第二届“粤港澳”
核物理论坛

河南师范大学

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

利用贝叶斯神经网络方法高精度预测炮弹碎裂反应余核截面

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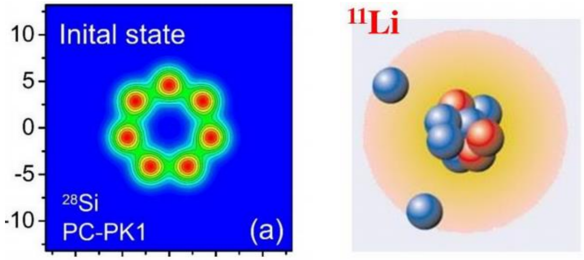
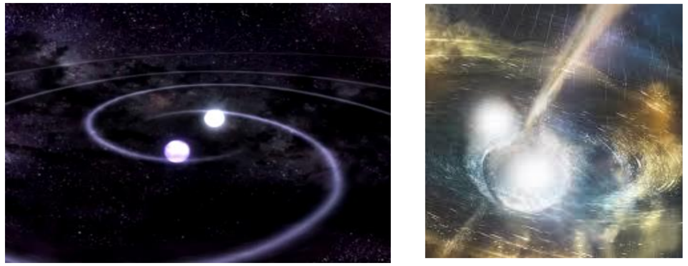
广州·华南理工大学
2023 年 06 月 19 日

随着放射性核束装置的发展，极大的促进了对**不稳定核素**研究，深化人们对原子核性质的认识，对**基础研究**具有根本性影响，并有重要的**应用价值**。

基础

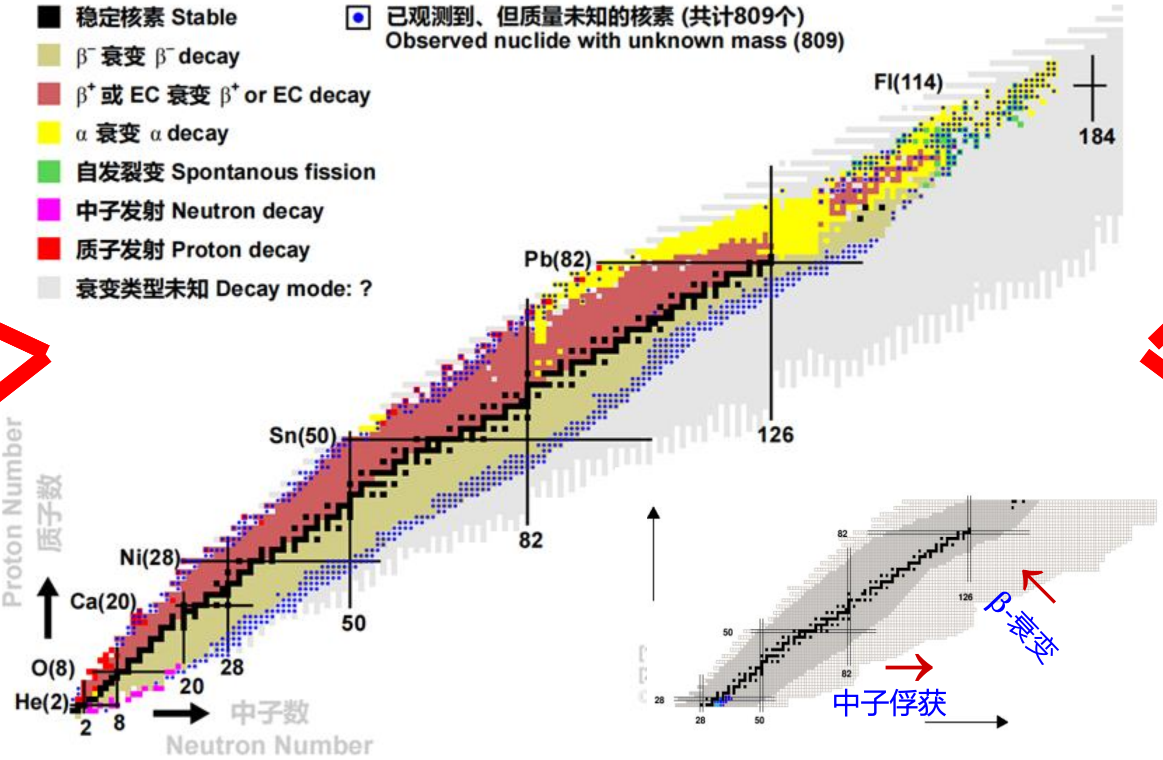


核结构性质



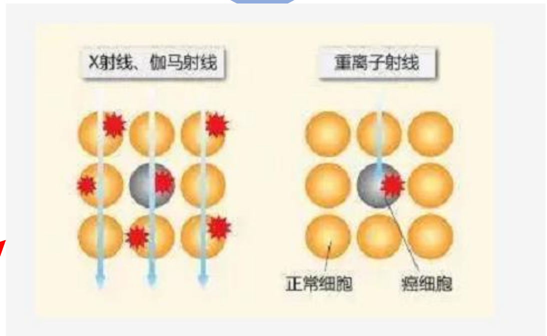
恒星演化、天体元素合成

稳定核素286种 → 现已发现核素3340种

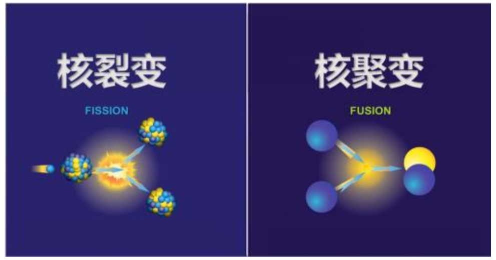


理论预言存在核素接近9000种

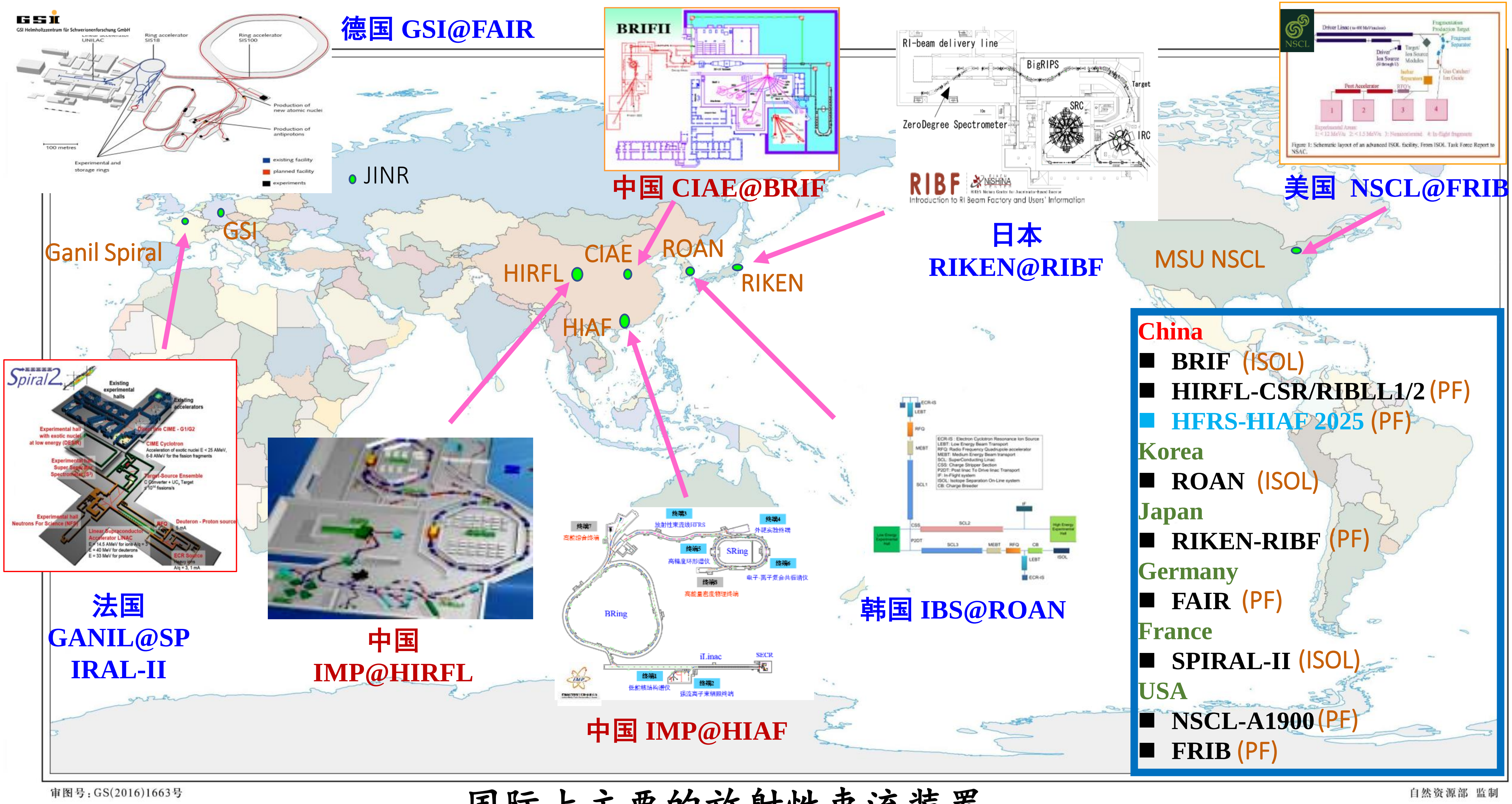
应用



医学治疗



核能



China
- BRIF (ISOL)
- HIRFL-CSR/RIBLL1/2 (PF)
- HFRS-HIAF 2025 (PF)

Korea
- ROAN (ISOL)

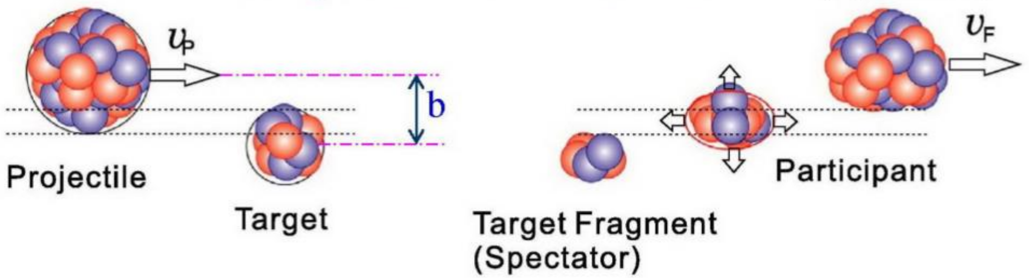
Japan
- RIKEN-RIBF (PF)

Germany
- FAIR (PF)

France
- SPIRAL-II (ISOL)

USA
- NSCL-A1900 (PF)
- FRIB (PF)

国际上主要的放射性束流装置



磨损消融(AA)模型：ABRABLA07;NUCF RAG3;SAA

统计多重碎裂模型：SMM

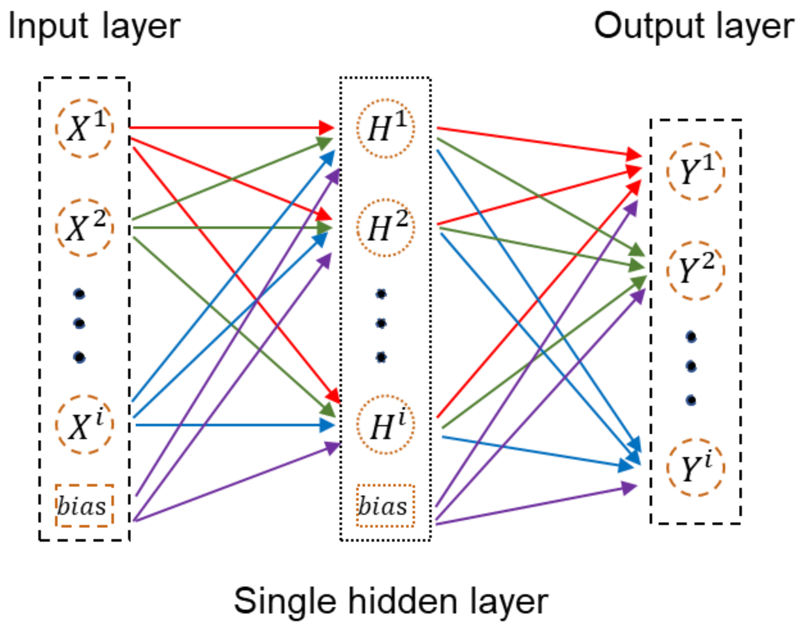
研究炮弹碎裂的理论与方法

输运模型：BUU;QMD

参数化经验公式：EPAX3；FRACS；FRACS-C等

炮弹碎裂反应作为产生放射性次级束流的主要方法，

次级束的流强取决于同位素的产生截面与束流装置的传输效率，前者主要由反应机制决定，而后者也同碎裂产物的动量分布等反应动力学性质密切相关，因此充分理解炮弹碎裂反应机制，精确预测余核截面非常重要，可以帮助优化实验条件，指导实验设计。



贝叶斯（BNN）神经网络优势

- 具有强大的数据拟合能力；
- 利用先验分布避免过拟合；
- 用概率分布来描述网络中的参数；
- 能够量化预测的不确定度；
- ……

贝叶斯(BNN)方法在核物理中的应用

- 核质量： Utama2016PRC, Niu2018PLB, Niu2019PRC, Rodriguez2019EPL；
- 散裂反应： Ma2020CPC；
- 核电荷半径： Utama2016JPG, Dong2022PRC；
- 裂变反应： Wang2019PRL, Qiao2021PRC ；
- 对称能: Xu2020PRC, Wang2021PLB ；
- 衰变: Niu2019PRC, Yuan2022CPC；

....

数据来源

- 文献，博士论文
- 五大核数据库：
  - ✓ CENDL: http://www.nuclear.csdb.cn/
  - ✓ NNDC: http://www.nndc.bnl.gov/
  - ✓ JENDL: http://wwwndc.jaea.go.jp/
  - ✓ JEFF: http://www.oecd-nea.org/
  - ✓ BROND: http://www-nds.iaea.org/

训练集

- 53 反应系统包含 6393 实验数据.
- 入射能量：几十 MeV/u 到 约 1 GeV/u
- 炮弹核：
  - ✓ 质量(A)范围: (40-208)
  - ✓ 电荷(Z)范围: (18-82)
- 碎片核:
  - ✓ 电荷(Z)范围: (Z=3-82)

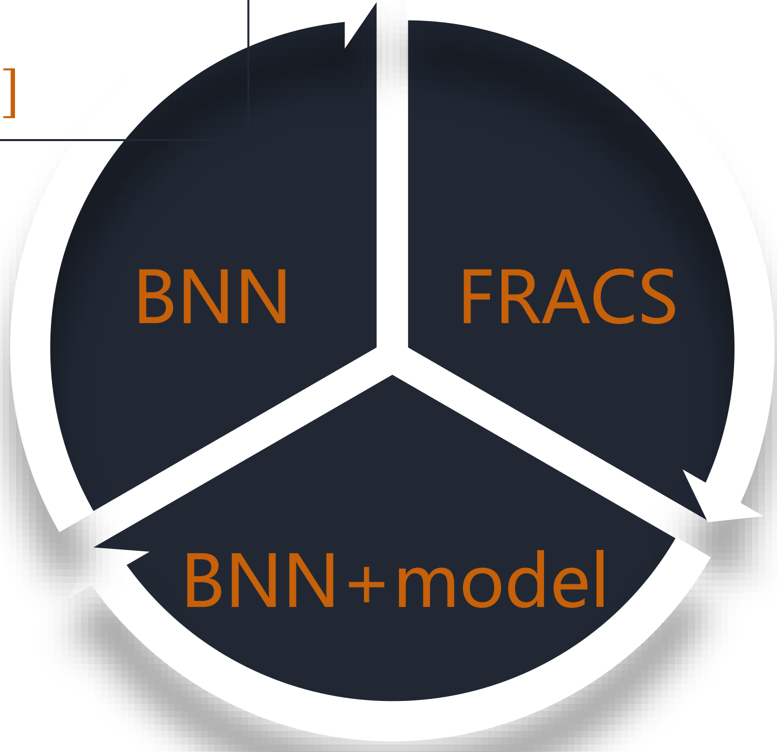
Reaction	$(I/A)_{pr}$	E	Data	Z_{fr}	Ref.	Reaction	$(I/A)_{pr}$	E	Data	Z_{fr}	Ref.
^{80}Kr+^{9}Be	0.100	1050	28	32-37	[58]	^{58}Ni+^{9}Be	0.034	140	196	5-29	[78]
^{112}Sn+^{9}Be	0.107	1015	66	38-52	[59]	^{58}Ni+^{181}Ta	0.034	140	189	5-28	[78]
^{112}Sn+^{112}Sn	0.107	1000	249	10-50	[60]	^{64}Ni+^{9}Be	0.125	140	243	5-29	[78]
^{124}Sn+^{124}Sn	0.194	1000	266	10-50	[60]	^{64}Ni+^{181}Ta	0.125	140	234	5-29	[78]
^{136}Xe+^{9}Be	0.206	1000	111	40-55	[61]	^{78}Kr+^{9}Be	0.077	140	10	32-34	[79]
^{124}Xe+^{208}Pb	0.129	1000	491	10-55	[62]	^{76}Ge+^{9}Be	0.158	132	111	14-27	[80]
^{136}Xe+^{208}Pb	0.206	1000	626	10-56	[62]	^{40}Ar+^{9}Be	0.100	128	69	4-15	[81]
^{208}Pb+^{9}Be	0.212	1000	191	70-83	[63]	^{40}Ar+^{58}Ni	0.100	128	67	4-16	[81]
^{208}Pb+^{64}Cu	0.212	1000	282	59-82	[64]	^{40}Ar+^{181}Ta	0.100	128	65	4-16	[81]
^{40}Ar+^{9}Be	0.100	1000	39	5-9	[65]	^{48}Ca+^{181}Ta	0.167	128	54	4-14	[81]
^{132}Sn+^{9}Be	0.242	950	46	45-51	[66]	^{112}Sn+^{9}Be	0.107	120	6	48-50	[82]
^{197}Au+^{9}Be	0.198	950	33	72-78	[67]	^{69}Cu+^{9}Be	0.159	98.1	106	17-31	[83]
^{129}Xe+^{27}Al	0.163	790	216	40-55	[68]	^{72}Zn+^{9}Be	0.167	95.4	137	17-31	[83]
^{58}Ni+^{9}Be	0.034	650	58	21-28	[69]	^{68}Ni+^{9}Be	0.176	94.3	89	17-29	[83]
^{86}Kr+^{9}Be	0.163	500	28	21-28	[70]	^{40}Ar+^{9}Be	0.100	94	13	5-9	[84]
^{92}Mo+^{9}Be	0.087	500	89	31-42	[71]	^{40}Ar+^{181}Ta	0.100	94	112	3-19	[85]
^{48}Ca+^{9}Be	0.167	345	47	5-16	[72]	^{64}Ni+^{9}Be	0.125	93.7	84	17-29	[83]
^{78}Kr+^{9}Be	0.077	345	14	22-36	[73]	^{40}Ar+^{9}Be	0.100	90	116	4-15	[86]
^{124}Xe+^{9}Be	0.129	345	37	42-52	[74]	^{70}Ge+^{58}Ni	0.086	71.6	16	29-33	[87]
^{40}Ar+^{12}C	0.100	213	72	8-16	[75]	^{86}Kr+^{9}Be	0.163	64	180	25-36	[78]
^{136}Xe+^{12}C	0.206	168	176	40-55	[76]	^{86}Kr+^{181}Ta	0.163	64	70	25-36	[78]
^{40}Ar+^{9}Be	0.100	140	69	4-15	[77]	^{48}Ca+^{181}Ta	0.167	60	36	11-17	[88]
^{40}Ar+^{181}Ta	0.100	140	63	4-15	[77]	^{40}Ar+^{9}Be	0.100	57	111	9-20	[89]
^{40}Ca+^{9}Be	0	140	111	5-21	[78]	^{40}Ar+^{181}Ta	0.100	57	96	9-20	[89]
^{40}Ca+^{181}Ta	0	140	116	5-21	[78]	^{129}Xe+^{90}Zr	0.163	44	29	47-50	[90]
^{48}Ca+^{9}Be	0.167	140	202	5-22	[78]	^{129}Xe+^{197}Au	0.163	44	29	47-50	[90]
^{48}Ca+^{181}Ta	0.167	140	199	6-22	[78]						

网络结构

- 输入量：7 $[E, A_P, Z_P, A_t, Z_t, A_f, Z_f]$
- 隐藏层神经单元数目：46
- 输出量：1 [碎片截面$\sigma(A_f, Z_f)$]

BNN方法直接学习

训练对象：$\lg\sigma_{exp}$



BNN+FRACS

训练对象：$\lg\sigma_{exp} - \lg\sigma_{FRACS}$

在BNN+model方法中，需要首先给出理论模型本身的计算结果，并且模型本身的计算精度会影响所的构建网络。

在本研究过程中，需要给53个反应系统，6393个产物截面，如用统计模型计算需要花大量的时间，故经验参数化方法成为最优的选择，其中FRACS相对与EPAX3在考虑了靶核效应与能量依赖后，能够对100 MeV/u能量上的炮弹碎裂反应做出很好的计算结果。

Chinese Physics C Vol. 46, No. 7 (2022) 074104

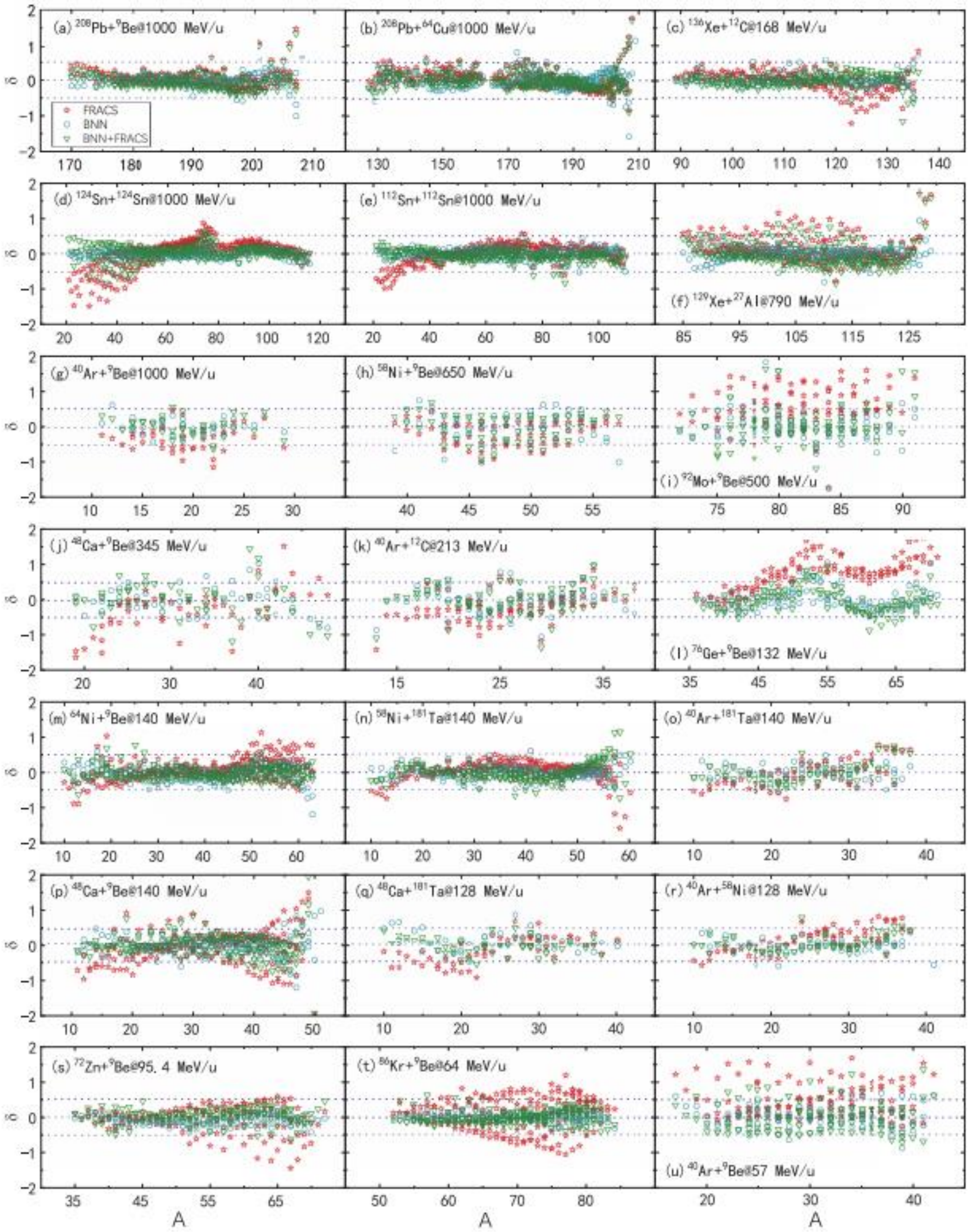
Precise machine learning models for fragment production in projectile fragmentation reactions using Bayesian neural networks*

Chun-Wang Ma(马春旺)[†] Xiao-Bao Wei(魏啸宝) Xi-Xi Chen(陈茜茜) Dan Peng(彭丹) Yu-Ting Wang(王玉廷)
Jie Pu(普洁) Kai-Xuan Cheng(程凯旋) Ya-Fei Guo(郭亚飞) Hui-Ling Wei(魏慧玲)
Institute of Particle and Nuclear Physics, College of Physics, Henan Normal University, Xinxiang 453007, China

利用贝叶斯神经网络机器学习方法高精度预测炮弹碎裂反应碎片截面

系统性检验模型对训练集的学习情况

- 同位素截面预测精度：定义$\delta = \log_{10}(\sigma_{th}/\sigma_{exp})$ 对比了21个反应系统中三种模型的计算精度。
- 对于整个训练集6393个数据点。FRACS,BNN,BNN+FRACS模型δ值介于-0.5到0.5之间的百分比分别为80.96%，95.40%，91.66%



PHYSICAL REVIEW C **78**, 024612 (2008)

Transport model simulations of projectile fragmentation reactions at 140 MeV/nucleon

M. Mocko,[1,2] M. B. Tsang,[2] D. Lacroix,[2,3] A. Ono,[4] P. Danielewicz,[2] W. G. Lynch,[2] and R. J. Charity[5]

利用余核的质量产额分布检验模型对训练集的学习情况

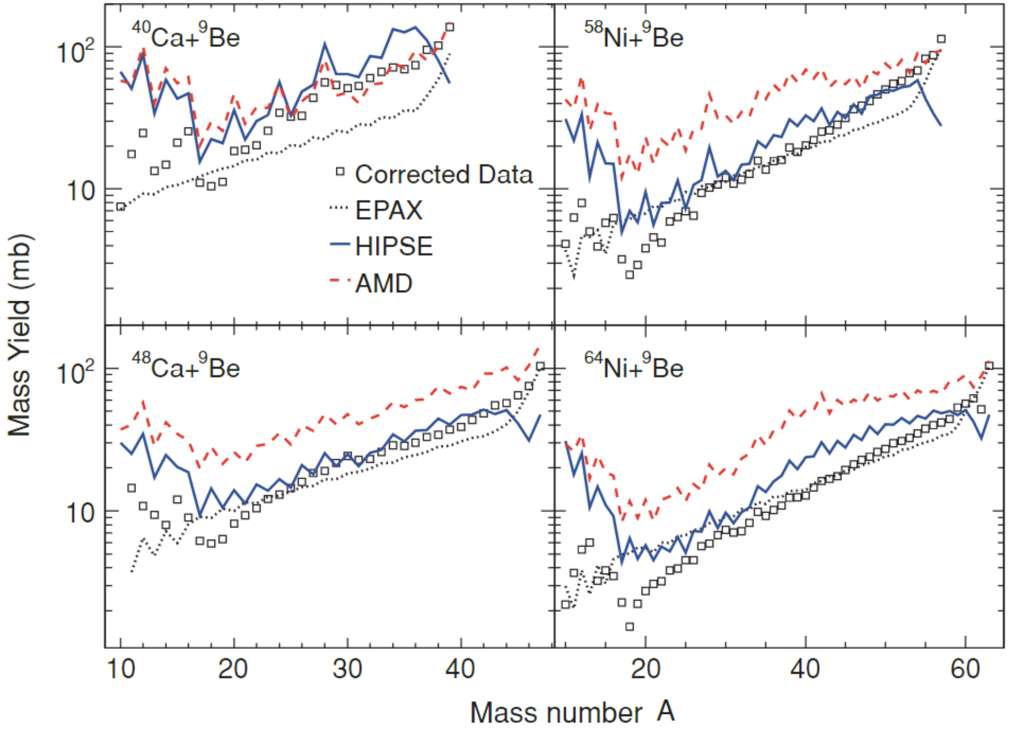


FIG. 7. (Color online) Previously published mass cross-section distributions [9,10] (open squares) for four reaction systems compared to predictions from two reaction models, HIPSE (solid lines) and AMD (dashed lines).

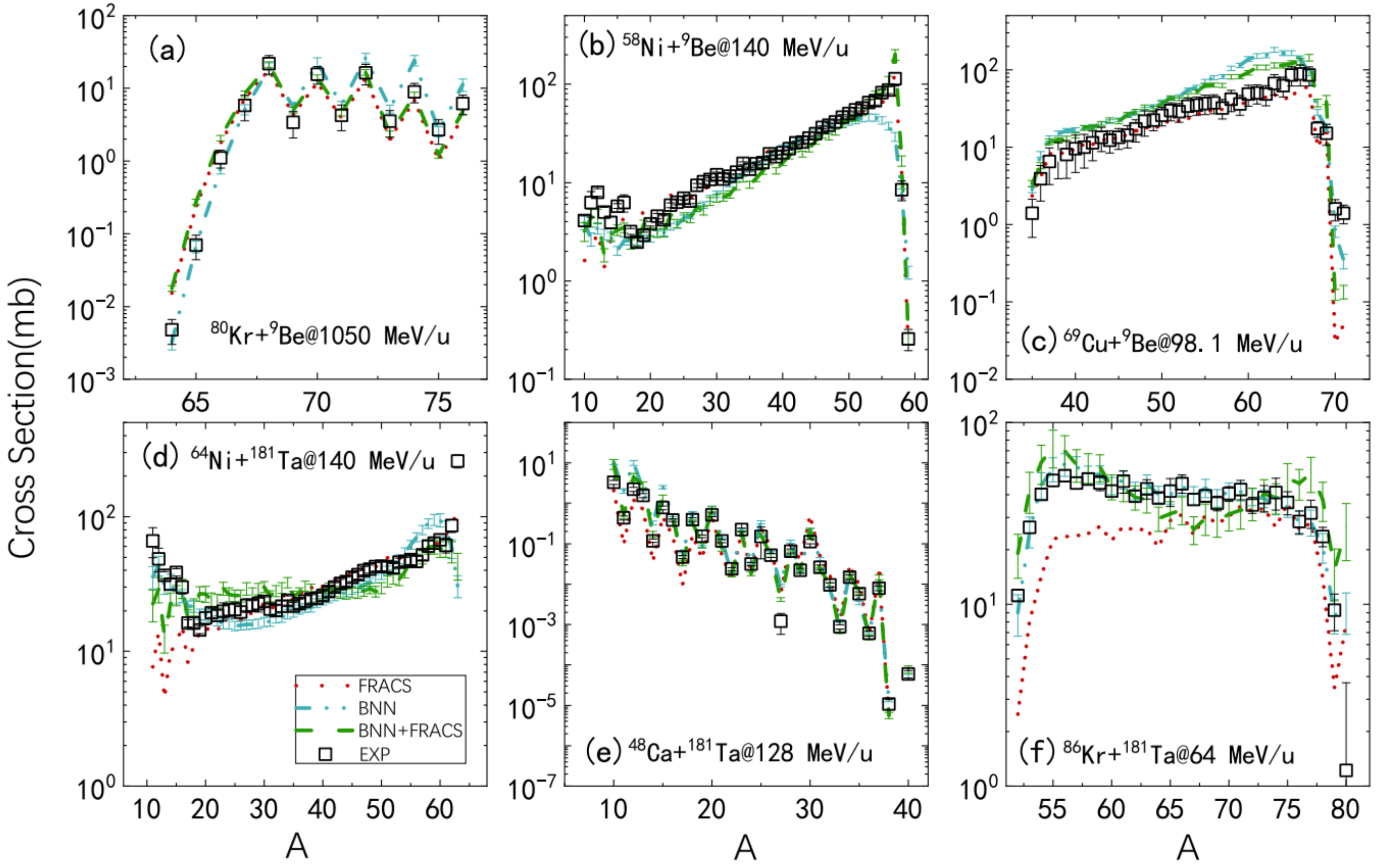


Fig. 3. (color online) Mass production distributions using the BNN (dash-dotted lines), BNN + FRACS (dashed lines), and FRACS (dotted lines) models compared to the measured data (squares) in reactions of 1050 MeV/u ^{80}Kr + ^{9}Be, 140 MeV/u ^{58}Ni + ^{9}Be, 98.1 MeV/u ^{69}Cu + ^{9}Be, 140 MeV/u ^{64}Ni + ^{181}Ta, 128 MeV/u ^{48}Ca + ^{181}Ta, and 64 MeV/u ^{86}Kr + ^{181}Ta. For the data source of the measured reactions, see Table 1.

EPL, **79** (2007) 12001
doi: 10.1209/0295-5075/79/12001
www.epljournal.org

Extrapolation of neutron-rich isotope cross-sections from projectile fragmentation

M. Mocko[1], M. B. Tsang[1(a)], Z. Y. Sun[1,2], L. Andronenko[1], M. Andronenko[1], F. Delaunay[1], M. A. Famiano[1], W. A. Friedman[3], V. Henzl[1], D. Henzlová[1], H. Hui[1], X. D. Liu[1], S. Lukyanov[1], W. G. Lynch[1], A. M. Rogers[1] and M. S. Wallace[1]

$$\sigma(A_f, Z_f) = C\exp\left[\frac{<B'> -8}{\tau}\right]$$

C is the normalization constant and τ is the inverse slope,

$$<B'> = (B - \varepsilon_{\text{pair}})/A_f,$$

$\varepsilon_{\text{pair}} = 1/2[(-1)^{N_f} + (-1)^{Z_f}]\varepsilon \cdot A_f^{-3/4}$ minimizes the observed odd-even variations

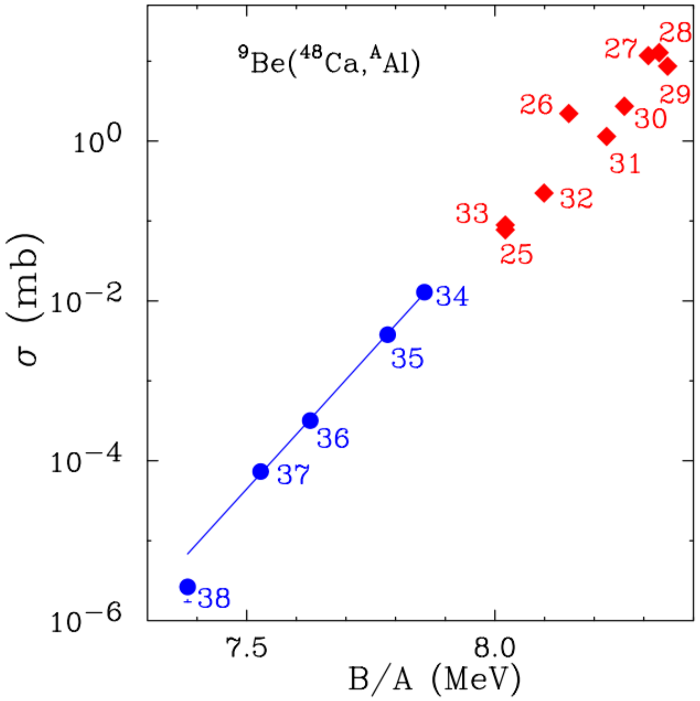


Fig. 2: (Color online) Fragmentation cross-sections of aluminum isotopes produced from ^{48}Ca + ^{9}Be reaction, plotted as a function of binding energy per nucleon. The mass numbers are labeled next to the symbols. The circles represent the five heaviest aluminum isotopes, ^{34}Al to ^{38}Al and the line is the best fits of $^{34-37}$Al isotopes using eq. (2). The lighter aluminum isotopes are denoted by the closed diamonds.

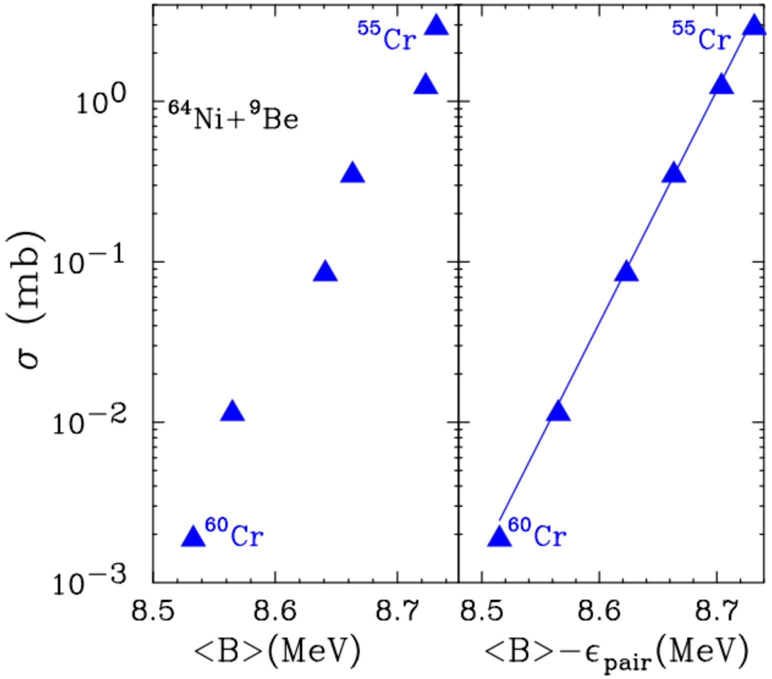
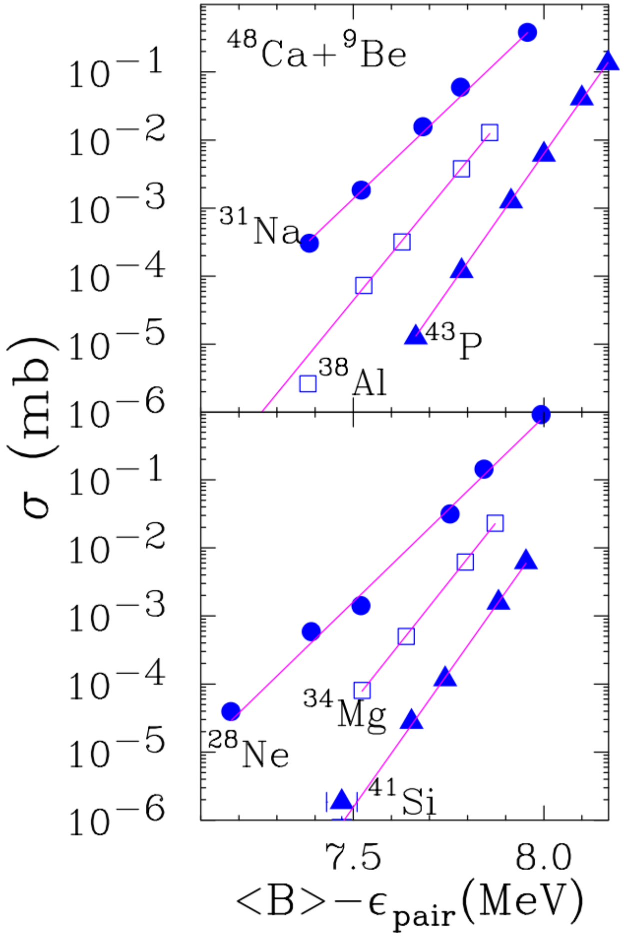


Fig. 4: (Color online) Fragmentation cross-section plotted as a function of average binding energy for neutron-rich chromium isotopes produced from the fragmentation of ^{64}Ni + ^{9}Be reaction. In the right panel, pairing energy has been subtracted from ^{56,58,60}Cr isotopes to minimize the odd-even effects. The line is the best fit through the data points using eq. (2) with the parameters listed in table 2.



背景介绍 研究方法 结果讨论 总结展望

PHYSICAL REVIEW C **76**, 041302(R) (2007)

Fragmentation cross sections and binding energies of neutron-rich nuclei

M. B. Tsang,[1] W. G. Lynch,[1] W. A. Friedman,[2] M. Mocko,[1] Z. Y. Sun,[3] N. Aoi,[4] J. M. Cook,[1] F. Delaunay,[1] M. A. Famiano,[1] H. Hui,[1] N. Imai,[4] H. Iwasaki,[5] T. Motobayashi,[4] M. Niikura,[6] T. Onishi,[5] A. M. Rogers,[1] H. Sakurai,[5] H. Suzuki,[5] E. Takeshita,[7] S. Takeuchi,[4] and M. S. Wallace[1]

$$\sigma(A_f, Z_f) = C\exp\left[\frac{< B' > -8}{\tau}\right]$$

C is the normalization constant and τ is the inverse slope,

$$< B' > = (B - \varepsilon_{\text{pair}})/A_f,$$

$\varepsilon_{\text{pair}} = 1/2[(-1)^{N_f} + (-1)^{Z_f}]\varepsilon \cdot A_f^{-3/4}$ minimizes the observed odd-even variations

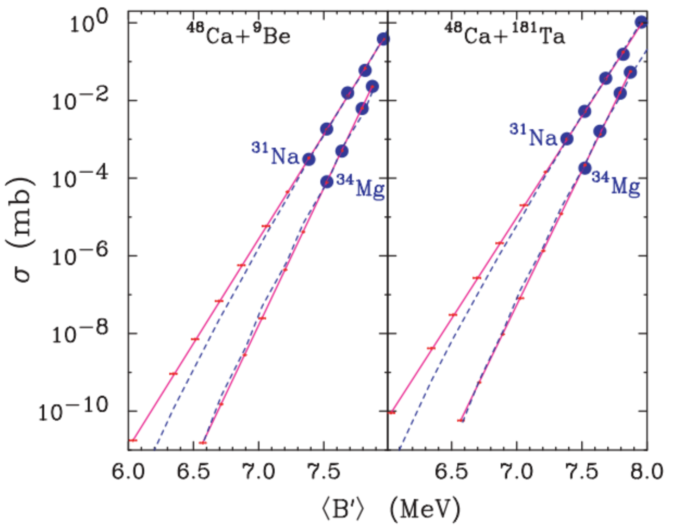


FIG. 3. (Color online) Fragment cross section [17] plotted as a function of $\langle B' \rangle$ for Mg and Na isotopes emitted in ^{48}Ca + ^{9}Be (left panel) and ^{48}Ca + ^{181}Ta (right panel). The dashed lines are best fits from the data using Eq. (1) and the solid lines are the best fit from Eq. (2). The solid lines end at the predicted cross sections of ^{39}Na and ^{40}Mg.

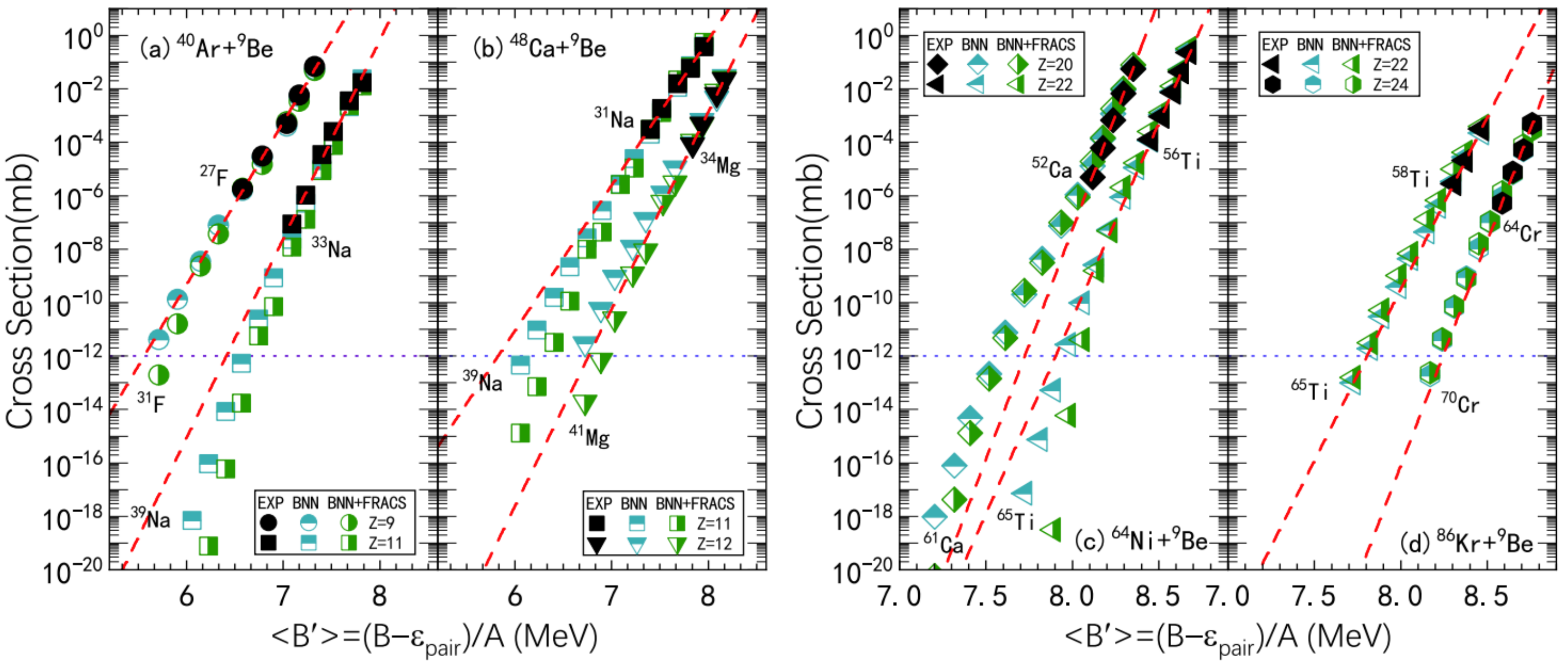


Fig. 4. (color online) Isotopic cross-section distributions of neutron-rich fragments produced in the 128 MeV/u ^{40}Ar + ^{9}Be [81], 140 MeV/u ^{48}Ca + ^{9}Be and ^{64}Ni + ^{9}Be [78], and 500 MeV/u ^{86}Kr + ^{9}Be [70] reactions plotted as a function of average binding per nucleon with pairing corrections $< B' >$. The dashed lines indicate the best fitting to the correlation from Eq. (11). The predicted cross sections by the BNN and BNN + FRACS models are denoted by half-full symbols with different colors (see text for details). For clarity, the $< B' >$ values for the fluorine (Z=9) and calcium isotopes (Z=20) are reduced by 0.3 and those for the magnesium (Z=12) and chromium (Z=24) isotopes are increased by 0.3.

使用截面与平均结合能的系统性关联检验模型的外推能力

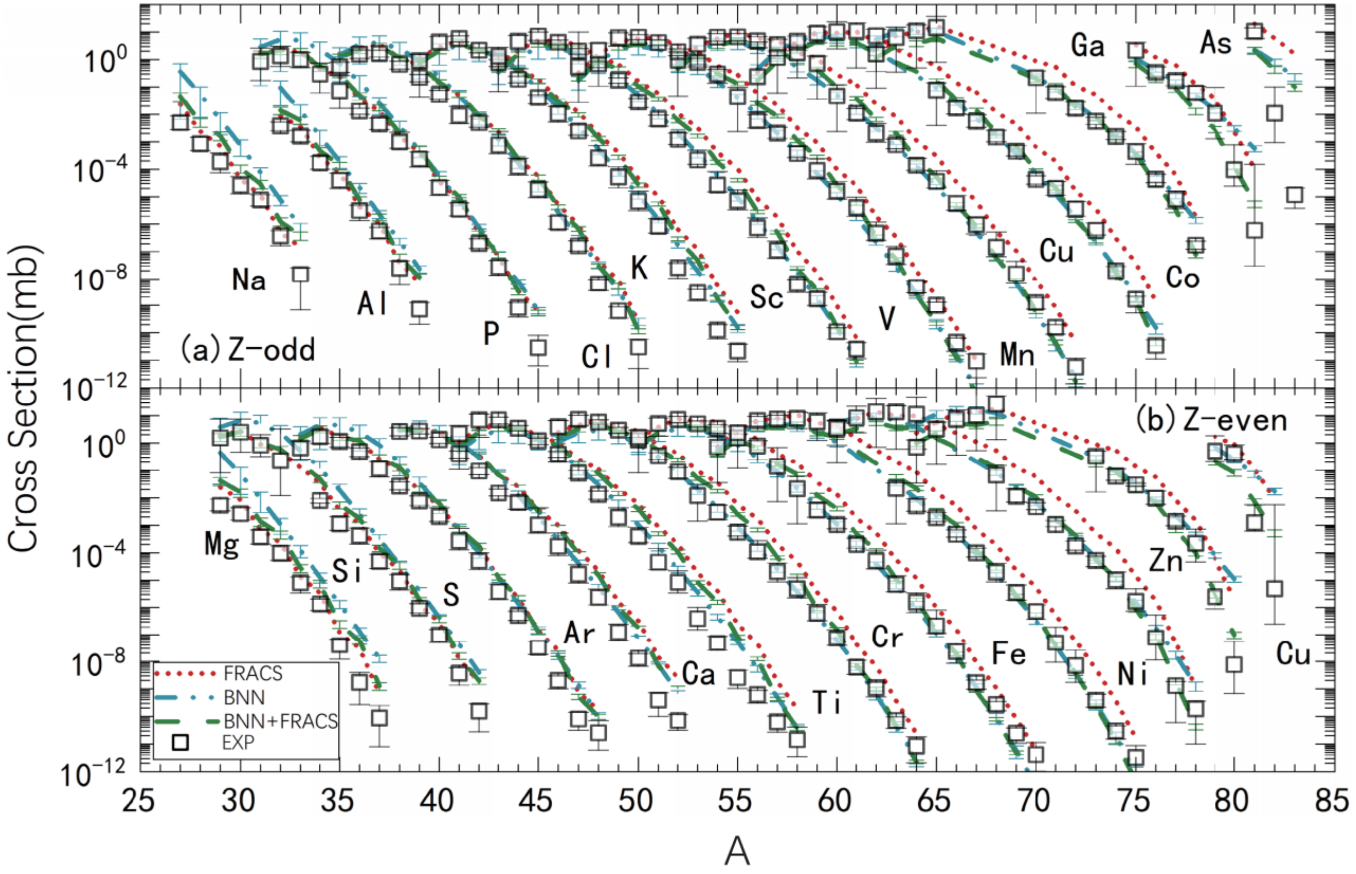
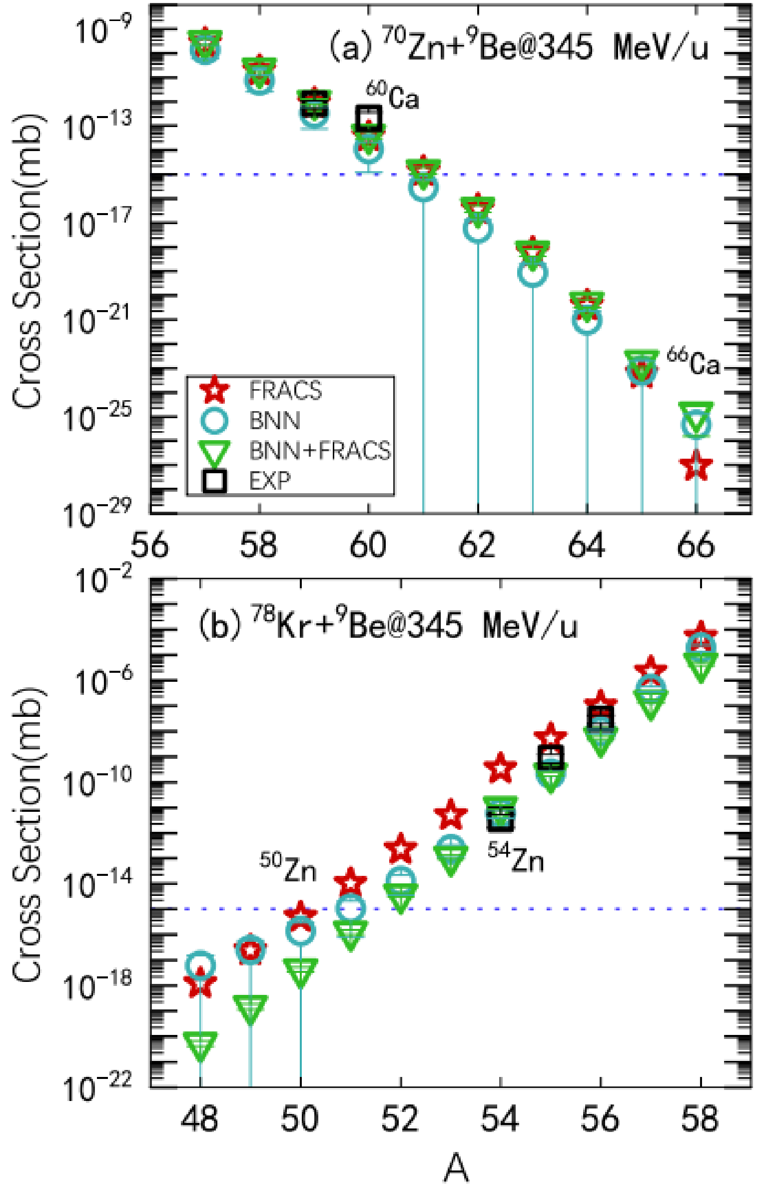


Fig. 5. (color online) Similar to Fig. 2 but for the 139 MeV/u ^{82}Se + ^{9}Be reaction (measured data taken from Ref. [100]).



对训练集之外的反应系统预测

- 丰中子炮弹核：$^{82}_{34}Se$，$^{70}_{30}Zn$
- 丰质子炮弹核：$^{78}_{36}Kr$

NUCL SCI TECH (2022) 33:155
https://doi.org/10.1007/s41365-022-01137-4

Check for updates

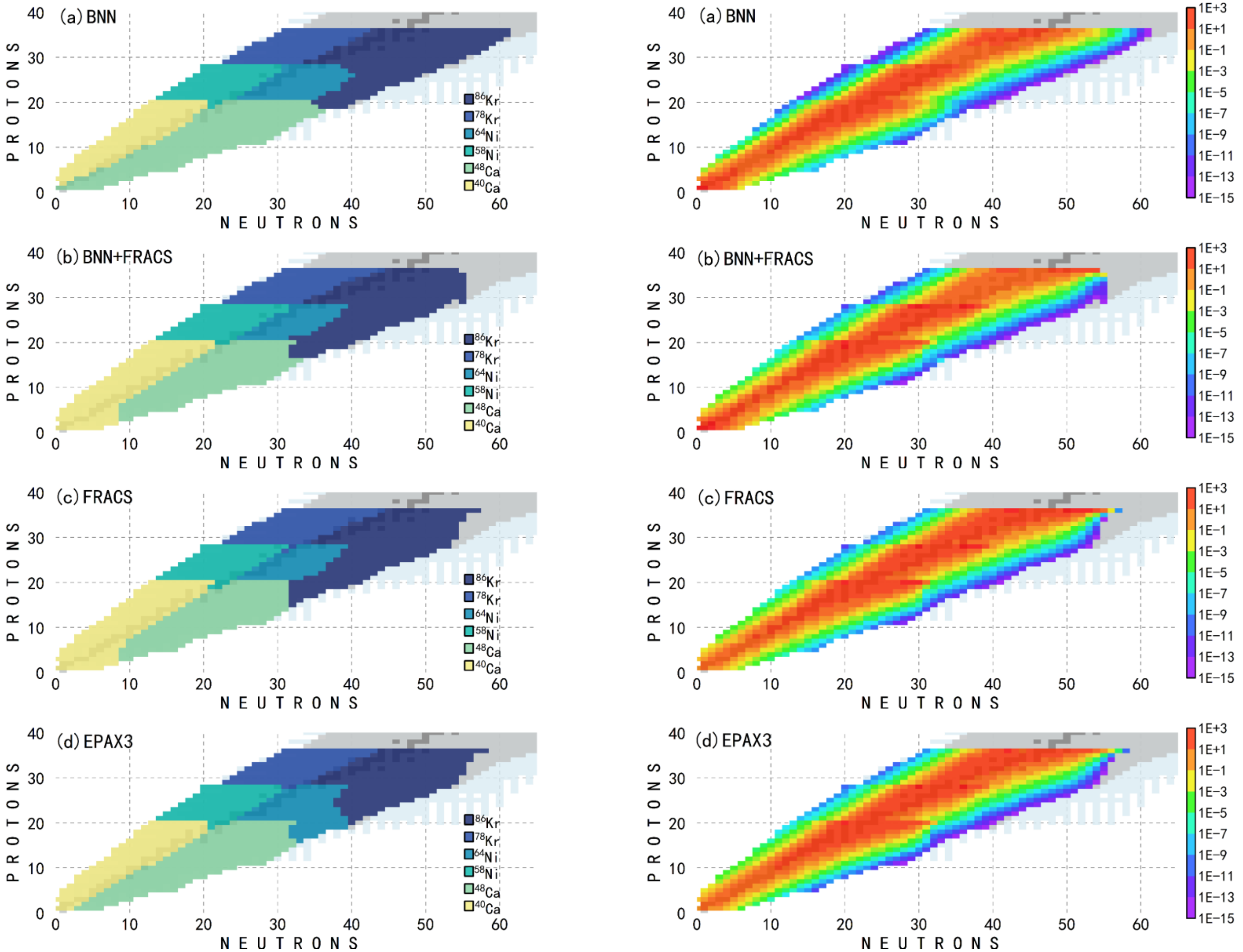
Multiple-models predictions for drip line nuclides in projectile fragmentation of ^{40,48}Ca, ^{58,64}Ni, and ^{78,86}Kr at 140 MeV/u

Xiao-Bao Wei[1] · Hui-Ling Wei[1] · Yu-Ting Wang[1] · Jie Pu[1] · Kai-Xuan Cheng[1] · Ya-Fei Guo[1] · Chun-Wang Ma[1]

探讨在新一代稀有核素工厂FRIB的极限探测条件下，利用典型稳定核束流炮弹碎裂反应中稀有核素产生截面的多模型预测结果

- 对于原子序数Z≤11的元素，在稀有核素产生截面的可探测下限(10^{-15}mb) 约束下，两侧滴线位置的核素都可以被探测到。
- 对于RIKEN新发现的钠元素的中子底线核^{39}Na,其预估的实验值与BNN模型的预测结果几乎相同，验证了所构建的炮弹碎裂反应模型的可靠性和精确预测能力。

Landscapes for predicted fragments with cross sections larger than 10^{-15}mb



近年来利用碎裂反应产生次级束，系统测量中等轻质量不稳定核束(C,N,O,Si)的碎裂数据逐渐丰富起来，受核结构影响，余核截面有明显的奇偶震荡现象。经过检验，由于目前版本BNN模型学习的数据为比^{40}Ar炮弹重的数据，不能很好的描述这些次级束碎裂的数据。

- 搜集整理不稳定核束碎裂反应截面，完善训练集更新神经网络版本。
- 探究学习不稳定核束余核截面与基本物理量如质量剩余，分离能等之间的系统学关联。

炮弹碎裂反应A+B的产物截面数据							
反应系统	E(MeV/A)	数据量	产物电荷范围	参考文献(DOI)	来源		
O18+C12	260	12	5-7	:10.1088/1674-1137/ac827c	HRIAF(RIBLL2/EFT)	已核对	2022
O17+C12	629	9	6-8	:10.1103/PhysRevC.65.064607	GSI	已核对	2002
O18+C12	573	10	6-8	:10.1103/PhysRevC.65.064607	GSI	已核对	
O19+C12	635	12	6-8	:10.1103/PhysRevC.65.064607	GSI	已核对	
O20+C12	585	15	6-8	:10.1103/PhysRevC.65.064607	GSI	已核对	
O21+C12	557	8	7-8	:10.1103/PhysRevC.65.064607	GSI	已核对	
C10,12-18+C12	390-430	31	5	:10.1103/PhysRevC.93.054601	GSI(R3B/LAND)	已核对	2016
B10-15+C12	390-430	22	4	:10.1103/PhysRevC.93.054601	GSI(R3B/LAND)	已核对	
C12+C12	450	10	3-6	:10.1103/PhysRevC.105.014611	GSI(R3B/LAND)		2022
N14+C12	450	15	4-7	:10.1103/PhysRevC.105.014611	GSI(R3B/LAND)		
O13+C12	397	10	4-7	:10.1103/PhysRevC.105.014611	GSI(R3B/LAND)		
O14+C12	349	13	4-7	:10.1103/PhysRevC.105.014611	GSI(R3B/LAND)		
O15+C12	308	15	4-8	:10.1103/PhysRevC.105.014611	GSI(R3B/LAND)		
O16+C12	450	17	4-8	:10.1103/PhysRevC.105.014611	GSI(R3B/LAND)		
O20+C12	415	25	4-8	:10.1103/PhysRevC.105.014611	GSI(R3B/LAND)		
O22+C12	414	30	4-8	:10.1103/PhysRevC.105.014611	GSI(R3B/LAND)		

近年来利用碎裂反应产生次级束，系统测量中等轻质量不稳定核束(C,N,O,Si)的碎裂数据逐渐丰富起来，受核结构影响，余核截面有明显的奇偶震荡现象。经过检验，由于目前版本BNN模型学习的数据为比^{40}Ar炮弹重的数据，不能很好的描述这些次级束碎裂的数据。

- 搜集整理不稳定核束碎裂反应截面，完善训练集更新神经网络版本。
- 探究学习不稳定核束余核截面与基本物理量如质量剩余，分离能等之间的系统学关联。

感谢各位老师指正！