



日中科学技術交流協会  
2024年6月18日

# 原子核物理学での日中共同研究 -理研を舞台にした今昔-

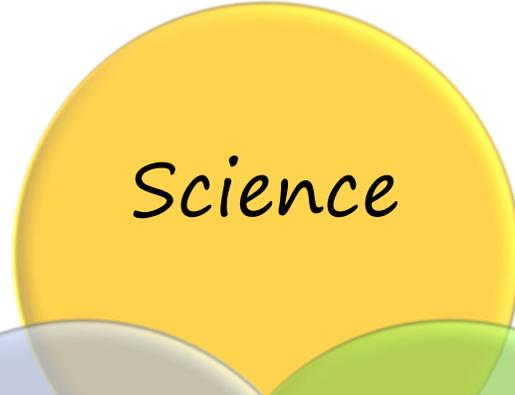
理化学研究所  
仁科加速器科学研究センター

櫻井 博儀

元素は宇宙でどうつくられたのか？

人類は元素を自在につくることができるのか？

中性子過剰な放射性同元素



元素周期表

|   |    |    |  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|---|----|----|--|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1 | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |    |
| 1 | H  |    |  |    |    |    |    |    |    |    |    |    |    |    |    |    |    | He |
| 2 | Li | Be |  |    |    |    |    |    |    |    |    |    | B  | C  | N  | O  | F  | Ne |
| 3 | Na | Mg |  |    |    |    |    |    |    |    |    |    | Al | Si | P  | S  | Cl | Ar |
| 4 | K  | Ca | Sc   | Ti | V  | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr |
| 5 | Rb | Sr | Y  | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I  | Xe |
| 6 | Cs | Ba | * Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 7 | Fr | Ra | * Ra Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

→ 超重元素      理論が合成した元素      実験が合成した元素

■ 自然界で発見された元素  
■ 人工合成により発見された元素

新元素生成

重イオン加速器  
同位元素分離技術



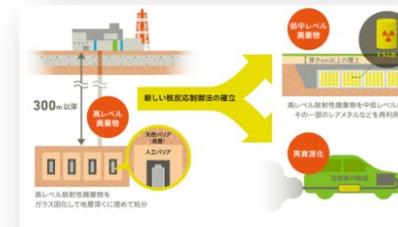
世界人類への貢献

宇宙利用半導体試験

重イオン育種

医療用RI製造

高レベル放射性廃棄物



# RIビームファクトリー：世界に冠絶する重イオン加速器施設

“超重元素研究”

重イオン加速器施設の国際研究拠点

陽子数  $Z$  最大の原子核

**核融合**  $\sim 5$  MeV/u

ニホニウム(113番元素)  
→119番元素

KEK: KISS

多様な超ウラン原子核

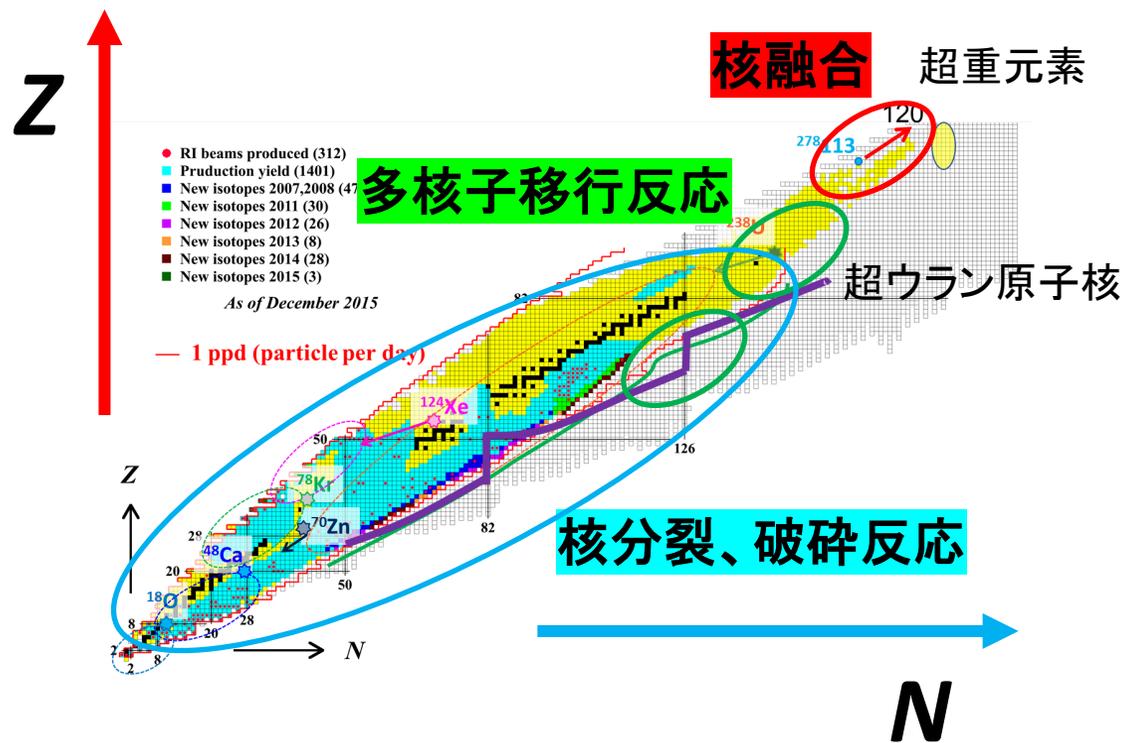
**多核子移行反応**  $\sim 10$  MeV/u

旧施設 (1986-)

新施設 (2006-)

“エキゾチック原子核”

中性子数  $N$  最大の原子核  
中性子過剰な原子核



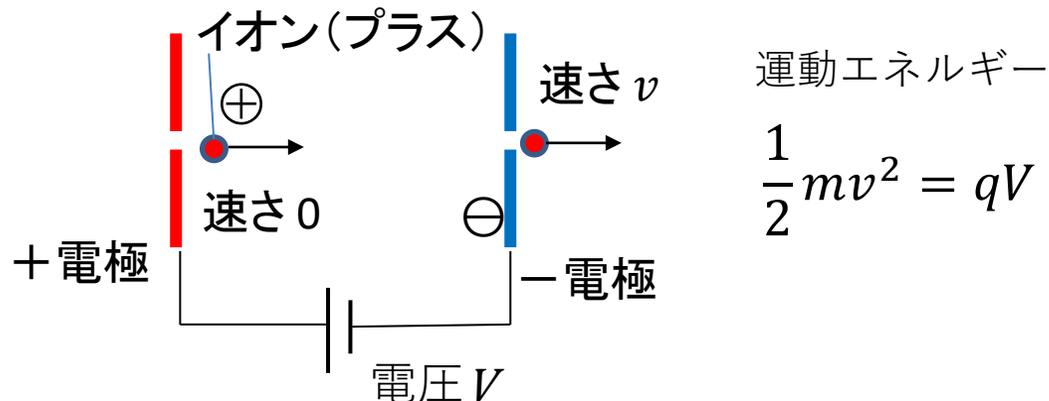
**核分裂、破砕反応**

345 MeV/u

# 加速器を利用した元素変換：現代の錬金術

加速器：イオンを加速させて、イオンにエネルギーを与える装置

水素、炭素、ウランなどのイオンを電気力で加速する



エネルギーをもったイオンを元素に照射して、反応を起こし、元素の陽子や中性子の数を変える

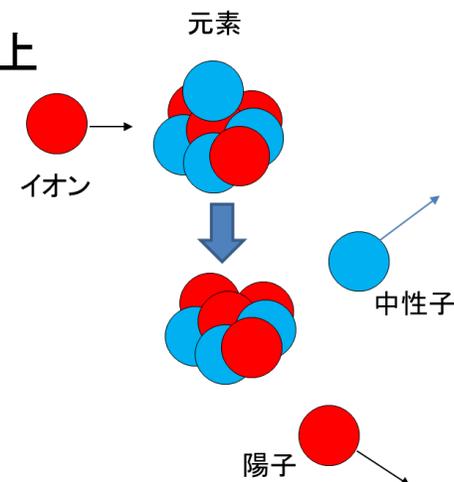
人工元素変換に必要なエネルギーは温度換算で100億度以上  
(太陽の内部の温度は約1500万度)

原子炉では中性子をくっつける反応のみ

加速器では多種多様なイオンを加速でき、  
エネルギーも可変

ニホニウム

亜鉛イオン(原子番号30) + ビスマス元素(原子番号83)  
= ニホニウム(原子番号113 (=30+83))

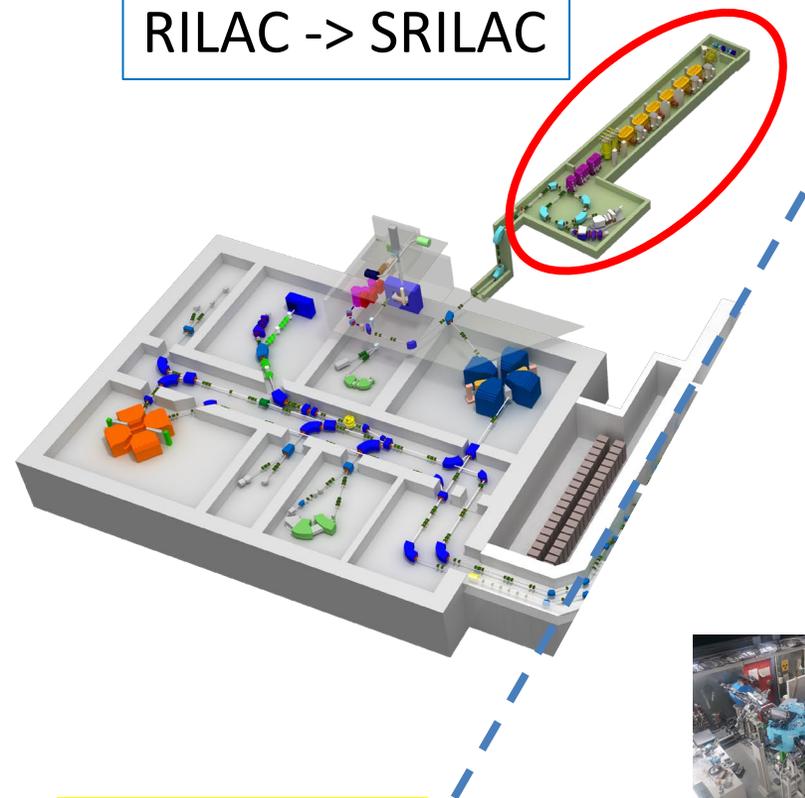


# 超重元素探索

“超重元素研究”

陽子数  $Z$  最大の原子核

RILAC -> SRILAC

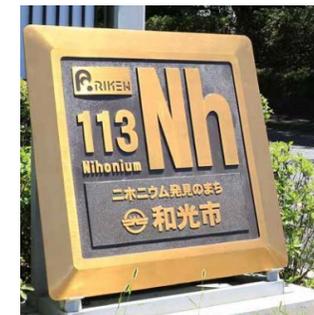


旧施設 (1986-)

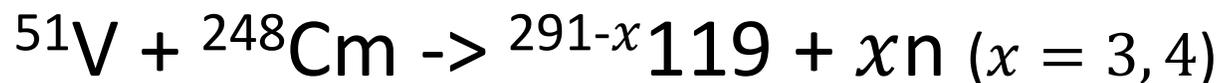
113番元素「ニホニウム」 (冷たい核融合反応)



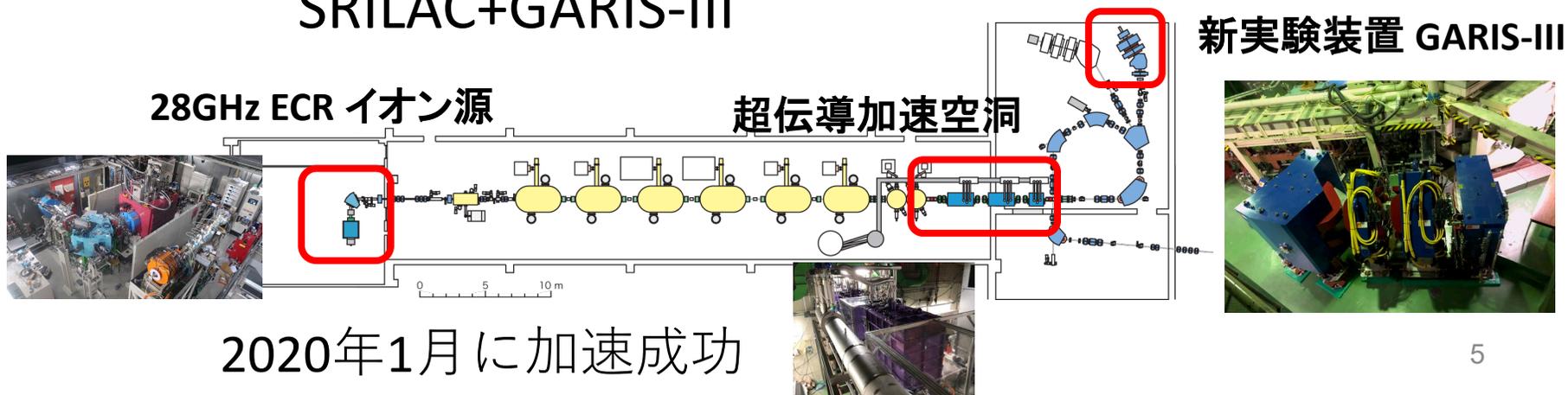
RILAC+GARIS



119番元素探索 (熱い核融合反応)



SRILAC+GARIS-III



# RI ビームファクトリー

“エキゾチック原子核”



超伝導リングサイクロトロン (SRC)  
 世界最強  
 エネルギー 345 MeV/u  
 ウランの全運動エネルギー  
 80 GeV (ギネス登録)

1次ビーム

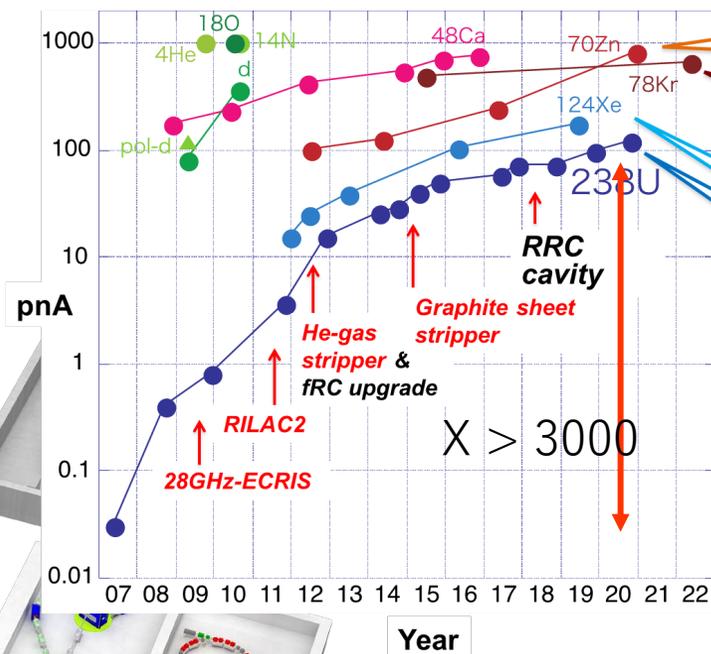
標的

新施設 (2006-)

RIビーム

200-250 MeV/u

超伝導RIビーム生成分離装置  
 世界最高のRI収集効率  
 核分裂、破砕反応



X > 3000

**<sup>70</sup>Zn: 788 pA  
=> 19.0 kW**

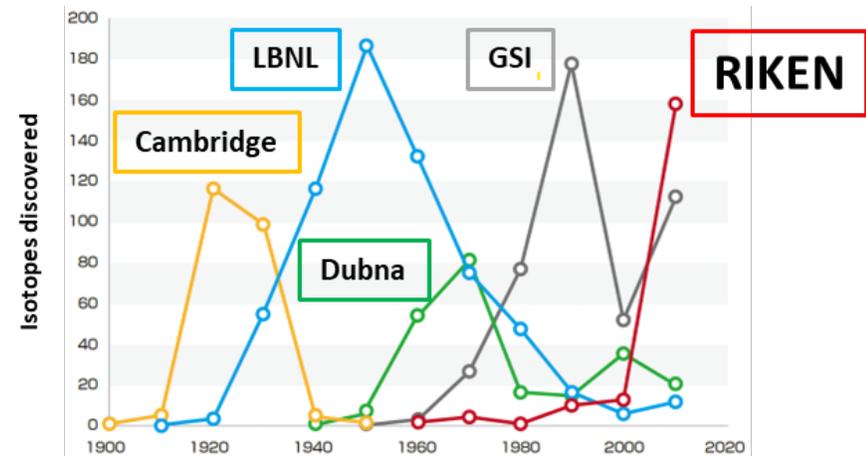
**<sup>78</sup>Kr: 690 pA  
=> 18.6 kW**

**<sup>124</sup>Xe: 173 pA  
=> 7.4 kW**

**<sup>238</sup>U: 117 pA  
=> 9.6 kW**

2007年稼働以来、  
 ウランビーム強度  
 3000倍以上  
 2013年以降  
 可用性 95%以上

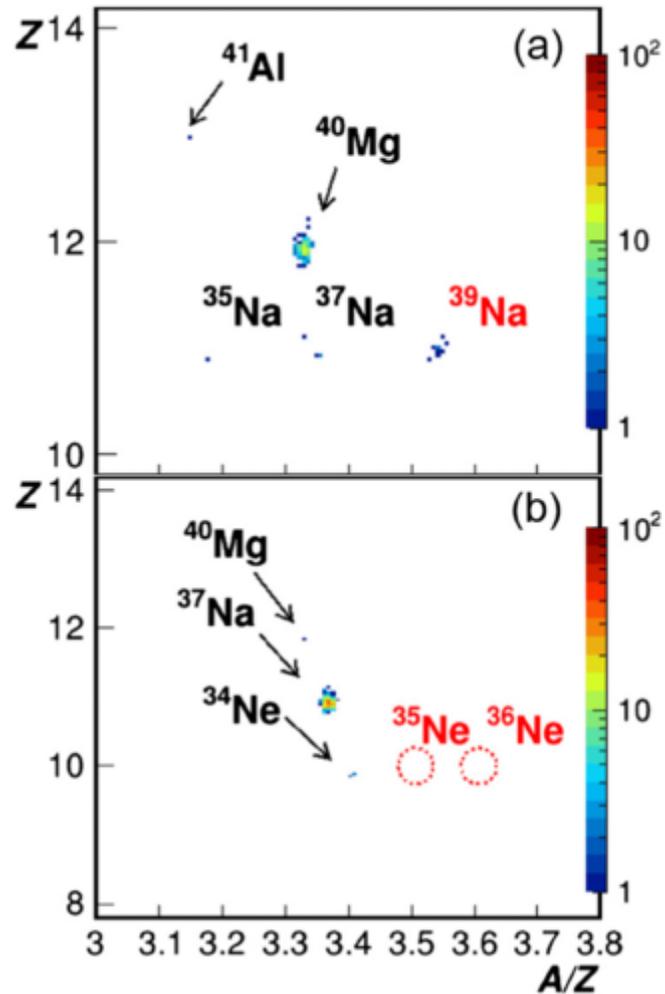
2007年稼働以来  
 新同位元素170核種以上



# $^{39}\text{Na}$ の生成と発見

## $^{39}\text{Na}$ の生成と発見

Ahn et al., PRL 129, 212502 (2022)



## A New Isotope of Sodium - Periodic Table of Videos

Prof. Martyn Poliakoff, University of Nottingham in UK

[https://www.youtube.com/watch?v=vI0\\_DElyTZU](https://www.youtube.com/watch?v=vI0_DElyTZU)

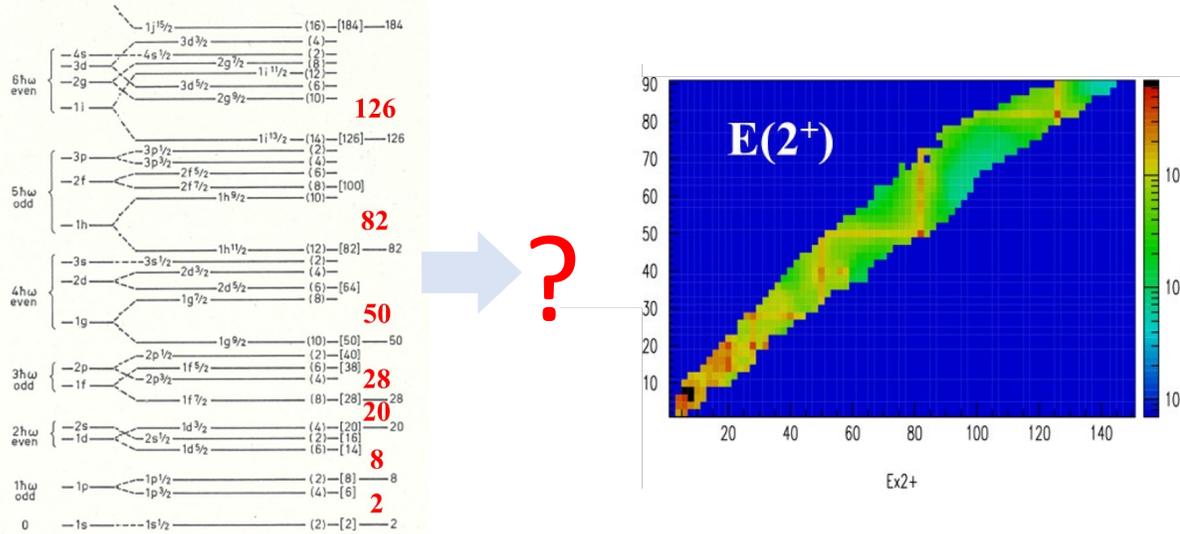


2023/04/04 リリース 14万回視聴

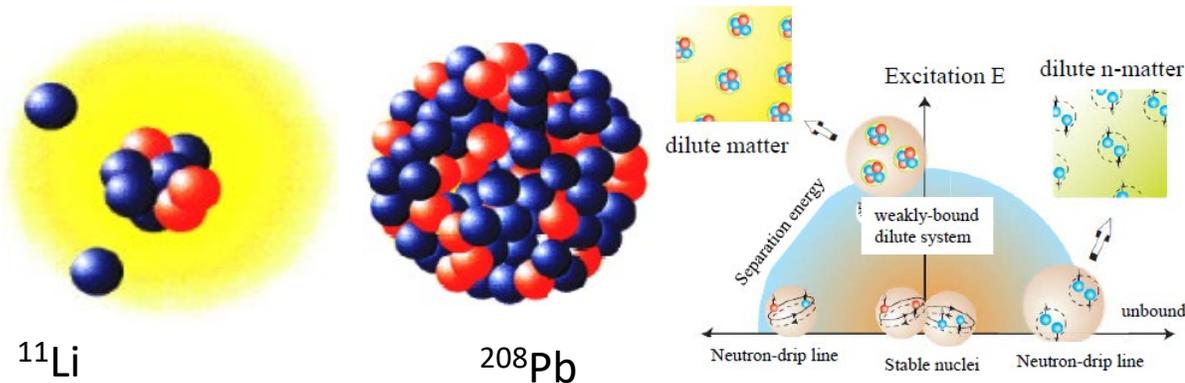
See also "Probing the Limits of Nuclear Existence" Blumenfeld, *Physics* 15, 177 (Nov. 16, 2022)

# エキゾチック原子核のテーマ

## 殻進化：魔法数の喪失と新魔法数



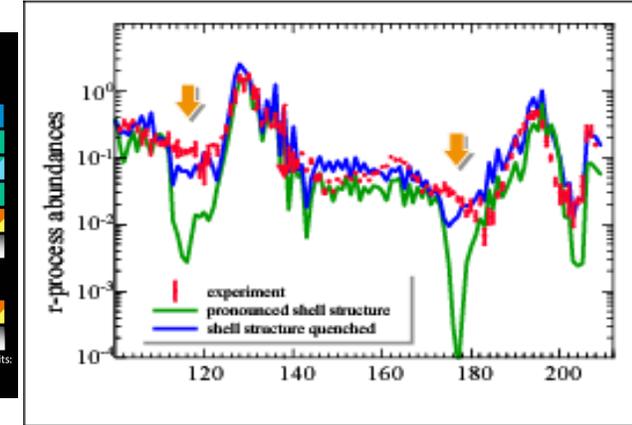
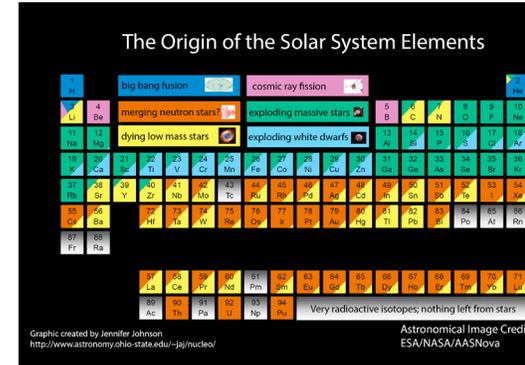
## 核子相関と凝縮 (核物質のBEC-BCSクロスオーバー)



$^{11}\text{Li}$   
(two neutron halo)

$^{208}\text{Pb}$

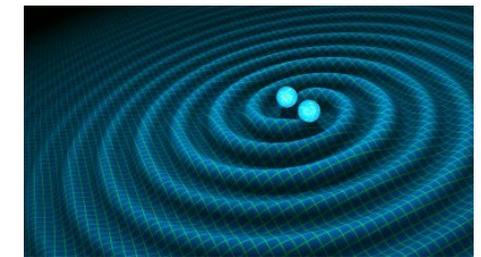
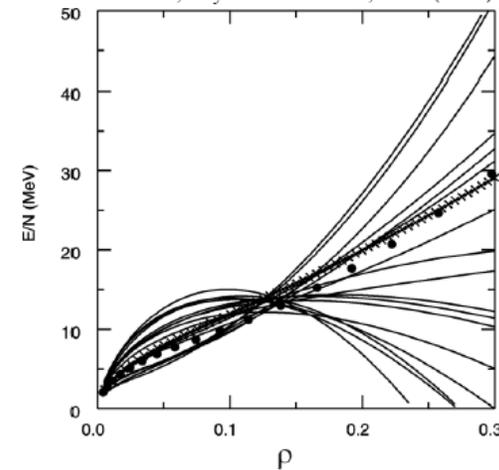
## 鉄からウランに至る宇宙での元素合成過程



Jennifer Johnson

<http://www.astronomy.ohio-state.edu/~jaj/nucleo/>

## 中性子過剰物質の状態方程式 超新星爆発、中性子星、重力波解析

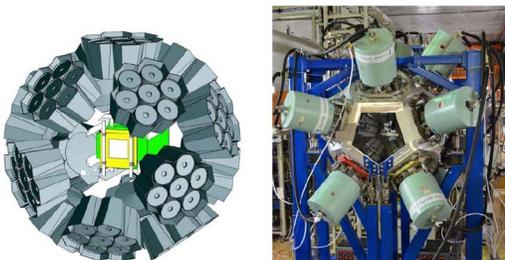


gravitation wave  
from neutron-star mergers

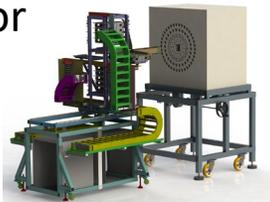
Space.com

# 国際共同研究

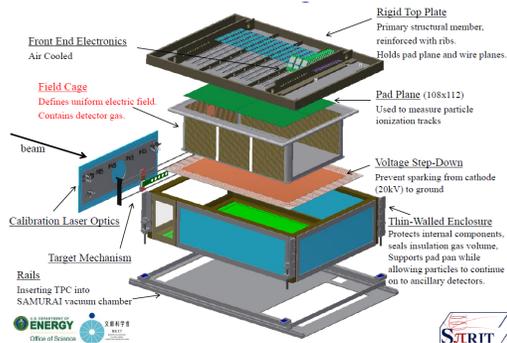
EURICA (2011-2016):  
EUroball-RIKEN Cluster Array



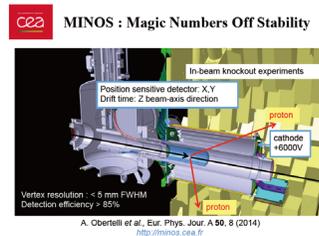
BRIKEN(2017-2021):  
He-3 detector array for  
beta-delayed neutron



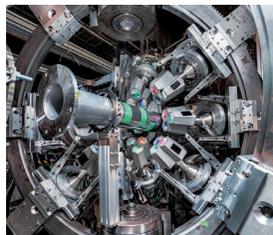
SpiRIT TPC (2015-):  
heavy-ion collision program for EOS



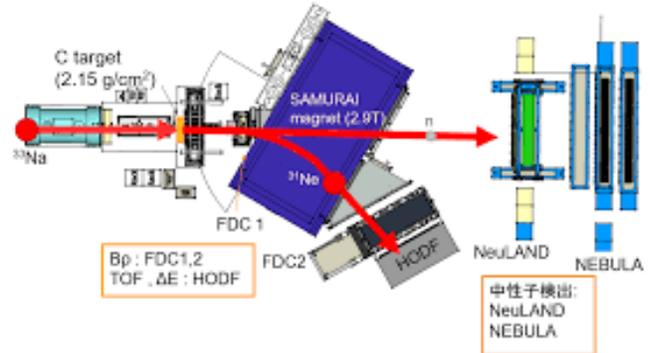
SEASTAR (2014-2017):  
thick liq. H<sub>2</sub> + TPC+NaI  
for in-beam gamma  
spectroscopy



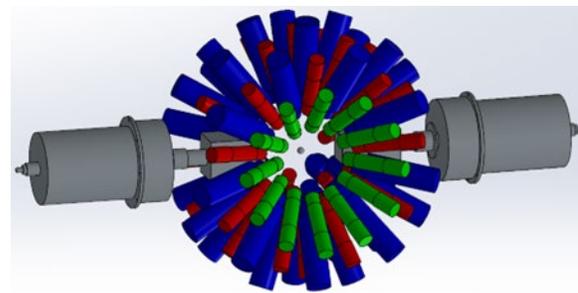
HiCARI (2019-2020):  
Tracking Ge detectors  
for in-beam gamma  
spectroscopy



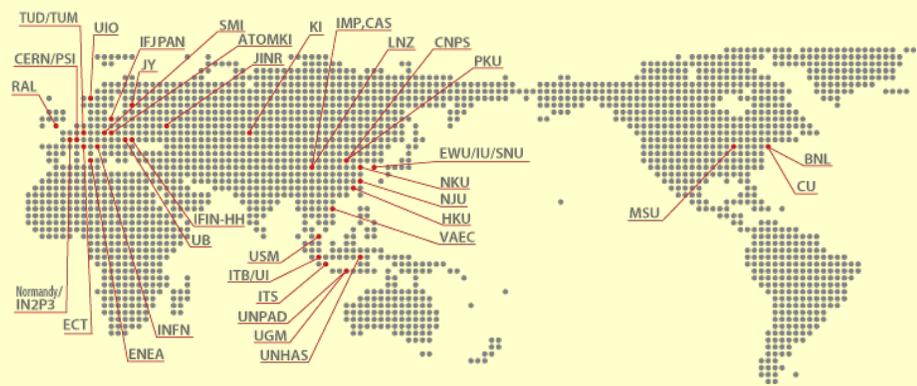
SAMURAI (2012-):  
neutron detectors + CsI+...  
for neutron correlation



IDATEN (2021-):  
84 LaBr<sub>3</sub> (Ce) + 2 Cover Ge detectors  
to measure lifetime of excited states



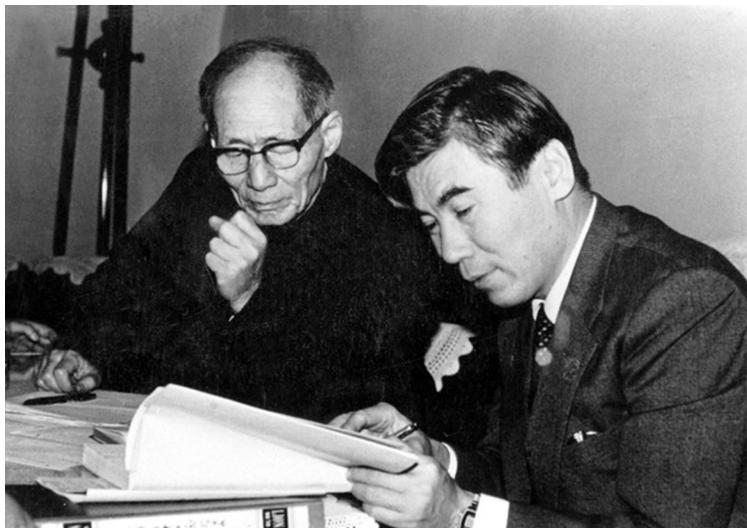
MoU with  
41 institutions and universities in 19 countries



1. 中国科学院・近代物理研究所
2. 北京大学
3. その他

# 中国科学院・近代物理研究所 (IMP) (1)

上坪宏道氏のIMP訪問。IMP所長Yang氏 (1979年2月)

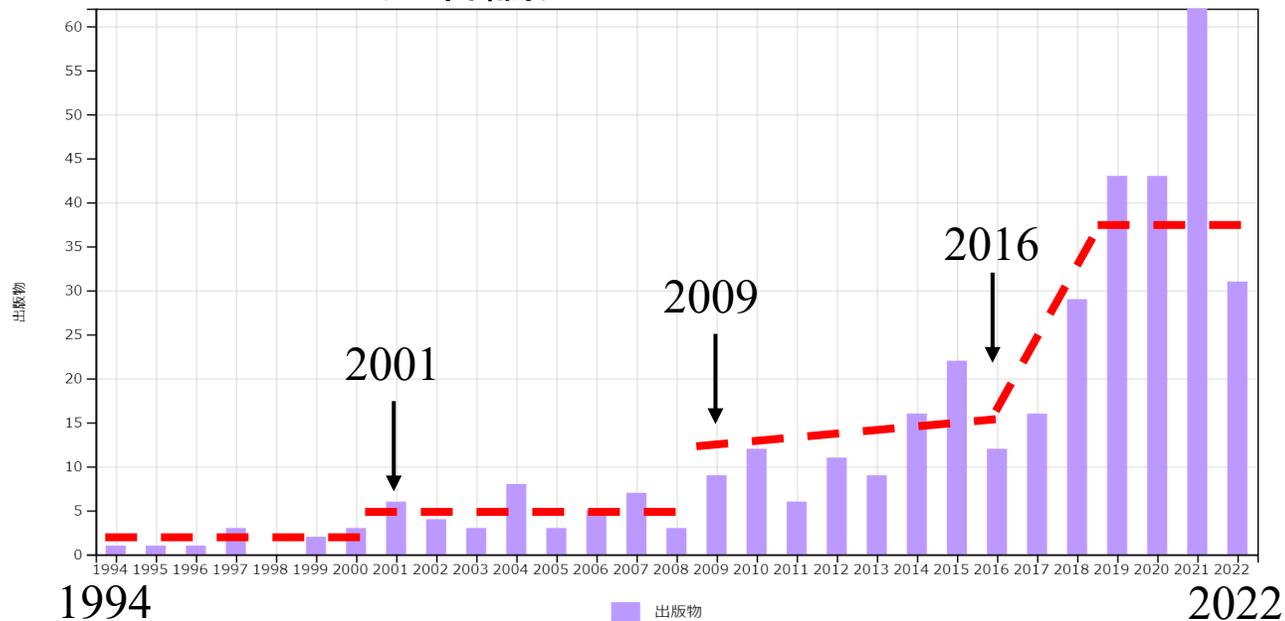


第一回日中加速器科学シンポジウム (1980年9月)



第一回日中加速器科学シンポジウム 於 熱海 新熱海ホテル S55. 9. 8~11

1994-2022の共著論文



## IMP

HIRFL (1988-)サイクロトン施設

不安定核ビーム (1992-) CSR (2008-)

HIAF (2025-) シンクロトン施設

## RIKEN

RARF (1987-) サイクロトン施設

不安定核ビーム (1989-)

RIBF (2007-) 高度化(202X-)

# 中国科学院·近代物理研究所(IMP)(2)

## 質量測定 IMP CSRe と理研 Rare-RI Ring (2011-)

PRL 106, 112501 (2011)

PHYSICAL REVIEW LETTERS

week ending  
18 MARCH 2011

### Direct Mass Measurements of Short-Lived $A = 2Z - 1$ Nuclides $^{63}\text{Ge}$ , $^{65}\text{As}$ , $^{67}\text{Se}$ , and $^{71}\text{Kr}$ and Their Impact on Nucleosynthesis in the $rp$ Process

X. L. Tu,<sup>1,2</sup> H. S. Xu,<sup>1,\*</sup> M. Wang,<sup>1</sup> Y. H. Zhang,<sup>1</sup> Yu. A. Litvinov,<sup>3,4,1</sup> Y. Sun,<sup>5,1</sup> H. Schatz,<sup>6</sup> X. H. Zhou,<sup>1</sup> Y. J. Yuan,<sup>1</sup> J. W. Xia,<sup>1</sup> G. Audi,<sup>7</sup> K. Blaum,<sup>3</sup> C. M. Du,<sup>1,2</sup> P. Geng,<sup>1,2</sup> Z. G. Hu,<sup>1</sup> W. X. Huang,<sup>1</sup> S. L. Jin,<sup>1,2</sup> L. X. Liu,<sup>1,2</sup> Y. Liu,<sup>1</sup> X. Ma,<sup>1</sup> R. S. Mao,<sup>1</sup> B. Mei,<sup>1</sup> P. Shuai,<sup>8</sup> Z. Y. Sun,<sup>1</sup> H. Suzuki,<sup>9</sup> S. W. Tang,<sup>1,2</sup> J. S. Wang,<sup>1</sup> S. T. Wang,<sup>1,2</sup> G. Q. Xiao,<sup>1</sup> X. Xu,<sup>1,2</sup> T. Yamaguchi,<sup>10</sup> Y. Yamaguchi,<sup>11</sup> X. L. Yan,<sup>1,2</sup> J. C. Yang,<sup>1</sup> R. P. Ye,<sup>1,2</sup> Y. D. Zang,<sup>1,2</sup> H. W. Zhao,<sup>1</sup> T. C. Zhao,<sup>1</sup> X. Y. Zhang,<sup>1</sup> and W. L. Zhan<sup>1</sup>

PHYSICAL REVIEW LETTERS 128, 152701 (2022)

### First Application of Mass Measurements with the Rare-RI Ring Reveals the Solar $r$ -Process Abundance Trend at $A = 122$ and $A = 123$

H. F. Li,<sup>1,2,3,4</sup> S. Naimi,<sup>3,\*</sup> T. M. Sprouse,<sup>5</sup> M. R. Mumpower,<sup>5</sup> Y. Abe,<sup>3</sup> Y. Yamaguchi,<sup>3</sup> D. Nagae,<sup>3,†</sup> F. Suzuki,<sup>3,‡</sup> M. Wakasugi,<sup>3</sup> H. Arakawa,<sup>6</sup> W. B. Dou,<sup>6</sup> D. Hamakawa,<sup>6</sup> S. Hosoi,<sup>6</sup> Y. Inada,<sup>6</sup> D. Kajiki,<sup>6</sup> T. Kobayashi,<sup>6</sup> M. Sakaue,<sup>6</sup> Y. Yokoda,<sup>6</sup> T. Yamaguchi,<sup>6</sup> R. Kagesawa,<sup>7</sup> D. Kamioka,<sup>7</sup> T. Moriguchi,<sup>7</sup> M. Mukai,<sup>7,8</sup> A. Ozawa,<sup>7</sup> S. Ota,<sup>8,‖</sup> N. Kitamura,<sup>8</sup> S. Masuoka,<sup>8</sup> S. Michimasa,<sup>8</sup> H. Baba,<sup>3</sup> N. Fukuda,<sup>3</sup> Y. Shimizu,<sup>3</sup> H. Suzuki,<sup>3</sup> H. Takeda,<sup>3</sup> D. S. Ahn,<sup>3,9</sup> M. Wang,<sup>1</sup> C. Y. Fu,<sup>1</sup> Q. Wang,<sup>1</sup> S. Suzuki,<sup>1</sup> Z. Ge,<sup>1,‡</sup> Yu. A. Litvinov,<sup>10</sup> G. Lorusso,<sup>11,12</sup> P. M. Walker,<sup>12</sup> Zs. Podolyak,<sup>12</sup> and T. Uesaka<sup>3</sup>



HIRFL CSRe



RIBF Rare-RI-Ring

## 原子核質量の評価、データベース:

AME2016, 2020, NUBASE2016, 2020

Chinese Physics C, 2017, 2021

Chinese Physics C Vol. 45, No. 3 (2021) 030003

The AME2020 atomic mass evaluation \*\*

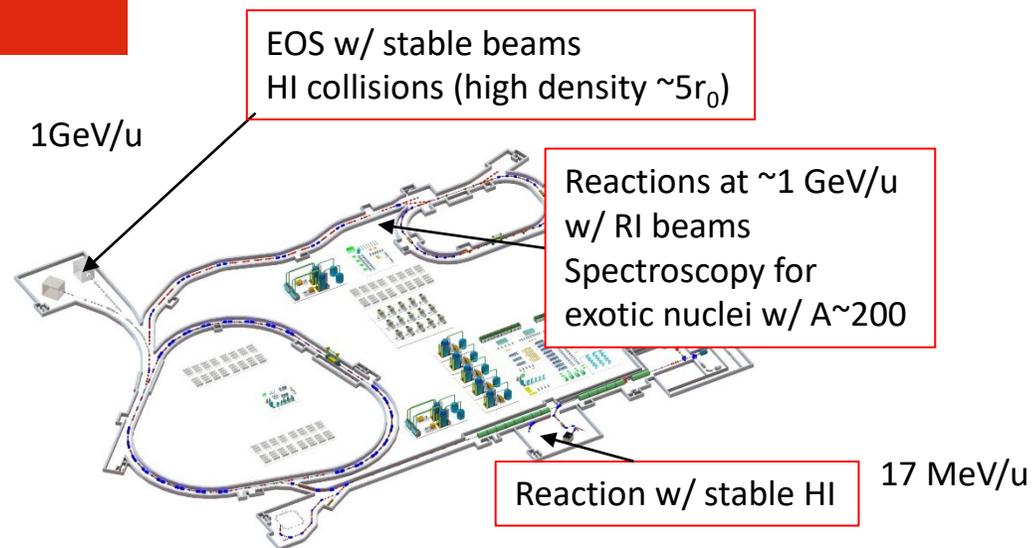
(II). Tables, graphs and references

Meng Wang (王猛)<sup>1,2,\*</sup> W.J. Huang(黄文嘉)<sup>1,3,4,5</sup> F.G. Kondev<sup>6</sup> G. Audi (欧乔治)<sup>5</sup> S. Naimi<sup>7</sup>

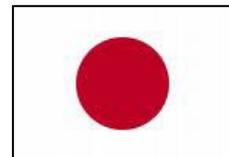
# 近代物理研究所の将来施設



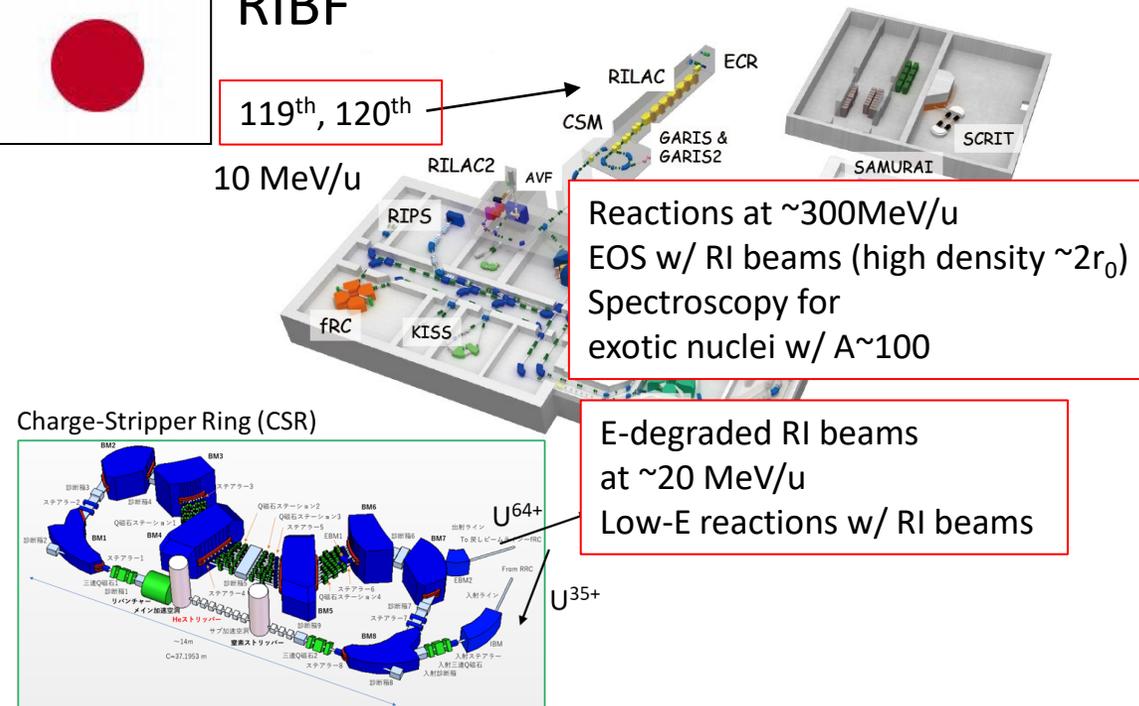
HIAF



HIAF:シンクロトロン施設(建設中)  
広東省惠州市  
高エネルギー重イオンビーム



RIBF



RIBF:サイクロトロン施設  
中間エネルギー重イオンビーム

ビームのエネルギーが異なり、相補的

# 北京大学・原子核物理学科

## 仁科スクール(2008年～)

学部学生の受入れ・実習(2週間/年)

大学院生の受入れ 1人/年

## 崩壊分光、反応研究

PHYSICAL REVIEW LETTERS 122, 212502 (2019)

### Proton Shell Evolution below $^{132}\text{Sn}$ : First Measurement of Low-Lying $\beta$ -Emitting Isomers in $^{123,125}\text{Ag}$

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PHYSICAL REVIEW LETTERS 131, 242501 (2023)

Editors' Suggestion

Featured in Physics

### Observation of the Exotic $0_2^+$ Cluster State in $^8\text{He}$

Z. H. Yang<sup>1,2,\*</sup>, Y. L. Ye<sup>1,3</sup>, B. Zhou<sup>3,4,5</sup>, H. Baba,<sup>2</sup> R. J. Chen,<sup>6</sup> Y. C. Ge,<sup>1</sup> B. S. Hu<sup>1</sup>, H. Hua,<sup>1</sup> D. X. Jiang,<sup>1</sup> M. Kimura,<sup>2,5,7</sup> C. Li,<sup>2</sup> K. A. Li,<sup>6</sup> J. G. Li,<sup>1</sup> Q. T. Li,<sup>1</sup> X. Q. Li,<sup>1</sup> Z. H. Li,<sup>1</sup> J. L. Lou<sup>1</sup>, M. Nishimura,<sup>2</sup> H. Otsu,<sup>2</sup> D. Y. Pang,<sup>8</sup> W. L. Pu,<sup>1</sup> R. Qiao,<sup>1</sup> S. Sakaguchi,<sup>2,9</sup> H. Sakurai,<sup>2</sup> Y. Satou,<sup>10</sup> Y. Togano,<sup>2</sup> K. Tshoo,<sup>10</sup> H. Wang,<sup>2,11</sup> S. Wang,<sup>2</sup> K. Wei,<sup>1</sup> J. Xiao,<sup>1</sup> F. R. Xu<sup>1</sup>, X. F. Yang<sup>1</sup>, K. Yoneda,<sup>2</sup> H. B. You,<sup>1</sup> and T. Zheng<sup>1</sup>

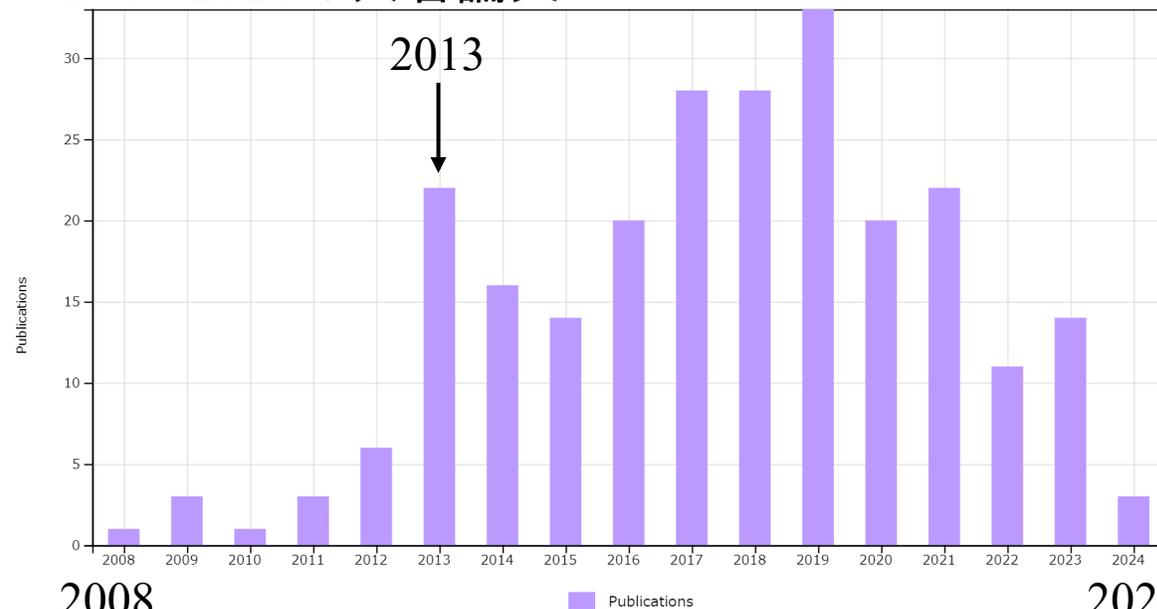
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2009年北京大-仁科スクール

## 2008-2024の共著論文



2008

2024

## C12: NEWS

### IUPAP YOUNG SCIENTIST PRIZE IN NUCLEAR PHYSICS 2019

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Xiaofei Yang



*“For her realization of a unique laser spectroscopy technique to be applied at the PF-type radioactive isotope beam facility and for the substantial contribution to the development and operation of the laser spectroscopy devices at ISOLDE which measure the basic properties of exotic atomic nuclei with high resolution and efficiency.”*

Xiaofei Yang received her Ph.D. degree in nuclear physics from Peking University, China, in 2014. Her Ph.D. research work was conducted at RIKEN Nishina Center, Japan, and focused on the development of a novel laser spectroscopy technique OROCHI until the completion of the associated first physics experiment. She worked at RIKEN for 3 years as an International Program Association joint student. She then joined the nuclear moment group at IKS, KU Leuven, Belgium, as a postdoctoral researcher. Her work there was mainly devoted to the laser spectroscopy experiments COLLAPS and CRIS to study the structure of exotic isotopes. She had been a local member of CERN-ISOLDE from 2016 till 2017, supported by Junior Mobility Program of KU Leuven and FWO Grant for a Long-Stay in Europe, Belgium. Since October 2017, she is a faculty member at Peking University, China. Her main research interests are the development of high-precision and high sensitivity laser spectroscopy techniques and the associated structure studies of exotic nuclei.

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# その他

## 香港大学

仁科スクール(2016年-)

ガンマ分光、質量測定

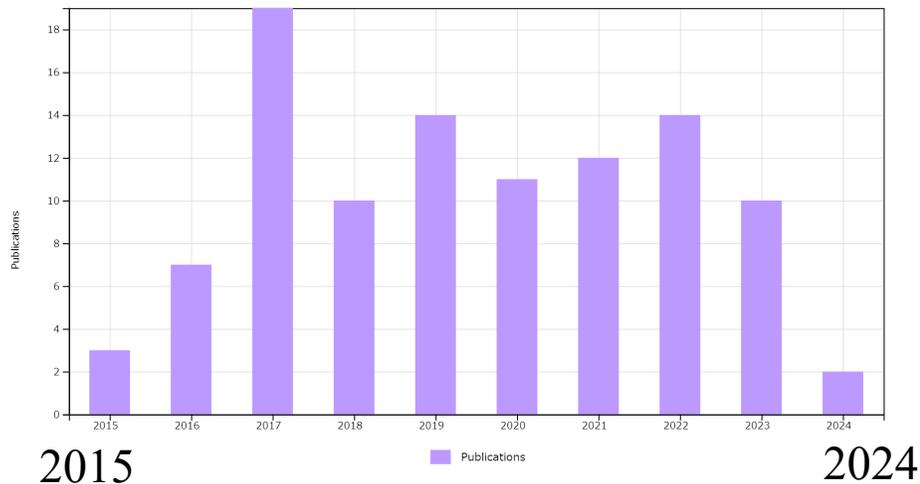
PHYSICAL REVIEW LETTERS **123**, 142501 (2019)

### Quasifree Neutron Knockout from $^{54}\text{Ca}$ Corroborates Arising $N=34$ Neutron Magic Number

S. Chen<sup>1,2,3,\*</sup>, J. Lee,<sup>1,†</sup> P. Doornenbal,<sup>2</sup> A. Obertelli,<sup>4,2,5</sup> C. Barbieri,<sup>6</sup> Y. Chazono,<sup>7</sup> P. Navrátil,<sup>8</sup> K. Ogata,<sup>7</sup> T. Otsuka,<sup>2,9,10</sup> F. Raimondi,<sup>11</sup> V. Somà,<sup>4</sup> Y. Utsuno,<sup>12,9</sup> K. Yoshida,<sup>12,7</sup> H. Baba,<sup>2</sup> F. Browne,<sup>2</sup> D. Calvet,<sup>4</sup> F. Château,<sup>4</sup> N. Chiga,<sup>2</sup> A. Corsi,<sup>4</sup> M. L. Cortés,<sup>2</sup> A. Delbart,<sup>4</sup> J.-M. Gheller,<sup>4</sup> A. Giganon,<sup>4</sup> A. Gillibert,<sup>4</sup> C. Hilaire,<sup>4</sup> T. Isobe,<sup>2</sup> J. Kahlbow,<sup>5,2</sup> T. Kobayashi,<sup>13</sup> Y. Kubota,<sup>2,14</sup> V. Lapoux,<sup>4</sup> H. N. Liu,<sup>4,15,5</sup> T. Motobayashi,<sup>2</sup> I. Murray,<sup>16,2</sup> H. Otsu,<sup>2</sup> V. Panin,<sup>2</sup> N. Paul,<sup>4</sup> W. Rodriguez,<sup>17,2</sup> H. Sakurai,<sup>2,18</sup> M. Sasano,<sup>2</sup> D. Steppenbeck,<sup>2</sup> L. Stuhl,<sup>14</sup> Y. L. Sun,<sup>4,5</sup> Y. Togano,<sup>19</sup> T. Uesaka,<sup>2</sup> K. Wimmer,<sup>18</sup> K. Yoneda,<sup>2</sup> N. Achouri,<sup>4</sup> O. Aktas,<sup>15</sup> T. Aumann,<sup>5,20</sup> L. X. Chung,<sup>21</sup> F. Flavigny,<sup>16</sup> S. Franchoo,<sup>16</sup> I. Gašparić,<sup>22,2</sup> R.-B. Gerst,<sup>23</sup> J. Gibelin,<sup>24</sup> K. I. Hahn,<sup>25</sup> D. Kim,<sup>25,2</sup> T. Koizumi,<sup>18</sup> Y. Kondo,<sup>26</sup> P. Koseoglou,<sup>5,20</sup> C. Lehr,<sup>5,2</sup> B. D. Linh,<sup>21</sup> T. Lokotko,<sup>1</sup> M. MacCormick,<sup>16</sup> K. Moschner,<sup>23</sup> T. Nakamura,<sup>26</sup> S. Y. Park,<sup>25,2</sup> D. Rossi,<sup>5</sup> E. Sahin,<sup>27</sup> D. Sohrler,<sup>28</sup> P.-A. Söderström,<sup>5</sup> S. Takeuchi,<sup>26</sup> H. Törnqvist,<sup>5,20</sup> V. Vaquero,<sup>29</sup> V. Wagner,<sup>5,2</sup> S. Wang,<sup>30</sup> V. Werner,<sup>5</sup> X. Xu,<sup>1</sup> H. Yamada,<sup>26</sup> D. Yan,<sup>30</sup> Z. Yang,<sup>2</sup> M. Yasuda,<sup>26</sup> and L. Zanetti<sup>5,2</sup>

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## 清華大学

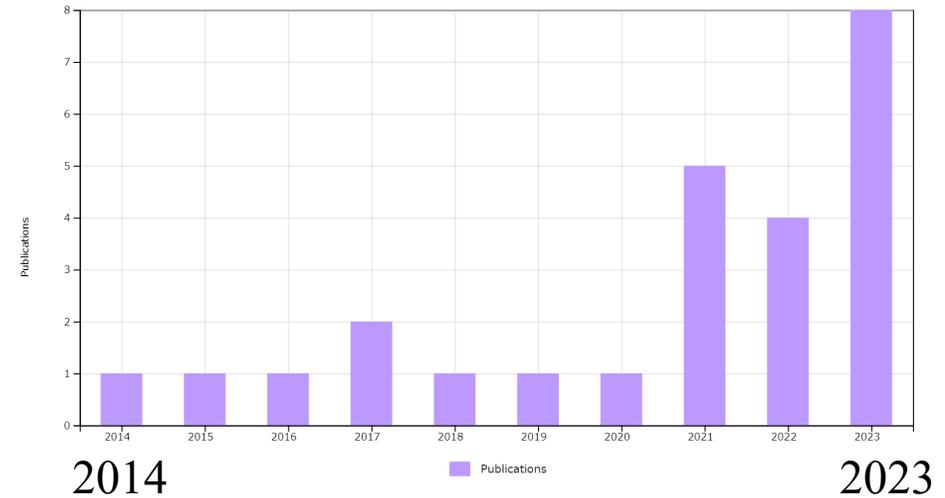
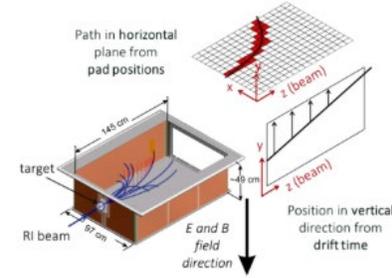
重イオン衝突反応、状態方程式

PHYSICAL REVIEW LETTERS **126**, 162701 (2021)

### Probing the Symmetry Energy with the Spectral Pion R

J. Estee,<sup>1,2,\*</sup> W. G. Lynch<sup>1,2,†</sup> C. Y. Tsang,<sup>1,2</sup> J. Barney,<sup>1,2</sup> G. Jhang,<sup>1</sup> M. B. Tsang,<sup>1,2,‡</sup> R. Wang,<sup>1</sup> M. Kaneko,<sup>3,4</sup> J. W. Lee,<sup>5</sup> T. Isobe,<sup>3,8</sup> M. Kurata-Nishimura,<sup>3</sup> T. Murakami,<sup>3,4,‡</sup> D. S. Ahn,<sup>3</sup> L. Atar,<sup>6,7</sup> T. Aumann,<sup>6,7</sup> H. Baba,<sup>3</sup> K. Boretzky,<sup>7</sup> J. Brzychczyk,<sup>8</sup> G. Cerizza,<sup>1</sup> N. Chiga,<sup>3</sup> N. Fukuda,<sup>3</sup> I. Gasparic,<sup>9,3,6</sup> B. Hong,<sup>5</sup> A. Horvat,<sup>6,7</sup> K. Ieki,<sup>10</sup> N. Inabe,<sup>3</sup> Y. J. Kim,<sup>11</sup> T. Kobayashi,<sup>12</sup> Y. Kondo,<sup>13</sup> P. Lasko,<sup>14</sup> H. S. Lee,<sup>11</sup> Y. Leifels,<sup>7</sup> J. Lukasik,<sup>14</sup> J. Manfredi,<sup>1,2</sup> A. B. McIntosh,<sup>15</sup> P. Morfouace,<sup>1</sup> T. Nakamura,<sup>13</sup> N. Nakatsuka,<sup>3,4</sup> S. Nishimura,<sup>3</sup> H. Otsu,<sup>3</sup> P. Pawłowski,<sup>14</sup> K. Pelczar,<sup>8</sup> D. Rossi,<sup>6</sup> H. Sakurai,<sup>3</sup> C. Santamaria,<sup>1</sup> H. Sato,<sup>3</sup> H. Scheit,<sup>6</sup> R. Shane,<sup>1</sup> Y. Shimizu,<sup>3</sup> H. Simon,<sup>7</sup> A. Snoch,<sup>16</sup> A. Sochocka,<sup>8</sup> T. Sumikama,<sup>3</sup> H. Suzuki,<sup>3</sup> D. Suzuki,<sup>3</sup> H. Takeda,<sup>3</sup> S. Tangwancharoen,<sup>1</sup> H. Toernqvist,<sup>6,7</sup> Y. Togano,<sup>10</sup> Z. G. Xiao,<sup>17</sup> S. J. Yennello,<sup>15,18</sup> and Y. Zhang<sup>17</sup>

(SπRIT Collaboration)



# まとめ

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理研を舞台にした加速器科学の日中協力は1979年より  
中国科学院・近代物理研究所が中心  
現在は、原子核物理学(実験)での共同研究

2008年から北京大学、  
2014、15年から香港大学、清華大学、  
などとの連携が急速に発展

理論研究も日中共同研究が進んでいる