安徽理工大学**"**基础物理研究中心**"**成立大会暨学术报告会 安徽 淮南**, 2024.05.22-05.25** 安徽理工大学"基础物理研究中心"成立大会暨学术报告会 文理工大学"基础物理研究中心"成立大会暨学术报告会 大学"基础物理研究中心"成立大会暨学术报告会 _Center Fundamental Physics, AUST Center for Fundamental Physics, AUST $\begin{CD} \textbf{E} \overline{W} \mathfrak{R} \textbf{H} \textbf{L} \textbf{U} \textbf{R} \textbf{L} \mathfrak{R} \textbf{E} \textbf{H} \textbf{L} \textbf{L} \textbf{S}^{\text{c}} \textbf{F} \textbf{R} \textbf{S} \textbf{S}^{\text{c}} \textbf{A} \textbf{S} \textbf{S} \textbf{S} \textbf{S} \textbf{S} \textbf{S}^{\text{c}} \textbf{A} \textbf{S} \textbf{S} \textbf{S} \textbf{S} \textbf{S} \textbf{S} \text$ <mark>中心"成立大会暨学术报告会</mark>
4.05.22-05.25
_{可β衰变寿命的理论描述} 工大会暨学术报告会

r-过程研究中原子核质量与β衰变寿命的理论描述 $\mathcal{C}_{\mathcal{C}_{\mathcal{C}_{\mathcal{C}_{\mathcal{C}_{\mathcal{C}_{\mathcal{C}}}}}}}$ r-过程研究中原子核质量与β衰变寿命的理论描述
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安徽大学 物理与光电工程学院 2024年05月23日 The $\mu_{\rm F}$

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Outline

1 Introduction

- ² Nuclear physics inputs
- \star Nuclear masses * Nuclear β-decay half-lives ³ r-process simulations Center for Fundamental Physics, AUST **O** Introduction
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 \star Nuclear masses
 \star Nuclear β-decay half-lives
 \bullet r-process simulations
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Nuclear masses * K^Ruclear β-decay half-lives ⁸ Center for Fundamental Physics, AUST **Introduction**

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- $W_{S/C_{S}}$ **4** Summary and perspectives
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Origin of elements

How were the heavy elements from iron to uranium made? DISCOVER:

The 11 greatest unanswered questions of Physics Center Fundamental Physics
Center for Fundamental Physics, AUST Center for

Introduction Introduction Intervention Intervention Intervention Intervention Intervention Intervention Interv

Key nuclear physics inputs:

✓ **Nuclear mass** ➔ **r-process path**

✓ **β-decay half-life** ➔ **r-process**

time scale

Accurate theoretical predictions of nuclear masses and β-decay half-lives are crucial to understanding the r-process. CENTER FUNDAMENTAL PHYSICS, AUSTRALIA PHYSICS, AUST

Niu Zhongming Tuesday, May 28, 2024 4/35

Experimental Physics, AUST Center for Fundamental Physics, AUST Center for

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- 2 Nuclear physics inputs
	- \star Nuclear masses
- * Kuclear β-decay half-lives $\frac{1}{3}$ r-process simulations Center for Fundamental Physics, AUST Center **Center for Fundamental Physics, AUST Center for Fundamental Physic Outline**

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- W_{S} (4 Summary and perspectives C_{S} \sim C_{S} \sim C_{S} \sim C_{S} \sim μ_{S} Center for Fundamental Physics, AUST Center for Fundamental Physi

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Nuclear masses

Nuclear mass is a fundamental quantity in nuclear physics. It plays important roles not only in nuclear physics, but also in other branches of physics, such as astrophysics and nuclear engineering. [Lunney2003RMP, Burbidge1957RMP] Center for Fundal Center for Fundamental Physics, AUST Center for Fundamen

Introduction Introduction Intervention Intervention Intervention Intervention Intervention Intervention Interv

 \star Nuclear physics: it contains wealth of nuclear structure information such as magic number and shape transition, and it is widely used to extract nuclear effective interactions.

 \star Other branches: it is essential to determine nuclear reaction and decay energies, so it is important in astrophysics and nuclear engineering. Introduction
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Interaction Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physi

Macroscopic mass models: BW, BW2 [Weizsäcker1935ZP, Bethe1937RMP, Kirson2008NPA] Macro-microscopic mass models: KTUY, FRDM, WS4 [Koura2005PTP, Moller2012PRL, Wang2014PLB] Microscopic DFT mass models: UNEDF1, BSkG2, HFB-31 [Kortelainen2012PRC, Ryssens2022EPJA, Goriely2016PRC] ★ Microscopic CDFT mass models: TMA, PC-PK1, DD-MEB2 [Geng2005PTP, Zhang2022ADNDT, Arteaga كالمستطيع Niu Zhongming
Niu Zhongming Niu Zhongming Niu Zhongming process: nuclear mass and half-lives Microscopic CDFT mass models: TMA, PC-PK1, DD-MEB2 [Geng2005PTP, Zhang2022ADNDT, Arteaga2016EPJA] CHENNET THE SERVICE CONTROLLING SUPPORT FOR FUNDAMENTAL PRINCIPLE SUPPORT AND MANUSORER THE SAME REVISE OF THE SAME PROCESS AUGRATION CONTROLLING THE MAY ARE CONTROLLING THE MAY ARE CONTROLLING THE MAY ARE CONTROLLING THE

Influence of mass uncertainties

Introduction Introduction Intervention Intervention Intervention Intervention Intervention Intervention Interv

Lighter and **darker** shaded bands represent the influence of mass uncertainties of **500 keV**

and **100 keV** to r-process abundances, respectively.

Accurate description of r-process abundance requires nuclear mass prediction accuracy within 100 keV. and 100 keV to r-process abundances, respectively.
 $\overline{\text{C}}_{\text{C}}$
 $\overline{\text{C}}$ Accurate description of r-process abundance requires nuclear mass
 $\overline{\text{prediction accuracy within 100 keV.}}$

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Mass deviations from different models

Introduction Introduction Intervention Intervention Intervention Intervention Intervention Intervention Interv

 \star Different nuclear mass models with comparable accuracy in the known region can extrapolate quite differently out to the neutron drip line. CHANGE FOR FUNDAMENTAL PHYSICS, AUST CENTER FUNDAMENTAL P $\frac{45}{\sqrt{2}}$ Center for Fundamental Physics, AUST Center for Fundamental

Macroscopic mass models: semi-empirical formulas

Matroscopic mass models: semi-empirical formulas

\n**BW:**
$$
B = \frac{a_x A^2 a_y A^{2/3}}{a_x A - a_y A^{2/3} + a_z A^{1/3}} = \frac{a_x \frac{Z^2}{A^{1/3}}}{a_x \frac{Z^3}{A^{1/3}} + a_x \frac{Z^{4/3}}{A^{1/3}}} = \frac{a_{\text{sym}} \frac{(N-Z)^2}{4A}}{a_{\text{sym}} \frac{N+Z}{4A}} = \frac{a_x (N-Z)^2}{A^{1/3} + a_x \frac{(N-Z)^2}{A}} = \frac{a_x (N-Z)^
$$

 \star The rms deviations with respect to the experimental masses in AME2020 (Z,N≥8) are reduced from 3.067 MeV of BW, 1.626 MeV (reduction: 46.98%) of BWK to 0.902 MeV (reduction: 44.53%) of BWN, which is **the first semi-empirical mass formula crossing the 1 MeV accuracy threshold**. are reduced from 3.067 MeV of BW, 1.626

MeV (reduction: 46.98%) of BWK to 0.902

MeV (reduction: 44.53%) of BWN, which

is the first semi-empirical mass formula

crossing the 1 MeV accuracy threshold.

BWK: C. F. Von Wei

$$
\frac{1}{2} \times \frac{1
$$

BW: C. F. Von Weizsacker, Z. Phys. 96, 431 (1935); H. A. Bethe *et al*., Rev. Mod. Phys. 8, 82 (1936). BWK: M. W. Kirson, Nucl. Phys. A 798, 29 (2008). Center Fundamental Physics, AUST Center Fundamental Physics, AUST Center for Fundamental Physics, AUST Center f

Macroscopic mass models: semi-empirical formulas

Fig: The difference between the experimental binding energies and the results of the semi-empirical formulas BW, BWK, and BWN, respectively. The black dashed line indicates the magic number.

BW2: the inclusion of the term $\alpha_m P + \beta_m P^2$ significantly improves the mass description of nuclei between magic number, which are generally deformed nuclei. EXTREM AND EXTREM IN THE INCIDENTIES THE MANUST CHANGE THE CHANGE T

 \star BWN: the inclusion of the shell correction term further significantly improves the mass description of nuclei near magic number, in which the shell effects are very important. CENTER FIGURE FIGHTINGLY, AUST CHENE STICH CHECES CITY AUST CHILI.
Niu Zhongming Fundamental Physics, AUST Center mass and half-lives

CDFT mass model: The DRHBc Mass Table Collaboration

The DRHBc Mass Table Collaboration (31 Universities and Institutions from China, South Korea, and Japan): Nuclear mass table in deformed relativistic Hartree-Bogoliubov theory in continuum.

Center for Fundamental Physics, AUST https://drhbctable.jcnp.org/collaboration.html

Results and discussion **Results and discussion** Results and discussion Results and discussion

CDFT mass predictions

 \star The σ_{rms} of DRHBc is 1.518 MeV, providing **one of the best microscopic descriptions for nuclear masses**. \star The DRHBc calculations generally predict a more extended neutron drip line than other DF calculations, mainly due to the proper treatment of the continuum and the density functional adopted. Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST
Niu Zhongming Niu Aust Center for Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Ce
 Center Fundamental Physics, Table Collaboration), ADNDT 144, 101488
 \star The $\sigma_{\rm rms}$ of DRHBc is 1.518 MeV, providing **one of the best microscopic descriptions for nuclear masses.**
 \star The DRHBc calculations generall

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Results and discussion Results and discussion Results and discussion Results and discussion

CDFT mass predictions

Machine learning in nuclear mass predictions

Machine learning in nuclear mass predictions Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST

- \star ANN: Gazula1992NPA, Athanassopoulos2004NPA, Bayram2014ANE,
	- **Zhang2017JPG, Ming2022NST,**Yuksel2021IJMPE, **Li2022PRC**
- BNN: Utama2016PRC, **Niu2018PLB, Niu2019PRC, Niu2022PRCL**, Rodriguez2019EPL, Rodriguez2019JPG Center Fundamental Physics, Australian Physics, AUST Center for Fundamental Physics, AUST Center Fundamental Physics, AUST CENTER For Fundamental Physics, AUST Center Fundamental Physics, AUST Center Fundamental Physics, EXERCTION STRAIN: Gazula1992NPA, Athanassopoulos2004NPA, Bayram2014ANE,

2hang2017JPG, Ming2022NST, Yuksel2021JJMPE, Li2022PRC

BNN: Utama2016PRC, Niu2018PLB, Niu2019PRC, Niu2022PRCL,

Rodriguez2019EPL, Rodriguez2019JPG

C Center Fundamental Physics, AUST Center Fundamental Physi
	- CNN: **Yang2023PRC**

Introduction **Introduction** Intervention and the control of the control

- LightGBM: **Gao2021NST**
- KRR: **Wu2020PRC, Wu2021PLB**
- NBP: **Liu2021PRC**
- RBF: **Wang2011PRC, Niu2013,2016PRC,2018SciB**
- BGP: Neufcourt2018,2020PRC, Neufcourt2019PRL
- SVM: Clark2006IJMPB
- CLEAN: Morales2010PRC

Bayesian Machine Learning (BML) mass model

 \star A nuclear mass model with accuracy smaller than 100 keV in the known region is constructed.

Its accuracies to S_x and Q_x are at least about 3 times higher than other mass models.

Z.M. Niu and H.Z. Liang, PRC 106, L021303 (2022)

Results and discussion Results and discussion Results and discussion Results and discussion Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST

Extrapolation of BML

Fig: Average theoretical uncertainties $\bar{\sigma}$ (squares) of mass predictions by BML as a function of minimum distance r to the isotopes in the learning set. The rms deviations $\sigma_{\rm rms}$ of BML mass predictions with respect to the corresponding FRDM12 values are shown with diamonds. Center for FRDM12 values are shown with diamonds.
Niu Zhongming Niu Physics, AUST Center mass and half-lives and half-lives, AUST Center fundamental Physics, AU

Taking the FRDM12 mass predictions as the Pseudoexperimental data:

 \star The BML model can well reproduce the Pseudoexperimental data within 100 keV for nuclei in the known region. Taking the FRDM12 mass predictions as the

Pseudoexperimental data:
 \star The BML model can well reproduce the

Pseudoexperimental data within 100 keV for
 \star The rms deviation between BML
 \star The rms deviation betwee Results and discussion
Caking the FRDM12 mass predictions as the
Pseudoexperimental data within 100 keV for
Pseudoexperimental data within 100 keV for

 \star The rms deviation between BML predictions and Pseudoexperimental data increases as the increase of the distance *r*. It is very similar to the average error of BML, which indicates **the BML model could give reasonable evaluations of the theoretical uncertainties**. The Center of BML,

Center for Fundamental uncertainties $\bar{\sigma}$ (squares) of mass

predictions by BML as a function of minimum distance r to

the isotopes in the learning set. The rms deviations σ_{rms} of

BML model cou Center Fundamental Physics, AUST Center Fundamental Physics, AUST Center Fundamental Physics, AUST Center Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fund CREATE THE PHYSICS CREATE THE SURVEY OF THE PHYSICS, AND THE PHYSICS, AUST CHANGE THE PROPERTIES OF THE PHYSICS, AUST CHANGE THE PHYSICS, AUST CHANGE THE PHYSICS, AUST CHANGE THE PHYSICS, AUST CHANGE THE PHYSICS, AUST CHA Taking the FRDM12 mass predictions as the
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Density functional: FNN+CNN

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² Nuclear physics inputs

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Constructing a nuclear model that accurately describes β-decay half-lives is critical to understanding the origin of heavy elements in the universe. CENTER FUNDAMENTAL PHYSICS, AUST CENTER FUNDAMENTAL PHYSICS IN THE CENTER FOR FUNDAMENTAL PHYSICS, AUST CENTER
Niu Zhongming Fundamental Physics, AUST Center mass and half-lives

Niu Zhongming Tuesday, May 28, 2024 20/35

Nuclear models for $β$ -decay half-lives

Phenomenological formula Pfeiffer2000Report, **Zhang2006PRC,2007JPG**, **Zhou2017SCPMA**, **Xia2024APS** Example 2006 PRC, 2007 JPG, Zhou 2017SCPMA, Xia2024APS

TE, Nakata1997NPA, Koura2017PRC, <u>Fang2022PRC Center for Fundamental Physics</u>, AUST Center 1993ADNDT, Nabi1999ADNDT

IIrsch1993ADNDT, Nabi1999ADNDT

NDT, Möller2003PR Introduction

C.2007JPG, Zhou2017SCPMA, <u>Xia2024APS</u>

IMPA, Koura2017PRC, <u>Fang2022PRC</u>

MP, Zhi2013PRC

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Introduction **Introduction** Intervention and the control of the control

- Gross theory Takahashi1969PTP, Tachibana1990PTP, Nakata1997NPA, Koura2017PRC, **Fang2022PRC**
- Shell model Pinedo1999PRL, Caurier2002PRC, Langanke2003RMP, **Zhi2013PRC**
- Quasiparticle random phase approximation (QRPA)

Nilsson BCS+QRPA: Staudt1990ADNDT, Hirsch1993ADNDT, Nabi1999ADNDT

FRDM+QRPA: Möller1997,2018ADNDT, Möller2003PRC

Woods-Saxon+QRPA: **Ni2012JPG**

SHF BCS+QRPA: Sarriguren2005, 2010, 2011PRC

DF(Fayans)+CQRPA: Borzov1996ZPA, Borzov2003,2005PRC, Borzov2008NPA

ETFSI(Skyrme)+CQRPA: Borzov1997NPA, Borzov2000PRC

SHF(BCS)+(Q)RPA: **Bai2010PRL**, Minato2013PRL, Minato2022PRC

SHFB+QRPA/FAM/QPVC: Engel1999PRC, **NiuYF2015PRL,2018PLB**, FAM: Ney2020PRC

RHB+QRPA: Nikšić2005PRC, Marketin2007,2016PRC, **Wang2016JPG**, **NiuZM2013PRC(R)** RHFB+QRPA: **NiuZM2013PLB** SHF(BCS)+(Q)RPA: Bai2010PRL, Minato2013PRL, Minato2022PRC

SHFB+QRPA/FAM/QPVC: Engel1999PRC, NiuYF2015PRL,2018PLB, FAM: Ney2020PRC

RHB+QRPA: Nikšić2005PRC, Marketin2007,2016PRC, Wang2016IPG, NiuZM2013PRC(R)

RHFB+QRPA: Ni CHER CENTER FORPA: Saringuren 2005, 2010, 2011 PRC

CHER BCS+QRPA: Sarriguren 2005, 2010, 2011 PRC

DF(Fayans)+CQRPA: Borzov19952PA, Borzov2003,2005PRC, Borzov2008NPA

ETFSI(Skyrme)+CQRPA: Borzov1997NPA, Borzov2000PRC

SHF Gross theory Takahashi1969PTP, Tachibana1990PTP, Nakata1997NPA, Koura2017PRC, <u>Fang2022PRC</u>

Contespanticle random phase approximation (QRPA)

Contespanticle random phase approximation (QRPA)

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Niu Zhongming Mini Physics, Austral Physics, Australia Physics, Australia Physics, Australia Physics, Australi Machine learning Costiris2009PRC, **Li2022SSPMA**, **Niu2019PRC**, **Li2024JPG**

Empirical formula of β-decay half-lives

According to the Fermi theory of β-decay, neglecting the effect of transition strength, taking the fine structure constant α as a small quantity, and using the extreme relativistic limit approximation *Ee*→*p^e c*, one obtains **Conter Finding the effect of transition strength, taking the fine structure**

streme relativistic limit approximation $\vec{E_e} \rightarrow p_e c$, one obtains
 $e^2 - 5 \ln(Q_\beta + m_e c^2) + \ln\left(\frac{2r_0}{\hbar c}\right) \alpha^2 Z^2 + \frac{1}{3} \ln(A) \alpha^2 Z^2 + \pi \alpha Z$
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effect of transition strength, taking the fine structure

vistic limit approximation $E_e \rightarrow p_e c$, one obtains
 $+m_e c^2$) + $\ln\left(\frac{2r_0}{\hbar c}\right) \alpha^2 Z^2 + \frac{1}{3} \ln(A) \alpha^2 Z^2 + \pi \alpha Z$ Results and discussion
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Formula 1:
$$
\ln(T_{1/2}) = \ln(30Dm_e^5c^{10}) + (\alpha^2 Z^2 - 5)\ln(Q_\beta + m_ec^2) + \ln\left(\frac{2r_0}{\hbar c}\right)\alpha^2 Z^2 + \frac{1}{3}\ln(A)\alpha^2 Z^2 + \pi\alpha Z
$$

Formula 2:
$$
\ln(T_{1/2}) = a_1 + (\alpha^2 Z^2 - a_2 - a_3 I) \ln(Q_\beta + m_e c^2 - a_4 \delta) + \ln\left(\frac{2r_0}{\hbar c}\right) \alpha^2 Z^2 + \frac{1}{3} \ln(A) \alpha^2 Z^2 - a_5 \alpha Z^2 C
$$

 $+ a_6 e^{-[(N-28)^2 + (Z-20)^2]/22} + a_7 e^{-[(N-50)^2 + (Z-40)^2]/33} + a_8 e^{-[(N-82)^2 + (Z-56)^2]/33} + a_9 e^{-[(N-132)^2 + (Z-56)^2]/33}$ $+ a_9 e^{-[(N-1)3]}$

Gross theory of β-decay half-lives

Gross theory:based on the **sum rule** of strength function, it treats the β-decay transitions to all final nuclear levels in a **statistical way** Results and discussion
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Results and discussion Results and discussion

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$$
M_{GT}(E)^{2} = 3 \int D_{GT}(E, \varepsilon) \frac{dN_{1}}{d\varepsilon} W(E, \varepsilon) d\varepsilon \qquad \qquad \frac{P}{2}
$$

$$
\int_{-\infty}^{\infty} D_{GT}(E, \varepsilon) dE =
$$

\n
$$
\lim_{\text{rule}} \int_{-\infty}^{\infty} ED_{GT}(E, \varepsilon) dE
$$

$$
\int_{-\infty}^{\infty} D_{GT}(E, \varepsilon) dE = 1
$$

$$
\int_{-\infty}^{\infty} ED_{GT}(E, \varepsilon) dE = \Delta E_{GT} \approx \Delta E_C
$$

$$
\int_{-\infty}^{\infty} E^2 D_{GT}(E, \varepsilon) dE = \sigma_{GT}^2 \approx \sigma_C^2 + \sigma
$$

Nuclear β-decay half-lives can be calculated only with $Q_β$ **from mass models** Center for Fundamental Physics, AUST Center $\sum_{\substack{c \text{rule } c \text{cm} \text{Nuclear} \text{B-decay half-lives can be calculated only with } Q_{\beta} \text{ from mass models}}$

Nuclear β -decay half-lives can be calculated only with Q_{β} from mass models

Gross theory of β-decay half-lives

J. Y. Fang *et al*., Phys. Rev. C 106, 054318 (2022) Results and discussion
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Results and discussion

Spin-orbit splitting extracted by CDFT is essential for the reliable description of GT centroid energy!

β -decay half-lives from the gross theory

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β -decay half-lives from the RQRPA approach

The self-consistent RQRPA approach was developed and it well reproduces the experimental βdecay half-lives for both even-even neutron-rich and neutron-deficient nuclei. CECAY NAIT-HVES TOT DOLIT EVEN-EVEN NEULTON-NCH ANU NEULTON-UEHCIENL NUCIEI.
Niu Zhongming Niu Zhongming physics, Auclear mass and half-lives

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β -decay half-lives from machine learning

The BNN-I4 approach well reproduces the experimental data, even completely agree with the experimental data within uncertainties for short-lived nuclei. THE BNN-I4 approach well reproduces the experimental data, even completely agree with the

experimental data within uncertainties for short-lived nuclei.

O When extrapolate from known region, the results of other models g

When extrapolate from known region, the results of other models generally agree with BNN-I4 predictions within uncertainties. Z. M. Niu *et al*., PRC 99, 064307 (2019) C. M. Niu et al., PRC 99, predictions within uncertainties.
Niu Zhongming Niu Alongming Niu Zhongming r-process: nuclear mass and half-lives

Nuclear models for β-decay half-lives

Introduction **Introduction** Intervention and the control of the control

Different models generally better reproduce β-decay half-lives of short-lived nuclei. The deviations between different predictions slowly increase to an order of magnitude even out to the drip line. Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Center Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Cent

β -decay half-lives from machine learning

The half-life uncertainties of the neural network are still smaller than those of the model averaging method within about 5–10 steps for nuclei with $35 \lesssim Z \lesssim 90$. W. F. Li *et al.*, J. Phys. G 51, 015103 (2024) Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST
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Outline **Outline Outline Countries and Countries and Countries and Countries and Countries of Countries and Coun** outime
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Outline

1 Introduction 2 Nuclear physics inputs Nuclear masses * K^{Ruc}lear β-decay half-lives ³ r-process simulations Center for Fundamental Physics, AUST Center Center Fundamental Physics, AUST Center for Fundamental Physics, AU **Outline**

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 W_{S} **4** Summary and perspectives
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Effect of mass uncertainty on r-process abundances Results and discussion
Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST
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Mass predictions from 10 mass models: Empirical formula: **β-decay half-lives** TALYS code: **neutron-capture rates** Center of Genter School Scruts and discussion

Center Center of Tunnels:

Center Fundamental Physics, Austral Fundamental Physics, AUST Code: neutron-capture rates

O The final r-process abundances include uncertainties introduced by the nuclear mass model **mainly through the variation of neutron-capture rates**, whereas the uncertaintiesof β-decay rates make a relatively small contribution. CRITER FOR THE STREET THE STREET THE STREET THE STREET THAT ALLYS CODE: neutron-capture rates

STREET THAT ALLYS CODE: neutron-capture rates

OF The final r-process abundances include

Mass model mainly through the varia

Fig: Green and red bands show the uncertainties in the systematic simulations with various neutron-capture rates and β-decay rates, respectively. Nith various neutron-capture rates and β-decay rates, respectively.
Niu Zhongming Niu Zhongming Center for Fundamental Physics: nuclear mass and half-lives

Z. Li *et al*., SCPMA 62, 982011 (2019)

Results and discussion Results and discussion Results and discussion Results and discussion Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST

Effect of half-life uncertainty on freeze-out time

Y_n/Y_{seed} decreases very quickly around the freeze-out time. Explis and discussion

Center Fundamental Physics, Australian Physics, Australian

Nuclear β-decay half-lives have a significant effect on the freezeout time.

O The freeze-out time is between $0.7 - 1.2$ s.

Outline **Outline Outline Countries and Countries and Countries and Countries and Countries of Countries and Coun** outime
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Outline

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Center for Fundamental Physics, AUST Cente **Outline**

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Summary and perspectives μ_{S} Center for Fundamental Physics, AUST Center σ_{S}

Summary and perspectives

Summary:

- \star Various theoretical models and machining learning methods are developed to predict nuclear masses and β-decay half-lives, and the accuracies are remarkably improved. Summary and perspectives
Center of Center Center of Tunchen
Center Fundamental Physics, AUST Center for Fundame
- \star The uncertainties of r-process abundances introduced by the nuclear mass uncertainties mainly through the variation of neutron-capture rates, while β-decay half-lives play an important role in determine the time scale of r-process. Center for Fundamental Physics, AUST Exercise of the methods and machining learning methods are developed to predict nuclear

masses and β-decay half-lives, and the accuracies are remarkably improved.
 \star The uncertainties of r-process abundances introduce Center for Fundamental Physics, AUST Center for Fundamental Physics, and the accuracies are remarkably improved.

The uncertainties of r-process abundances introduced by the nuclear mass uncertainties mainly

through the Center Fundamental Physics and Physics, AUST Center for Fundamental Physic Center Fundamental Physics and the accuracies are remarkably improved.

Specifical models and machining learning methods are developed to predict nuclear

physics of r-process abundances introduced by the nuclear mass unce Content for Fundamental Physics and machining learning methods are developed to predict nuclear

If-lives, and the accuracies are remarkably improved.

Process abundances introduced by the nuclear mass uncertainties mainly Continuing learning methods are developed to predict nuclear
the accuracies are remarkably improved.
Audances introduced by the nuclear mass uncertainties mainly
apture rates, while β -decay half-lives play an important
	- Perspectives:
		- \star Develop theoretical models and machining learning methods to improve the accuracies of nuclear mass and β-decay half-life by including more and more physics effects.
- \star Constrcut high-precision nuclear inputs for r-process simulations including nuclear masses, half-lives, and neutron-capture rates. \star Develop theoretical models and machining learning methods to improve the accuracies of

nuclear mass and β -decay half-life by including more and more physics effects.
 \star Constrcut high-precision nuclear inputs

Acknowledgements and the control of Acknowledgements
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Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Cente

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Thank you!

Mass extrapolation

The smooth deviations can be improved with both BNN approaches, while **the odd-even staggering can only remarkably reduced with BNN-I4 approach**. ▶ The BNN corrections are still reasonable if the extrapolation is not far away from Example Proton number N

Example 2004-

Podd-even staggering can only remarkably reduced with BNN-I4 approache.

The BNN corrections are still reasonable if the extrapolation is not far away from

the training region.

Exa

Center Fundamental Physics, AUST Center for Fundamental Physics, AUST Cent the training region. \mathbb{Z}^2 z.M. Niu and H.Z. Liang, PLB 778, 48 (2018)

Niu Zhongming Tuesday, May 28, 2024 36/35

Mass predictions of RMF+BNN model

Smooth mass deviations can be easily removed by both BNN approaches, while the odd-even staggering can be well reproduced only using BNN-I4 approach. Results and discussion

Center of Fundamental Physics, AUST Center for Fun Results and discussion
Center for Fundamental Physics, Australian Physics, AUST Center for Fundamental Physics,

The extrapolation of BNN correction show more structure information for the BNN-I4 approach, especially the shell effects around (*Z*,*N*)=(28, 82) and (50, 126).

Figure: (a) Mass differences between the experimental data in AME16 and the predictions of the RMF model. (b) BNN corrections. (c) Mass differences after BNN improvement. Niu and Liang, PLB 778, 48 (2018) Center Genter For Fundamental Physics, AUST Center For Fundamental Physics, AUST Center for Fundamental Physics, AU
Niu Zhongming Tuesday, Aust Center for Fundamental Physics, AUST Center for Fundamental Physics, Austral P

BML predictions

Example 126 shell.
 Example 126 shell.

Niu Zhongming Tuesday, Austral Physics, Austral Physics, AUST Center for Tuesday, Austral Physics, AUST Center for Tuesday, Z.M. Niu and H.Z. Liang, PRC 106, L021303 (2022)

 \star The shell structure in the known region is well reproduced.

 \star Several important features in the unknown region are predicted, such as the magic numbers around **N=40 and N=184**, the **robustness of N=82 shell**, the **quenching of N**

Niu Zhongming **Represent Controller Controller Controller Controller May 2004** 2024 39/35

BML predictions and the state

Results and discussion **Results and discussion** Results and discussion Results and discussion

Fig: Mass differences between M_{exp} in AME16 and M_{th} from BML, NewBML, HFB-31, and FRDM12 models. The new experimental data from [Mougeot2018PRL; Orford2018PRL] are denoted by spheres.

 \star The BML model well reproduces new experimental masses within errors. If new data are included in Lset, the errors near new data reduce to about half of original values. Fig: Mass differences between M_{exp} in AME16 and M_{th} from BML, NewBML, HFB-31, and FRDM12 models,
The new experimental data from [Mougeot2018PRL; Orford2018PRL] are denoted by spheres.
 \star The BML model well reproduc

Gross theory of β-decay half-lives

Results and discussion **Results and discussion** Results and discussion Results and discussion

Gross theory

Results and discussion Results and discussion Results and discussion Results and discussion

在近滴线核区,新提出的 Gamow-Teller 跃迁中心能量与微观 QRPA 的结 果更为接近。

Gross theory

Theoretical framework Nuclear β-decay half-lives Nuclear β-decay half-lives Nuclear β-decay half-lives

Z+1, N-1

Nuclear β-decay half-lives

The nuclear β-decay half-life in allowed GT approximation reads as follows: Nuclear ß-decay half-lives
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Therefore the product of the function
$$
\beta
$$
-decay half-life in allowed GT approximation reads as\n
$$
T_{\gamma2} = \frac{\ln 2}{\lambda_{\beta}} = \frac{D}{g_{A}^{2} \sum_{m} B_{\text{GT}}(E_{m}) f(Z, A, E_{m})}
$$
\n
$$
\rightarrow T_{\gamma2} = a / f(Z, A, E_{m} = Q_{\beta} - c(\delta - 1) / \sqrt{A})
$$
\n
$$
\frac{r_{2\pi^{3}} \ln 2}{g^{2} m_{\text{g}}^{5} c^{4}} = 6163.4 \text{ s}, g_{A} = 1, B_{\text{GT}}(E_{m}) \text{ is the transition}
$$
\n
$$
F_{\text{on}} = \frac{r_{2\pi^{3}} \ln 2}{g^{2} m_{\text{g}}^{5} c^{4}} = 6163.4 \text{ s}, g_{A} = 1, B_{\text{GT}}(E_{m}) \text{ is the transition}
$$
\n
$$
F_{\text{on}} = \frac{1}{m_{\text{g}}^{5}} \int_{m_{\text{g}}^{E_{m}}}^{E_{m}} p_{\text{g}} E_{\text{g}}(E_{m} - E_{\text{g}})^{2} F(Z, A, E_{m}) dE_{\text{g}},
$$
\n
$$
F_{\text{on}}^{E_{\text{exp}}}
$$
\n
$$
F_{\text{on}}^{E_{\text{exp}}
$$

where $D = \frac{h^2 Z \pi^2 \ln Z}{\sigma^2 \ln 5 \sigma^4} = 6163.4$ s, $g_A = 1$, $B_{GT}(E_m)$ is the transition probability, and *E^m* is the maximum value of β-decay energy. **A**
 a in allowed GT approximation reads
 $\frac{D}{A \sum_{m} B_{\text{GT}}(E_m) f(Z, A, E_m)}$
 A, $E_m = Q_\beta - c(\delta - 1) / \sqrt{A}$

, $g_A = 1$, $B_{\text{GT}}(E_m)$ is the transition
 $\frac{1}{\sqrt{A}}$
 $\frac{1}{\sqrt{A}}$
 $\frac{1}{\sqrt{A}}$ **Solution Protocol**

ife in allowed GT approximation reads as for
 $g_A^2 \sum_m B_{\text{GT}}(E_m) f(Z, A, E_m)$
 $\therefore A, E_m = Q_\beta - c(\delta - 1)/\sqrt{A}$
 $\therefore g_A = 1, B_{\text{GT}}(E_m)$ is the transition

ximum value of β -decay energy,
 $\frac{1}{m_\phi^5} \int_{m_\phi}$ *e* Nuclear β -decay half-lives

approximation reads as follows:
 $\overline{A, E_m}$)
 $\sqrt{\sqrt{A}}$

is the transition
 \overline{A} -decay energy
 \overline{A} and

The phase volume is

$$
f(Z, A, E_m) = \frac{1}{m_e^5} \int_{m_e}^{E_m} p_e E_e (E_m - E_e)^2 F(Z, A, E_m) dE_e,
$$

Z, N

Capability of Producing Nuclides Results and discussion
 CENTER PHYSICS

The production rate of one nuclide per day, which enable the "discovery experiments"
Niu Zhongming Center for Center for Fundamental Physics: nuclear mass and half-lives

Niu Zhongming **reprocess: nuclear mass and half-lives** Tuesday, May 28, 2024 45/35

- \checkmark uncertainties of BNN predictions are similar in the training region
- \checkmark they will be decreased about 3 times when extrapolate to the region far
- C. M. Niu et al., PRC 99, 064307 (2019)
Niu Zhongming Niu Zhongming r-process: nuclear mass and half-lives from known region. \leq \leq

Niu Zhongming **Represent Controller Controller Controller Controller May 2004** 16/35 and half-lives **Tuesday, May 28, 2024** 46/35

Predictions of r-process abundances

Results and discussion Results and discussion Results and discussion Results and discussion

Uncertainties from β-decay half-lives lead to large uncertainties for the *r*-process abundances of elements with A>~140, which can be remarkably reduced if we can further measure three more β-decay half-lives. Z. M. Niu et al., PRC 99, 064307 (2019) C. M. Marchan, The Sy, 604507 (2015)
Niu Zhongming Center for Center for Fundamental Physics, Australia Physics, Austral Physics, Austral Physics,
Tuesday, Tuesday, **CENTER SALL PROPERTY CONTROLLAND MASS NUMBER A**
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Results and discussion **Results and discussion** Results and discussion Results and discussion

Half-life predictions of NN

Fig. 2 Nuclear *β*-decay half-lives of Pb isotopes. The experimental half-lives in NUBASE2020 are denoted by squares. For comparison, the theoretical results from FRDM + QRPA are shown by the dashed line.

 \blacklozenge NN-I4 δ : There are obvious odd-even staggering in the region far away from the known nuclei.

 \blacklozenge The odd - even staggering predicted can be eliminated by removing δ input from the neural network input layer. Content for Center and Physics. For Comparison, the theoretical results from FRDM + QRPA are shown by the dashed line.

NOWELLAGE: There are obvious odd-even staggering in the region far away from the known nuclei.

The o

Center Fundamental Physics MV-LAT CENT-13 in the unknown region.
Niu Zhongming **Center for Fundamental Physics**, AUST Center for Tuesday, uncertainties : $NN-I4T < NN-I3$ in the unknown region.

Niu Zhongming **Reproduces and Australian Constantine C**

Results and discussion **Results and discussion** Results and discussion Results and discussion

Half-life predictions of NN

Fig. 3 Nuclear *β*-decay half-lives of Pm, Sm, Eu, and Gd isotopes. The new measurements of nuclear *β*-decay half-lives from Ref. [Kiss2022ApJ] are shown with open circles to test the extrapolation ability of the NN-I4T.

◆The prediction of the neural network is good agreement with the new measurements half-lives within the error range.

◆For the nuclei whose half-lives from NUBASE2020 and new measurements deviate with each other, such as $165,166$ Sm and 168 Eu, the NN-I4T better reproduce the half-lives from new measurements. Center for Fundamental Physics, AUST CENTER FUNDAMENTAL PHYSICS, AUST CENTER FOR FUNDAMENTAL PHYSICS, AUST CEN

Niu Zhongming Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamenta
 The prediction of the neural network is good agreement with the new measurements
half-lives within the error range.

For the nuclei whose half-lives from NUBASE2020 and new measurements deviate

with each other, such as ¹

Half-life predictions of NN and model averaging

Results and discussion **Results and discussion** Results and discussion Results and discussion

Fig. 4 Nuclear *β*-decay half-lives of Ni, Sn, and Pb isotopes. The uncertainties with NN-I4T and the averaging method are shown by the green hatched regions and slash hatched regions.

◆In the known region, the uncertainties of NN-I4T is generally smaller than that of the model averaging method.

◆ Near the very neutron-rich region, the uncertainties of NN-I4T increases rapidly and is even larger than that of the model averaging method. Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST
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The isoscalar pairing strengths determined by the BNN can reproduce experimental data with the same accuracy as other theoretical works. F. Minato *et al.*, PRC 106, 024306 (2022) Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST
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Monte-Carlo simulations of β-decay half-lives

- ⚫ The β-decay half-lives: randomly produced by multiplying the factors that range from 0.1 to 10: ➢ Opposite odd-even oscillations ➢ Monotonically increases **CENTER FOR FUNDAMENTAL PHYSICS**

CREATIVES TRANSPORTED THE B-decay half-lives: randomly produced by multiplying

the factors that range from 0.1 to 10:
 $\frac{1}{26}$ Produced by multiplying
 $\frac{1}{26}$ Produced by multiply Center for Fundamental Physics, AUST **Example 18 AUST CENTER FOR FUNDAMENTAL PHYSICS, AUSTRAL PHYSICS, AUSTRAL Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental Physics, AUST Center for Fundamental** Centroduction
Center Center Fundamental Physics, Australian Center for Fundamental Physics, Australian Physics, Australian Physics, Australian Physics, Australian Physics, Australian Physics, Australian Physics, Australian
	- ⚫ Nuclear β-decay models can avoid these non-physical trends

 \bullet investigate the effect of β-decay half-life uncertainties on the r-process simulations based on the predictions of various nuclear models. Center for G-decay half-life uncertaintie

Sa $\frac{1}{83}$ $\frac{1}{84}$ $\frac{1}{85}$ $\frac{1}{86}$ $\frac{1}{87}$ $\frac{1}{100}$ and the r-process simulations based on the predictions of

Fig: Diagram of Monte-Carlo simulation sampling.

Fig: Diagram of Monte-Carlo simulation sampling. Center Fundamental Physics, Australia Physics, Austral Physics, Austra

Introduction **Introduction** Intervention and the control of the control

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Results and discussion Results and discussion Results and discussion Results and discussion

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r-process abundances

Fig: r-process abundances calculated with different β-decay half-Iffe predictions at the moment of 10 Gyr. $\frac{1}{2}$ and the moment of 10 Gyr. In the set al., ApJ 943, 102 (2023)