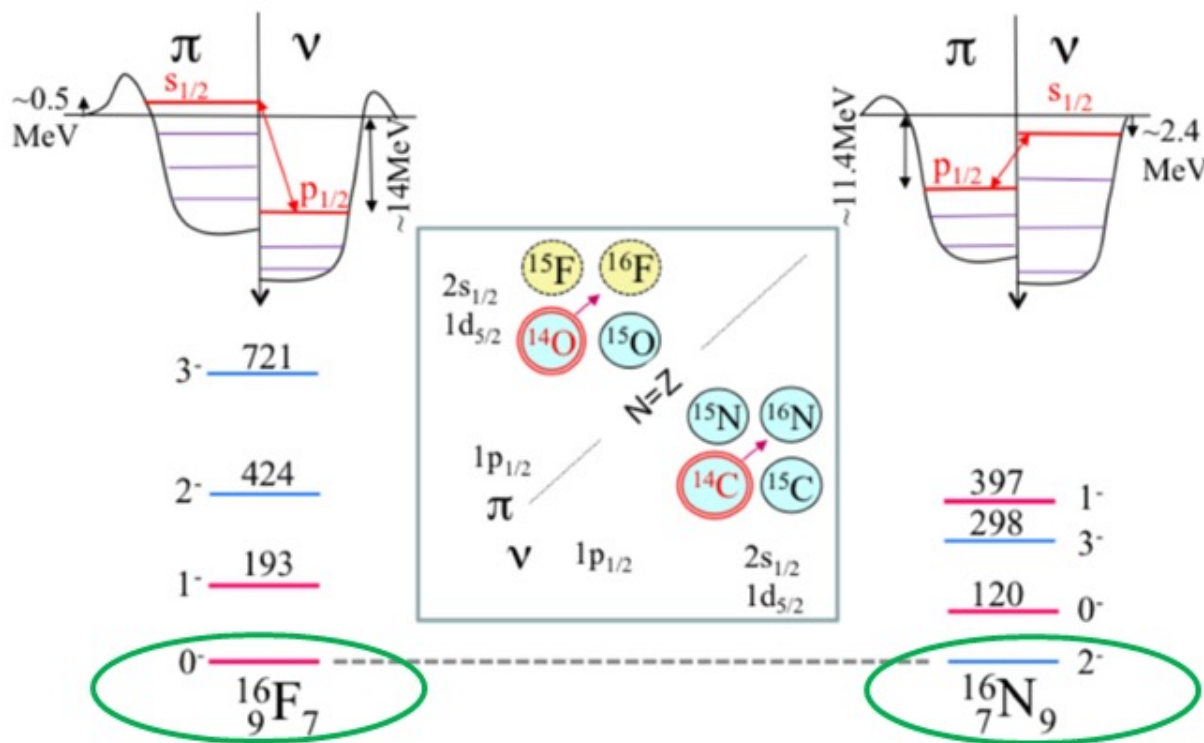
D.E.M. Hoff *et al.*, Nature, 580, 52 (2020).

^{71}Kr -- ^{71}Br 镜像对

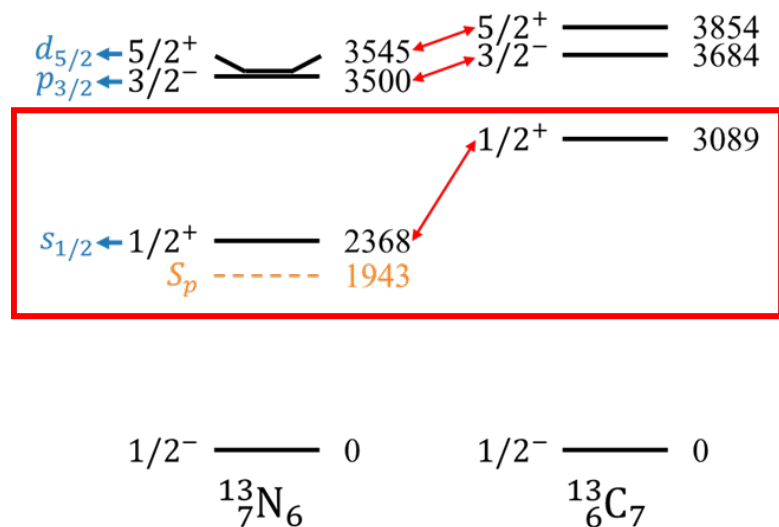
A. Algorta *et al.*, Phys. Rev. Lett. 134, 162502 (2025).

原子核基态镜像对称性破缺—能级

II. Thomas-Ehrman shift引起(非束缚-束缚镜像对)



Thomas-Ehrman shift



R. G. Thomas, Phys. Rev., 88, 1109 (1952).
J. B. Ehrman, Phys. Rev., 81, 412 (1951).

^{16}F -- ^{16}N I. Stefan *et al.*, Phys. Rev. C, 90, 014307 (2014).

^{29}Cl -- ^{29}Mg I. Mukha *et al.*, Phys. Rev. Lett. 115, 202501 (2015); X.D. Xu *et al.*, Phys. Rev. C 97, 034305 (2018).

^{20}Al -- ^{20}N X.D. Xu *et al.*, Phys. Rev. Lett. 135, 022502 (2025).

原子核基态镜像对称性破缺—形状

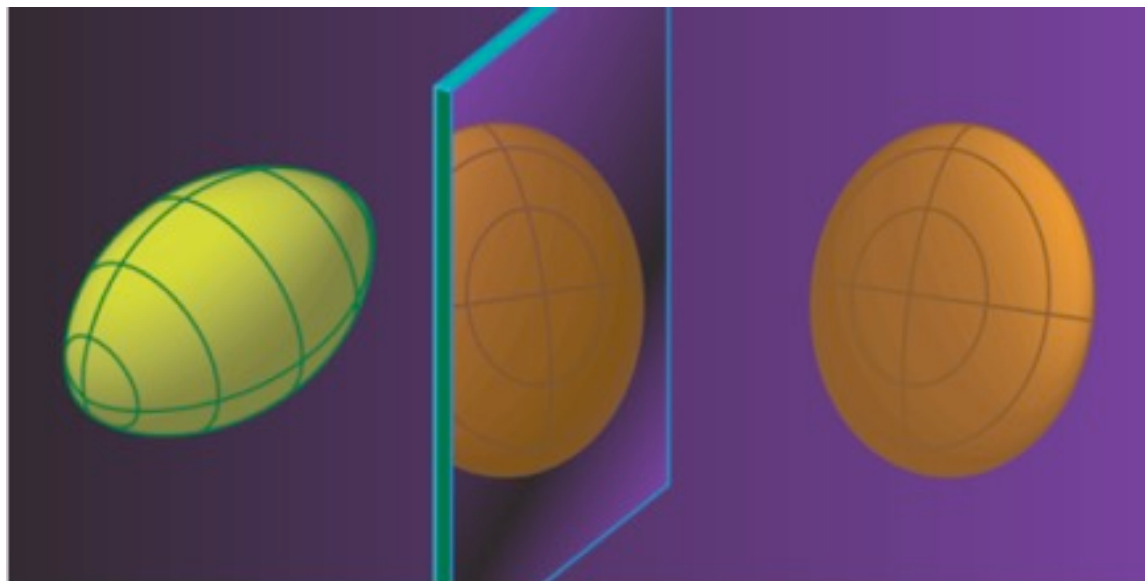
PHYSICAL REVIEW LETTERS 126, 072501 (2021)

Editors' Suggestion

Featured in Physics

Shape Changes in the Mirror Nuclei ^{70}Kr and ^{70}Se

K. Wimmer^{1,2,3,*}, W. Korten,⁴ P. Doornenbal,³ T. Arici,^{5,6} P. Aguilera,⁷ A. Algora,^{8,9} T. Ando,² H. Baba,³ B. Blank,¹⁰ A. Boso,¹¹ S. Chen,³ A. Corsi,⁴ P. Davies,¹² G. de Angelis,¹³ G. de France,¹⁴ J.-P. Delaroche,¹⁵ D. T. Doherty,⁴ J. Gerl,⁵ R. Gemhäuser,¹⁶ M. Girod,¹⁵ D. Jenkins,¹² S. Koyama,² T. Motobayashi,³ S. Nagamine,² M. Niikura,² A. Obertelli,^{4,†} J. Libert,¹⁵ D. Lubos,¹⁶ T. R. Rodríguez,¹⁷ B. Rubio,⁸ E. Sahin,¹⁸ T. Y. Saito,² H. Sakurai,^{2,3} L. Sinclair,¹² D. Steppenbeck,³ R. Taniuchi,² R. Wadsworth,¹² and M. Zielinska⁴



通过中能非弹性散射提取了 ^{70}Kr 的约化跃迁概率 $B(E2; 0^+ \rightarrow 2^+)$ ，与镜像核 ^{70}Se 的值存在明显差别。研究表明这对镜像核的基态具有不同的形状。

原子核基态镜像对称性破缺-质量

PHYSICAL REVIEW LETTERS 133, 222501 (2024)

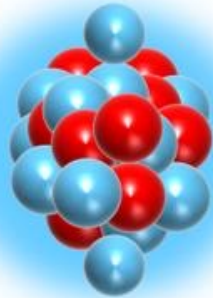
Nuclear Structure of Dripline Nuclei Elucidated through Precision Mass Measurements of ^{23}Si , ^{26}P , $^{27,28}\text{S}$, and ^{31}Ar

Y. Yu,^{1,2,*} Y. M. Xing^{1,2,*} Y. H. Zhang^{1,2,†} M. Wang^{1,2,‡} X. H. Zhou,^{1,2} J. G. Li,^{1,2} H. H. Li,^{1,2} Q. Yuan,¹ Y. F. Niu^{1,3}
Y. N. Huang^{1,3} J. Geng,³ J. Y. Guo^{1,4} J. W. Chen,⁵ J. C. Pei,⁵ F. R. Xu^{1,5} Yu. A. Litvinov^{6,8} K. Blaum⁷
G. de Angelis^{8,1} I. Tanihata^{9,10} T. Yamaguchi¹¹ X. Zhou,^{1,2} H. S. Xu,^{1,2} Z. Y. Chen,^{1,2} R. J. Chen,^{1,6} H. Y. Deng,^{1,2}
C. Y. Fu,¹ W. W. Ge,¹ W. J. Huang,^{12,1} H. Y. Jiao,^{1,2} Y. F. Luo,^{1,2} H. F. Li¹ T. Liao,^{1,2} J. Y. Shi,^{1,2} M. Si¹ M. Z. Sun,¹
P. Shuai,¹ X. L. Tu,¹ Q. Wang,¹ X. Xu¹ X. L. Yan¹ Y. J. Yuan^{1,2} and M. Zhang¹

^{31}Ar



^{31}Al



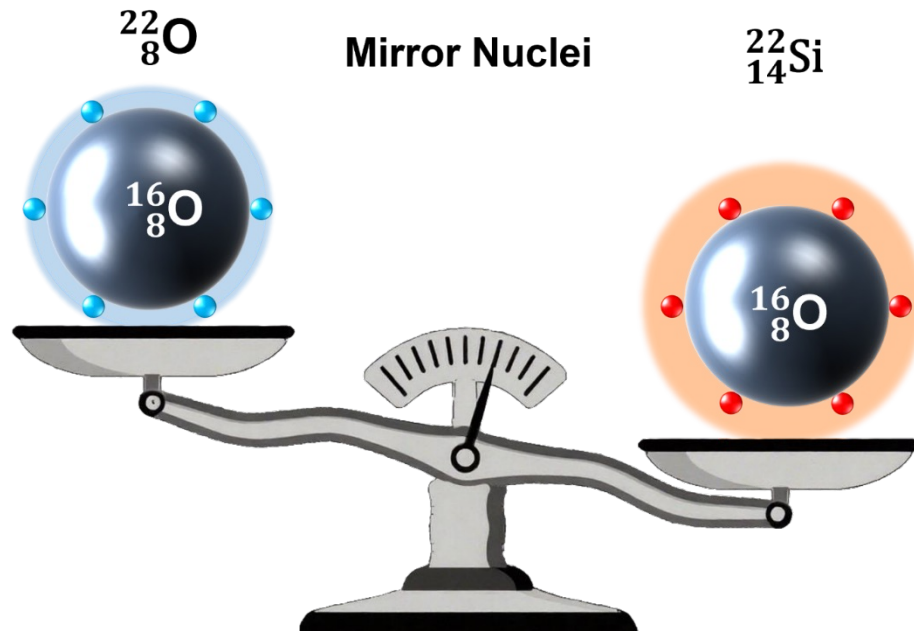
近代物理所原子核质量测量研究团队基于兰州重离子加速器冷却储存环，精确测量了 ^{23}Si , ^{26}P , $^{27,28}\text{S}$, 和 ^{31}Ar 的质量，提取了镜像能差，支持 ^{26}P , ^{27}S 和 ^{31}Ar 等是质子晕候选核。

原子核基态镜像对称性破缺-质量

PHYSICAL REVIEW LETTERS 135, 012501 (2025)

$Z=14$ Magicity Revealed by the Mass of the Proton Dripline Nucleus ^{22}Si

Y. M. Xing^{1,2,*} Y. F. Luo^{1,2,*} Y. H. Zhang^{1,2,†} M. Wang^{1,2} X. H. Zhou,^{1,2} J. G. Li^{1,2,3,‡} K. H. Li,^{1,4} Q. Yuan,¹
Y. F. Niu^{5,6} J. Y. Guo,⁷ J. C. Pei⁸ F. R. Xu^{8,3} G. de Angelis^{9,1,§} Yu. A. Litvinov^{10,11} K. Blaum¹²
I. Tanihata^{13,14} T. Yamaguchi¹⁵ Y. Yu,^{1,2} X. Zhou,¹ H. S. Xu,^{1,2} Z. Y. Chen,^{1,2} R. J. Chen^{1,10} H. Y. Deng,^{1,2}
C. Y. Fu,¹ W. W. Ge,¹ W. J. Huang^{16,1} H. Y. Jiao,^{1,2} H. F. Li,¹ T. Liao^{1,2} J. Y. Shi,^{1,2} M. Si,¹ M. Z. Sun,¹
P. Shuai,¹ X. L. Tu,^{1,2} Q. Wang,¹ X. Xu^{1,2} X. L. Yan,^{1,2} Y. J. Yuan^{1,2} and M. Zhang¹



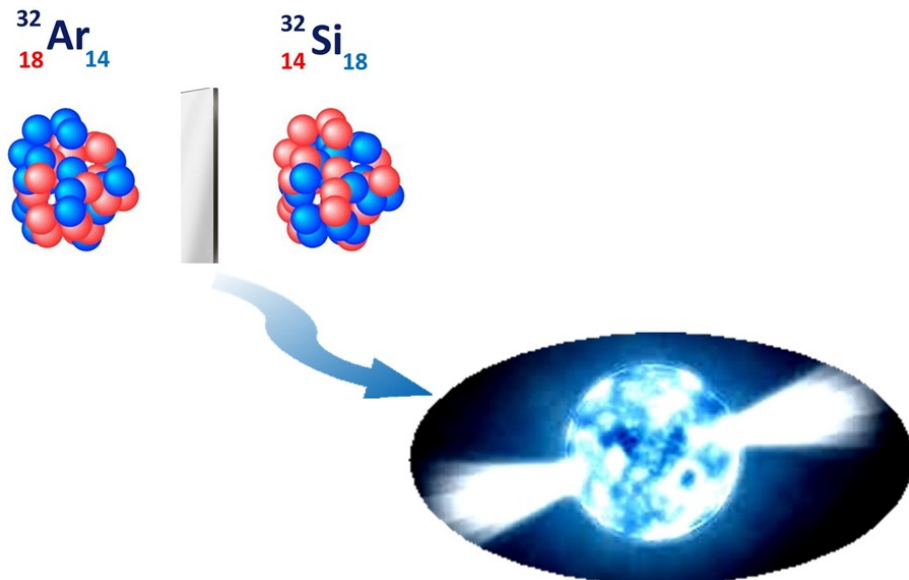
近代物理所原子核质量测量研究团队基于兰州重离子加速器冷却储存环，成功测量了 ^{22}Si 的基态质量，研究发现，虽然 ^{22}Si 具有和镜像核 ^{22}O 相似的双幻特性，但其与 ^{22}O 存在轻微的对称性破缺。

原子核基态镜像对称性破缺-电荷半径

PHYSICAL REVIEW LETTERS 132, 162502 (2024)

Nuclear Charge Radii of Silicon Isotopes

Kristian König^{1,2,*} Julian C. Berengut³ Anastasia Borschevsky⁴ Alex Brinson⁵ B. Alex Brown^{1,6}
Adam Dockery^{1,6} Serdar Elhatisari^{7,8} Ephraim Eliav⁹ Ronald F. Garcia Ruiz^{5,†} Jason D. Holt^{10,11}
Bai-Shan Hu^{12,13} Jonas Kartheim⁵ Dean Lee^{1,6} Yuan-Zhuo Ma^{1,6} Ulf-G. Meißner⁸ Kei Minamisono^{1,6,‡}
Alexander V. Oleynichenko^{14,15} Skyy V. Pineda^{1,16,8} Sergey D. Prosnyak^{14,17} Marten L. Reitsma⁴
Leonid V. Skripnikov^{14,17} Adam Vernon⁵ and Andréi Zaitsevskii^{14,18}



中子星的性质由核状态方程决定，其影响双中子星合并产生的引力波形式等。利用共线激光谱测量了 ^{32}Si 的电荷半径，镜像对 ^{32}Ar - ^{32}Si 的半径差值与核状态方程中对称能的斜率 L 密切相关。该工作的结果表明 $L \leq 60 \text{ MeV}$ ，这与其它的观测结果（例如GW170817两中子星合并）一致。

原子核基态镜像对称性破缺-核力等

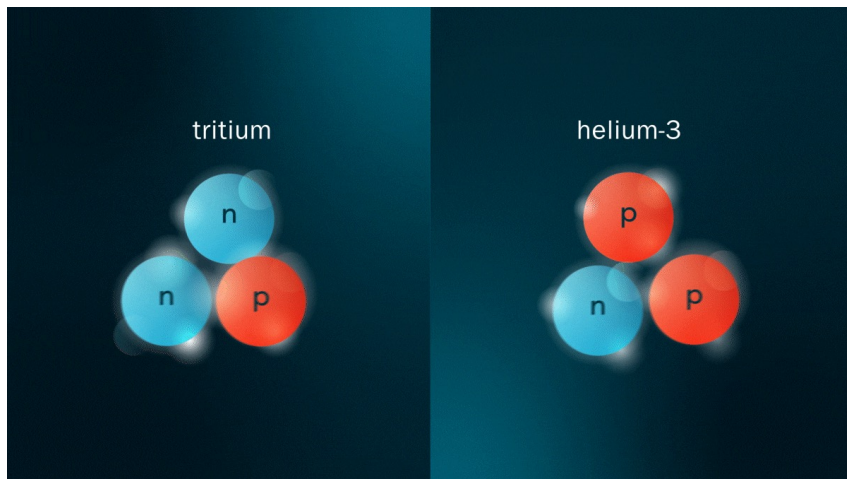
Article

Nature | Vol 609 | 1 September 2022 | **41**

Revealing the short-range structure of the mirror nuclei ^3H and ^3He

PHYSICAL REVIEW LETTERS 132, 162501 (2024)

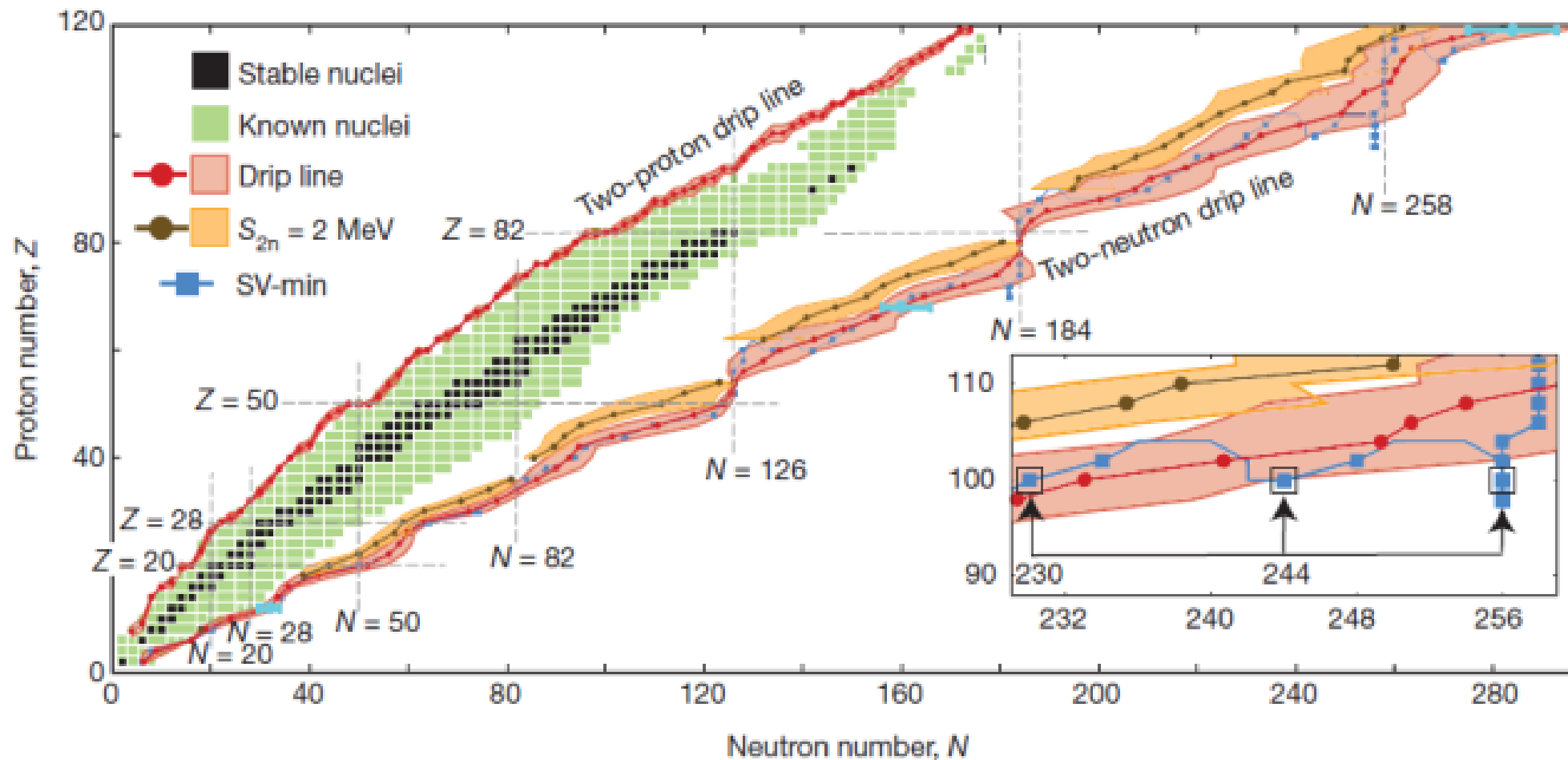
Novel Measurement of the Neutron Magnetic Form Factor from $A = 3$ Mirror Nuclei



利用镜像核 ^3H 和 ^3He 的高能电子准弹性散射，提取了质量数为3的系统中比以往实验精度高一个数量级的短程核力(SRC)的 np/pp 比值。利用镜像核 ^3H 和 ^3He 的高能电子准弹性散射测量了中子磁形状因子。

二、研究工作

质子/中子滴线



J. Erler et al., Nature 486, 509 (2012)

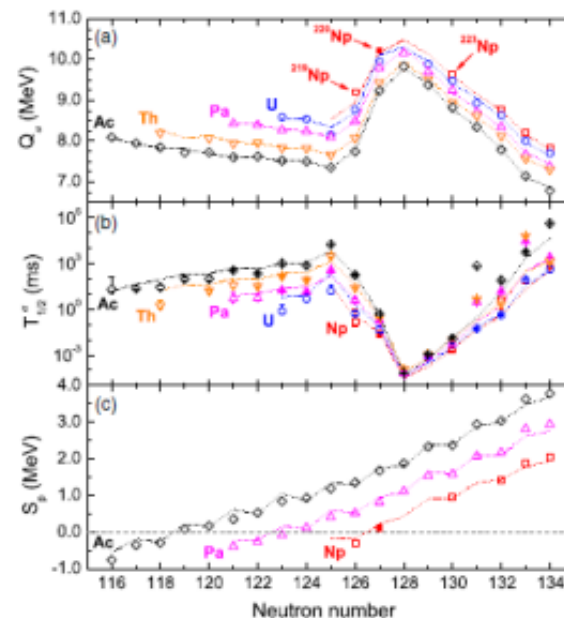
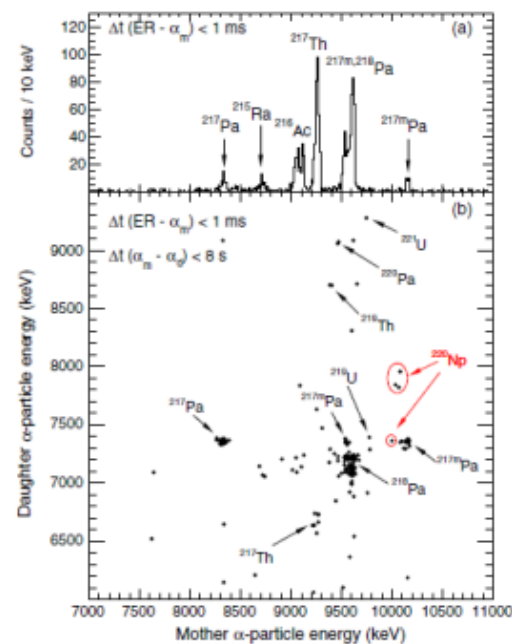
质子滴线已经到Np(Z=93)

PHYSICAL REVIEW LETTERS 122, 192503 (2019)

Editors' Suggestion

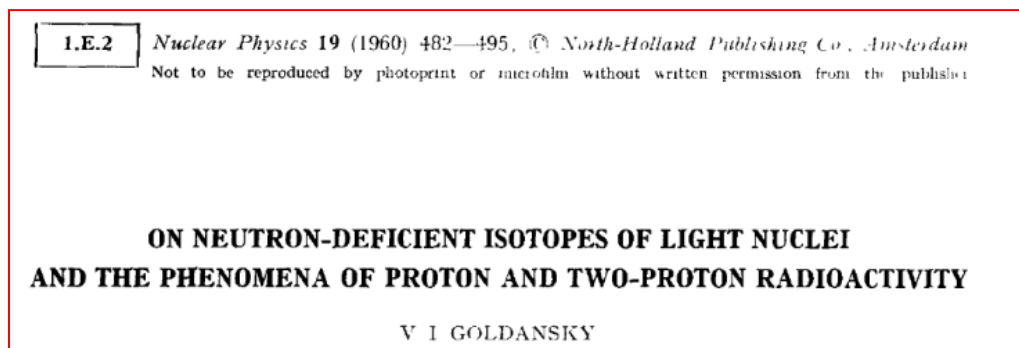
New Isotope ^{220}Np : Probing the Robustness of the $N = 126$ Shell Closure in Neptunium

Z. Y. Zhang (张志远),^{1,2} Z. G. Gan (甘再国),^{1,2,*} H. B. Yang (杨华彬),¹ L. Ma (马龙),¹ M. H. Huang (黄明辉),^{1,2}
C. L. Yang (杨春莉),^{1,2} M. M. Zhang (张明明),^{1,2} Y. L. Tian (田玉林),^{1,2} Y. S. Wang (王永生),^{1,2,3}
M. D. Sun (孙明道),^{1,2,3,†} H. Y. Lu (卢洪洋),^{1,2} W. Q. Zhang (张文强),^{1,2} H. B. Zhou (周厚兵),⁴ X. Wang (王翔),⁵
C. G. Wu (武晨光),⁵ L. M. Duan (段利敏),^{1,2} W. X. Huang (黄文学),^{1,2} Z. Liu (刘忠),^{1,2} Z. Z. Ren (任中洲),⁶
S. G. Zhou (周善贵),^{7,8} X. H. Zhou (周小红),^{1,2} H. S. Xu (徐珊珊),^{1,2} Yu. S. Tsyganov,⁹
A. A. Voinov,⁹ and A. N. Polyakov⁹



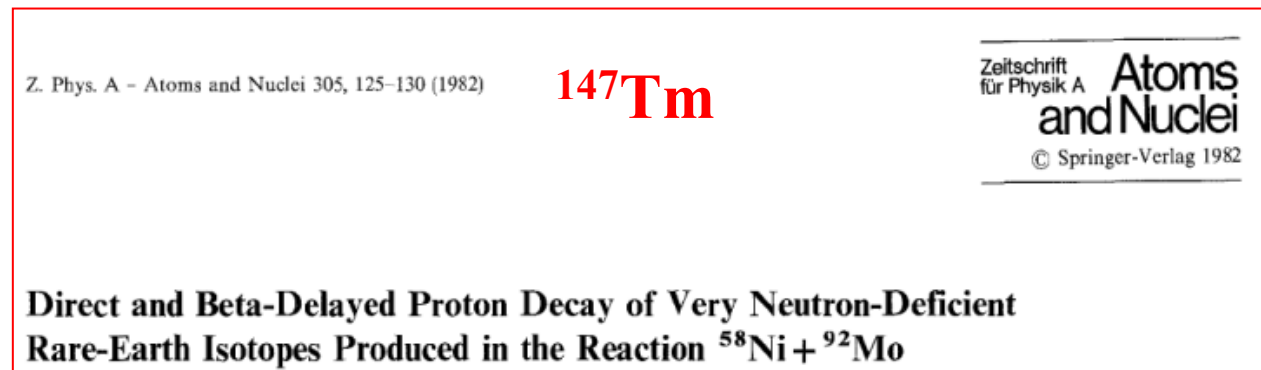
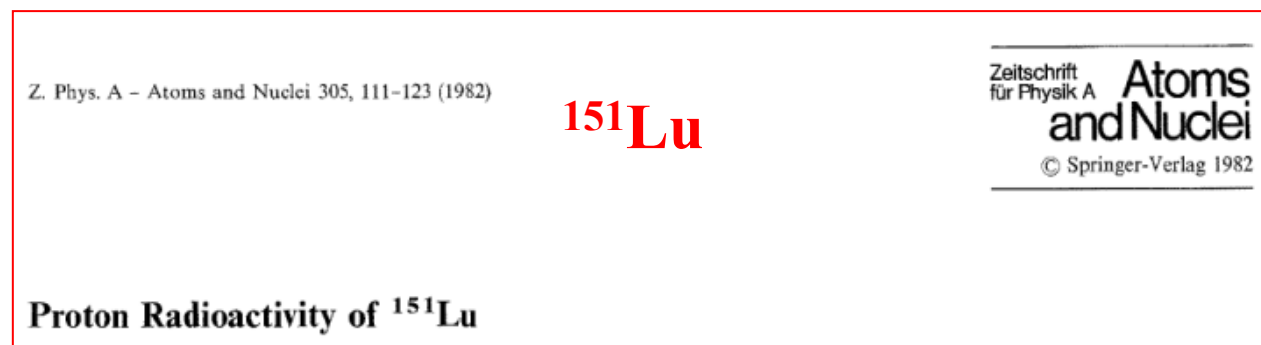
质子滴线区衰变(质子发射)研究现状

➤ 上世纪60年代Goldansky理论预言



到目前为止，发现的基态和长寿命激发态具有单质子放射性的原子核主要集中在中等质量质子滴线区($83 > Z > 50$)。

➤ 上世纪80年代首先在 ^{151}Lu 和 ^{147}Tm 原子核中观察到基态单质子衰变



质子滴线区衰变(质子发射)研究现状

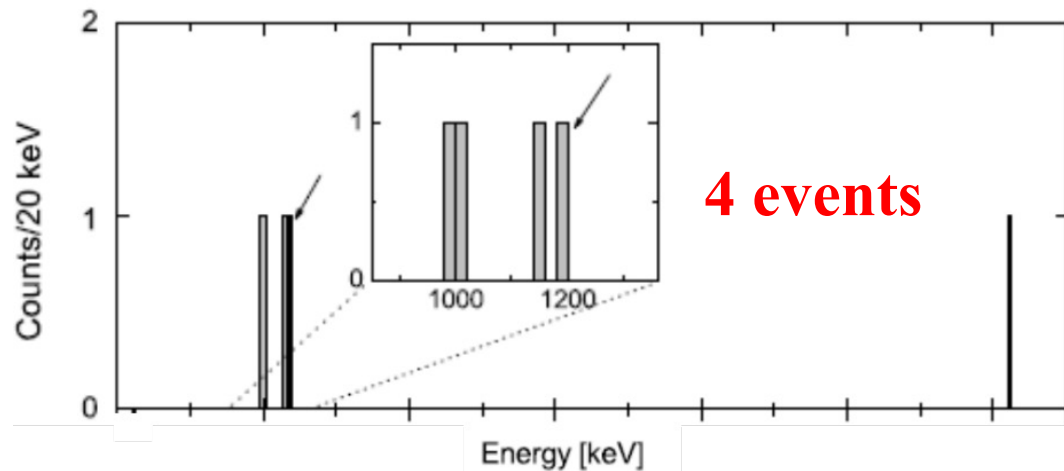
➤ 2002年德国GSI和法国Ganil在 ^{45}Fe 核中首次观测到基态双质子发射现象。

Eur. Phys. J. A 14, 279-285 (2002)
DOI 10.1140/epja/i2002-10033-9

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PHYSICAL JOURNAL A
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Short Note

First evidence for the two-proton decay of ^{45}Fe

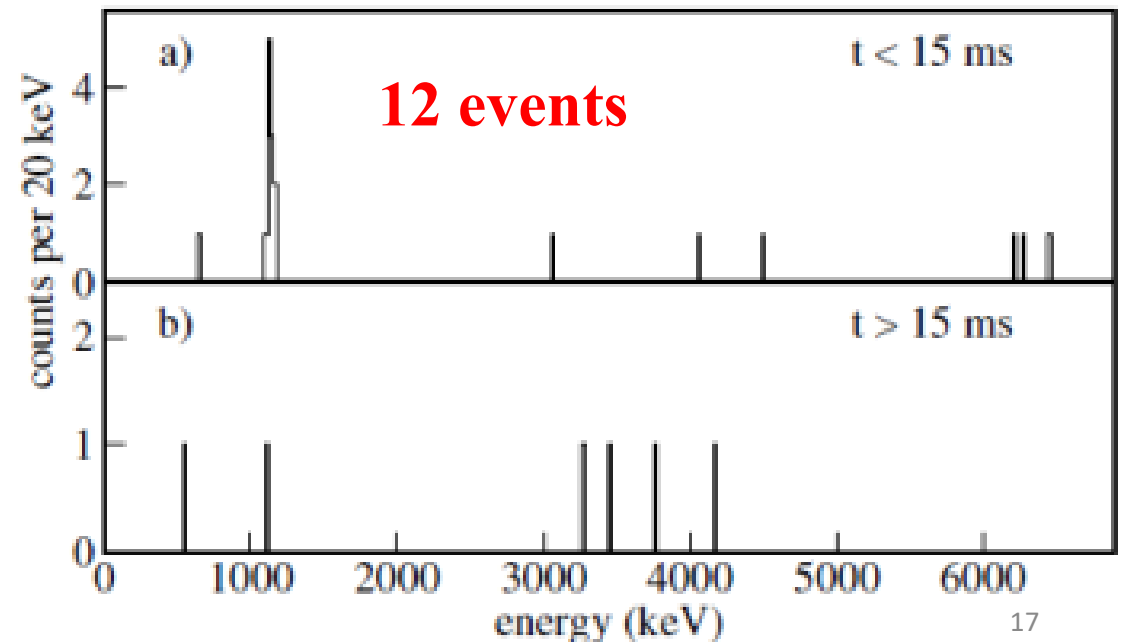


VOLUME 89, NUMBER 10

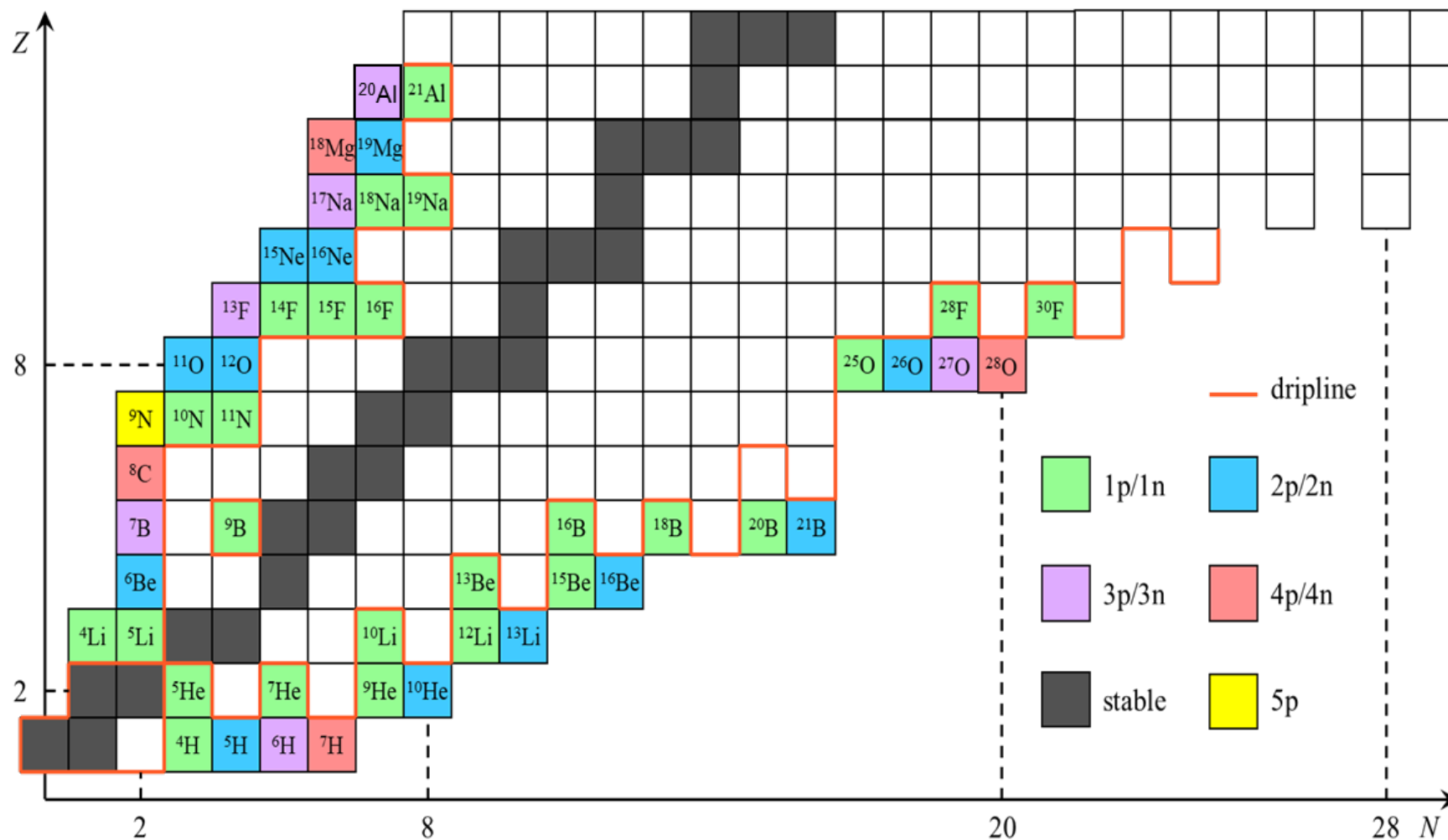
PHYSICAL REVIEW LETTERS

2 SEPTEMBER 2002

Two-Proton Radioactivity of ^{45}Fe



轻质量区原子核基态质子和中子发射研究现状

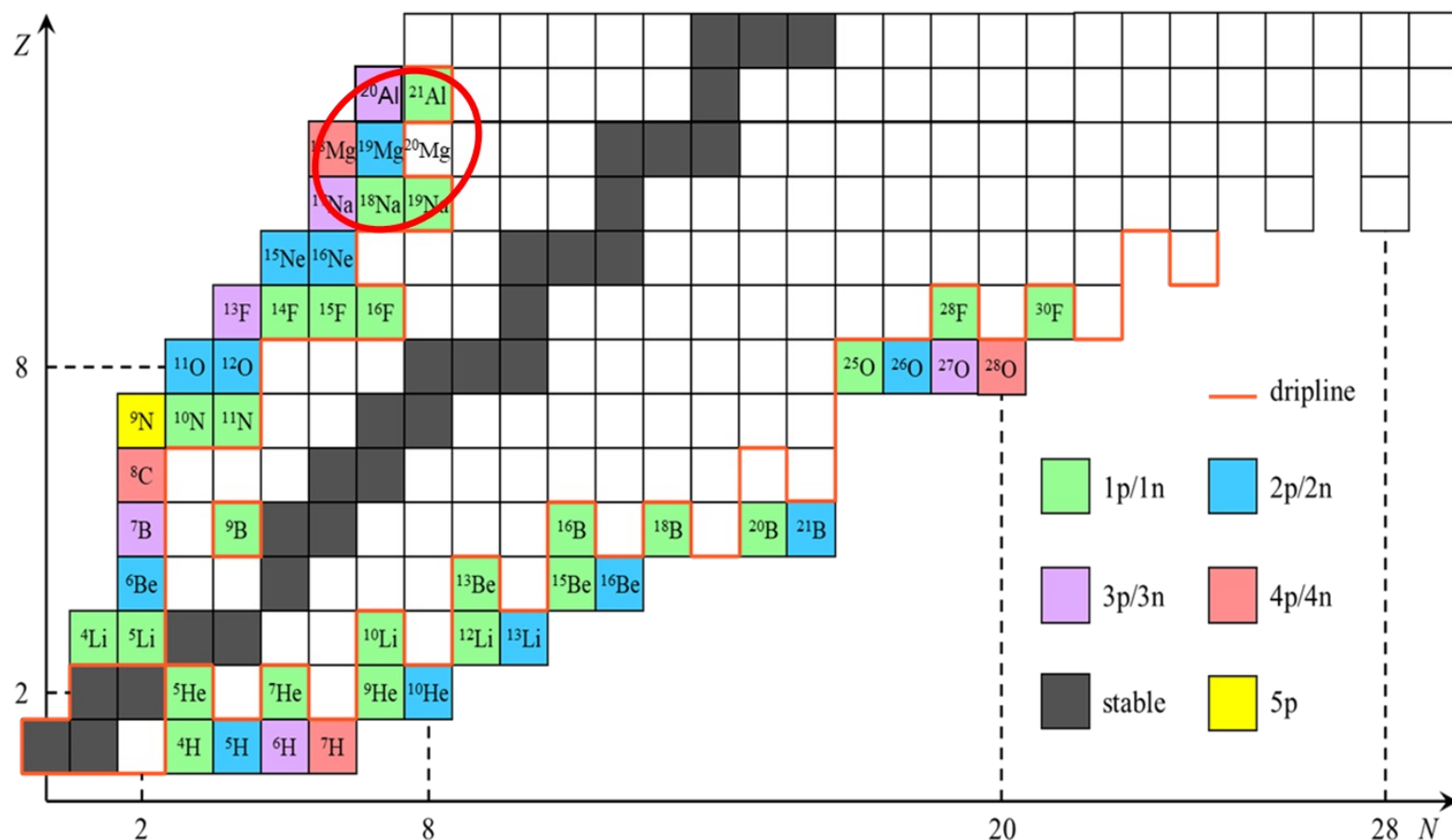


1) 倪磊等, 科学通报71, 883 (2026).

2) H. Hua, Science Bulletin 68, 645 (2023).

3) 金瑜等, 原子核物理评论 40, 327(2023).

我们的研究工作

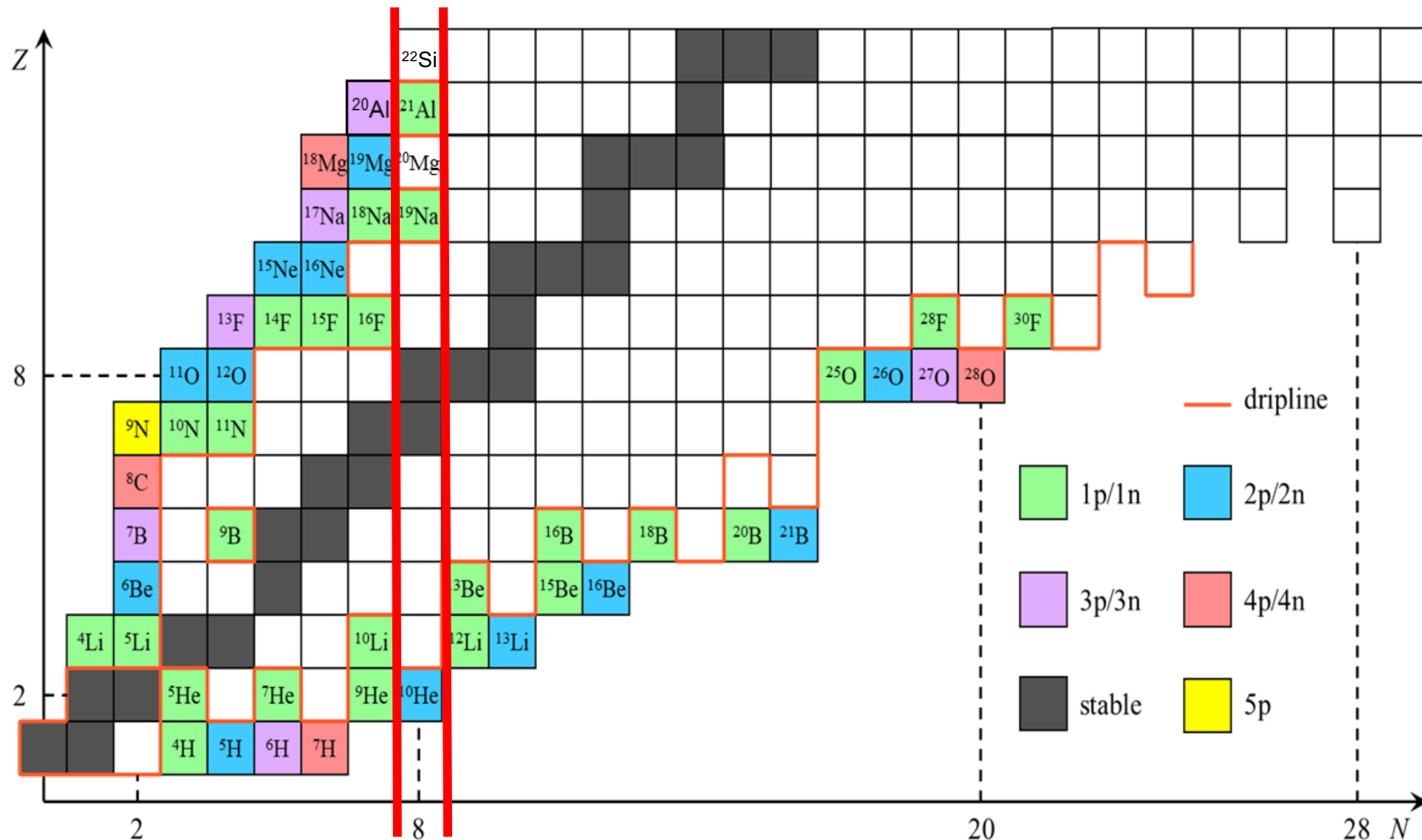


多质子发射

- 1、 ^{18}Mg ----- $4p$
- 2、 $^{17}\text{Na}, ^{21}\text{Al}$ -- $3p$
- 3、 $^{19,20}\text{Mg}$ ----- $2p$
- 4、 $^{18,19}\text{Na}$ ----- $1p$

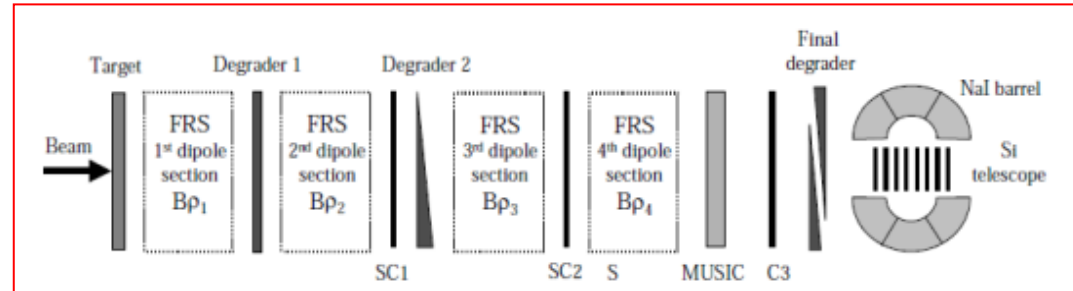
- [1] Y. Jin, *et al.*, Phys. Rev. Lett. 127, 262502 (2021) [4] L. Ni, *et al.*, Phys. Rev. C 112, 024321 (2025).
 [2] L. Ni, *et al.*, Phys. Rev. C 110, L061301 (2024). [5] L. Ni *et al.*, Particle 9, 32 (2026).
 [3] L. Ni, *et al.*, Phys. Lett. B 868, 139660 (2025). [6] L. Ni, *et al.*, submitted to Phys. Rev. Lett.

轻质子滴线区域 $N=8$ 壳层的稳健性

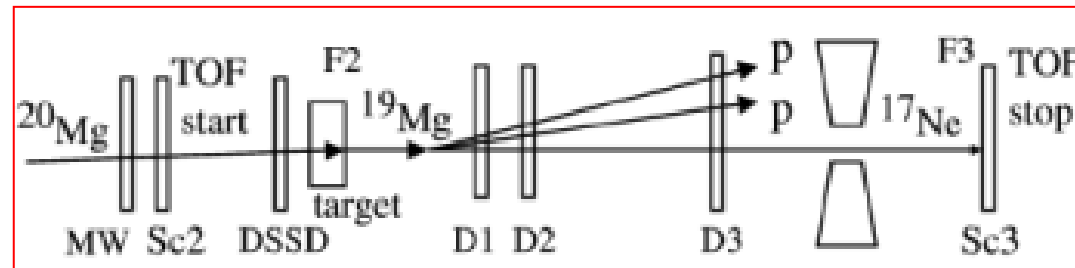


实验方法

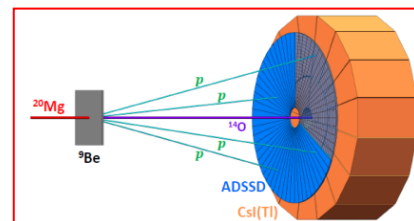
1) 注入衰变法 (寿命 $> 10^{-7}$ s)



2) 飞行衰变法 (寿命 $10^{-7} - 10^{-12}$ s)



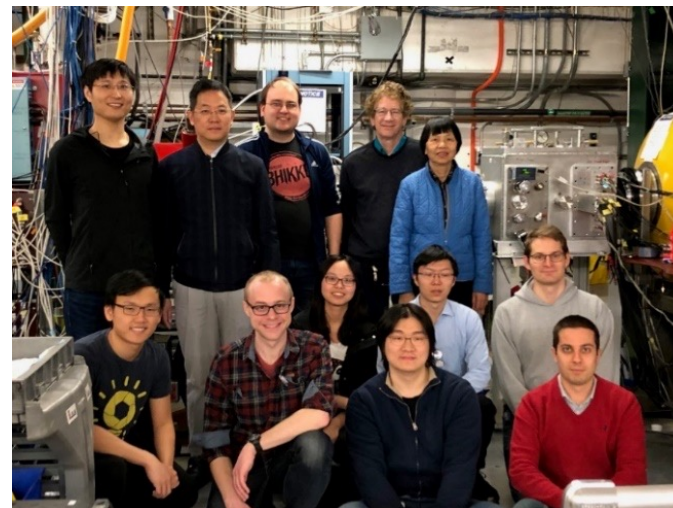
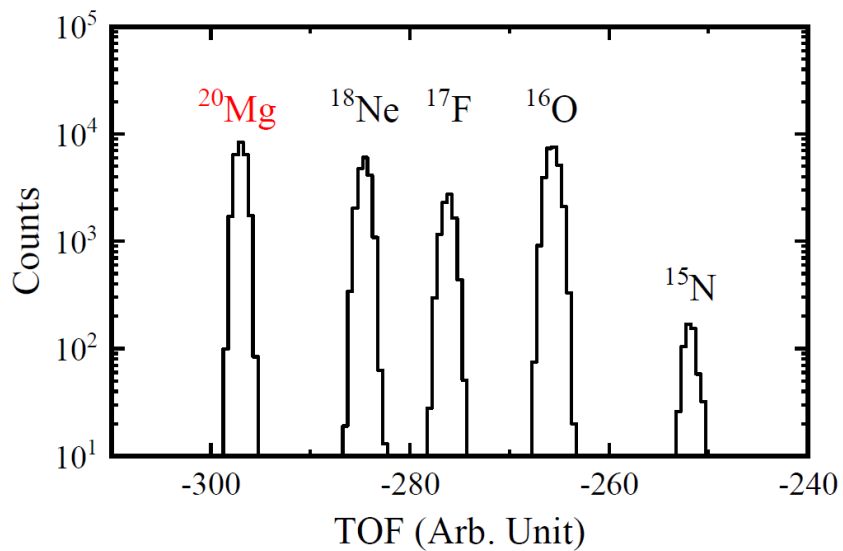
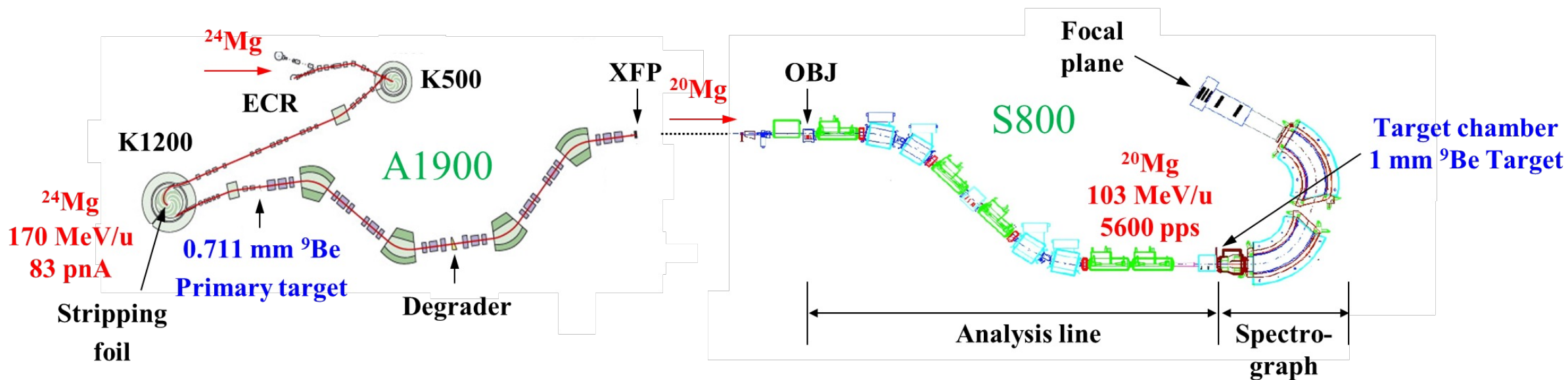
3) 不变质量法 (寿命 $< 10^{-12}$ s)



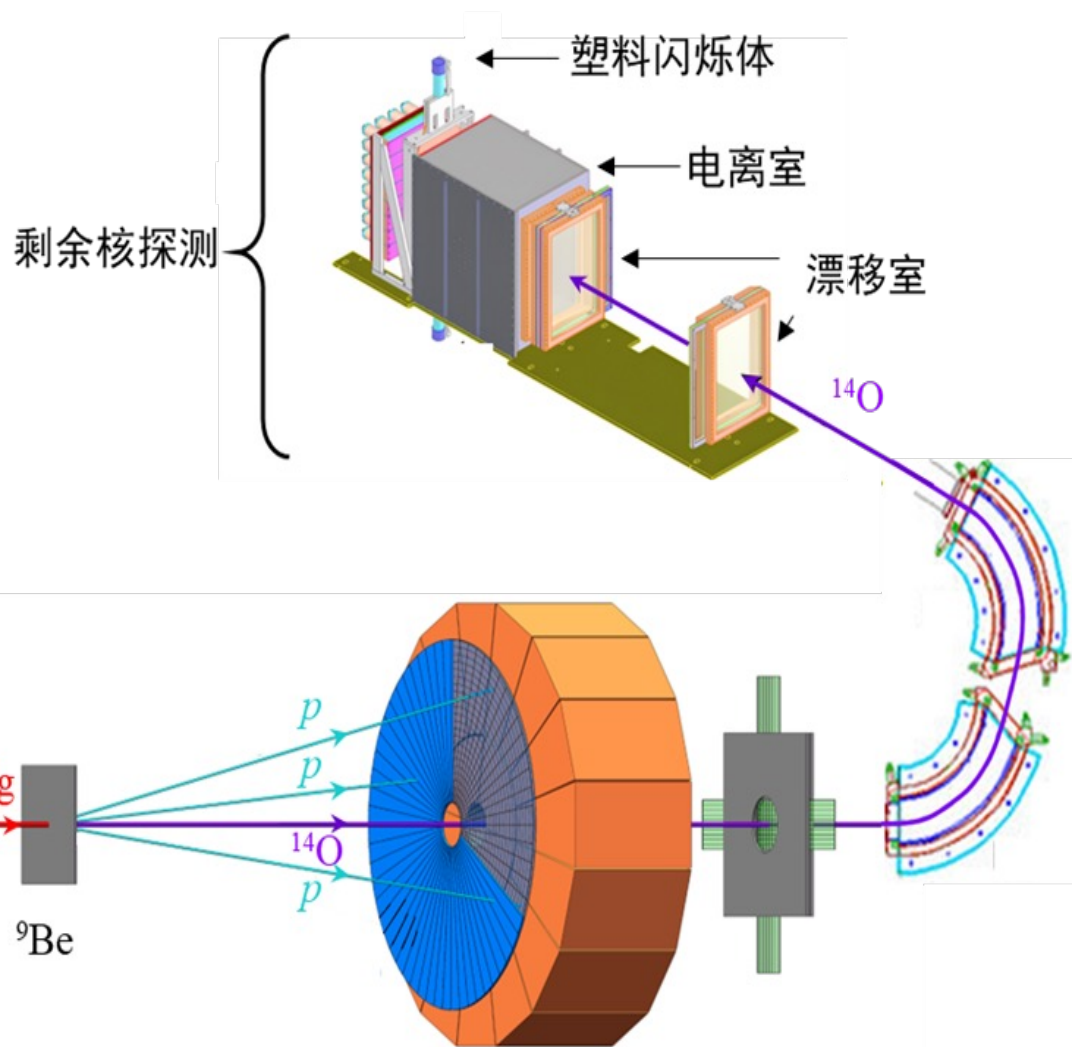
or



实验设置

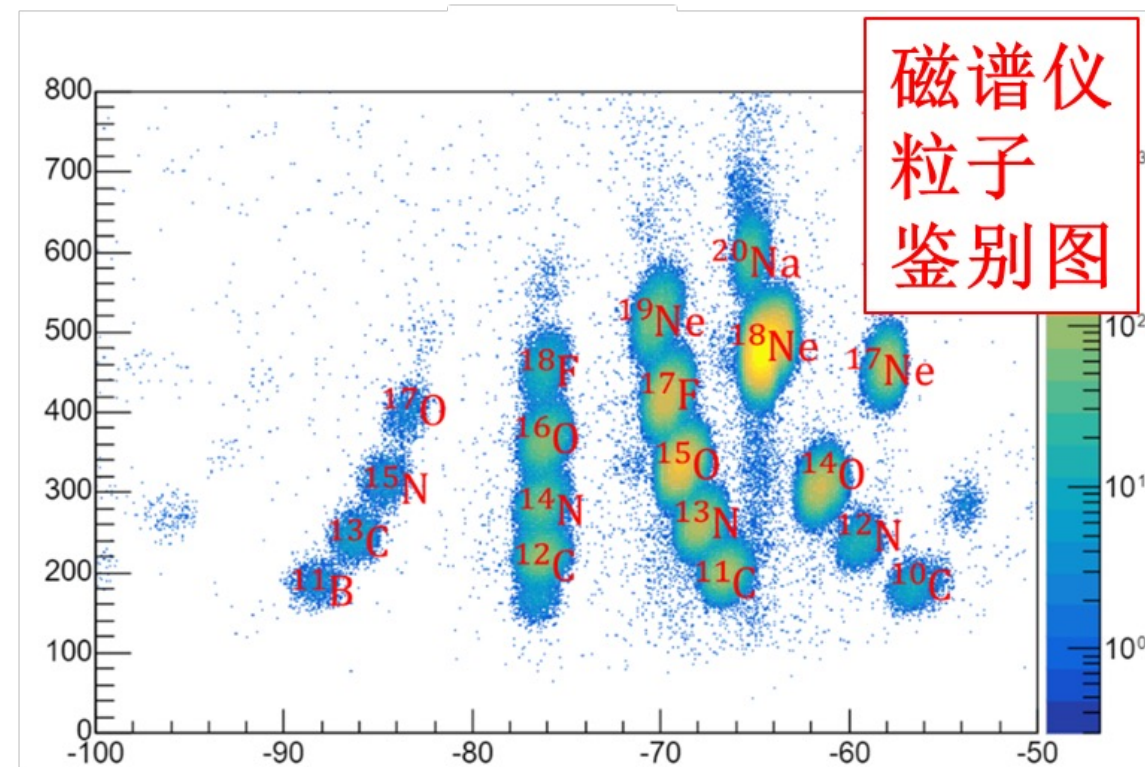
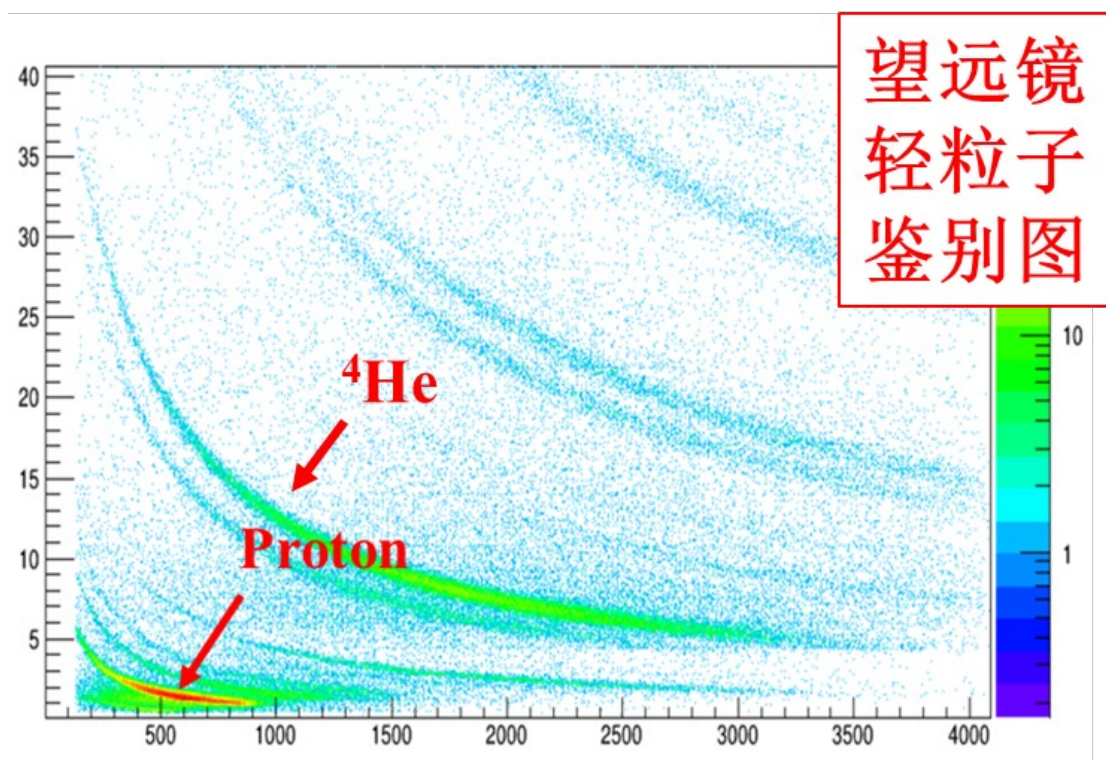


实验设置

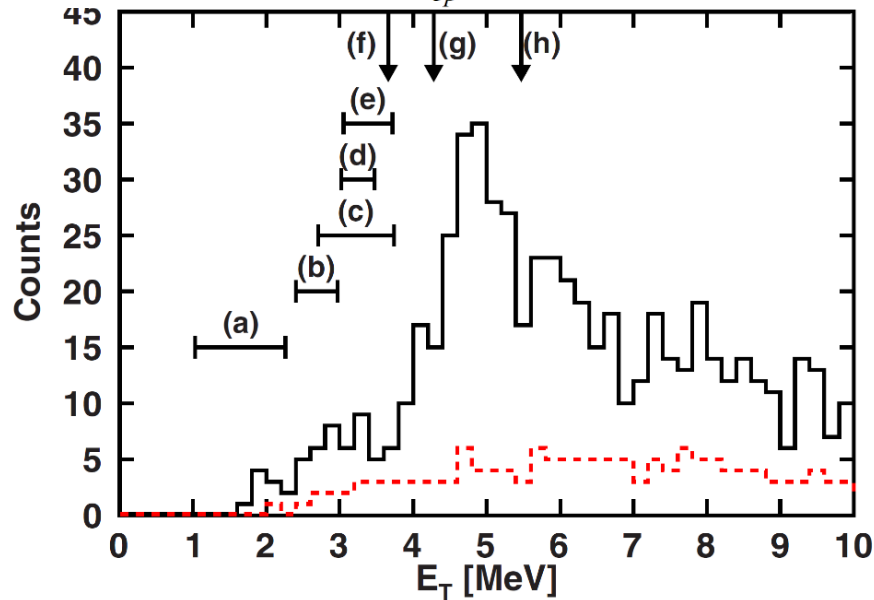
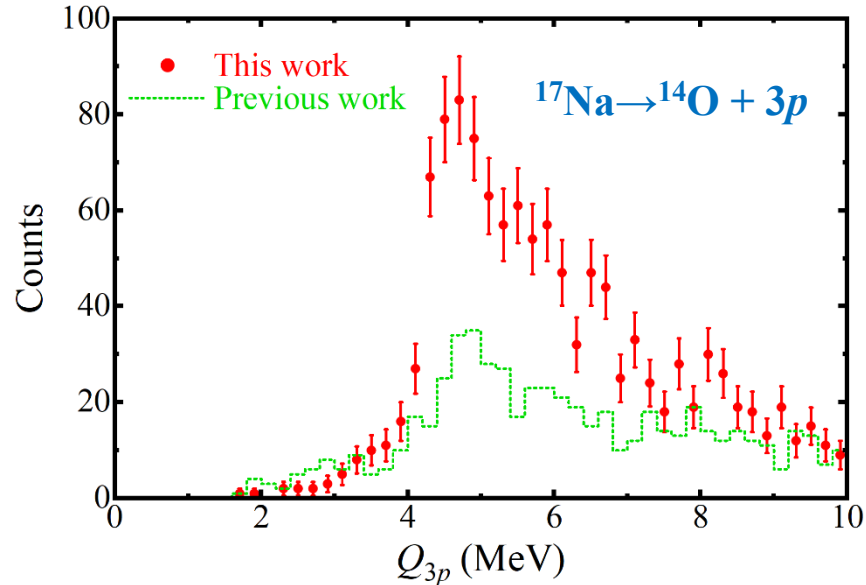


- $1p2n$ knockout $\rightarrow$ ^{17}Na $\rightarrow$ $^{14}\text{O} + 3p$
- $1p1n$ knockout $\rightarrow$ ^{18}Na $\rightarrow$ $^{17}\text{Ne} + 1p$
- $1p$ knockout $\rightarrow$ ^{19}Na $\rightarrow$ $^{18}\text{Ne} + 1p$
- $2n$ knockout $\rightarrow$ ^{18}Mg $\rightarrow$ $^{14}\text{O} + 4p$
- $1n$ knockout $\rightarrow$ ^{19}Mg $\rightarrow$ $^{17}\text{Ne} + 2p$
- Inelastic $\rightarrow$ ^{20}Mg $\rightarrow$ $^{18}\text{Ne} + 2p$
- $1p$ transfer $\rightarrow$ ^{21}Al $\rightarrow$ $^{18}\text{Ne} + 3p$

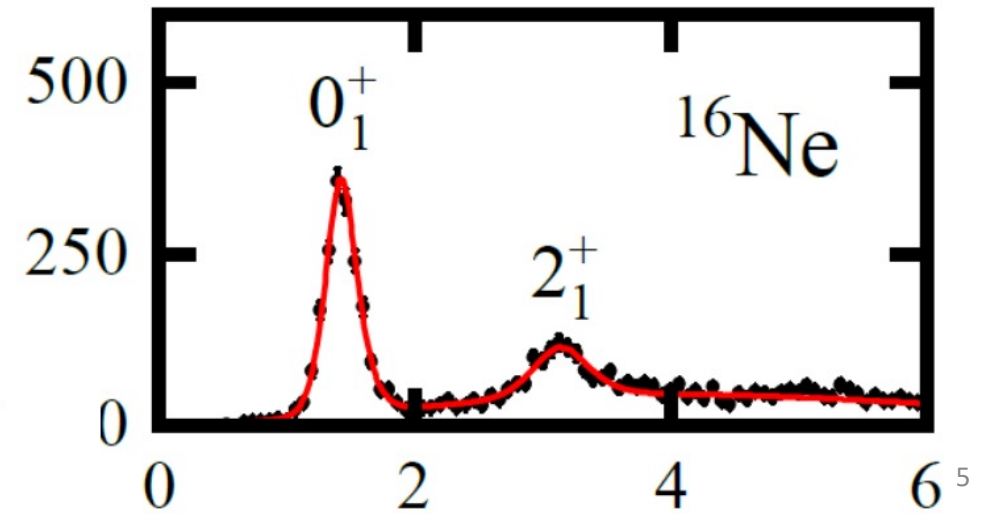
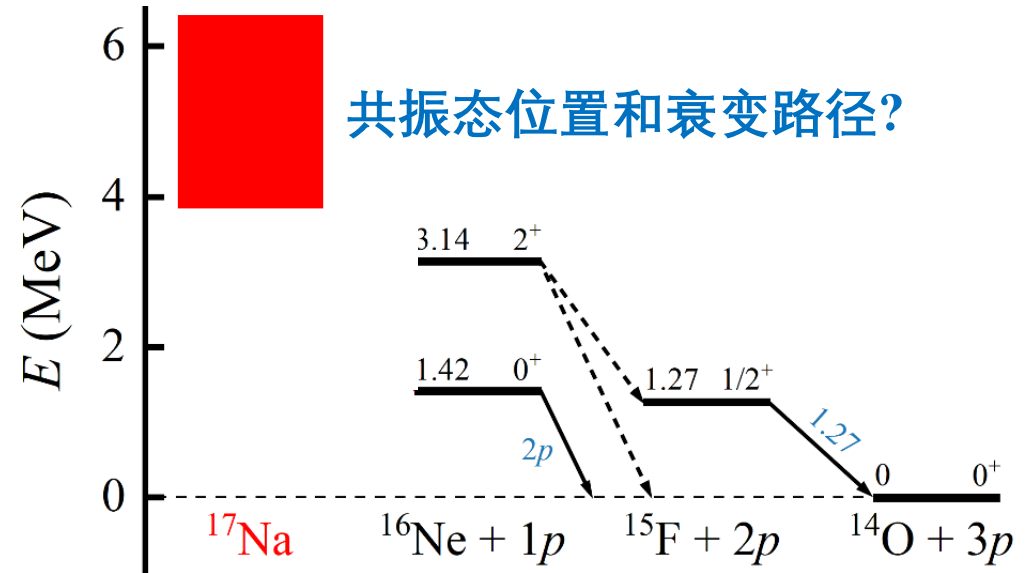
衰变出射的粒子鉴别谱



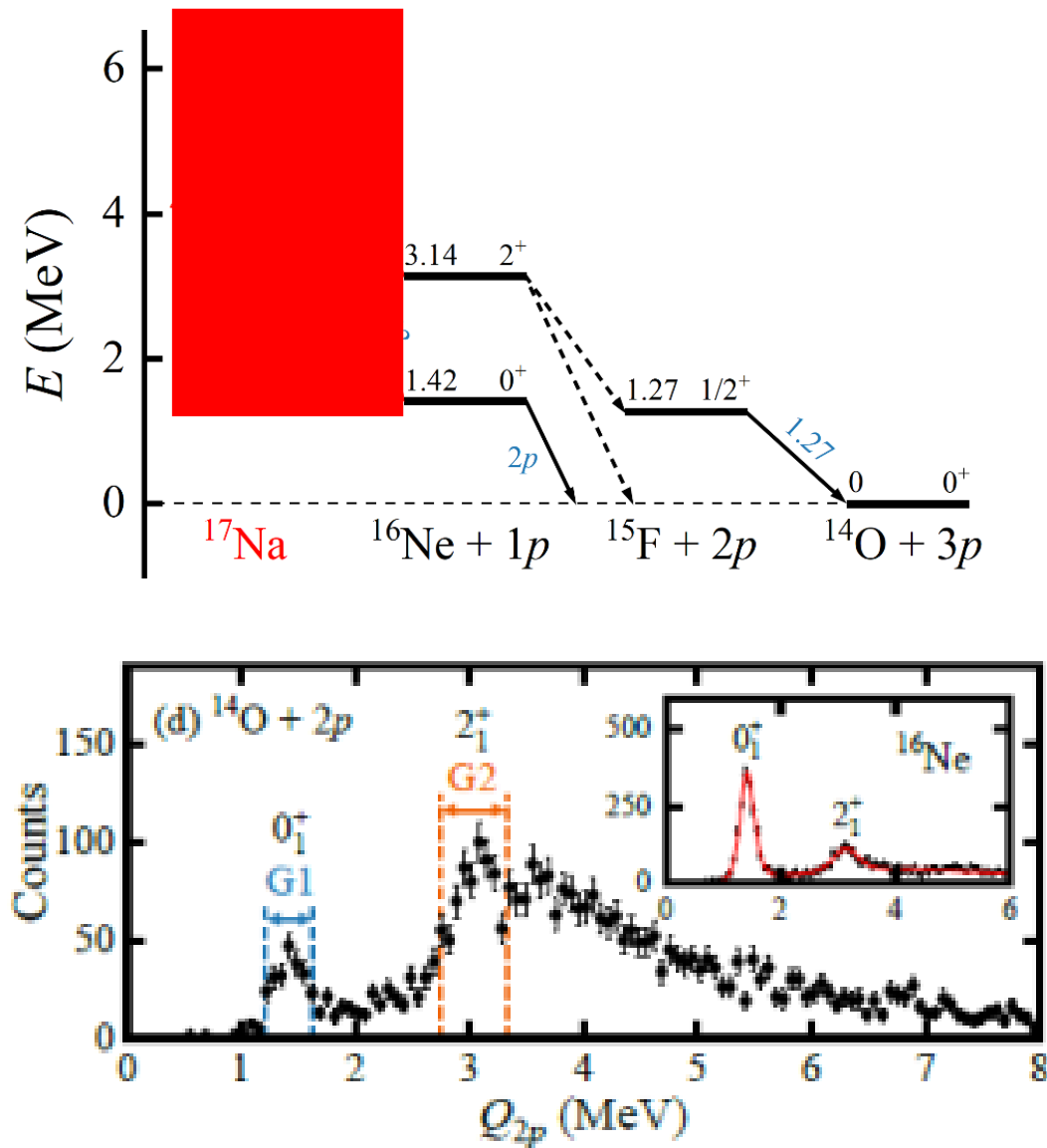
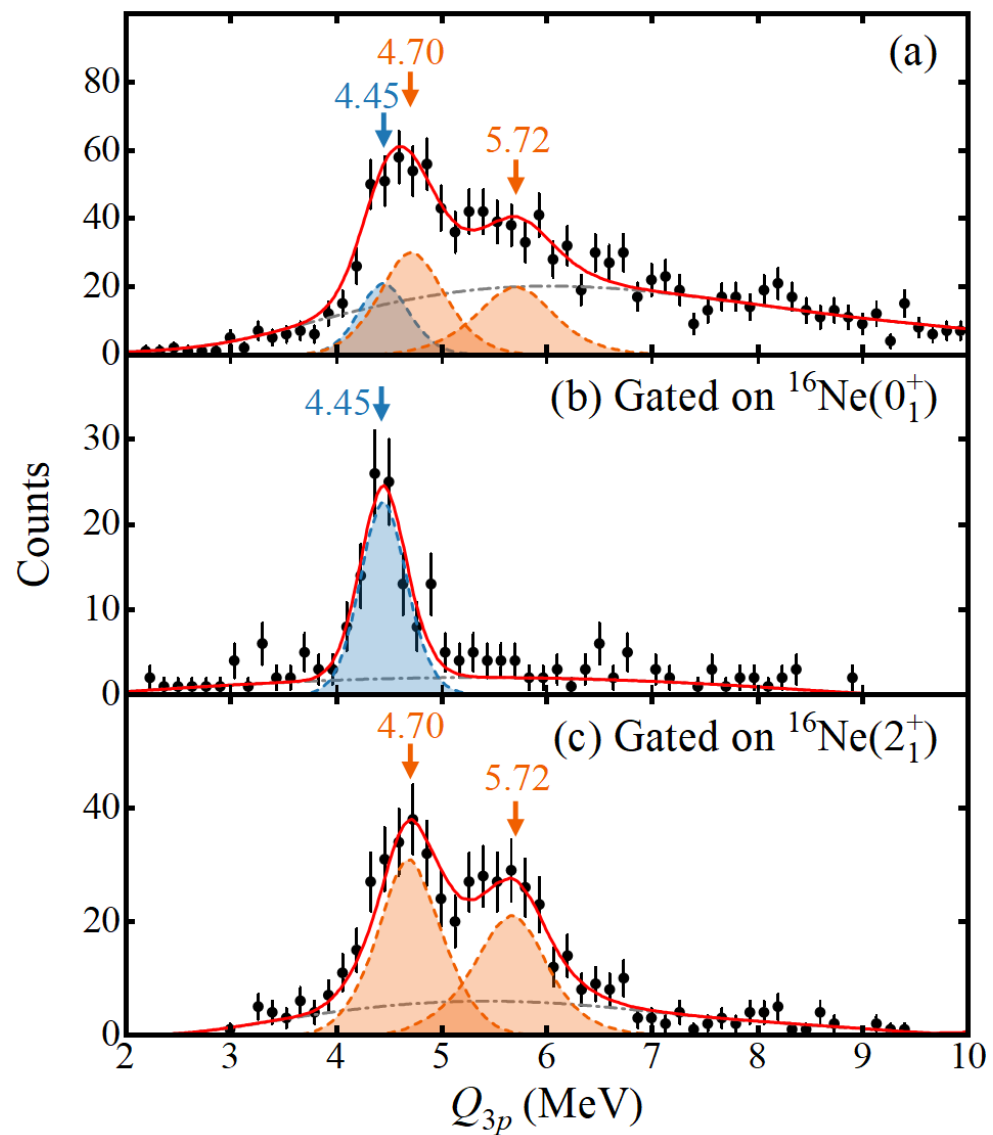
^{17}Na 的三质子衰变能谱



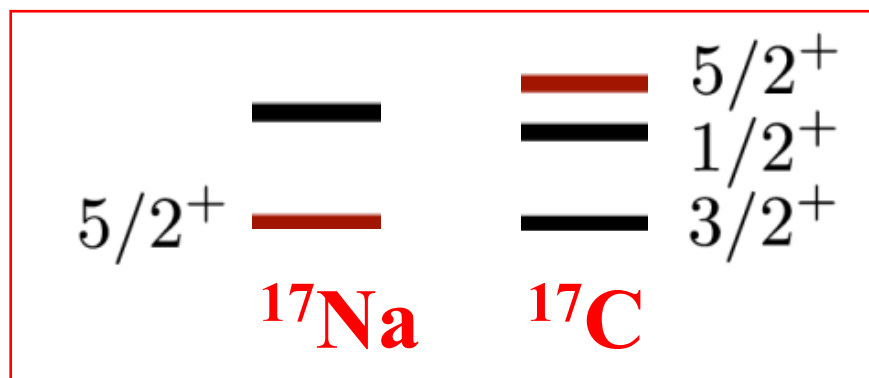
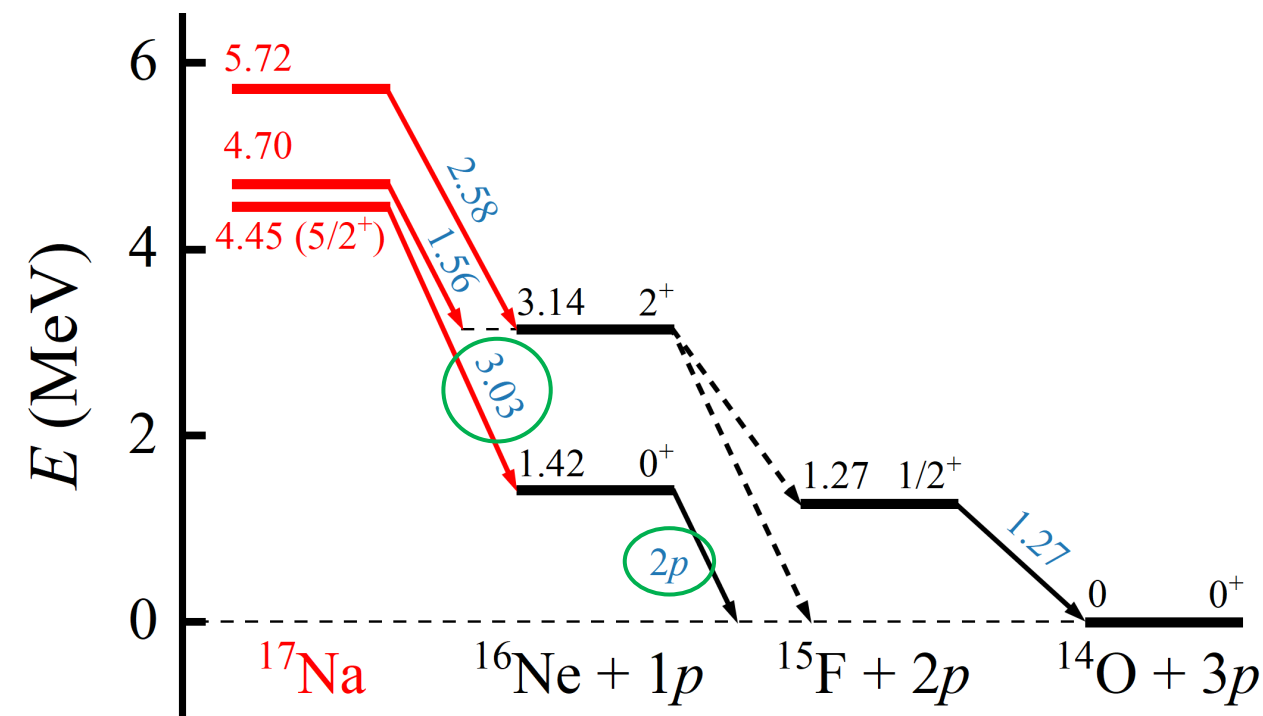
K. W. Brown *et al.*, Phys. Rev. C, 95, 044326 (2017).



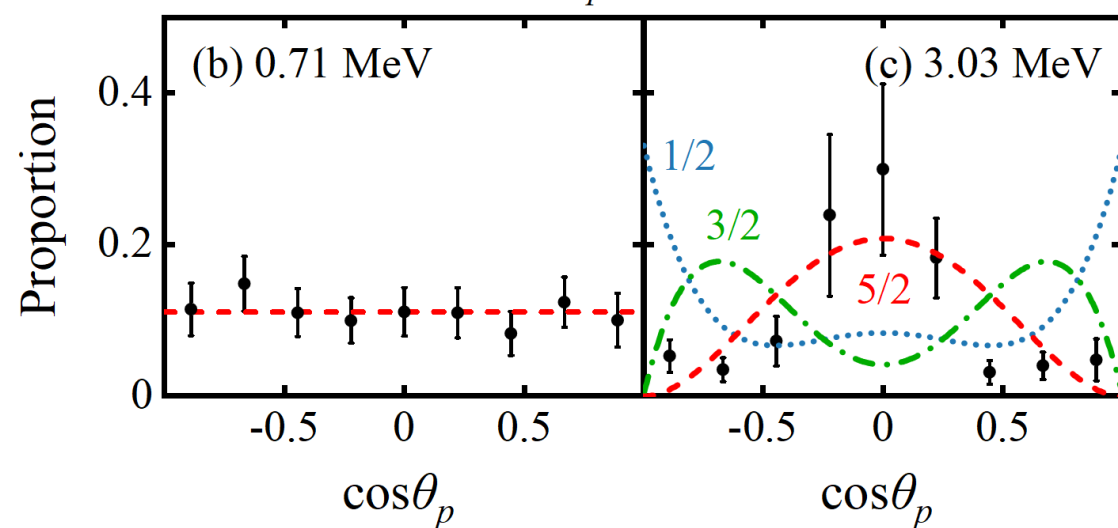
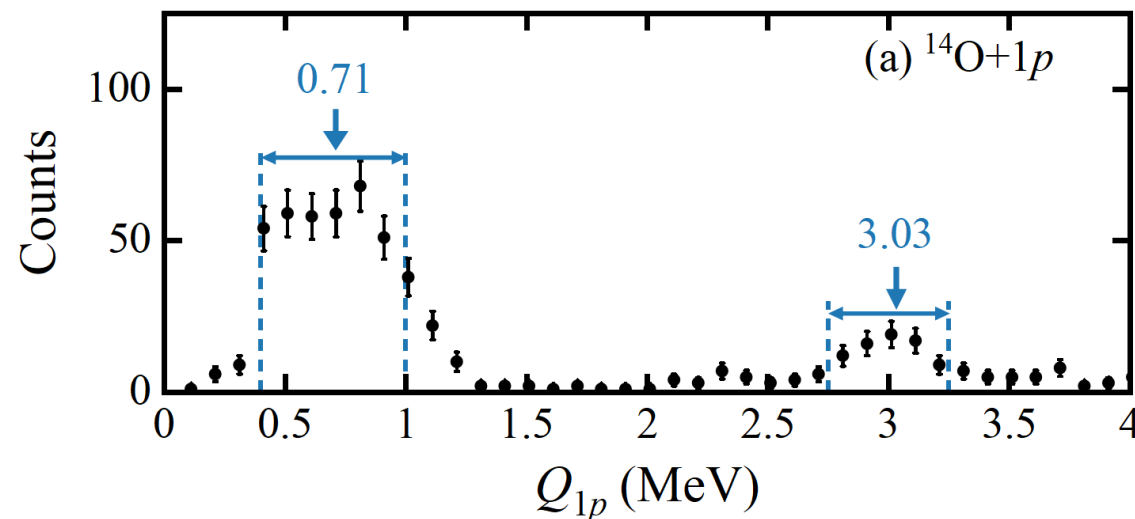
^{17}Na 共振态位置的确定和衰变路径



^{17}Na 基态自旋和宇称的确定

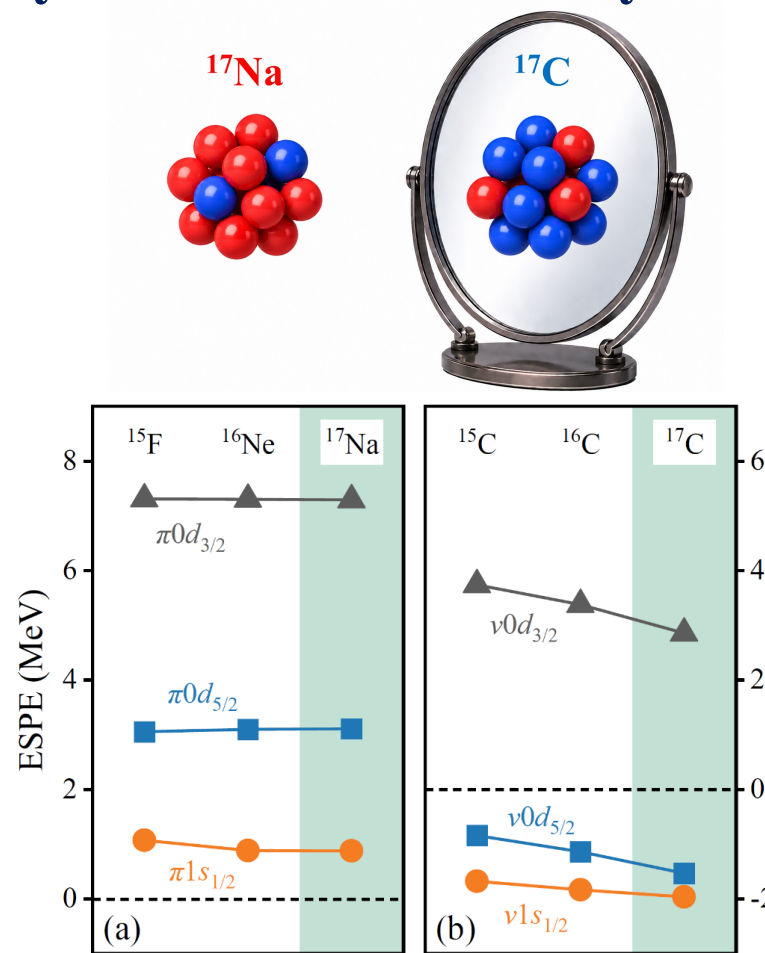
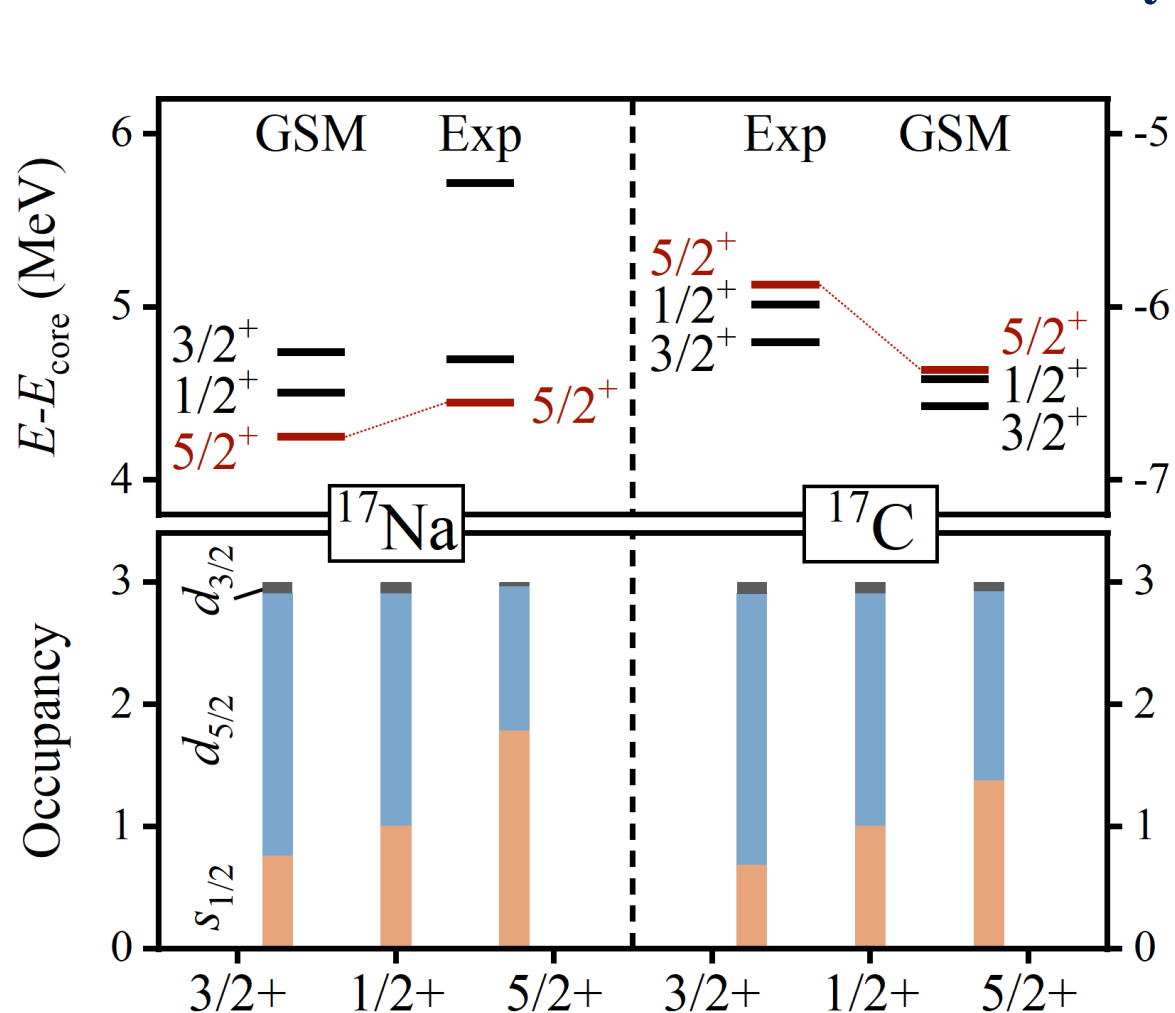


基态镜像对称性破缺



^{17}Na - ^{17}C 基态镜像对称性破缺机制

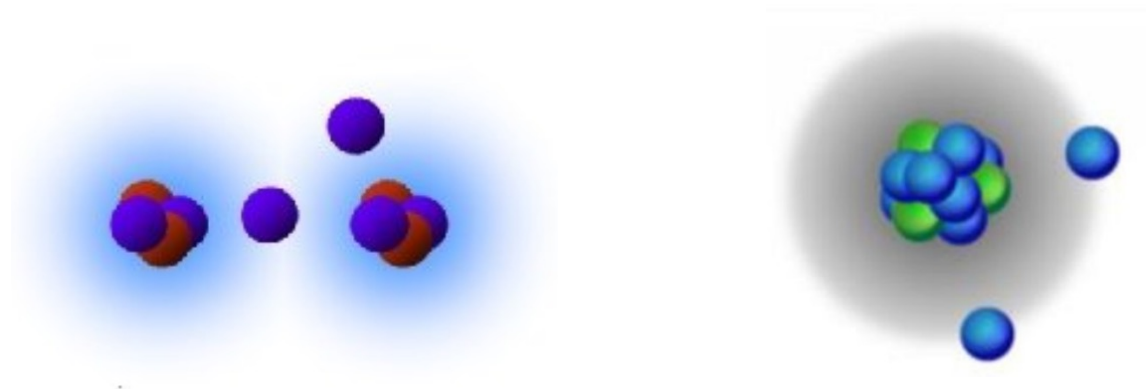
Gamow shell model + Many-Body Perturbation Theory



L. Ni *et al.*, submitted to Phys. Rev. Lett.

三、总结和展望

- 1、首次确定了 ^{17}Na 的基态位置，指认其自旋宇称为 $5/2^+$ 。针对 ^{17}Na - ^{17}C 中基态镜像对称性破缺，发现了一种全新的破缺机制。
- 2、多体关联的研究将有助于理解极端同位旋不对称条件下的原子核奇特结构(例如：集团结构和多核子晕结构等)。



- 3、基于实验确定的 ^{17}Na 基态质量，通过镜像核质量的对称性破缺，研究质子滴线区原子核的结构。

谢谢大家!!

合作单位:



北京大学
PEKING UNIVERSITY



复旦大学
FUDAN UNIVERSITY



中山大学
SUN YAT-SEN UNIVERSITY



北京航空航天大学
BEIHANG UNIVERSITY



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