Tetraneutron and its isospin analogues

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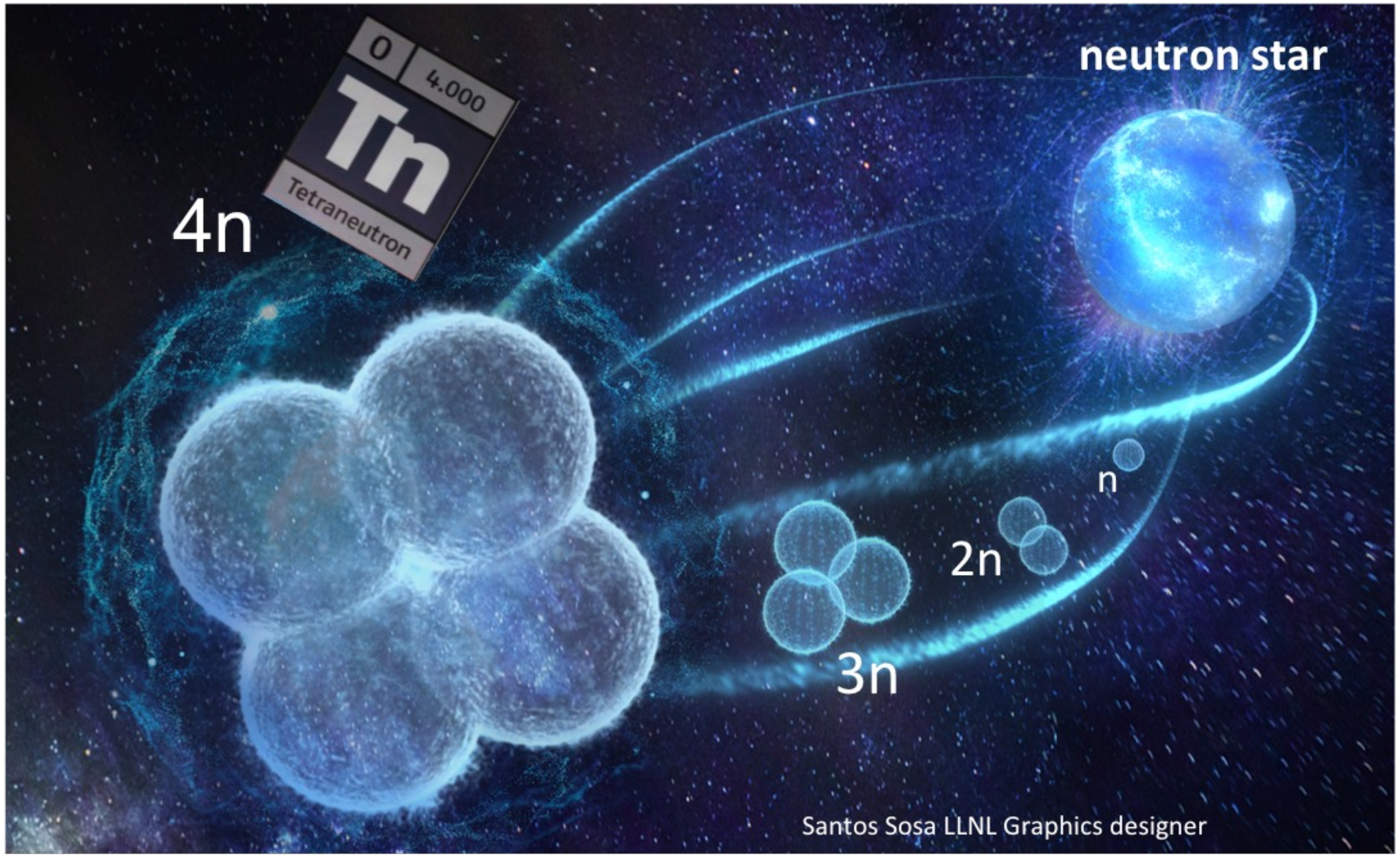

Neutron & neutron star
Is there anything in between?

FBS-2024, Хабаровск, 2 октября 2024

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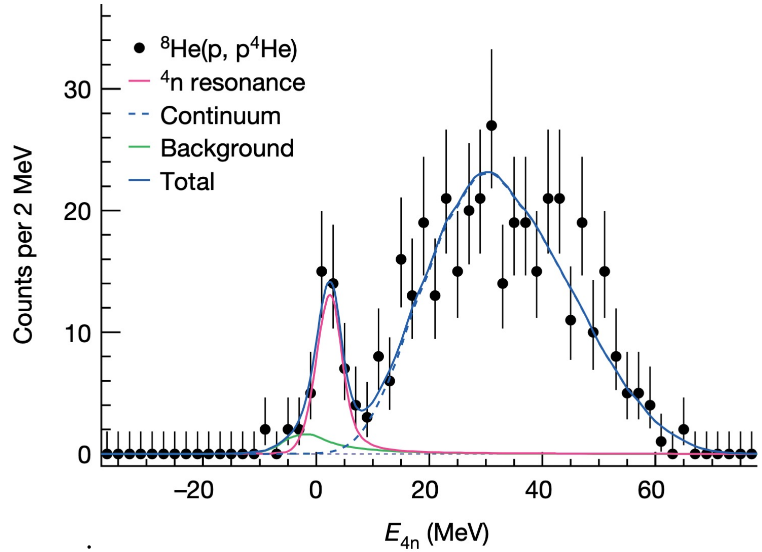
Neutron & neutron star
Is there anything in between?

Тетранейтрон:

- Система из 4 нейтронов. Нестабильна, т. е. представляет собой резонанс: образуется на короткое время $\sim(3.8 \pm 0.8) \times 10^{-22}$ с и распадается. Время жизни резонанса t обратно пропорционально его ширине Γ: $t \sim \frac{1}{\Gamma}$.
- Резонанс тетранейтрона предсказан нами в 2014 г. Впервые наблюдался с малой статистикой (4 события) в 2016 г.; окончательно подтвержден в эксперименте с хорошей статистикой в 2022 г.

Тетранейтрон:



- Система из 4 нейтронов. Нестабильна, т. е. представляет собой резонанс: образуется на короткое время ∼(3.8 ± 0.8) × 10^{-22} с и распадается. Время жизни резонанса t обратно пропорционально его ширине Γ: $t \sim \frac{1}{\Gamma}$.
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Изотопический спин (изоспин):

- Изоспин T и его проекция T_z – характеристики элементарных частиц и ядер
- Нуклоны: $T = \frac{1}{2}$; причем протоны: $T_z = +\frac{1}{2}$, нейтроны: $T_z = -\frac{1}{2}$
- Сложение иоспинов аналогично сложению моментов в квантовой механике
- Ядра $A = Z + N, T_z = \frac{1}{2}(Z - N), T \geq |T_z|$
- Изоспиновые аналоги – состояния разных ядер с одинаковыми A и T

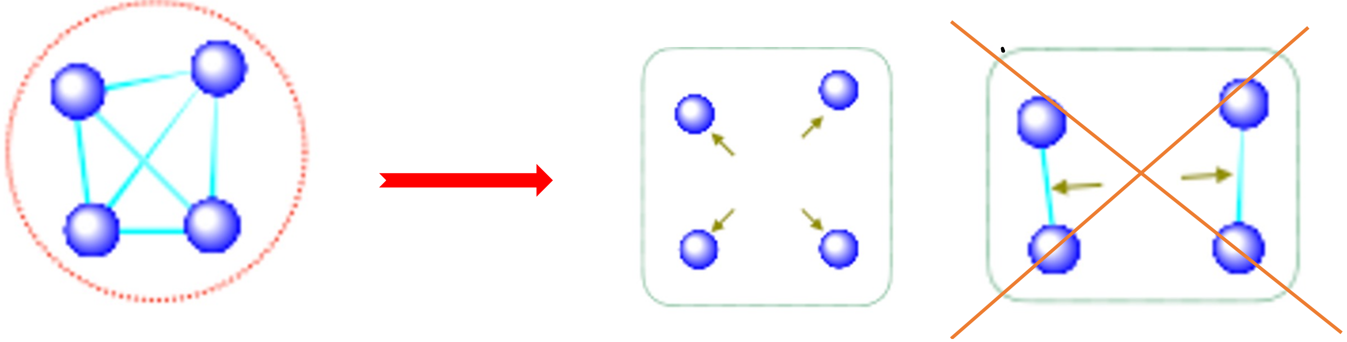
Пример, интересный для нашего обсуждения:

^{4}H: $A = 4, Z = 1, N = 3$:
Binding energy: 5.604 MeV
Spectrum: $2^-, T = 1$ – g.s., $E_x = 0$
$1^-, T = 1,\ E_x = 0.310$ MeV, $\Gamma = 6.73$ MeV
$0^-, T = 1,\ E_x = 2.080$ MeV, $\Gamma = 8.92$ MeV
$1^-, T = 1,\ E_x = 2.830$ MeV, $\Gamma = 12.99$ MeV

^{4}Li: $A = 4, Z = 3, N = 1$:
Binding energy: 4.619 MeV
Spectrum: $2^-, T = 1$ – g.s., $E_x = 0$
$1^-, T = 1,\ E_x = 0.320$ MeV, $\Gamma = 7.35$ MeV
$0^-, T = 1,\ E_x = 2.080$ MeV, $\Gamma = 9.35$ MeV
$1^-, T = 1,\ E_x = 2.850$ MeV, $\Gamma = 13.51$ MeV

Демократический распад:

- Распад тетранейтрона – демократический распад, т. е. никакая подсистема не имеет связанных состояний.
- Демократические распады на 3 частицы исследовались теоретически и экспериментально; с демократическим распадом резонанса на 4 частицы мы сталкиваемся впервые, теория такого распада не разработана.



Тетранейтрон

- Демократический распад (нет связанных подсистем)
- Метод гиперсферичеких гармоник
- В 3-мерном пространстве число переменных для системы 4 нейтронов $3 \cdot 4 - 3_{\text{ц.м.}} = 9$; вводится длина ρ в 9-мерном пространстве и 8 углов:

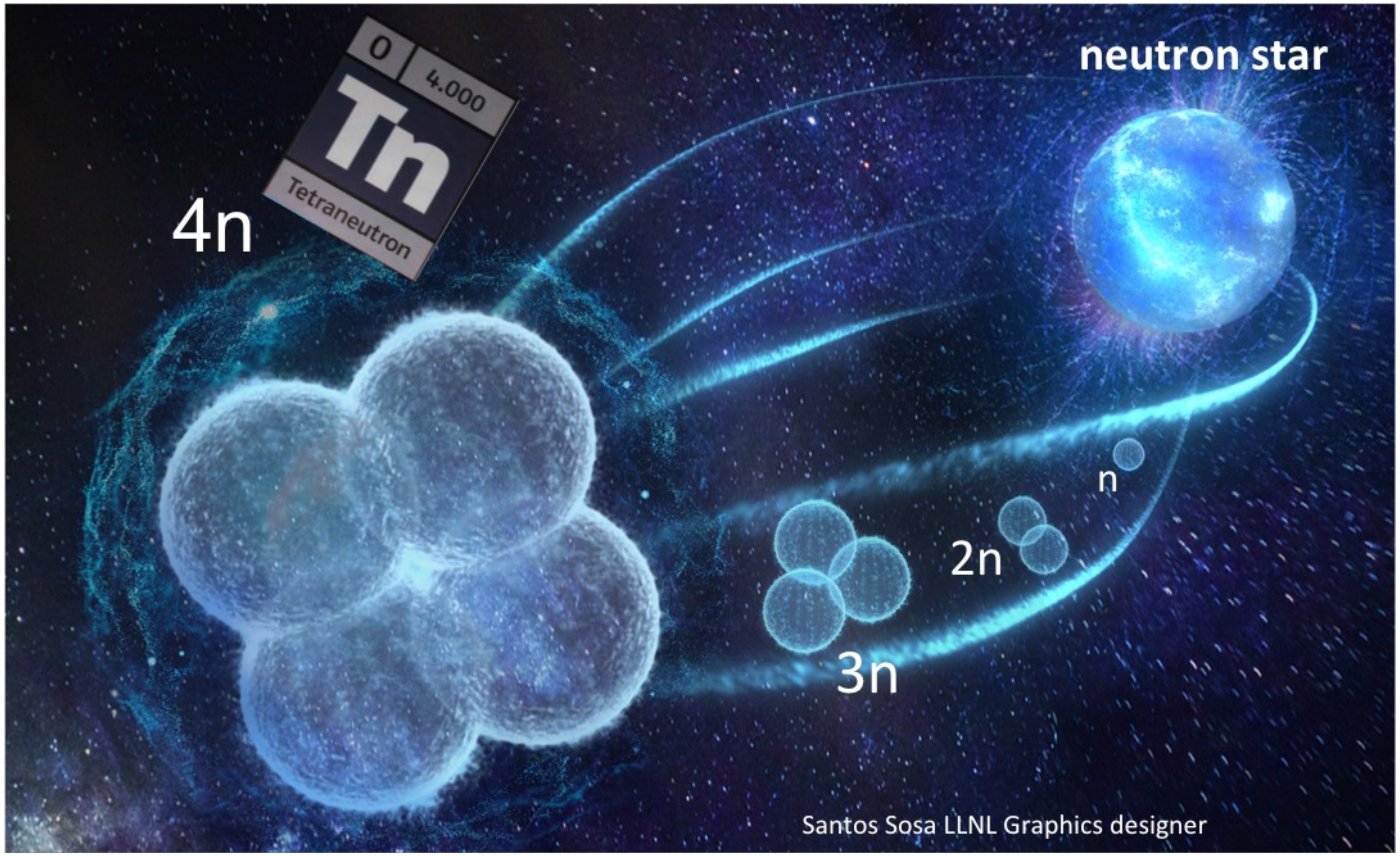
$$\Psi(\boldsymbol{r}_1, \boldsymbol{r}_2, ..., \boldsymbol{r}_A) = \Phi(\rho)\mathcal{Y}_{k\nu}(\Omega), \quad \rho = \sqrt{\sum_{i=1}^{A}(\boldsymbol{r}_i - \boldsymbol{R})^2},$$

$$\Phi_{nK} \equiv \Phi_n^{\mathcal{L}}(\rho) = \rho^{-(3A-4)/2}\varphi_{nK}(\rho), \quad \mathcal{L} = K + \frac{3A-6}{2};$$

$$\frac{\hbar^2}{2m}\left[-\frac{d^2}{d^2\rho} + \frac{\mathcal{L}(\mathcal{L}+1)}{\rho^2}\right]\Phi_n^{\mathcal{L}}(\rho) + \sum_{\mathcal{L}'} V_{\mathcal{L},\mathcal{L}'}\Phi_n^{\mathcal{L}'}(\rho) = E\Phi_n^{\mathcal{L}}(\rho).$$

- Приближение: учтен открытый канал распад а с $\mathcal{L} = \mathcal{L}_{\min} = K_{\min} + 3 = 5.$
- Но все возможные каналы каналы учтены в МОБИК как закрытые каналы

Чем интересен тетранейтрон?



Neutron & neutron star
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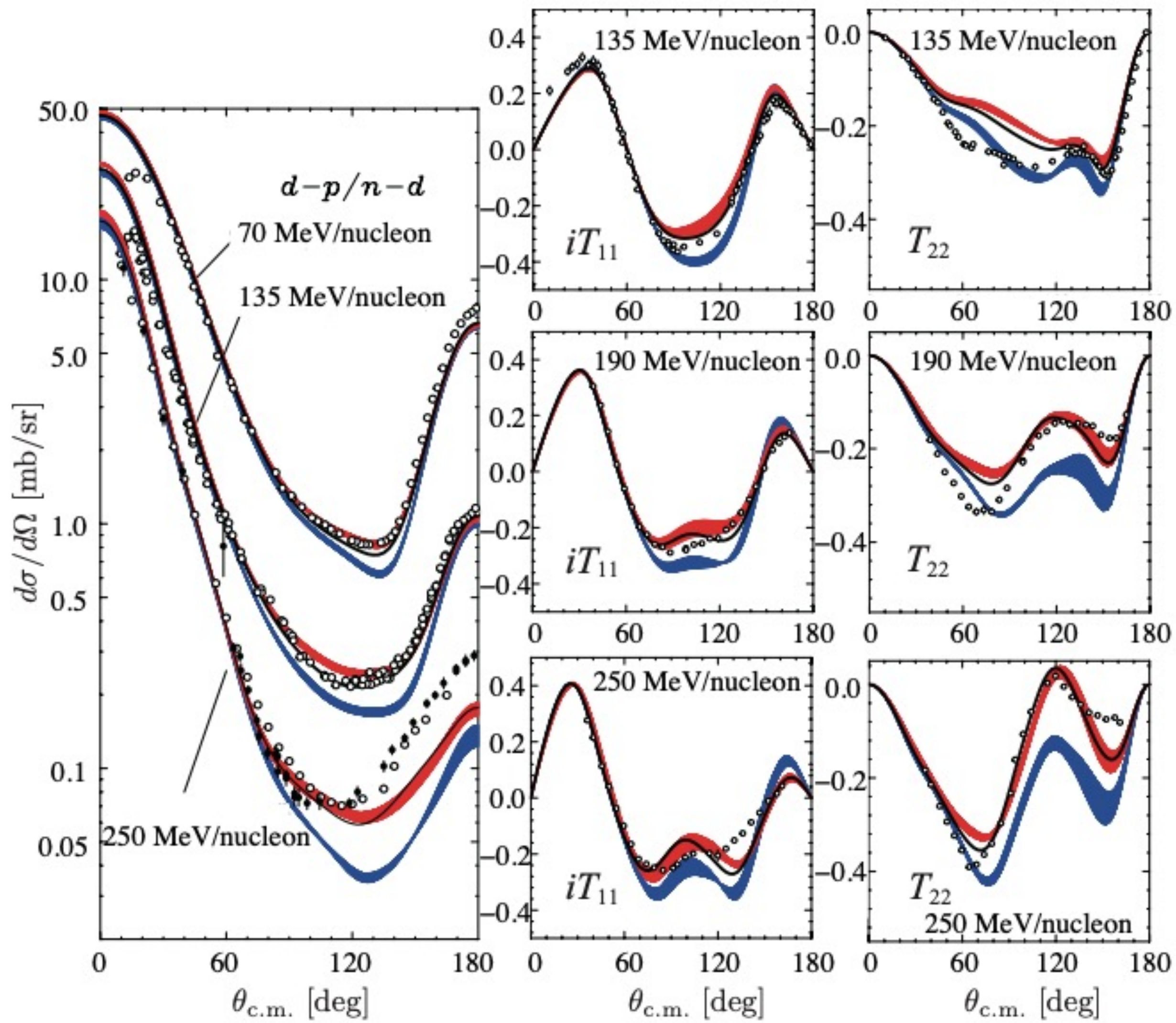
Чем интересен тетранейтрон?

- Экспериментальные поиски тетранейтрона велись около 60 лет, окончательно обнаружен резонанс тетранейтрона в 2022 г.
- Граница стабильности ядер, ядра на границе стабильности и вблизи ее, в том числе и за ее пределами
- Нейтронная материя, в том числе и с небольшим числом нейтронов
- Взаимодействие нейтронов друг с другом, в том числе и трехчастичные получено только в разных моделях (есть данные по *pp*- и *np*-рассеянию, прямых данных по *nn*-взаимодействию нет)

N-d рассеяние

- Из статьи Kimiko Sekiguchi в трудах NTSE-2018



History of the tetraneutron studies

- 1963: First experiments: $^{4}\mathrm{He}(\pi^{-},\pi^{+})4n$ reaction and searches in nuclear fission – no bound, no resonant states found
- Around 1980: Theory of democratic decays (no one subsystem has a bound state) into 3 and 4 fragments suggested (R. Jibuti, R. Kezerashvili, K. Sigua et al)
- End of 1980s: Experiments with heavy ions: $^{7}\mathrm{Li}(^{11}\mathrm{B},\,^{14}\mathrm{O})\;^{4}n$, $^{7}\mathrm{Li}(\,^{7}\mathrm{Li},\,^{10}\mathrm{C})\;^{4}n$, etc.
- 2002 г.: F. M. Marqués et al., Phys. Rev. C **65**, 044006 (2002) – $^{12}\mathrm{C}(^{14}\mathrm{Be},\,^{10}\mathrm{Be})\;^{4}n$ reaction: bound tetraneutron discovered (6 events)!

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- 2002 г.: F. M. Marqués et al., Phys. Rev. C **65**, 044006 (2002) – $^{12}\mathrm{C}(^{14}\mathrm{Be},\, ^{10}\mathrm{Be})\ ^{4}n$ reaction: *Was the bound tetraneutron really found?*

No confirmation in later experiments

- This work give rise to a number of theoretical studies
- Conclusion: bound tetraneutron is impossible with modern *NN* interactions
- Attempt to create a tree-nucleon force with isospin $T = \frac{3}{2}$ to bind the tetraneutron
- Conclusion: it destroys description of nuclei with $A \geq 4$

History of the tetraneutron studies

- 2002 г.: F. M. Marqués et al., Phys. Rev. C **65**, 044006 (2002) – $^{12}\mathrm{C}(^{14}\mathrm{Be},\, ^{10}\mathrm{Be})\ ^{4}n$ reaction: *Was the bound tetraneutron really found?*

No confirmation in later experiments

- Detailed studies of a possibility to obtain a low-energy tetraneutron resonant state, narrow enough to be measured experimentally. Various *NN* and *NNN* interactions used, various approaches explored (Faddeev –Yakubovsky equations, Gamow shell model, complex scaling, analytical continuation of coupling constant, etc.)
- Conclusion: no narrow resonances found
- Note: theory of the decay in 4 fragments is not well-developed; really, we had no experience with such decays

History of the tetraneutron studies

Eur. Phys. J. A **19**, 187–201 (2004)
DOI 10.1140/epja/i2003-10124-1

THE EUROPEAN PHYSICAL JOURNAL A

Broad states beyond the neutron drip line

Examples of ^{5}H and ^{4}n

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Abstract. Theoretical studies of broad states in the few-body systems beyond the neutron drip line have been performed. We introduce a theoretical model which allows to incorporate the initial structure of colliding nuclei, reaction mechanism, few-body effects and final-state interactions in studies of broad unbound states. The model is directly related to the sudden-removal approximation for high-energy knock-out or break-up reactions. We apply this model to qualitative studies of some general properties of broad few-body states including correlations for emitted fragments. The theoretical ideas are illustrated mainly using

History of the tetraneutron studies

L. Grigorenko, N. Timofeyuk, M. Zhukov, Eur. Phys. J. A 19, 187 (2004)

Theoretical study of $^{8}\mathrm{He}(p;\ ^{4}\mathrm{He},p)\ ^{4}n$ reaction. Fast knock-out of ^{4}He from ^{8}He, Schrödinger equation with a source:

$$(H_4 - E)\Psi_4^{(+)} = F^0_{^4n},$$
$$\Psi_4^{(+)} = G^+(E)F^0_{^4n}.$$

$F^0_{^4n}$ is a wave function of 4 neutrons in the initial ^{8}He outside the ^{4}He core described within COSMA, $\Psi_4^{(+)}$ is the ^{4}n wave function in the Hyperspherical approach. There is no ^{4}n resonance; however, the initial distribution of 4 neutrons in ^{8}He within this mechanism produce a wide bump in the cross section at large energies.

History of the tetraneutron studies

L. Grigorenko, N. Timofeyuk, M. Zhukov, Eur. Phys. J. A 19, 187 (2004)

$^{8}\mathrm{He}(p;\ ^{4}\mathrm{He},p)\ ^{4}n$ reaction

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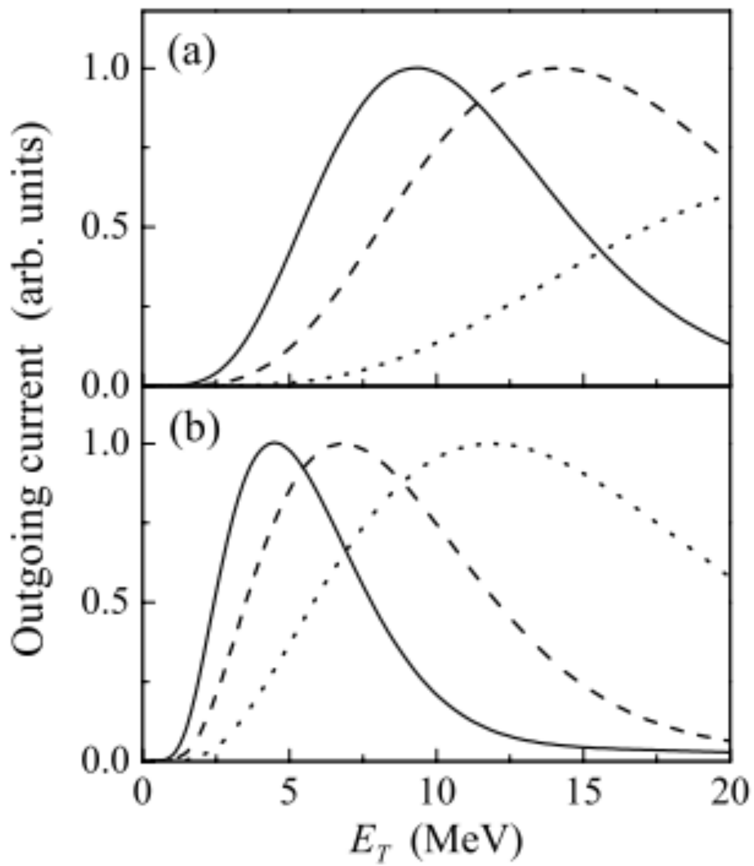

History of the tetraneutron studies

- 2016:
- Japanese experiment $^{4}\mathrm{He}(^{8}\mathrm{He}, 2\alpha)\,^{4}n$ (K. Kisamori, et al., Phys Rev. Lett. **116**, 052501 (2016)): tetraneutron resonance (marginal statistics: 4 events), $E_r = 0.83 \pm 0.65(\mathrm{stat}) \pm 1.25(\mathrm{syst})$ MeV, $\Gamma < 2.6$ MeV.
- 2016:
- First description (prediction) of the tetraneutron resonance (A. M. Shirokov, G. Papadimitriou, A. I. Mazur, I. A. Mazur, R. Roth, J. P. Vary, Phys. Rev. Lett. **117**, 182502 (2016)): $E_r = 0.844$ MeV, $\Gamma = 1.378$ MeV. No-core shell model plus SS-HORSE method for resonance description, democratic decay, JISP16 *NN* interaction
- Publicity, mass media (Phys.org, International Business Times, etc.)

Our later (preliminary) tetraneutron studies

- 2016: Our description (prediction) of the tetraneutron resonance (A. Shirokov et al, AIP Conf. Proc. **2038** (2018)): $E_r = 0.98$ MeV, $\Gamma = 1.6$ MeV. No-core shell model plus SS-HORSE method for resonance description, democratic decay, Daejeon16 *NN* interaction
- Democratic decay experiences high centrifugal barrier $\frac{\mathcal{L}(\mathcal{L}+1)}{\rho^2}$ with $\mathcal{L} = \mathcal{L}_{\min} = K_{\min} + 3 = 5.$
- We can expect that system will prefer to arrange dynamically a 2-body channel $n + {}^3n$ with trineutron resonance or ${}^2n + {}^2n$ channel
- In this cases we get the ${}^4n$ resonance at slightly smaller energy of E_r and essentially smaller width Γ. Hence 2-body channels with smaller width will be suppressed and system will decay democratically into 4 neutrons.

History of the tetraneutron studies

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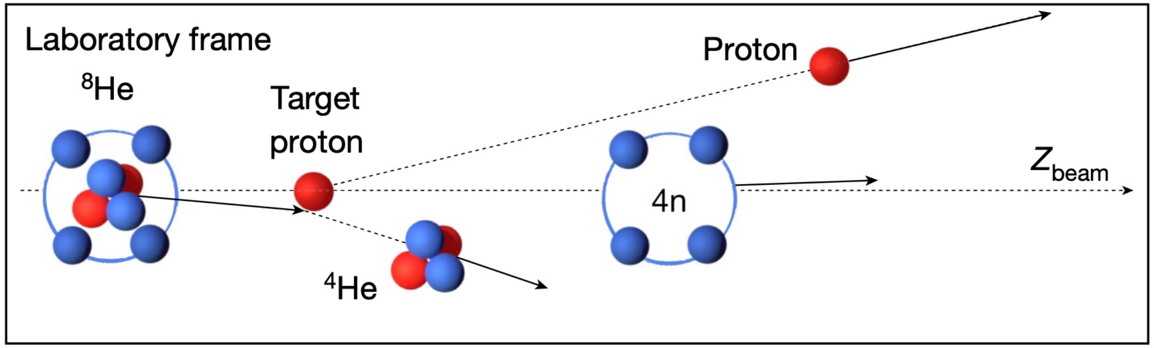
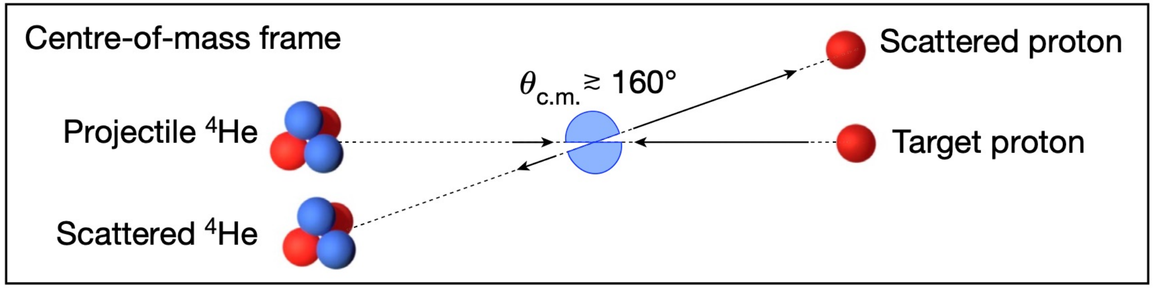
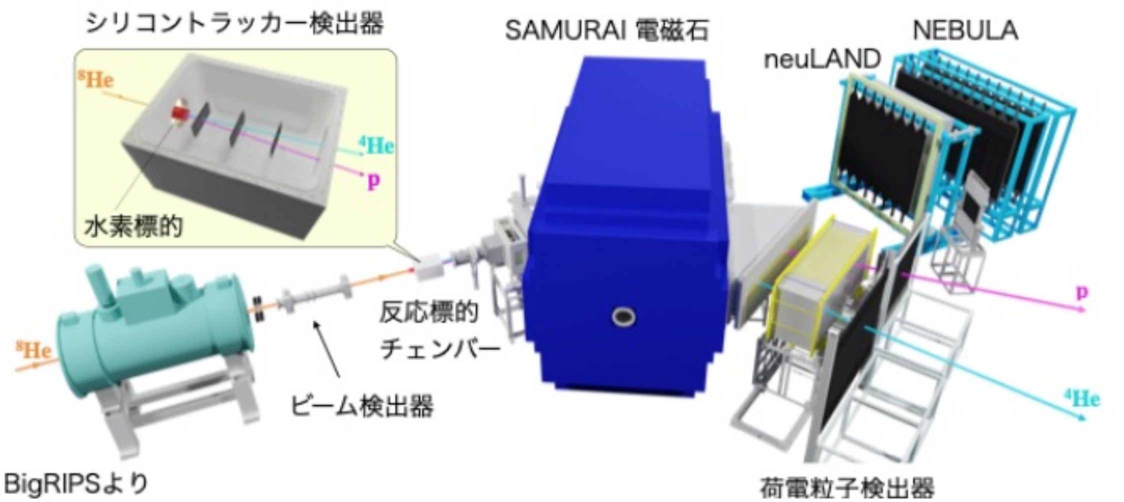
- 2019: One more theoretical prediction: Gamow shell model with SRG-softened chiral EFT *NN* interaction (J. G. Li, N. Michel, B. S. Hu, W. Zuo, F. R. Xu, Phys. Rev. C **100**, 054313 (2019)): $E_r = 2.64$ MeV, $\Gamma = 2.38$ MeV
- 2022: Darmstadt experiment $^{1}\mathrm{H}(^{8}\mathrm{He}, p\alpha)\ ^{4}n$ (M. Duer et al., Nature **606**, 678 (2022)): statistically approved resonance $E_r = 2.37 \pm 0.38(\mathrm{stat}) \pm 0.44(\mathrm{syst})$ MeV, $\Gamma = 1.75 \pm 0.22(\mathrm{stat}) \pm 0.30(\mathrm{syst})$ MeV.

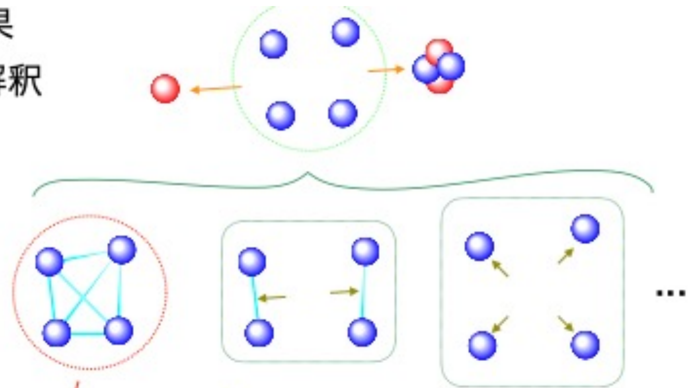
Experiment

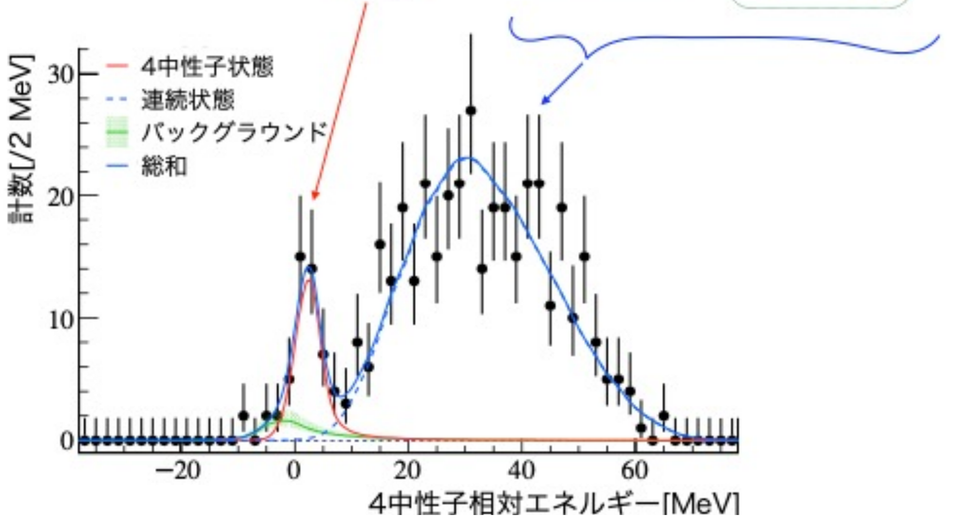






^{8}He$(p,p^4$He) 反応結果
とその解釈





$$E_r = 2.37 \pm 0.38(\text{stat.}) \pm 0.44(\text{sys.})\ \text{MeV},$$

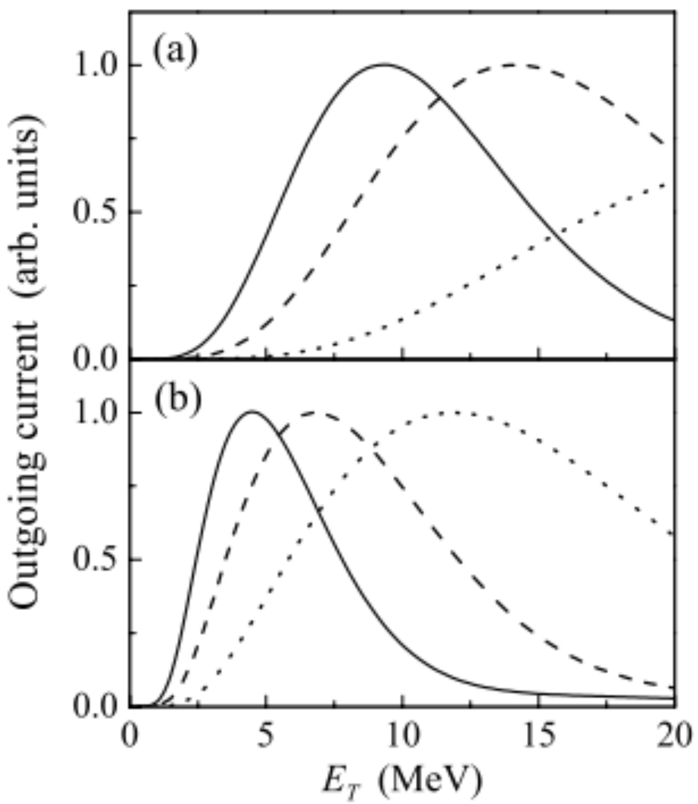
$$\Gamma = 1.75 \pm 0.22(\text{stat.}) \pm 0.30(\text{sys.})\ \text{MeV}.$$

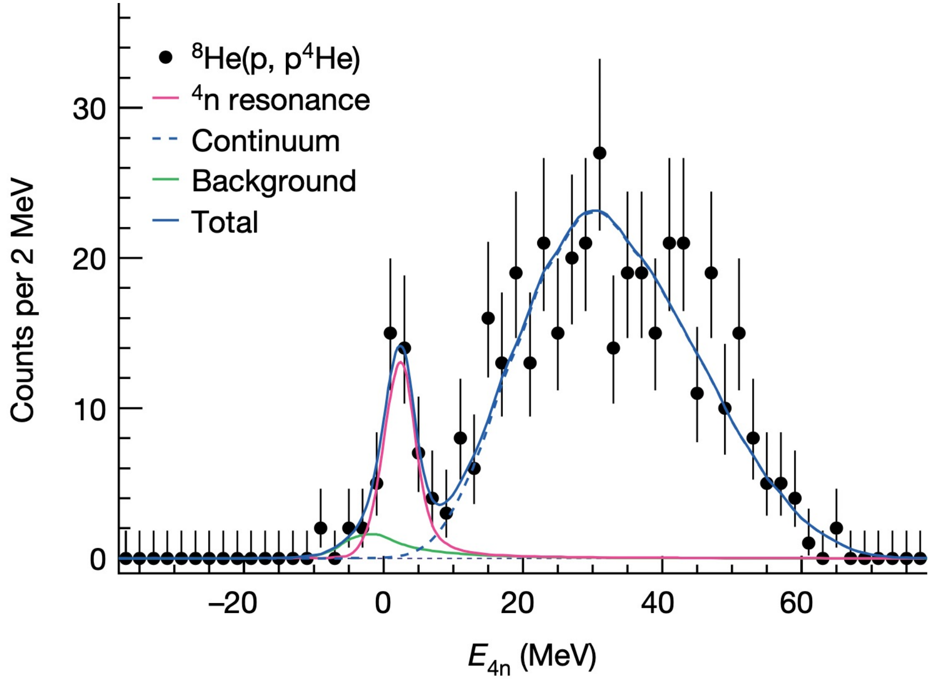
corresponding lifetime of $(3.8 \pm 0.8) \times 10^{-22}$ s.

History of the tetraneutron studies

L. Grigorenko, N. Timofeyuk, M. Zhukov, Eur. Phys. J. A 19, 187 (2004)

$^{8}\mathrm{He}(p;\ ^{4}\mathrm{He},p)\ ^{4}n$ reaction



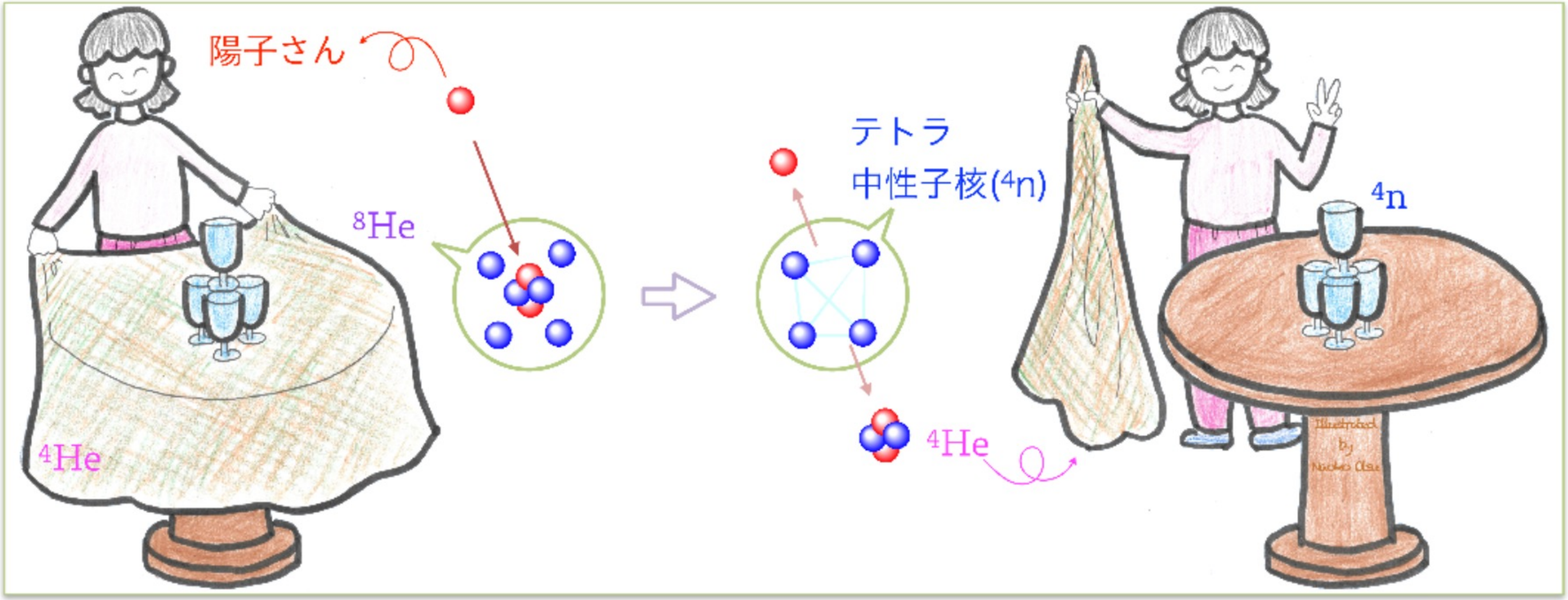


Blue dashed curve in 2022 experiment is taken from Grigorenko et al, 2004

PRESS RELEASE

2022 年 6 月 22 日

理化学研究所、ダルムシュタット工科大学
東京大学大学院理学系研究科、東京工業大学



テトラ中性子核を生成する手法のイメージ

科学道
Dreams to the Future

Проблемы описания тетранейтрона

Существование резонанса тетранейтрона подтверждено.

В чем проблема теоретического описания?

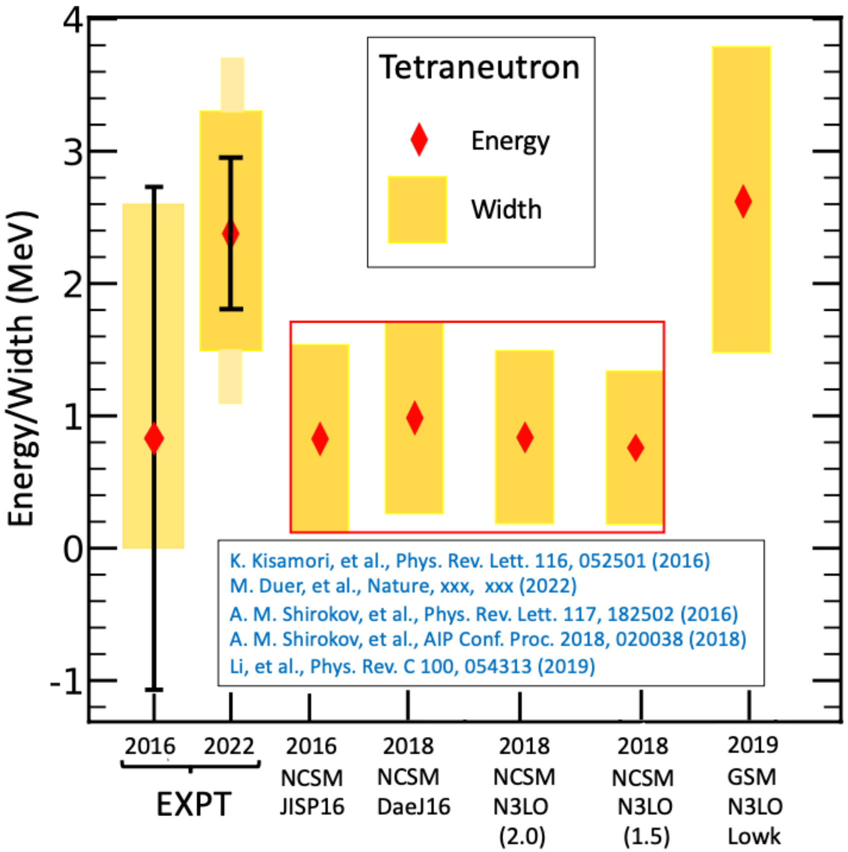
Видимо,

1) метод описания демократического распада резонанса на 4 частицы;

2) взаимодействие нейтронов друг с другом

Проблемы описания тетранейтрона

Взаимодействие нейтронов друг с другом в описании резонанса ^4n:



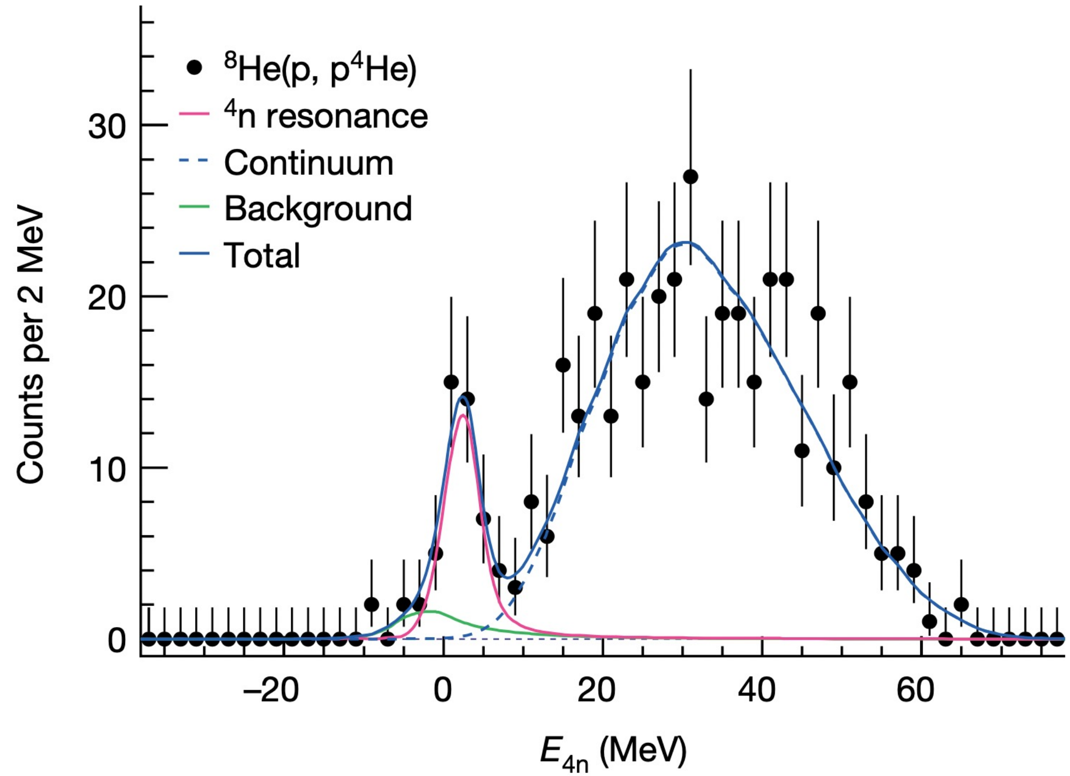
На данный момент резонанс тетранейтрона получен только с этими *NN*-взаимодействиями:
JISP16, Daejeon16: мягкие взаимодействия, предложенные нами, не требуют *NNN*-сил; остальные взаимодействия, искусственно смягченные, требуют *NNN*-силы, но *NNN*-силы с $T = 3/2$ неизвестны.
Например, с *NN*-взаимодействием N3LO без смягчения резонанс тетранейтрона не получается

- Открытие тетранейтрона ставит вопрос о серьезном переосмыслении взаимодействия нуклонов друг с другом

Tetraneutron?

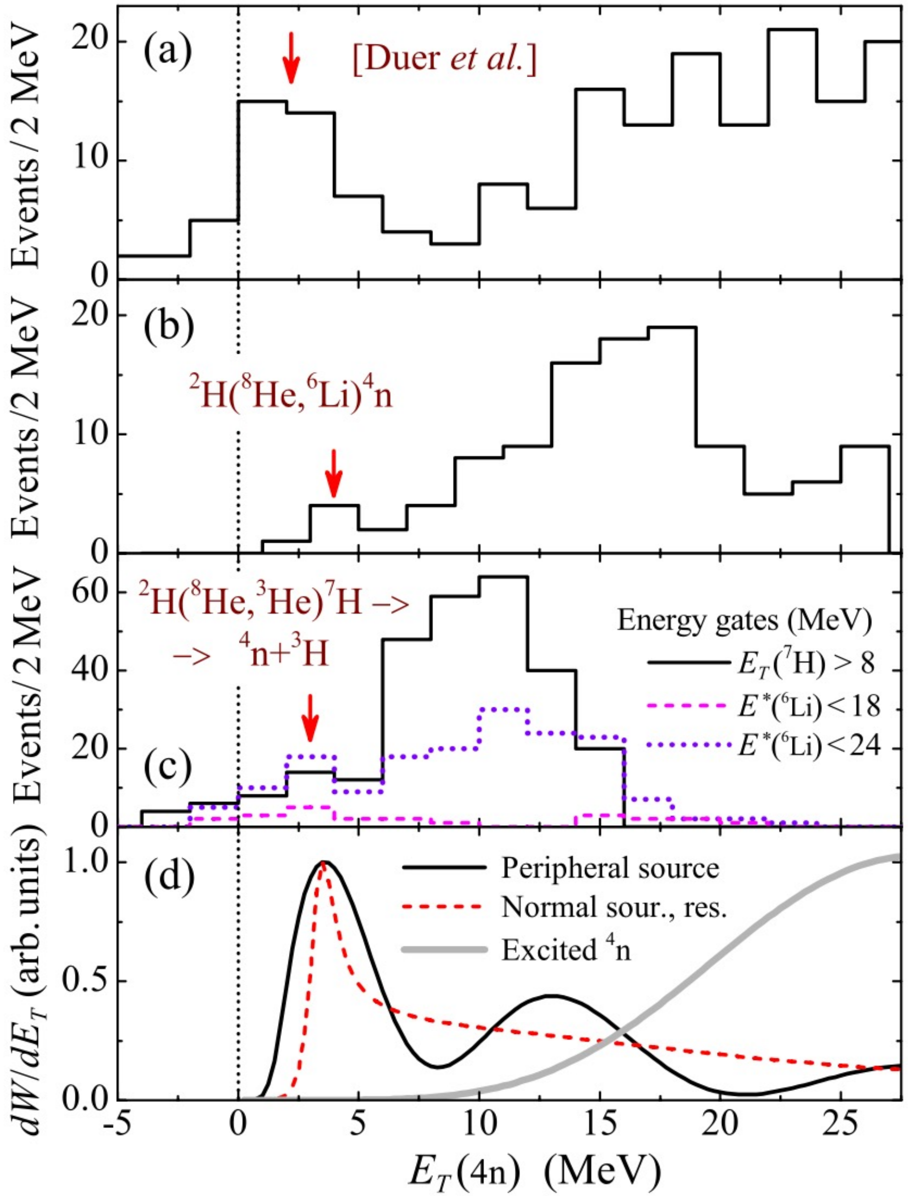
There are still some people who are skeptical about the tetraneutron resonance. In particular,

1) L. G. Sobotka, M. Piarulli, Nature **606**, 656 (2022)
2) R. Lazauskas, E. Hiyama, J. Carbonell, Phys. Rev. Lett. **130**, 102501 (2023)
3) I. A. Muzalevskii et al., arXiv: 2312.17354



Tetraneutron?

- I. A. Muzalevskii et al., arXiv: 2312.17354
- Reactions: $^{2}\mathrm{He}(\,^{8}\mathrm{He},\ ^{6}\mathrm{Li})\ ^{4}n$, $^{2}\mathrm{He}(\,^{8}\mathrm{He},\ ^{3}\mathrm{He})\ ^{7}\mathrm{H} \rightarrow\ ^{3}\mathrm{H} +\ ^{4}n$
- The later reaction transforms to $^{2}\mathrm{He}(\,^{8}\mathrm{He},\ ^{6}\mathrm{Li}^{*})\ ^{4}n$ in the limit of the highest ^{7}H decay energies and $^{6}\mathrm{Li}^{*} \rightarrow\ ^{3}\mathrm{H} +\ ^{3}\mathrm{He}$
- Interpretation: the low-energy peak is not related to the tetraneutron *per se*, but to the ^{8}He structure and the reaction mechanism
- *"The existence of low-energy tetraneutron resonance would mean a radical revision of everything we know about neutron-rich nuclei and neutron matter. Our vision of the problem is that a solution can be found, which is much less radical"*



Speculations about tetraneutron analogues

- If the tetraneutron resonance exists with an energy around $E_r \approx 2.4$ MeV, we should expect its isospin analogues: tetraproton (^{4}Be) resonance $(0^+, T = 2)$; excited resonant states of ^{4}Li$(0^+, T = 2)$; ^{4}He$(0^+, T = 2)$; ^{4}H$(0^+, T = 2)$.
- Studies of these states is very interesting. If found, they can confirm the existence of the tetraneutron resonance. Their studies are interesting from various other aspects.

Speculations: ^{4}H

- Binding energy: 5.604 MeV
- Spectrum: $2^-, T = 1$ – g.s., $E_x = 0$

  $1^-, T = 1,\ E_x = 0.310$ MeV, $\Gamma = 6.73$ MeV

  $0^-, T = 1,\ E_x = 2.080$ MeV, $\Gamma = 8.92$ MeV

  $1^-, T = 1,\ E_x = 2.830$ MeV, $\Gamma = 12.99$ MeV
- Expected: $0^+, T = 2,\ E_x \approx 8.0$ MeV, $\Gamma \approx 1.8$ MeV
- Simplest reaction like $n + {}^3\mathrm{H}$ at the energy of this $T = 2$ state is **forbidden by isospin**; if observed, it will be direct observation of isospin violation
- $^4\mathrm{H}^*(0^+, T = 2)$ may be created in various other reactions, e.g., in α particle transfer reaction $^8\mathrm{Li} + {}^{14}\mathrm{C} \rightarrow {}^{18}\mathrm{O} + {}^4\mathrm{H}^*(0^+, T = 2)$

Speculations: ^{4}Li

- Binding energy: 4.619 MeV
- Spectrum: $2^{-}, T = 1\ -$ g.s., $E_x = 0$

  $1^{-}, T = 1,\ E_x = 0.320\ \text{MeV}, \Gamma = 7.35$ MeV

  $0^{-}, T = 1,\ E_x = 2.080\ \text{MeV}, \Gamma = 9.35$ MeV

  $1^{-}, T = 1,\ E_x = 2.850\ \text{MeV}, \Gamma = 13.51$ MeV
- Expected: $0^{+}, T = 2,\ E_x \approx 8.0\ \text{MeV}, \Gamma \approx 2$ MeV
- Simplest reaction like $p + {}^{3}\text{He}$ at the energy of this $T = 2$ state is **forbidden by isospin**; if observed, it will be direct observation of isospin violation
- $^{4}\text{Li}^{*}(0^{+}, T = 2)$ may be created in various other reactions.

Speculations: ^{4}Be (tetraproton)

- Binding energy: ? Expected approximately -3.5 MeV
- Spectrum: ? Expected $2^-, T = 1$ – g.s., $E_x = 0, \Gamma \approx 2.5$ MeV

  ?
- ^{4}Be($0^+, T = 2$) may be hopefully created in some reactions…

Speculations: ^{4}He

- Binding energy: 28.296 MeV
- Spectrum: $0^+, T = 0\ -$ g.s., $E_x = 0$

$$0^+, T = 0,\ E_x = 20.210 \text{ MeV}, \Gamma = 0.50 \text{ MeV}$$
$$0^-, T = 0,\ E_x = 21.010 \text{ MeV}, \Gamma = 0.84 \text{ MeV}$$
$$2^-, T = 0,\ E_x = 21.840 \text{ MeV}, \Gamma = 2.01 \text{ MeV}$$

…

- Expected: $0^+, T = 2,\ E_x \approx 31 \text{ MeV}, \Gamma \approx 2$ MeV
- I am pessimistic about direct observation of this state: the density of states in ^{4}He at 30+ MeV excitation energy is very high…
- However…

Speculations: ^{4}He

- What about ^{4}He + ^{4}He*(0^{+},T=2)?
- That is ^{8}Be* (0^{+},T=2): $E_x = 27.4941$ MeV, $\Gamma = 5.5$ keV
- ^{4}He*(0^{+},T=2) seems to be more bound in the presence of ^{4}He(0^{+},g.s.)
- What about ^{8}Be + ^{4}He*(0^{+},T=2)?
- That is ^{12}C* (0^{+},T=2): $E_x = 27.595$ MeV, $\Gamma < 30$ keV
- Note, ^{8}Be is approximately 90 keV unbound!
- What about ^{8}Be*(2^{+},$E_x = 3.03$ MeV)+ ^{4}He*(0^{+},T=2)?
- That is ^{12}C* ((2^{+}),T=2): $E_x = 29.63$ MeV, $\Gamma < 200$ keV
- What about ^{12}C + ^{4}He*(0^{+},T=2)?
- That is ^{16}O* (0^{+},T=2): $E_x = 22.721$ MeV, $\Gamma = 12.5$ keV
- Note, ^{12}C is 7.275 MeV bound with respect 3α threshold. ^{4}He*(0^{+},T=2) seems to be less bound in the presence of ^{12}C as compared with ^{8}Be
- What about ^{12}C*(2^{+},$E_x = 4.4$ MeV)+ ^{4}He*(0^{+},T=2)?
- That is ^{16}O* (2^{+},T=2): $E_x = 24.522$ MeV, $\Gamma < 50$ keV

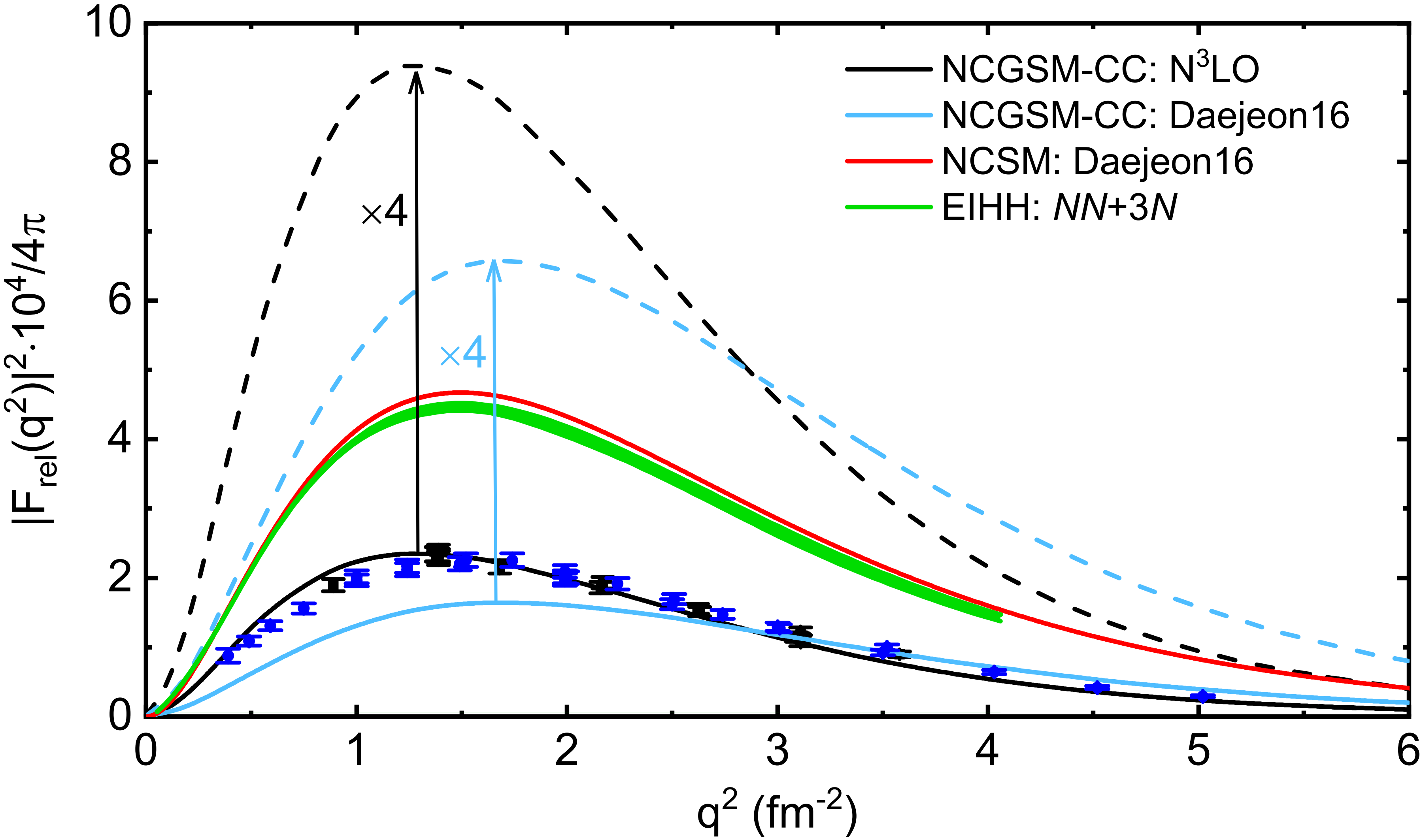
Conclusions

- Do the tetraneutron and its analogues exist?
- There are people who doubt
- However, it seems interesting to search for them
- Is it possible?

- Спасибо

за

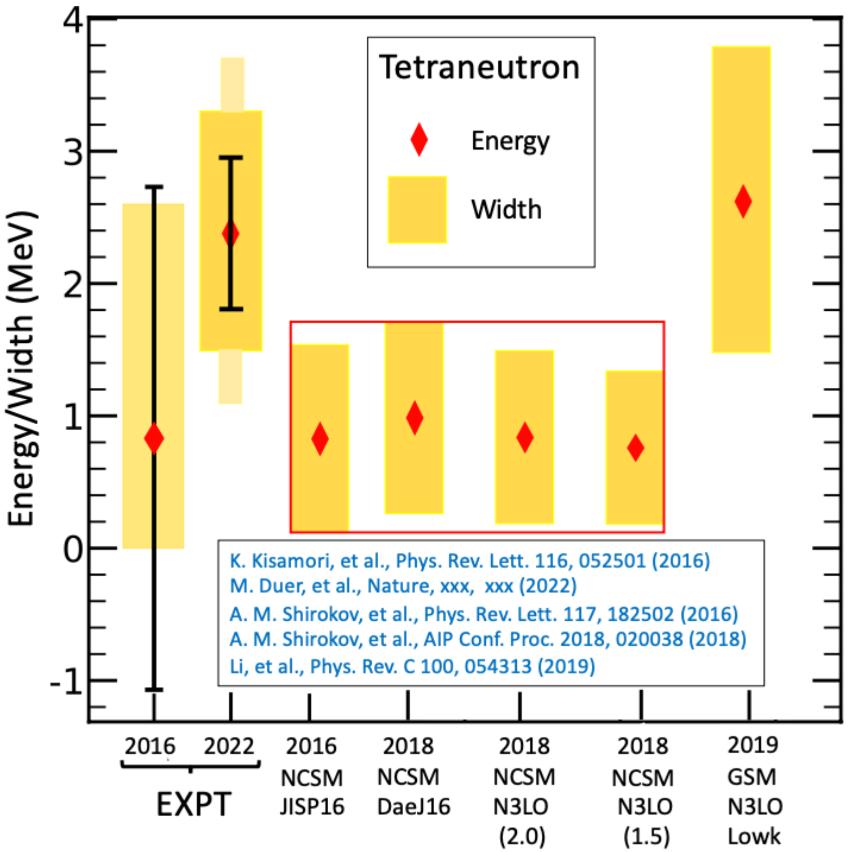
ваше терпение!



10
8
6
4
2
0
0
1
2
3
4
5
6
$|F_{rel}(q^2)|^2 \cdot 10^4/4\pi$
q^2 (fm^{-2})
NCGSM-CC: N^{3}LO
NCGSM-CC: Daejeon16
NCSM: Daejeon16
EIHH: *NN*+3*N*
×4
×4

Tetraneutron theory summary

NN interactions and tetraneutron resonance:



Tetraneutron resonance has been obtained with our *NN* interactions JISP16, Daejeon16 which do not require *NNN* forces and *NN* interactions softened by SRG or Low-k approaches (which require *NNN* forces but they were avoided). Standard modern meson-exchange or chiral EFT *NN* interactions (require *NNN*) do not support the tetraneutron resonance. *NNN* interactions with $T = \frac{3}{2}$ are unknown.

4 particle decay theory is not well established

- Thank you

for your

patience!