Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

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Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

- **Introduction.**
- **Experiments to search for the dineutron and neutral nuclei.**
- **Nucleon – nucleon interaction at very low energy:**

  - Effective range theory.

  - Description of the NN interaction with help of R-matrix model. Singlet deuteron as subthreshold resonance.
- **Search for the singlet deuteron in thermal neutron radiative capture by protons.**
- **Another possible experiments.**
- **Conclusions.**

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

N. Feather, Nature (London), "Properties of a Hypothetical Dineutron", 162, p. 213, 1948.

1. **The possible beta decay lifetime 1-5 sec.**
2. **Maximal dineutron binding energy can be estimated from the condition the dineutron decays to the deuteron, electron and antineutrino.**

The neutron mass is bigger than proton mass on 1.293 MeV.

The calculations give the value of maximal binding energy for dineutron:

$$B_2 = 2m_n - m(^2n) <= m_n - m_p + B_d - m_e = 3.01\ \text{MeV}$$

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

Search for the dineutron and lightest neutral nuclei.

M. Sakisaka, M. Tomita, "Experiments on Possible Existence of a Bound Di-Neutron", J. Phys. Soc. Japan, v. 16, p. 2597-2598, 1961.

$$d + t \rightarrow {}^{3}He + 2n$$

The activation method have been used. The sample of ^{27}Al was used as indicator.

If the indicator capture the dineutron then the activity of ^{29}Al should be observed.

The deuterons with the energy of 160 – 185 keV bombard tritium – titan target. The target was in the paraffine or water shield. The sample of Al was placed at the distance of 12.5-27.5 cm from the target and it was surrounded by Cd foil with the thickness of 1 mm. After irradiation the induced activity with half times 6.6 and 18 minutes **have been observed**. The authors made the conclusion, the activity 6.6 min. is due to decay of ^{29}Al, which appeared as result of **dineutron's capture by ^{27}Al and they get the estimation for dineutron binding energy B(^{2}n) = 2.90 – 3.01 MeV.**

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

Dineutron and lightest neutral nuclei.

C. **Detraz, "**Possible existence of bound neutral nuclei", **Phys. Lett., 1977, 66B, p. 333.**

$p + W$ Synchrotron CERN, $E_p = 24$ GeV.

Activation: $^{64,66,67,68,70}Zn(^{A}n, xn)^{72}Zn$

$$^{72}_{30}Zn \rightarrow ^{72}_{31}Ga + e^{-} + \tilde{\nu}_e$$

^{72}Ga : $T_{1/2}$ = 14.10(2) h. The five lines of gamma quanta have been observed.

$$^{2}n + ^{70}Zn \rightarrow ^{72}Zn$$

Dineutron and lightest neutral nuclei.

K.K. Seth, B. Parker, "Evidence for dineutrons in extremely neutron-rich nuclei", Phys. Rev. Lett., 66(19), p. 2448 - 2451, 1991.

•**Set and Parker** investigated the interaction of mesons with ^{6}Li and ^{9}Be nuclei. The spectra of mesons or protons from next reactions have been measured:

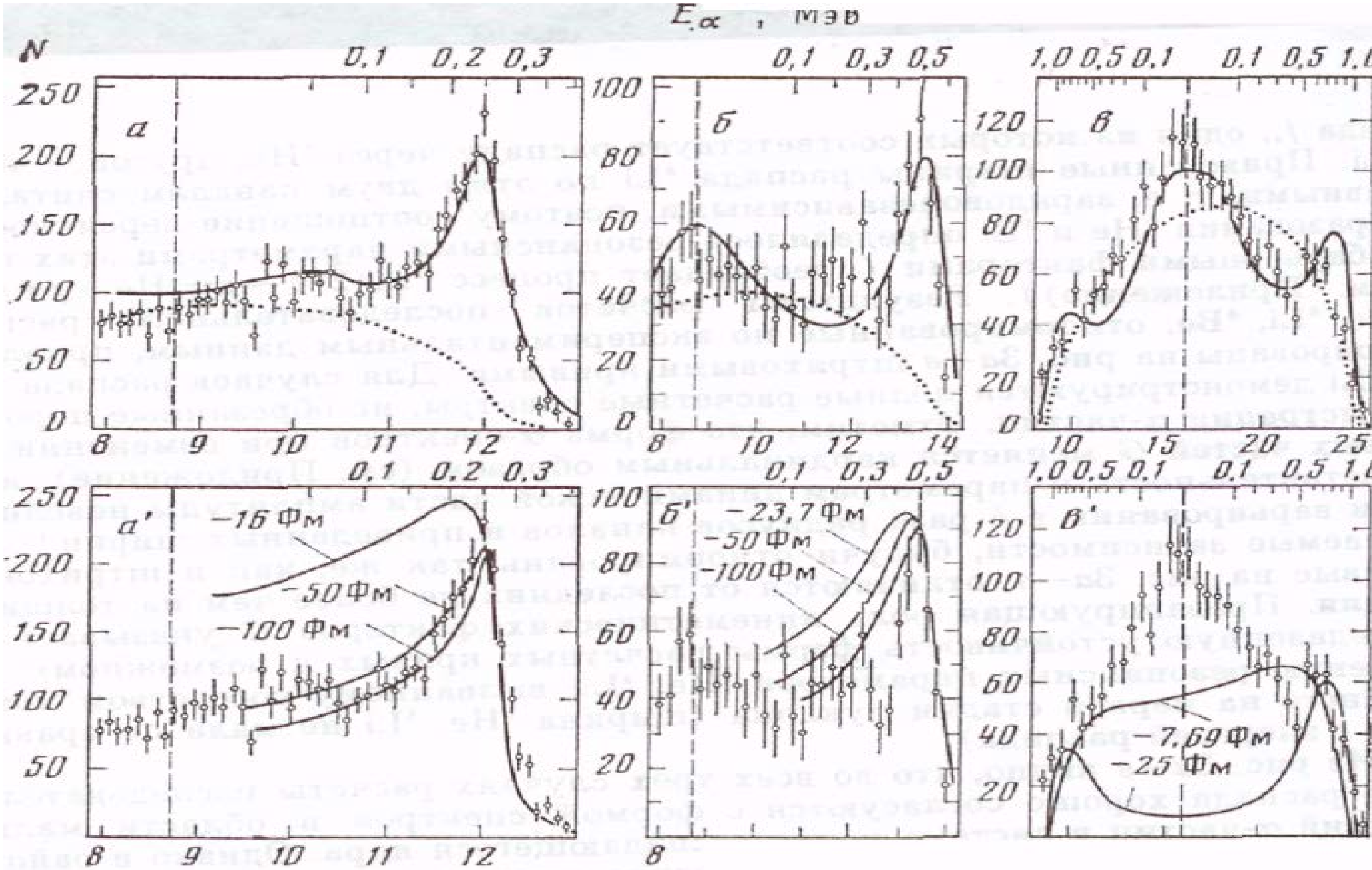
a) $^{6}Li\ (\pi^{-}, \pi^{+})\ ^{6}H$; b) $^{9}Be\ (\pi^{-}, p)\ ^{8}He$; c) $^{6}Li\ (\pi^{-}, p)\ ^{5}H$.

•The measurements have been carried out at the energy of incident mesons of 220 MeV (for reaction ***a***) and 125 MeV (reactions ***b*** and ***c***). The final products of all three reactions was unstable nuclei. The yield of detected particles as a function of the effective mass is in better agreement with experimental data if we assume the formation of a dineutron. The dineutron binding energy was assumed to be zero.

Bochkarev O.V. … Physics of Atomic Nuclei (ЯФ), v. 46, No. 1(7), 1987.

ТРЕХЧАСТИЧНЫЙ РАСПАД СОСТОЯНИЯ 2+ ЯДЕР ^{6}He, ^{6}Li, ^{6}Be

БОЧКАРЕВ О. В., КОРШЕНИННИКОВ А. А., КУЗЬМИН Е. А., МУХА И. Г., ОГЛОБЛИН А. А., ЧУЛКОВ Л. В., ЯНЬКОВ Г. Б.,



Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

O.V. Bochkarev, A.A. Kotsheninnikov, E.A. Kuz’min, I.G. Mukha, A.A. Ogloblin, L.V. Chulkov, G.B. Yan’kov, “Dineutron emission from excited state of ^{6}He”, JETPh Letters, v. 42, No. 7, p. 303- 305, 1985.

Письма в ЖЭТФ, том 42, вып. 7, стр. 303 – 305 *10 октября 1985 г.*

ЭМИССИЯ "ДИНЕЙТРОНА"
ИЗ ВОЗБУЖДЕННОГО СОСТОЯНИЯ ЯДРА ^{6}He

О.В.Бочкарев, А.А.Коршенинников, Е.А.Кузьмин,
И.Г.Муха, А.А.Оглоблин, Л.В.Чулков, Г.Б.Яньков

В работе экспериментально исследовался распад возбужденного состояния 2^{+} ядра ^{6}He, образованного в реакции ^{7}Li (d, ^{3}He) ^{6}He* при энергии дейтронов 30,5 МэВ. Показано, что механизм эмиссии динейтрона ^{2}n (T = 1, S = 0) объясняет 45% случаев распада.

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

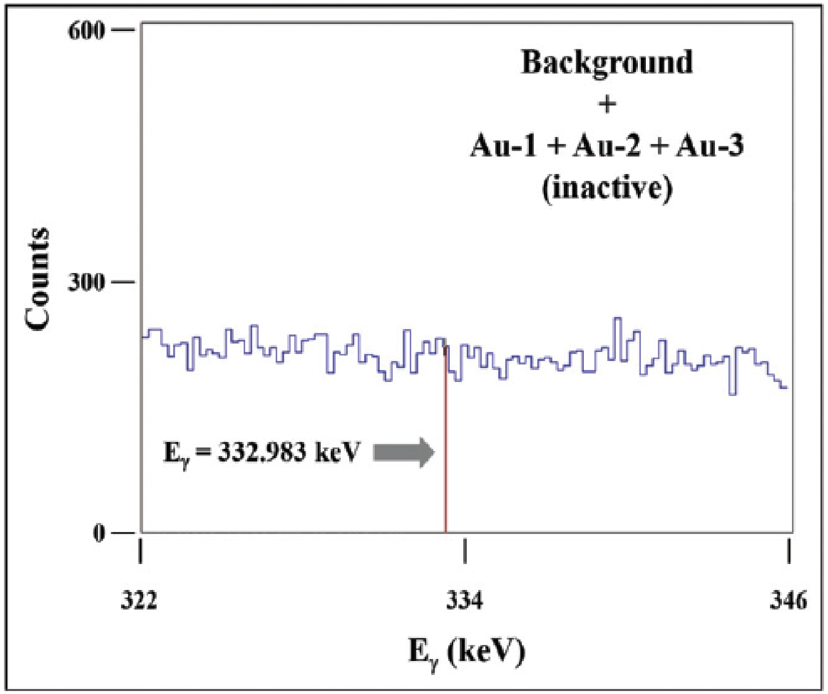
Statistically significant observation of and cross sections for a new nuclear reaction channel on ^{197}Au with bound dineutron escape

IHOR M. KADENKO [1(a)], BARNA BIRÓ[2], ANDRÁS FENYVESI[2]

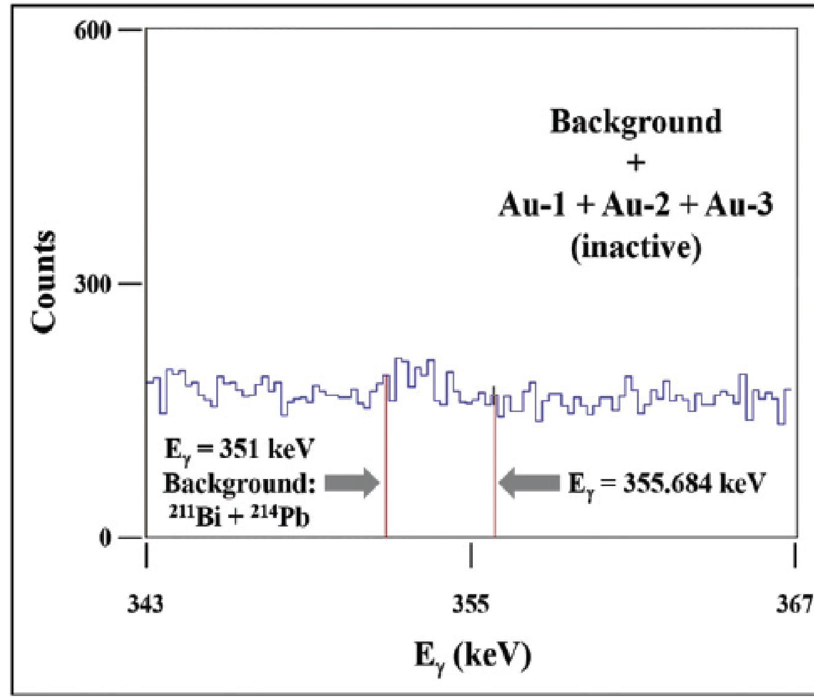
[1] *International Nuclear Safety Center of Ukraine; Department of Nuclear Physics, Taras Shevchenko National University of Kyiv – St. Volodymyrs`ka, 64/13, 01601, Kyiv, Ukraine*
[2] *Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), Bem tér 18/c, H-4026 Debrecen, Hungary*

PACS 21.45.Bc - Two-nucleon system
PACS 25.90.+k - Other topics in nuclear reactions: specific reactions
PACS 27.10.+h - A ≤ 5

Abstract – A new nuclear reaction channel on ^{197}Au with the neutron as a projectile and a bound dineutron (^{2}n) in the output channel is considered based on available experimental observations. The dineutron is assumed to be formed as a particle-satellite, separated from the volume but not from the potential well of ^{196}Au nucleus. The dineutron was identified by statistically significant radioactivity detection due to decay of ^{196g}Au nuclei. Cross sections for the ^{197}Au $(n,^{2}n)$ ^{196g}Au reaction are determined as 180 ± 60 μb and 37 ± 8 μb for [6.09-6.39] and [6.175-6.455] MeV energy ranges, correspondingly. Possible outcomes of dineutron detection near the surface of deformed nuclei are also raised and discussed.


Background
+
Au-1 + Au-2 + Au-3
(inactive)
Counts
600
300
0
E_γ = 332.983 keV
322
334
346
E_γ (keV)

(a)


Background
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Au-1 + Au-2 + Au-3
(inactive)
Counts
600
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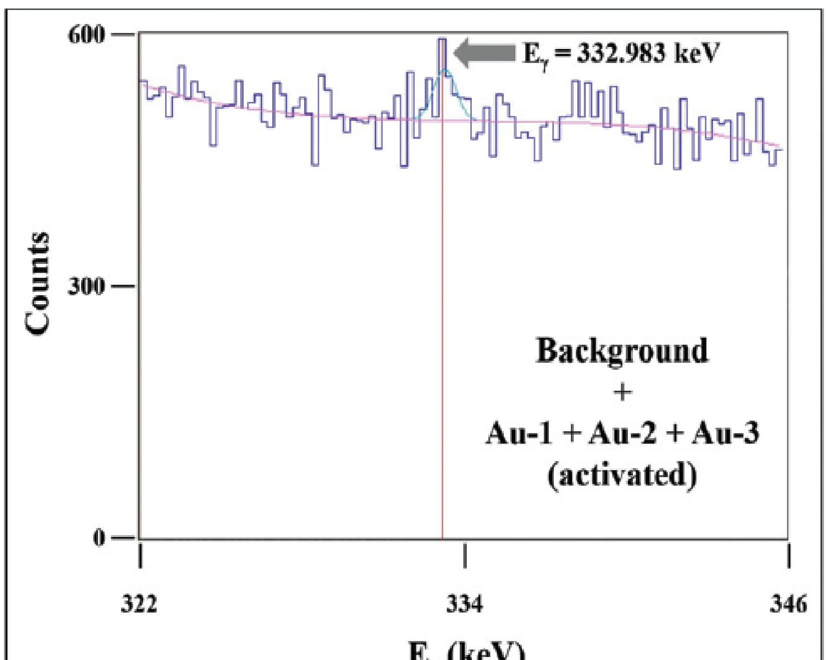
E_γ = 351 keV
Background:
$^{211}Bi + ^{214}Pb$
E_γ = 355.684 keV
343
355
367
E_γ (keV)

(a)


E_γ = 332.983 keV
Counts
600
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Background
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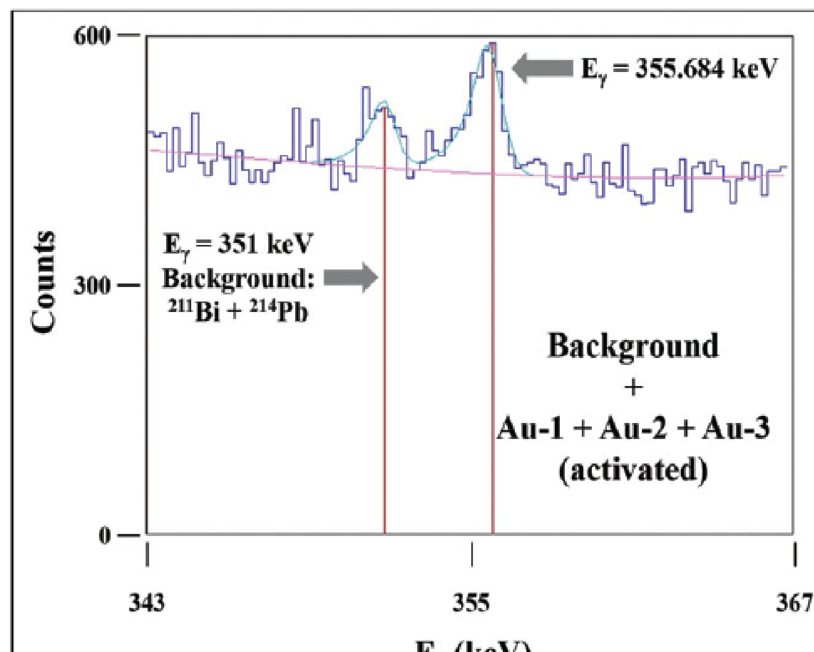
Au-1 + Au-2 + Au-3
(activated)
322
334
346


E_γ = 355.684 keV
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$^{211}Bi + ^{214}Pb$
Background
+
Au-1 + Au-2 + Au-3
(activated)
343
355
367

Dineutron and lightest neutral nuclei.

I.M. Kadenko, B. Biro, A. Fenyvesi, “Statistically significant observation of and cross sections for a new nuclear reaction channel on ^{197}Au with bound dineutron escape”, EPL, 2020, v. 131, No. 5, 52001.

$${}_1^2d + {}_1^2d \rightarrow {}_2^3He + {}_0^1n$$

Reaction threshold $^{197}Au(n,2n)^{196g}Au$ E_{thr} = 8.11372 МэВ.

$$T_{1/2} = 6.183D$$

Nuclide	E_γ, keV	I_γ, %	S ± ΔS	σ, μb
^{196}Au	332.983	22.9 ± 0.5	307 ± 119	180 ± 60
	355.684	87	867 ± 133	

2-nd irradiation: $\sigma = 37 \pm 8\_\mu b$

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

B.G. Novatski, E.Yu. Nikolskii, S.B. Sakuta, D.N. Stepanov, “Possible observation of light neutral nuclei in the fission of ^{238}U by alpha - particles”, JETPh Letters, v. 96, No. 5, p. 310 - 314, 2012;
(Б.Г. Новацкий, Е.Ю. Никольский, С.Б. Сакута, Д.И. Степанов, “Возможное обнаружение легких нейтральных ядер в делении ^{238}U α-частицами”, Письма в ЖЭТФ, т. 96, вып. 5, с. 310-314, 2012).

B.G. Novatski, S.B. Sakuta, D.N. Stepanov, “Observation of light neutral nuclei in the fission of ^{238}U by alpha – particles with help of activation of ^{27}Al”, JETPh Letters, v. 98, No. 11, p. 747 - 751, 2013;
(Б.Г. Новацкий, С.Б. Сакута, Д.Н. Степанов, “Обнаружение легких нейтральных ядер в делении ^{238}U α-частицами методом активации изотопа ^{27}Al”, Письма в ЖЭТФ, т. 98, вып. 11, с. 747-751, 2013).

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

The group from Tomsk Polytechnic Institute investigated the decay of ^{252}Cf and observed ^{232}U, which can appear as result of the **octaneutron** emitting only.

Arguments for Detecting Octaneutrons in Cluster Decay of ^{252}Cf Nuclei

G.N. Dudkin, A.A. Garapatskii and V.N. Padalko

Tomsk Polytechnic University, 634050 Tomsk, Russia

E-mail: dudkin@tpu.ru

Abstract

A new method of searching for neutron clusters (multineutrons) composed of neutrons bound by nuclear forces has been introduced and implemented. The method is based on the search for daughter nuclei that emerge at the nuclei cluster decay of ^{252}Cf to neutron clusters. The effect of long-time build-up of daughter nuclei with a high atomic number and long half-life was utilized. As a result, the cluster decay of ^{252}Cf to a daughter nucleus ^{232}U (half- life of $T_{1/2}$= 68.9·years) was discovered. It is assumed that the emergence of ^{232}U nuclei is attributed to emission of neutron clusters consisting of eight neutrons - octaneutrons. The emission probability of octaneutrons against α-decay probability of ^{252}Cf is defined equal to $\lambda_C/\lambda_\alpha = 1.74\cdot10^{-6}$.

Dineutron and neutral nuclei.

Experiments with radioactive nuclei.

1. **F.M. Marques et al.** have observed 6 events when tetraneutrons appeared. The beam of ^{14}Be nuclei was used: $^{14}Be \to {}^{10}Be + 4n.$

F.M. Marques et al., Phys. Rev. **C65** (2002) 044006.

2. **A. Spyrou et al.** observed the decay of ^{16}Be with simultaneous emission of two neutrons.

Phys. Rev. Lett., 108, 102501, 2012

Analogous process have been observed in the reaction ^{26}O – ^{24}O +2n.

K. Hagino, H. Sagawa, "Correlated two-neutron emission in the decay of unbound nucleus ^{26}O", ArXiv: nucl-th: 1307.55021v1, 2013.

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

T. Faestermann, A. Bergmaier, R. Gernhauser, D. Koll, M. Mahgoub,

“Indications for a bound tetraneutron”, Phys. Lett. B 824, 136799, 2022.

$$^{7}Li + ^{7}Li \rightarrow ^{10}C + ^{4}n$$

$$B\left(^{4}n\right) = 0.42 \pm 0.16\_MeV$$

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

Tritium puzzle.

Total binding energy B(T) = 8.48 MeV;

Neutron binding energy: B_n= 6.26 MeV;

$${}^1_0n + {}^2_1d \rightarrow {}^3_1t; \quad B_n + B_d = 6.26 + 2.22 = 8.48\_MeV;$$

If dineutron is unbound, then B_p = 8.48 MeV. Why proton binding energy bigger than neutron binding energy?

This fact contradicts to the principle of isotopic invariance!

For example: ^{4}He: $B_n = 20.6\_MeV;$ $B_p = 19.8\_MeV$

The difference is due to Coulomb interaction.

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

Total momentum for two nucleons: $\vec{J} = \vec{S}_1 + \vec{S}_2 + \vec{L}$

If $\vec{L} = 0$ then $\vec{J} = \vec{S}_1 + \vec{S}_2 = 1$ Triplet state: [***np*(³*S*₁)**]

or $\vec{J} = \vec{S}_1 + \vec{S}_2 = 0$ Singlet state [***nn*, *np***($^1S_0$), ***pp***]

Total scattering cross-section:

$$\sigma = \frac{2 \cdot J^+ + 1}{2 \cdot (2 \cdot I + 1)} \sigma_+ + \frac{2 \cdot J^- + 1}{2 \cdot (2 \cdot I + 1)} \sigma_- = \frac{3}{4} \sigma_t + \frac{1}{4} \sigma_s$$

$$\sigma_{scat} = 4 \cdot \pi \cdot |F|^2$$

$$\sigma = \frac{3}{4} \sigma_t + \frac{1}{4} \sigma_s = \pi \cdot \left(3 \cdot |F_t|^2 + |F_s|^2\right)$$

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

Low Energy Nucleon-Nucleon Interaction.

Scattering amplitude (if $E_n \longrightarrow 0$):

$$F = \frac{1}{p \cdot ctg\delta - i \cdot p} = \frac{1}{g(k) - i \cdot p}$$

$$p = \frac{1}{\hbar}\sqrt{2 \cdot \mu \cdot E} - impulse \qquad \mu = \frac{m_n \cdot m_p}{m_n + m_p}$$

S matrix: $$S = 1 + 2ipF(p)$$

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

Low energy *NN* interaction.

"Effective range theory"

H.A. Bethe, "Theory of effective Range in Nuclear Scattering", Phys. Rev. v. 76, No.1, p. 38-50, 1948.

- Scattering amplitude:

$$F = \frac{1}{-\frac{1}{a} + \frac{1}{2} r p^2 - ip} = \frac{1}{g(p) - ip}$$

$$p = \frac{1}{\hbar}\sqrt{2 \cdot \mu \cdot E}$$

- neutron impulse.

$a - scattering \quad length;$

$r - effective \quad range;$

$$g(k) = -\frac{1}{a} + \frac{1}{2} r p^2 + P p^4 + Q p^6$$

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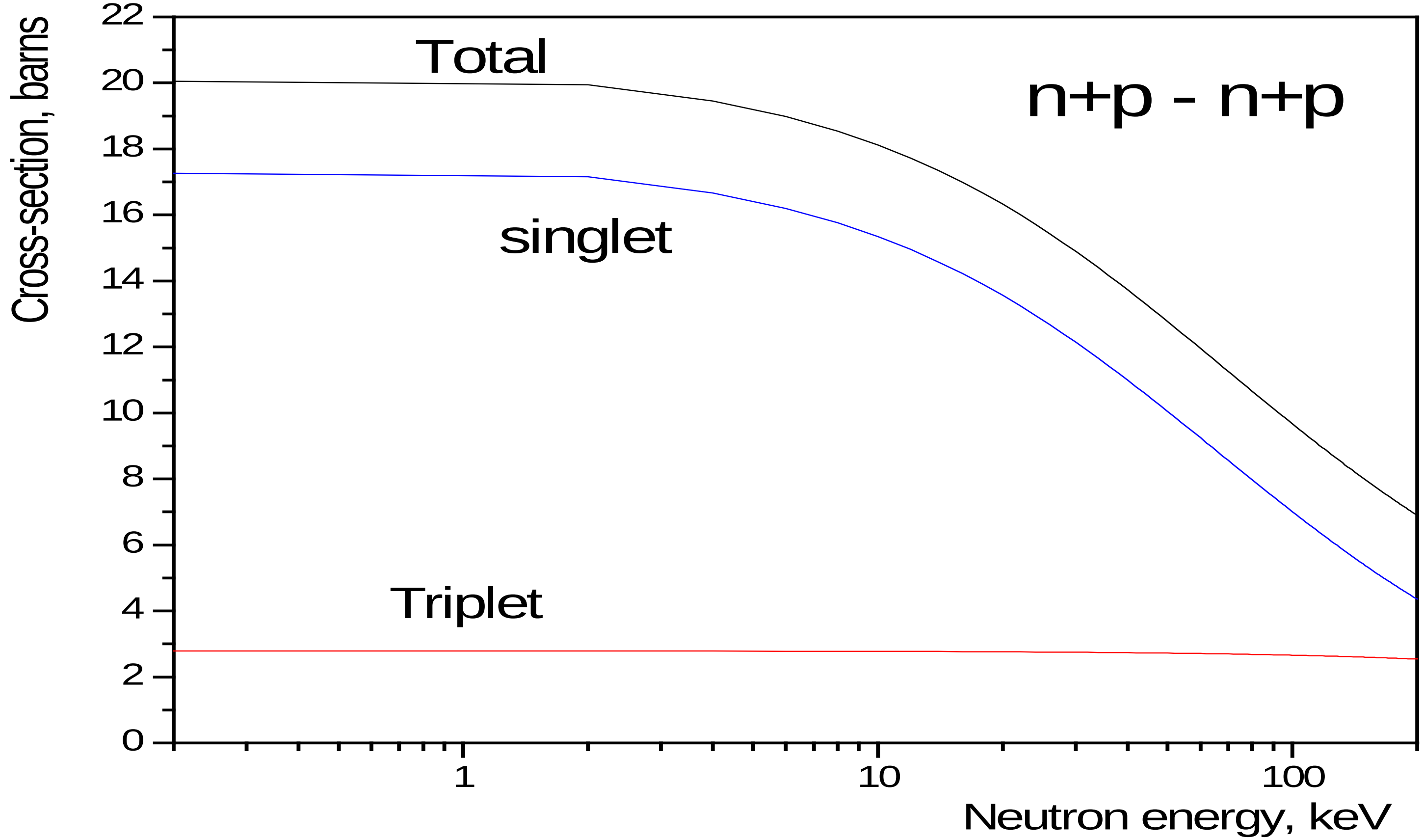
Experimental values for scattering parameters.

NN	Scattering length, Fm.	Effective range, Fm.	P	Q
pp	-7,822 ± 0,004	2,83 ± 0,017	0,051 ± 0,014	0,028 ± 0,013
$np(^1S_0)$	-23,719 ± 0,013	2,76 ± 0,05		
nn	-18,95 ± 0,4 -16.5 ± 0.9			
$np(^3S_1)$	5,414 ± 0,005	1,75 ± 0,05	0,13 ± 0,09	

Low energy *NN* interaction.



Neutron-proton scattering cross-section.

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n – p – cross section

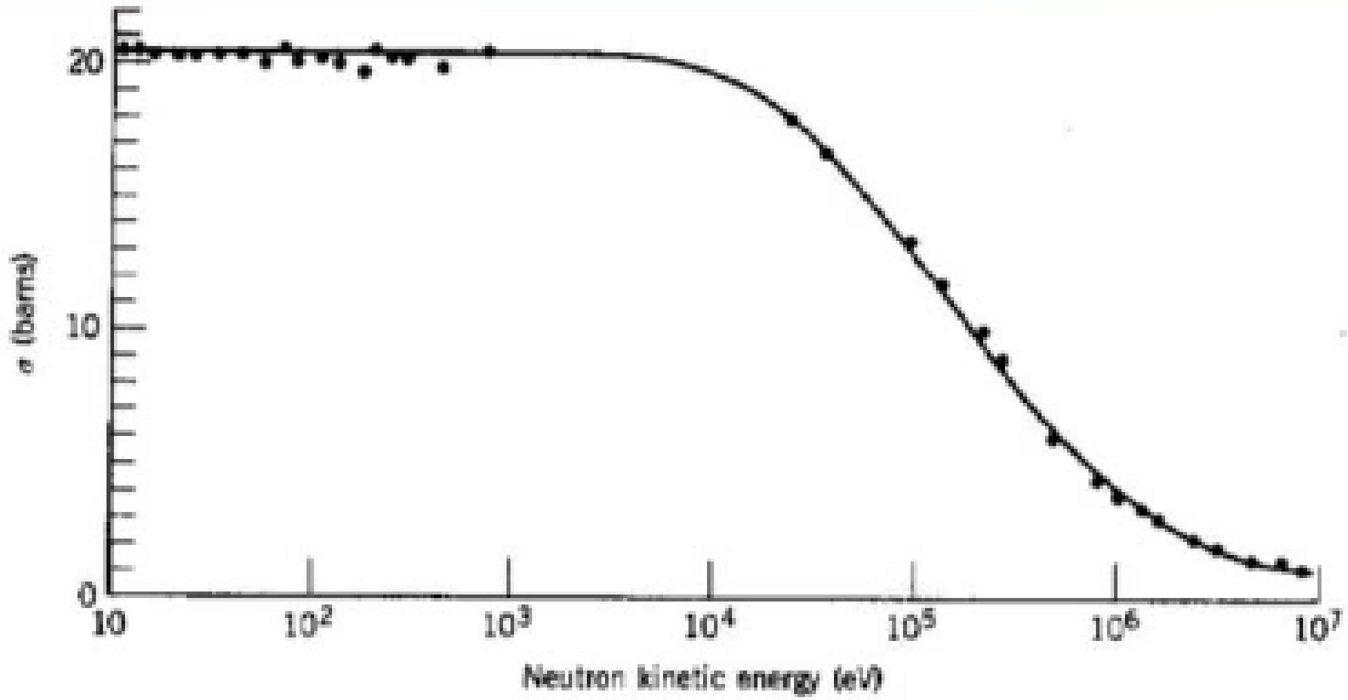

Figure 4.6 The neutron–proton scattering cross section at low energy. Data taken from a review by R. K. Adair, *Rev. Mod. Phys.* **22**, 249 (1950), with additional recent results from T. L. Houk, *Phys. Rev. C* **3**, 1886 (1970).

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Low energy *NN* interaction. S-matrix: $S = 1 + 2ipF$

Negative energy: $E \langle 0 \quad \Rightarrow \quad p = i\kappa \quad (\kappa -$ real value)

Poles of S-matrix: $-\frac{1}{a} - \frac{1}{2} r\kappa^2 + \kappa = 0$

Two poles for each spin state:

$$\kappa_{1,2} = \frac{1}{r} \pm \sqrt{\frac{1}{r^2} - \frac{2}{ar}}$$

State	κ, 1/Fm	E, MeV	Comment
$^3S_1$, $a_t > 0$	0.232	- 2.225	Deuteron
	0.911	- 34.4	?
$^1S_0$, $a_s < 0$	- 0.044	- 0.080	Virtual level
	0.68	- 19.2	?

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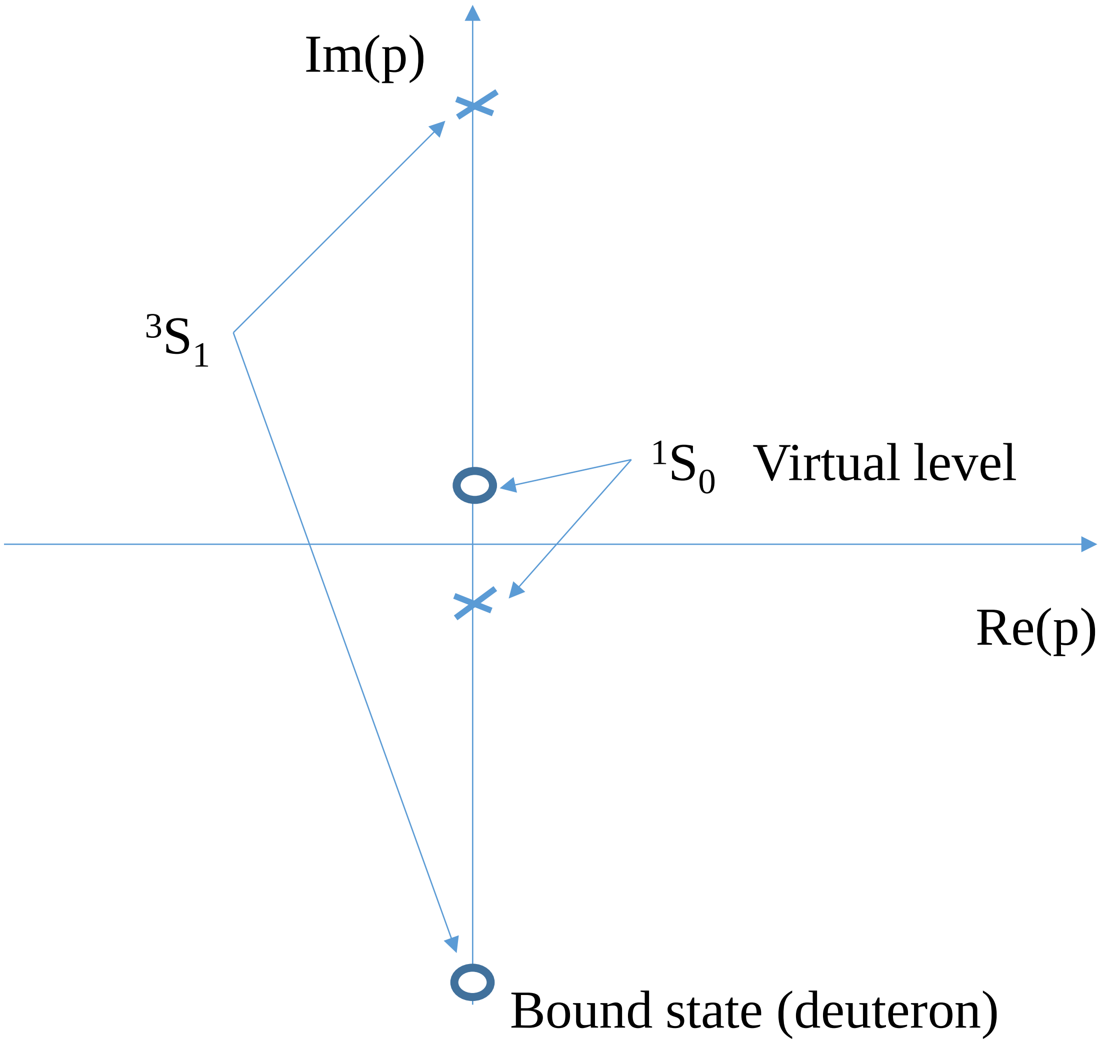
S – matrix poles.



Low energy *NN* interaction.

Problems:

- How to measure the energy of virtual level?
- What physical sense of another poles of the S - matrix?
- How to observe the virtual level in the electromagnetic interactions?
- The radiative capture of thermal neutrons by protons ***np - dγ*** occurs from the singlet state. How to take into account radiation capture in the theory of effective range?

For thermal neutrons: $$\sigma_{n\gamma} = 334 \pm 0.5 mb$$

REVIEWS OF MODERN PHYSICS VOLUME 25, NUMBER 4 OCTOBER, 1953

Interpretation of the Virtual Level of the Deuteron

S. T. MA*

Division of Physics, National Research Council, Ottawa, Canada

$$E_r = \frac{2}{ar}\frac{h^2}{2\mu}$$

"Only if there is no bound state capable to account

for the low-energy cross section one is entitled to give definite

statements about the existence of antibound states"

V. de Alfaro, T. Regge, "Potential scattering",
North-Holland Publishing Company - Amsterdam, 1965, p. 72.

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Low energy *NN* interaction.

G.M. Hale, L.S. Brown, M.W. Paris, "Effective field theory as a limit of R-matrix theory for light nuclear reactions", Phys. Rev. C89, 014623, 2014.

$$R(E,a) = \frac{\gamma^2(a)}{E_\lambda(a) - E}$$

$$e^{2\cdot i\cdot\delta_0(E)} = e^{-2i\cdot p\cdot\cdot a}\,\frac{1 + i\cdot p\cdot a\cdot R(E,a)}{1 - i\cdot p\cdot a\cdot R(E,a)}$$

$$g^2 = a\cdot\gamma^2$$

$$p\cdot\cot\delta_0(E) = \frac{1}{g^2}\left(E_\lambda - E\right)$$

$\boldsymbol{a} \longrightarrow 0$ $\quad E_\lambda = -1.27$ MeV

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

Low energy *NN* interaction.

Two channels (elastic scattering and radiative capture): $A = a - ib$

$$n + p \to n + p; \qquad n + p \to d + \gamma$$

Radiative capture cross-section: $\sigma_c = \dfrac{4\pi b}{p}$ (1/v law)

The value of thermal neutron radiative capture:

$$\sigma_{n\gamma} = 334 \pm 0.5 mb$$

Possible experiments to search for singlet deuteron and the problem of the existence of neutral nuclei

Virtual level or dibaryon resonance?

$$F = \frac{1}{-\frac{1}{a-ib} + \frac{1}{2} r p^2 - ip} = \frac{1}{2p} \frac{\frac{4}{r} p}{p^2 - \frac{2}{ra} - i\frac{1}{2}\left(\frac{4p}{r} + \frac{4b}{ra^2}\right)}$$

$$= \frac{1}{2p} \frac{\Gamma_n}{E - E_r - i\frac{1}{2}(\Gamma_n + \Gamma_\gamma)}$$

(Breit – Wigner formula)

Resonance energy.

$$E_r = \frac{2}{ar} \frac{h^2}{2\mu}$$

Neutron width

$$\Gamma_n = \frac{4p}{r} \propto \sqrt{E_n}$$

Radiative width

$$\Gamma_\gamma = \frac{4b}{ra^2}$$

S.T. Ma, Rev. Mod. Phys., v.25, p.853, 1953.

S.B. Borzakov, “Interaction of low energy neutrons with protons and possible existence of the resonance $J^\pi = 0^+$”, JINR Communications, P15-93-29, Dubna, 1989;

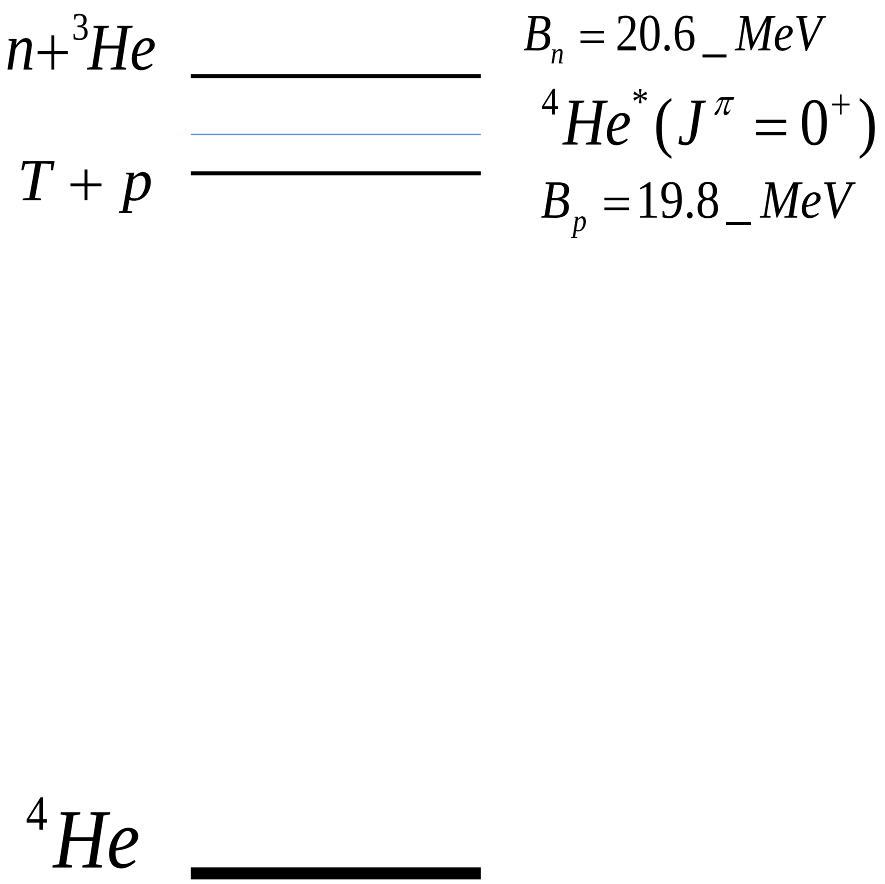
S. B. Borzakov, Physics of Atomic Nuclei, v. 57, p. 517, 1994.

Possible experiments to search for singlet deuteron and the problem of the existence of neutral nuclei

Analogy: $n + {}^3He \to {}^3He + n;$ $n + {}^3He \to T + p;$

For thermal neutrons: $\sigma_{th}\left(n + {}^3He \to T + p\right) \approx 5400\_b$

A.A. Bergman, A.I. Isakov, Yu.P. Popov, F.L. Shapiro, JETPh, v. 33, p. 9, 1957.



С.Б. Борзаков, Х. Малецки, Л.Б. Пикельнер, М. Стэмпински, Э.И. Шарапов, “Особенности отклонения от закона 1/v сечения реакции $n + {}^3He \to T + p$. Возбуждённый уровень ^{4}He. ЯФ, т. 35, вып. 3, с. 532, 1982.

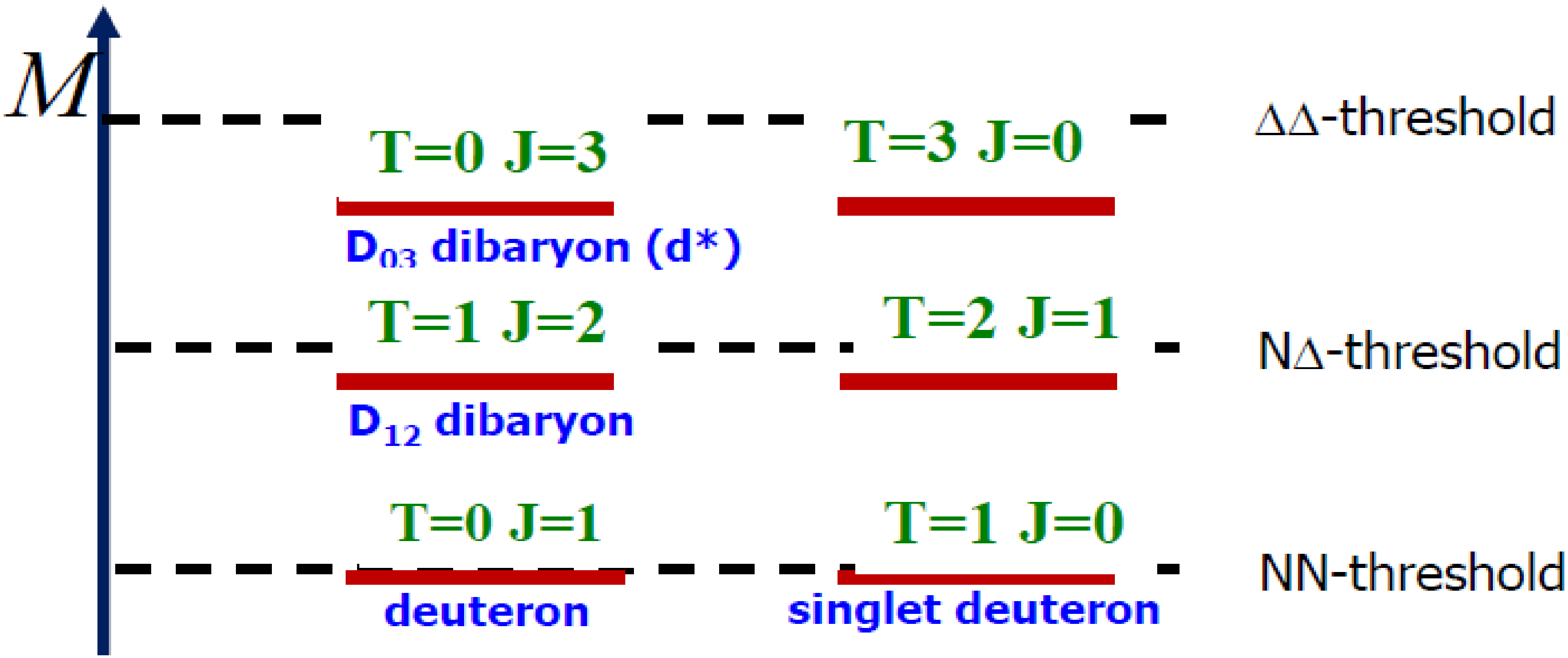
Confirmed in the reaction:

$$T + p \to T + p$$

Possible experiments to search for singlet deuteron and the problem of the existence of neutral nuclei

6q states with the baryon number B=2

1. F.J. Dyson and N.-H. Xuong, PRL **13**, 815 (1964)



From report of O.A. Rubtsova et. al.

Possible experiments to search for singlet deuteron and the problem of the existence of neutral nuclei

- **F.J. Dyson, N. H. Xuong, Phys. Rev. Lett. v. 13, No. 26, 1964.**
- **K. Maltman, N. Isgur, Phys. Rev., D29, No. 5, p.952, 1984.**

"Nuclear physics and the quark model: Six quarks with chromodynamics",

Binding energies: $B_d = 2.9$ МэВ $B(^1S_0) = (0.4 +/- 0.4)$ MeV

- **A.N. Ivanov, M. Cargnelli, M. Faber, H. Fuhrmann, V.A. Ivanova, J. Marton, N.I. Trotskaya, J. Zmeskal, "Quantum field theoretic model of metastable resonant spin-singlet state of the np pair", e-Arxiv: nucl-th/0407079, 2004.** $E_S = - 79 +/- 12$ keV

- **R. Hackenburg, Preprints BNL, BNL-77482-2007-IR, BNL-77483-2007-JA .**

$$\sigma(n + p \rightarrow d + 2\gamma) = 27\,\mu b$$

Eγ1 = 66 keV; Eγ2 = 2157 keV

Possible experiments to search for singlet deuteron and the problem of the existence of neutral nuclei

T. Yamazaki, Y. Kuzamashi, A. Ukawa, Phys. Rev. D84, 054506, 2011.

We address the issue of bound state in the two-nucleon system in lattice QCD. Our study is made in the quenched approximation at the lattice spacing of $a = 0.128$ fm with a heavy quark mass corresponding to $m_\pi = 0.8$ GeV. To distinguish a bound state from an attractive scattering state, we investigate the volume dependence of the energy difference between the ground state and the free two-nucleon state by changing the spatial extent of the lattice from 3.1 fm to 12.3 fm. A finite energy difference left in the infinite spatial volume limit leads us to the conclusion that the measured ground states for not only spin triplet but also singlet channels are bounded. Furthermore the existence of the bound state is confirmed by investigating the properties of the energy for the first excited state obtained by a 2×2 diagonalization method. The scattering lengths for both channels are evaluated by applying the finite volume formula derived by Lüscher to the energy of the first excited states.

$$-\Delta E_\infty = \begin{cases} 7.5(0.5)(0.9)\ \text{MeV} & \text{for } {}^3\text{S}_1 \\ 4.4(0.6)(1.0)\ \text{MeV} & \text{for } {}^1\text{S}_0 \end{cases},$$

Possible experiments to search for singlet deuteron and the problem of the existence of neutral nuclei

Dibaryon resonances.

- Kukulin V.I. (MSU)
- The dibaryon mass in the deuteron, that is, in the channels $^3S_1$-$^3D_1$, as well in the singlet channel $^1S_0$ should be very close to the mass of two nucleons (1.88 GeV), while the mass of bare dibaryons in these channels is completely different, and is probably 2.1 – 2.2 GeV. Thanks to the meson and baryon loops, the mass of the “dressed” dibaryon shifts down to the experimental value corresponding to the deuteron binding energy or singlet deuteron.

Possible experiments to search for singlet deuteron and the problem of the existence of neutral nuclei

Dibaryon resonances.

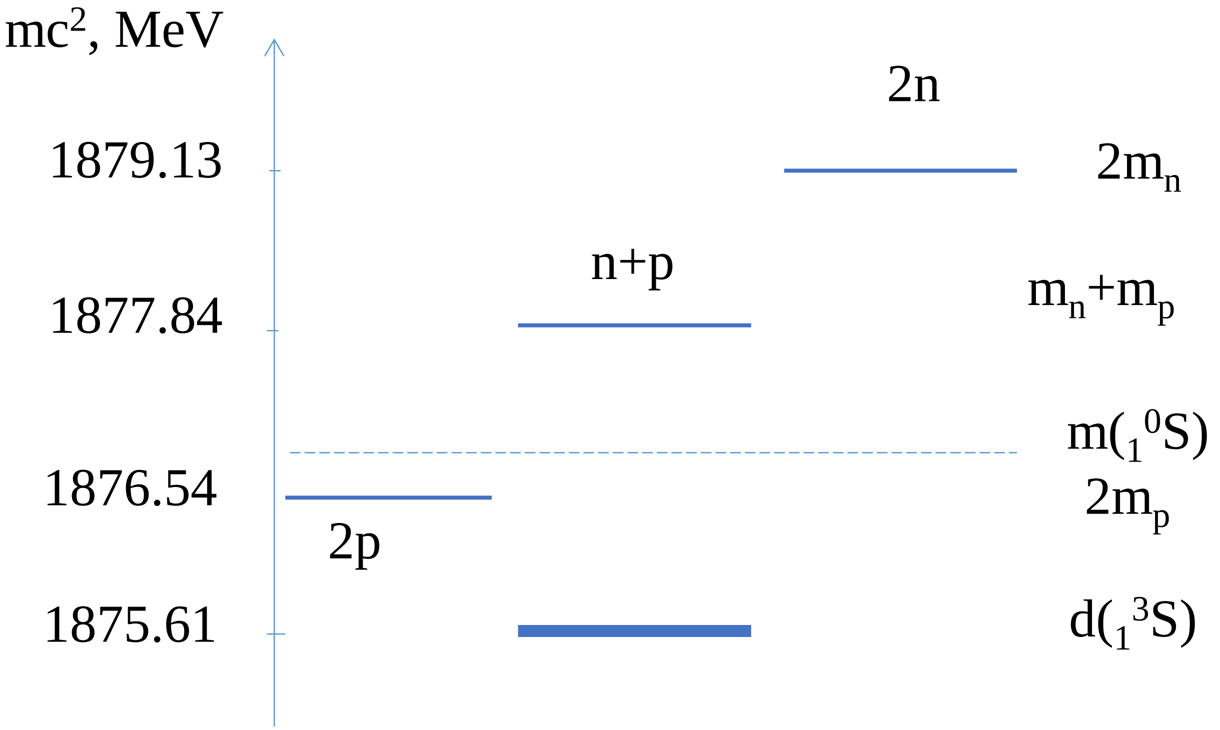
H. Clement, “On the history of dibaryons and their final observation”, Progress in Particle and Nuclear Physics 93, 2017, p. 195-242.

Virtual level = dibaryon resonance.

What exact value of the resonance energy?

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

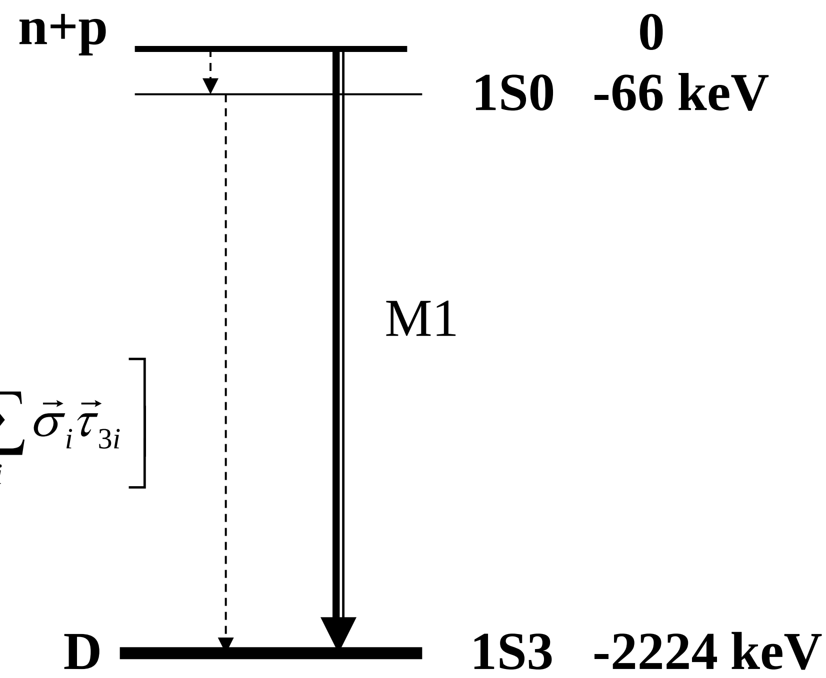
Masses of different nucleon pairs.



Singlet deuteron - the virtual level or dibaryon resonance?

Experimental Search for the Singlet Deuteron in the Radiative *n-p* Capture

Radiative capture.



$$M = \int \psi_f(^1S_0)\widehat{M}1 \cdot \psi_i(^3S_1)dr$$

$$\psi_i = \chi_s \sin(kr + \delta_s)/k$$

$$\psi_f = \chi_s c_f \exp(-\gamma_s r)$$

$$\widehat{M}1 = \left(\frac{e\hbar}{2mc}\right)\left[\frac{1}{2}(\mu_p + \mu_n)\sum_i \vec{\sigma}_i + \frac{1}{2}(\mu_p - \mu_n)\sum_i \vec{\sigma}_i \vec{\tau}_{3i}\right]$$

$$\frac{\sigma_{2\gamma}}{\sigma_\gamma} = \frac{(\gamma_s - a_t^{-1})^2(k + a_s^2)}{(k^2 + a_t^2)(\gamma - a_s^{-1})^2}$$

$$\frac{\sigma_{2\gamma}}{\sigma_\gamma} = 10^{-3} - 10^{-4}$$

For thermal neutrons: $\sigma_\gamma = 334 \pm 0.5 mb$

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

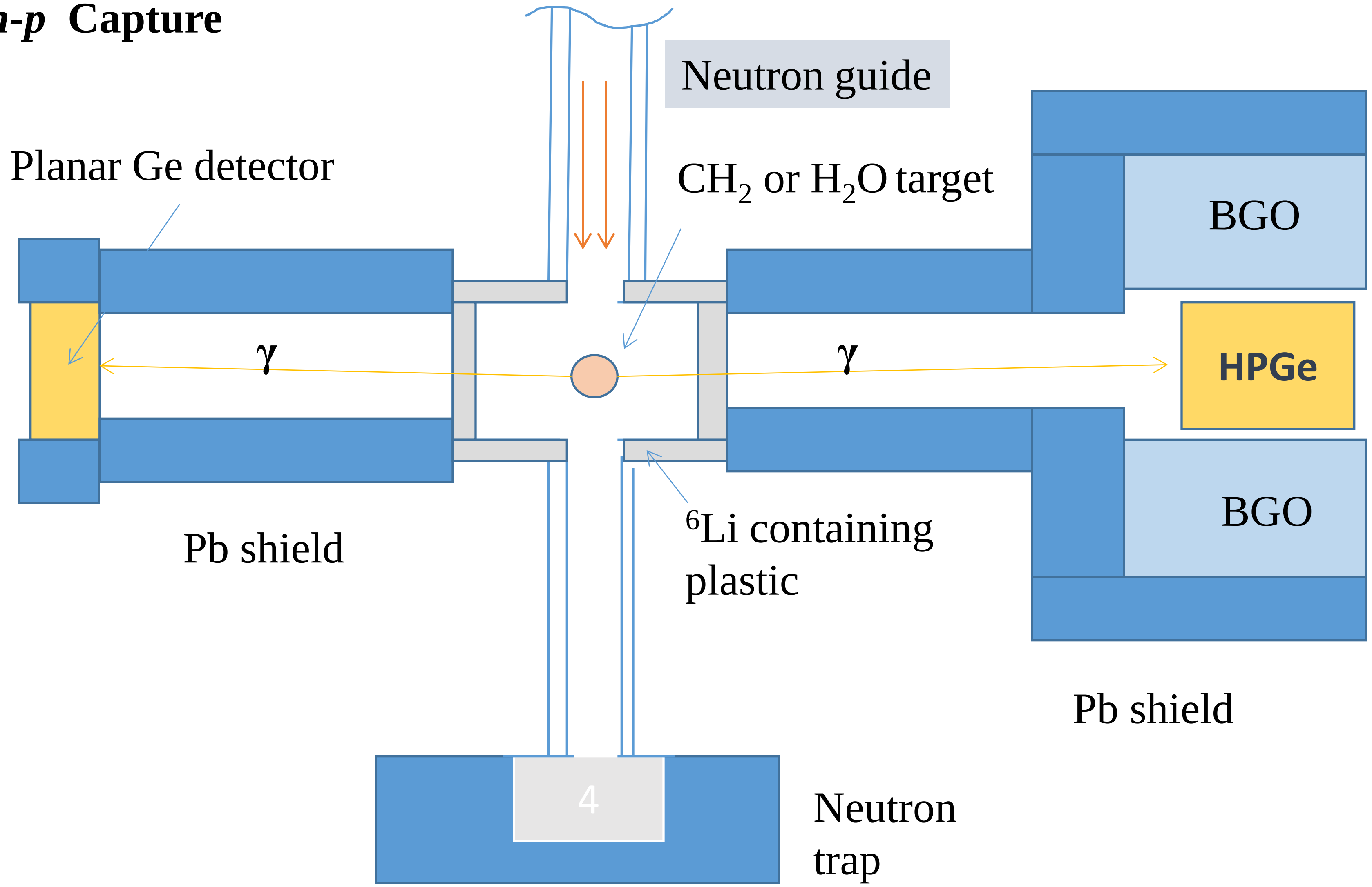
Experimental Search for the Singlet Deuteron in the Radiative *n-p* Capture

Idea of the experiment: search for the two-step gamma ray transition in addition to the direct one with energy 2223.25 keV.
Two-step transition: $^3S_1$(continuum) – $^1S_0$(metastable)-$^3S_1$(deuteron ground state)

Cold neutron prompt gamma activation analysis facility of the Budapest Neutron Center;
Neutron flux 10^7 n/(sec·cm^2);
Target – polyethylene (diameter 2 cm);
HPGe detector with anti-Compton shielding.

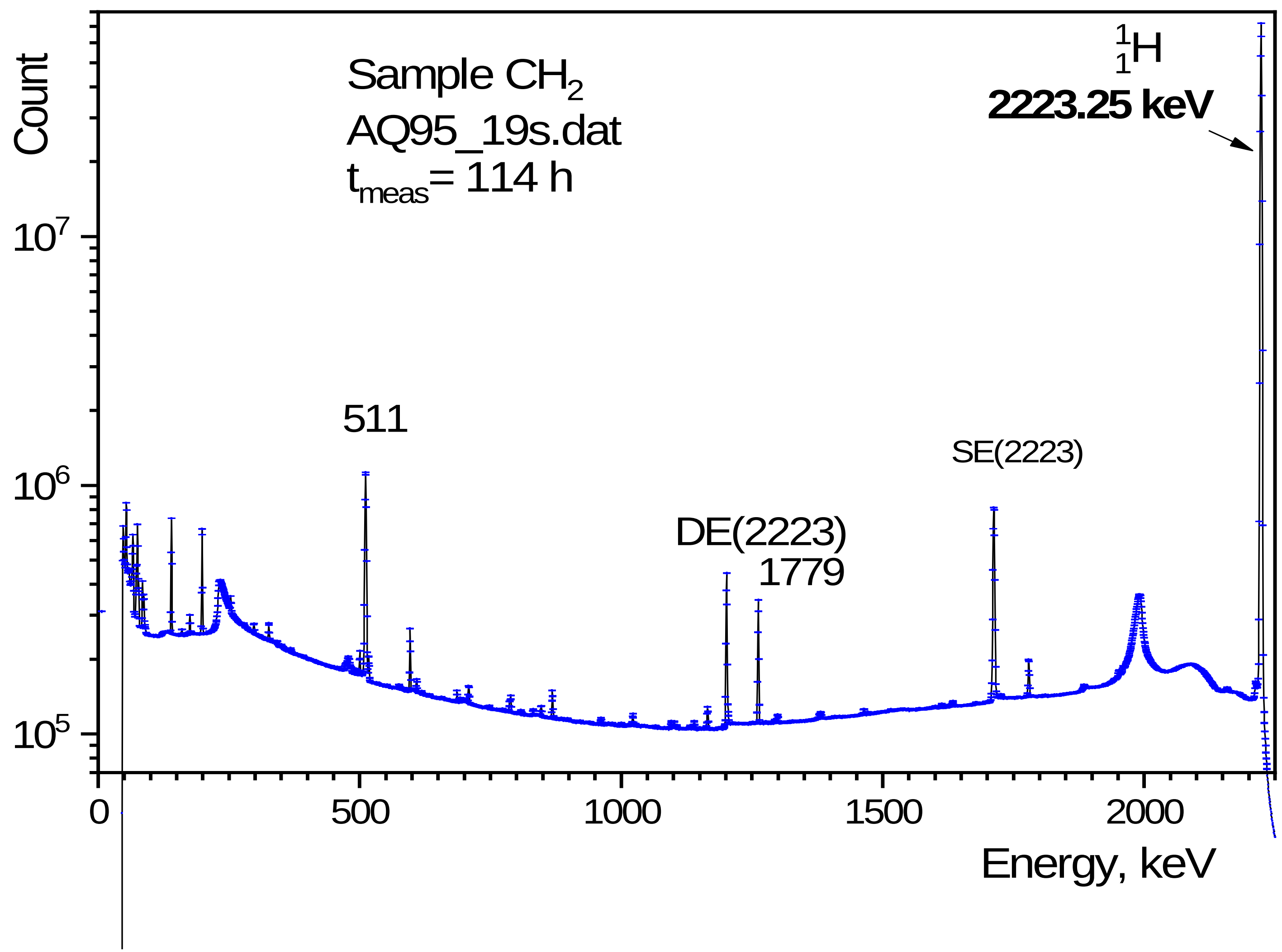
T. Belgya, S.B. Borzakov, M. Jentschel, B. Maroti, Yu. N. Pokotilovski, L. Szentmiklosi, "Experimental Search for the Bound State Singlet Deuteron in the Radiative ***n-p*** Capture", **Phys. Rev. C99, 044001, 2019.**

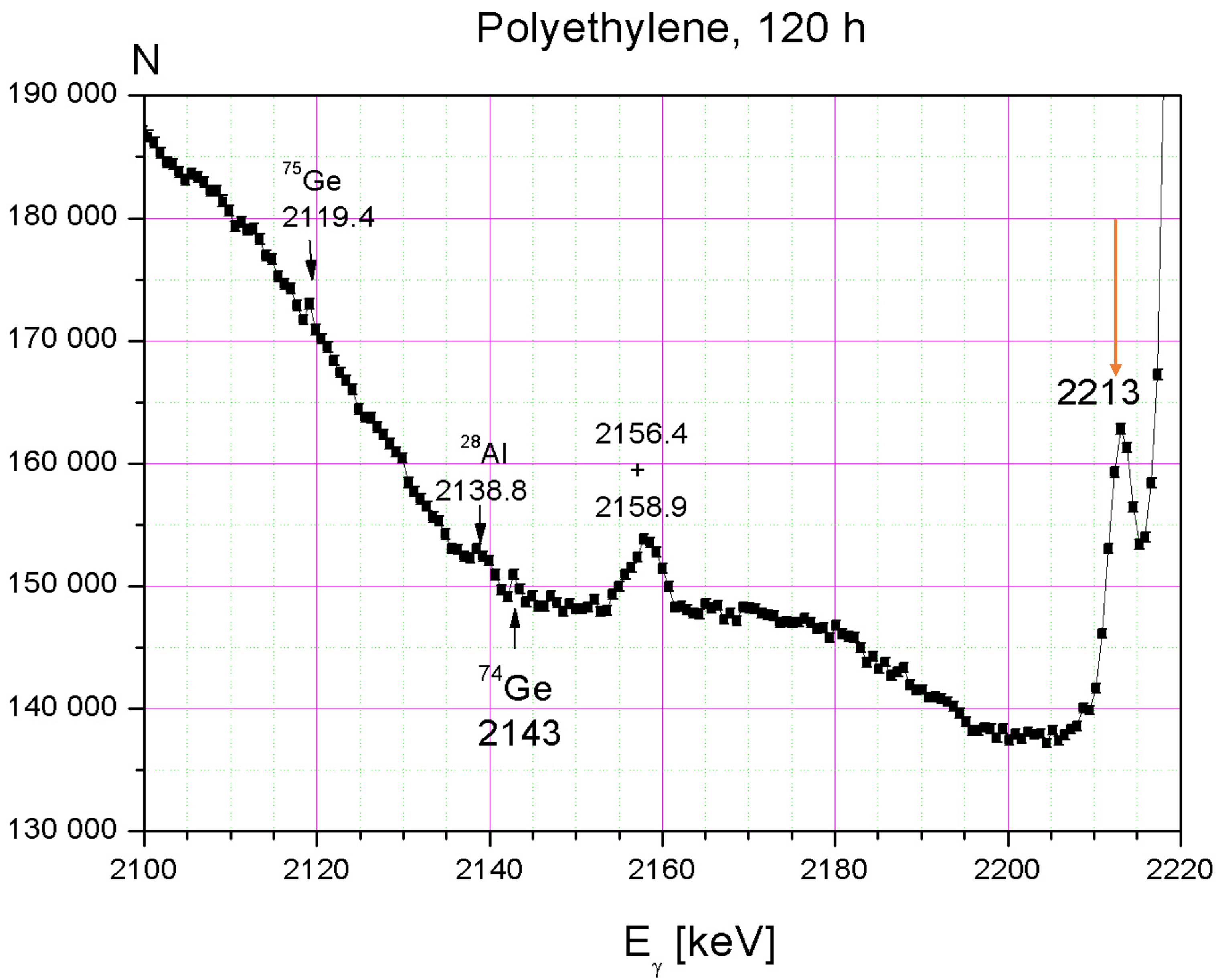
Experimental Search for the Bound State Singlet Deuteron in the Radiative *n-p* Capture



Principal scheme of the experiment.

Experimental Search for the Bound State Singlet Deuteron in the Radiative *n-p* Capture

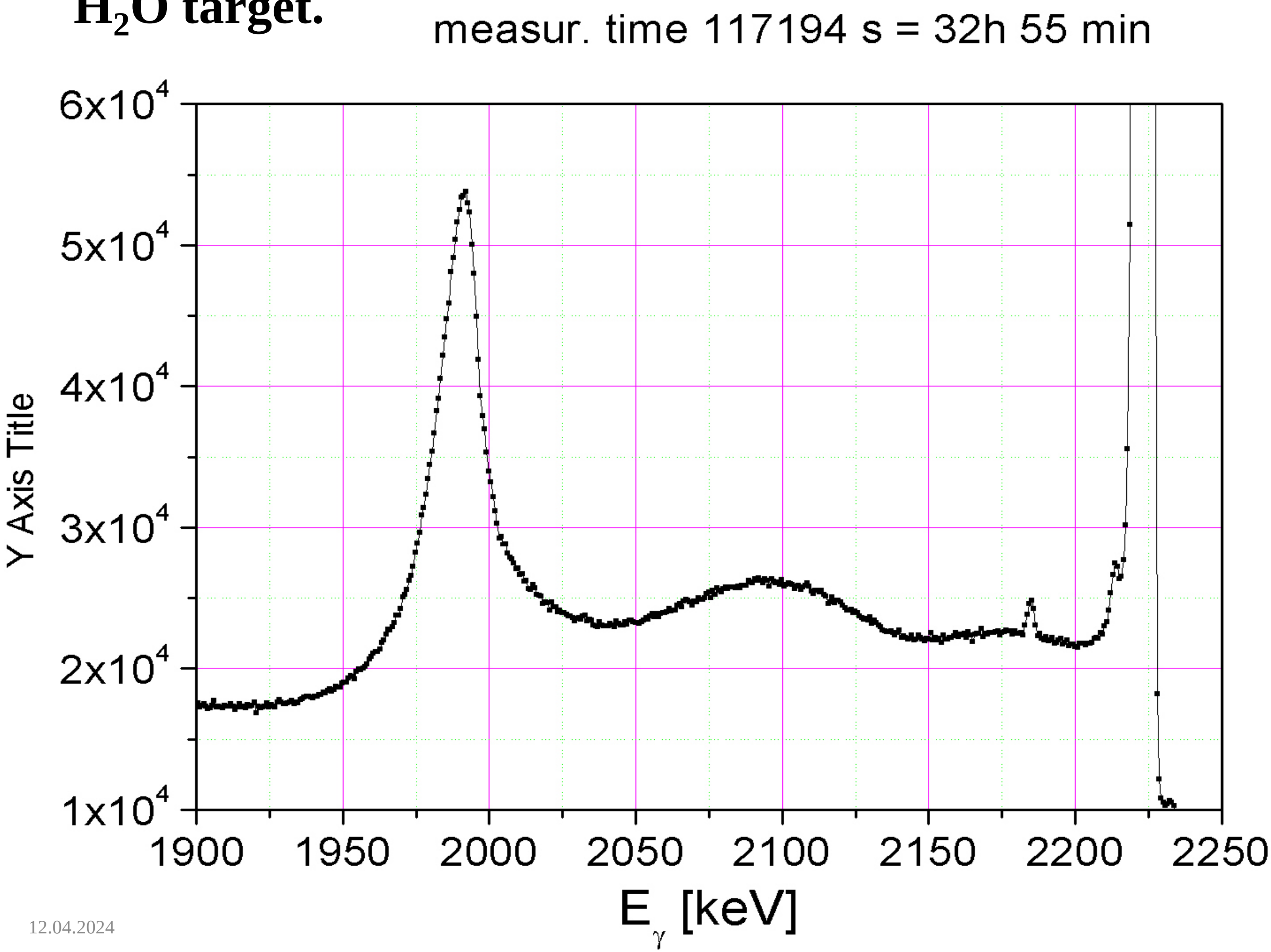




Polyethylene, 120 h
N
190 000
180 000
170 000
160 000
150 000
140 000
130 000
75Ge
2119.4
28Al
2138.8
2156.4
+
2158.9
74Ge
2143
2213
2100
2120
2140
2160
2180
2200
2220
Eγ [keV]

Experimental Search for the Bound State Singlet Deuteron in the Radiative *n-p* Capture

H_2O target.



Experimental Search for the Bound State Singlet Deuteron in the Radiative *n-p* Capture.

Main transition: $S(2223.25 \text{ keV}) = 2.8 \cdot 10^8$ counts

$$\sigma_{2\gamma} = \frac{3 \times \sqrt{N_2}}{N_1} \sigma_\gamma \frac{\varepsilon_1}{\varepsilon_2}$$

$$\sigma_{2\gamma} < 2 \mu b$$

In the interval 2099 – 2209 keV for gamma energy

(interval 15 – 125 keV for binding energy).

There is no nuclide which gives the gamma quanta with the energy 2212.9 keV!
Probably it is that line which we are searching for.

Ratio of peak areas: $R = \frac{S(2213)}{S(2223)} = 2.5 \cdot 10^{-4}$

Experimental Search for the Bound State Singlet Deuteron in the Radiative *n-p* Capture

The possible explanation of the line 2212.9 keV is the next process: as a result of photoeffect an X-rays appear which fly out of the detector and 10 keV is lost. But the probability of such process is very small. We tested this effect on our detector with help of very active Na-24 and found nothing at the level 10^{-5}.

Experimental Search for the Bound State Singlet Deuteron in the Radiative *n-p* Capture

Our result implies that there is no evidence for two-proton transition in the *np* capture with one of gamma-rays in the region 2100 – 2209 keV with branching ratio R < 6 •10^{-6} or with the cross-section $\sigma_{n2\gamma}$ < 2 μb (two standard deviations)

There is no nuclide which gives the gamma quanta with the energy 2212.9 keV! Probably this line is from hydrogen.

ISINN-26, Yu.N. Pokotilovski, report A10; isinn.jinr.ru/past-isinns/isinn-26/program.html

We must find second line with the energy approximately 10.4 keV.
It is necessary to carry out the experiment to search for cascade of two gamma quanta with help of coincidences!

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

Possible experiments:

$$1.\_\_ n + p \rightarrow d + \gamma_1 + \gamma_2 \quad (0 < E_{\gamma 1}, E_{\gamma 2} < 2224\_кэВ; \quad E_{\gamma 1} + E_{\gamma 2} = 2224\_keV)$$

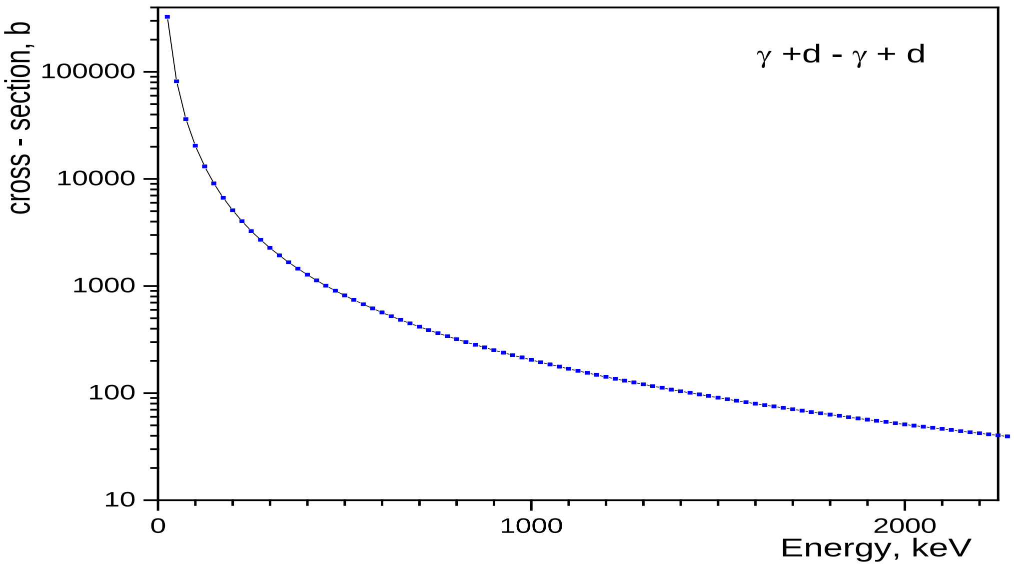
$$2.\_\_ \gamma + d \rightarrow d^*({}_0^1S) \rightarrow d + \gamma$$

$$3.\_\_ n + d \rightarrow {}^2n + p$$

$$4.\_\_ {}_1^2d + {}_1^3t \rightarrow {}_2^3He + {}_0^2n$$

Possible experiments to search for singlet deuteron and the problem of the existence of neutral nuclei

Resonance scattering of gamma quanta by deuteron.



Maximal value of cross-section.

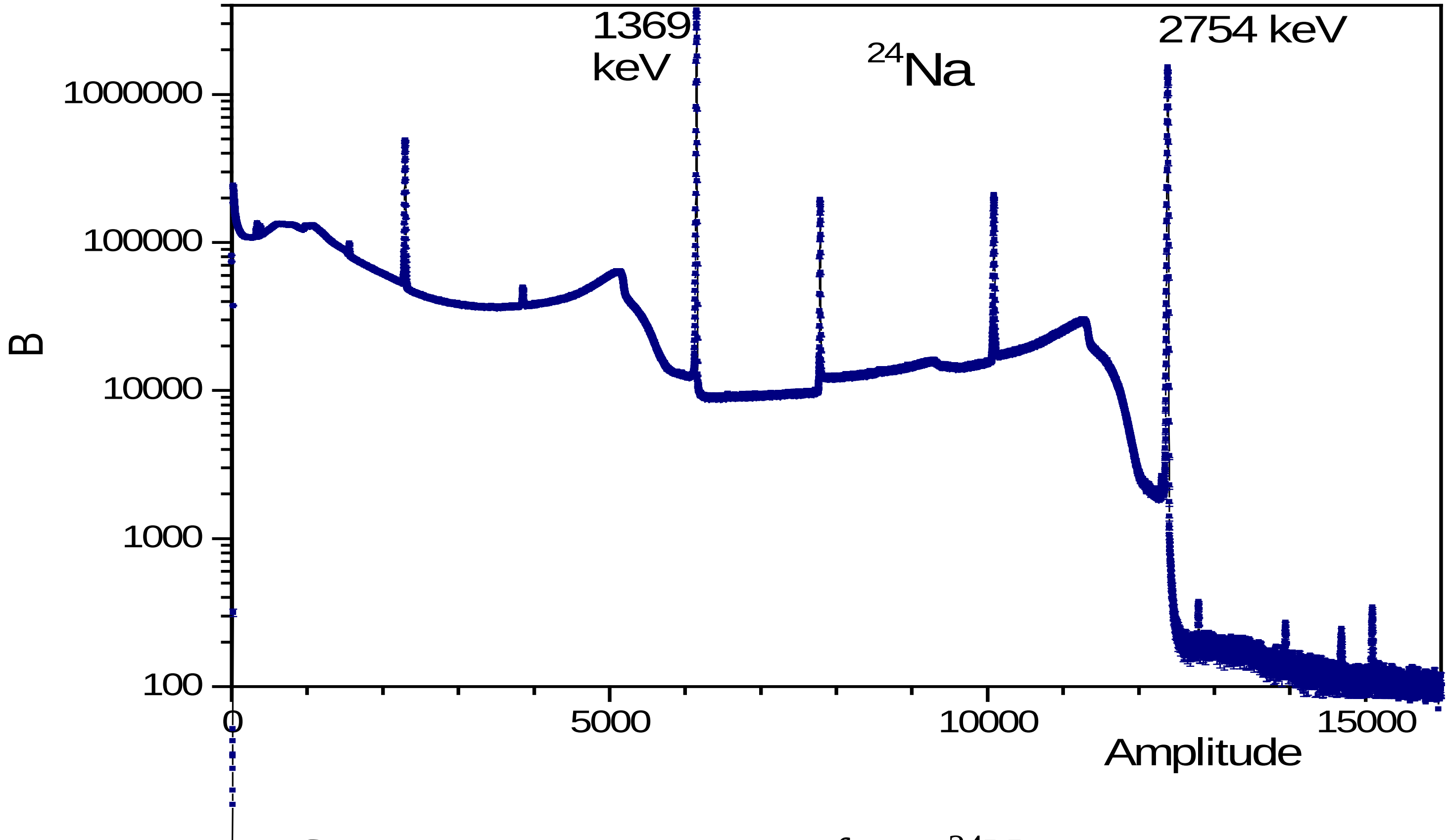
Energy width is very small – approximately 20 eV.

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

- **Conclusions.**
- **There are no physical laws which prohibit the existence of the singlet deuterons and dineutrons;**
- **Modern theoretical models predict the existence of the singlet bound state of two nucleons;**
- **New experiments are needed!**

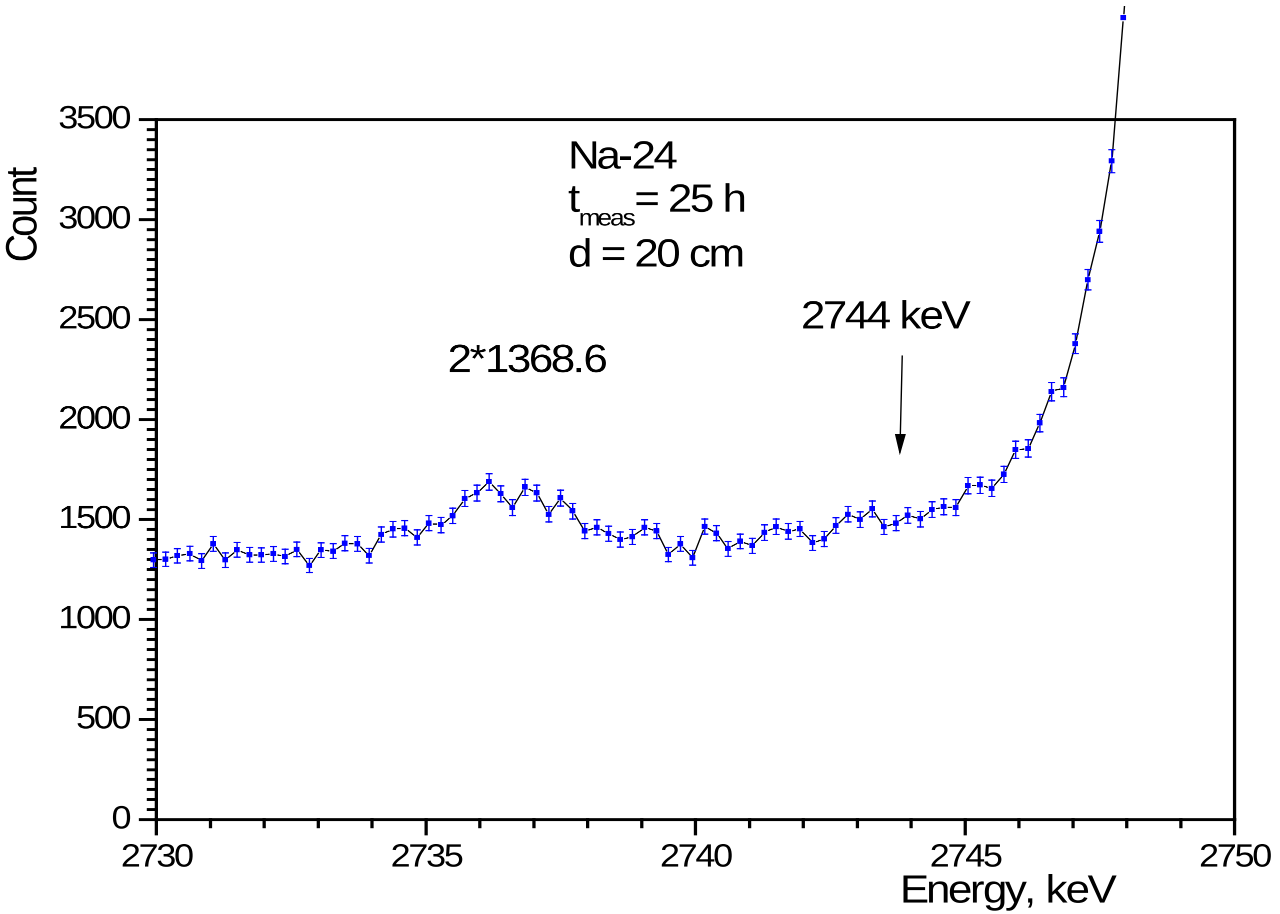
Thank you for your attention!

Experimental Search for the Bound State Singlet Deuteron in the Radiative *n-p* Capture



Gamma quanta spectrum from ^{24}Na source.

Experimental Search for the Bound State Singlet Deuteron in the Radiative *n-p* Capture



Part of gamma quanta spectrum from ^{24}Na source.

Low Energy Nucleon-Nucleon Interaction.

F.J. Dyson, N. H. Xuong, Phys. Rev. Lett. v. 13, No. 26, 1964.

$Y = 2$ STATES IN SU(6) THEORY*

Freeman J. Dyson† and Nguyen-Huu Xuong
Department of Physics, University of California, San Diego, La Jolla, California
(Received 30 November 1964)

VOLUME 13, NUMBER 26 PHYSICAL REVIEW LETTERS 28 DECEMBER 1964

Table I. $Y = 2$ states with zero strangeness predicted by the $\underline{490}$ multiplet.

Particle	T	J	SU(3) multiplet	Comment	Predicted mass
D_{01}	0	1	$\underline{10}$*	Deuteron	A
D_{10}	1	0	$\underline{27}$	Deuteron singlet state	A
D_{12}	1	2	$\underline{27}$	S-wave N-N^* resonance	$A+6B$
D_{21}	2	1	$\underline{35}$	Charge-3 resonance	$A+6B$
D_{03}	0	3	$\underline{10}$*	S-wave N^*-N^* resonance	$A+10B$
D_{30}	3	0	$\underline{28}$	Charge-4 resonance	$A+10B$

Search for the dineutron and lightest neutral nuclei.

A. Siepe et al.

"Neutron-proton and neutron-neutron quasifree scattering in the ***n-d*** breakup reaction at 26 MeV", Phys. Rev. C65, 034010, 2002,

The neutron source: $^{2}H(d,n)^{3}He$

$E_d = 27.3\_MeV;$ $E_n = (26 \pm 4)\_MeV$

Investigated reaction:

$$n + d \rightarrow p + n + n$$

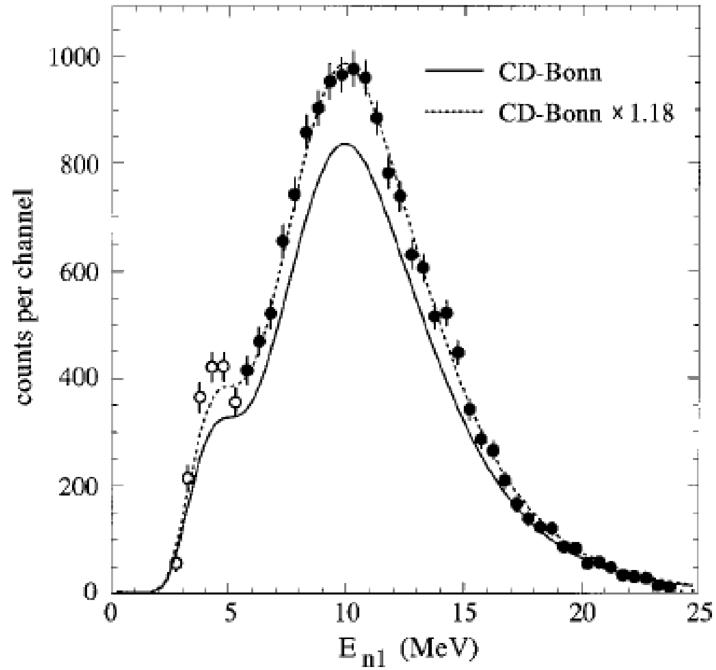


FIG. 4. HE data of Fig. 3, projected onto the E_{n1} axis. The solid curve represents the finite-geometry Monte Carlo prediction using CD-Bonn, the dotted line is the MC result normalized to the experiment by multiplication with a factor of 1.18. Only events with E_{n1} and $E_{n2} > 6$ MeV have been included in the analysis.

Dineutron and lightest neutral nuclei.

PHYSICAL REVIEW C **83**, 034004 (2011)
The *nn* quasifree *nd* breakup cross section: Discrepancies with theory and implications for the $^1S_0$ *nn* force.
H. Witała, W. Gl¨ockle

Large discrepancies between quasifree neutron-neutron (*nn*) cross section data from neutron-deuteron (*nd*) breakup and theoretical predictions based on standard nucleon-nucleon (*NN*) and three-nucleon (3*N*) forces are pointed out. The *nn* 1*S*0 interaction is shown to be dominant in that configuration and has to be increased to bring theory and data into agreement. Using the next-to-leading order 1*S*0 interaction of chiral perturbation theory, we demonstrate that the *nn* quasifree scattering cross section depends only slightly on changes of the *nn* scattering length but is very sensitive to variations of the effective range parameter. In order to account for the reported discrepancies one must decrease the *nn* effective range parameter by ≈12% from its value implied by charge symmetry and charge independence of nuclear forces.

Dineutron and lightest neutral nuclei.

H.W. Hammer, S. Konig, “Constraints on a possible dineutron state from pionless EFT”, Phys. Lett. B736, 208-213, 2014.

Low energy *NN* interaction.

L.P. Kok, "Accurate Determination of the Ground State Level of the ^{2}He nucleus", Phys. Rev. Lett., 45, 427, 1980.

$p + p \rightarrow p + p$ $E_r =$ -0.140 - i ·0.467 МэВ

Resonance.

$p + p \rightarrow p + p$ E_r = 0.4 MeV; $\Gamma = 0.15$ MeV

Dineutron and lightest neutral nuclei.

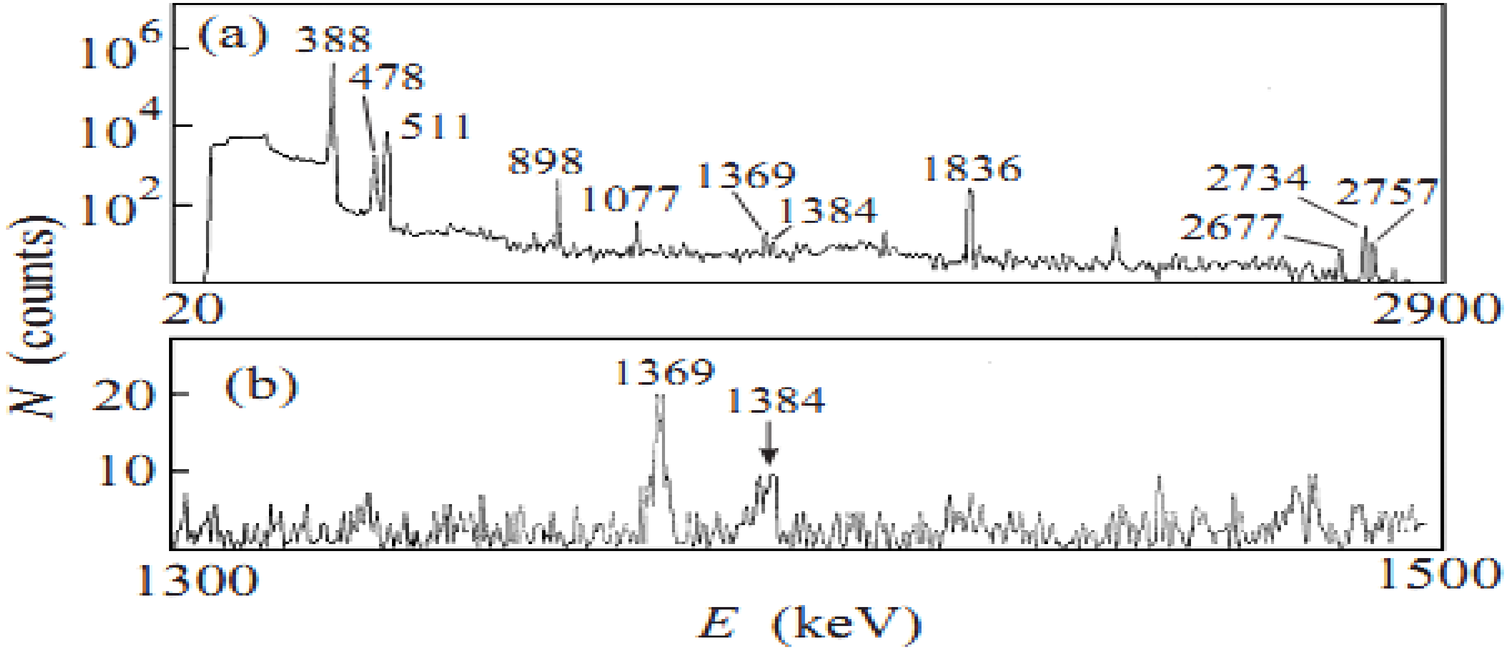
D.V. Aleksandrov et al. investigated emission of the neutral nuclei in the spontaneous fission. They used the source ^{252}Cf with the intensity 10^7 fission acts per a second. The samples of ^{26}Mg (masses from 0.1 to 6 g) was irradiated. They were placed at the distance 3 mm from the source and were used as indicators.

$$^{27}Al + {}^{x}n \rightarrow {}^{28}Mg + p + (x-2)n$$

The gamma quanta spectra have been measured with help of HPGe detector (volume 120 cm^3). The gamma line with the energy of 1342.27 keV have been observed.

Dineutron and lightest neutral nuclei.

B.G. Novatskii, E.Yu. Nikols'kii, S.B. Sakuta, D.N. Stepanov, "Возможное обнаружение легких нейтронных ядер в делении ^{238}U α-частицами", JETPh Letters, v. 96, No. 5, p. 310-314, 2012.



$$^{92}Sr \rightarrow {}^{92}Y \qquad E_\gamma = 1384\_keV$$

$$T_{1/2} = 2.71\_h$$

Dineutron and Singlet Deuteron.

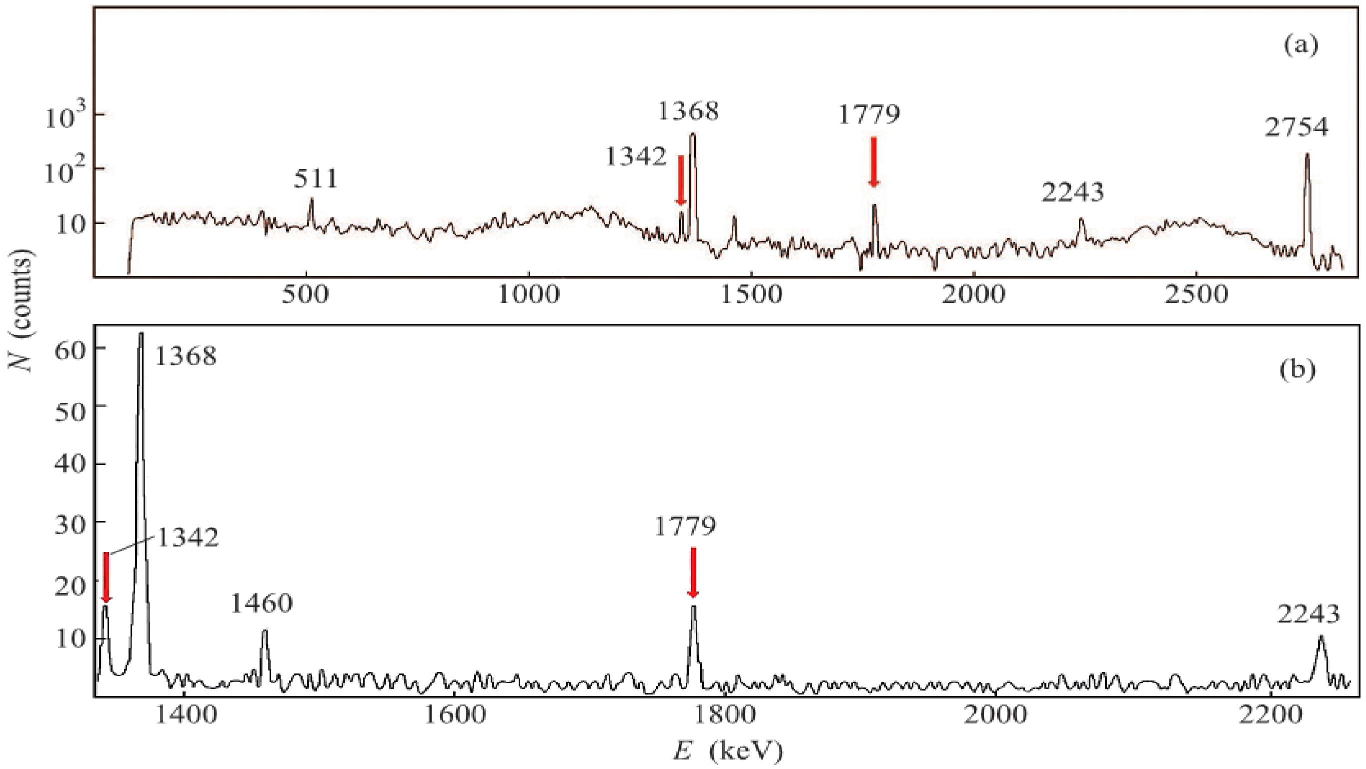


Рис. 2. (a) – Энергетический спектр γ-квантов активируемого образца ^{27}Al, облученного продуктами вынужденного деления ^{238}U α-частицами. (b) – Выделенный участок γ-спектра в диапазоне энергий 1330–2250 кэВ. Стрелками отмечены γ-линии, сопровождающие β-распад ядер ^{28}Mg (1342 кэВ) и ^{28}Al (1779 кэВ)

B.G. Novatskii, E.Yu. Nikols’kii, S.B. Sakuta, D.N. Stepanov, “Observation of light neutral nuclei делении
^{238}U α-частицами”, JETPh Letters, v. 96, No. 5, p. 310-314, 2012.

Possible experiments to search for the singlet deuteron and the problem of the existence of neutral nuclei

Search for the dineutron in the reaction $n + d \rightarrow {}^2n + p$ **.**

The first experiment to search for dineutron in the reaction ***n*+*d* – *n*+*d*** have been made by Glasgow and Foster. They have measured the scattering cross-section n+d at 241 energy points in the interval 2.25-15 MeV (in laboratory system). The accuracy was 1.2-5.6%. The upper limit for the dineutron exit have been obtained 100-1000 microbarns.

Calculations: R. Alzetta, G.C. Ghirardi, A. Rimini, Phys.Rev., v. 131, p. 1740, 1963.
Experiment: Glasgow D.W., Foster D.G., Phys. Rev., v. 157, p. 764, 1967.

УДК 539.172.4

ПОИСК ДИНЕЙТРОНА ВО ВЗАИМОДЕЙСТВИИ НЕЙТРОНОВ С ДЕЙТРОНАМИ

С. Б. Борзаков, Ц. Пантелеев, А. В. Стрелков

PEPAN Letters, № 2[111], p. 45, 2002.

$$n + d \rightarrow {}^2n + p$$

The proportional counter was used. Gas mixture consists of 1.5 atm. D_2, + 0.5 atm. Ar and 10^{-2} Hg mm of ^3He.

The proton energy is equal to: $E_p = \frac{2}{3}\left(B_2 - B_d + E_n\right)$

$$N_p = \Phi_n n_d \sigma_d t\varepsilon \qquad N_3 = \Phi_n n_3 \sigma_3 t\varepsilon \qquad \sigma_d = \frac{n_3 \sigma_3}{n_d} \frac{N_d}{N_3}$$

The small amount of ^3He was added into the detector to determine the neutron flux density with help of reaction n+^3He – T + p.

Dineutron and Singlet Deuteron.

20. K. Hagino, H. Sagawa, “Correlated two-neutron emission in the decay of unbound nucleus ^{26}O”, ArXiv: nucl-th 1307.55021v1, 2013.

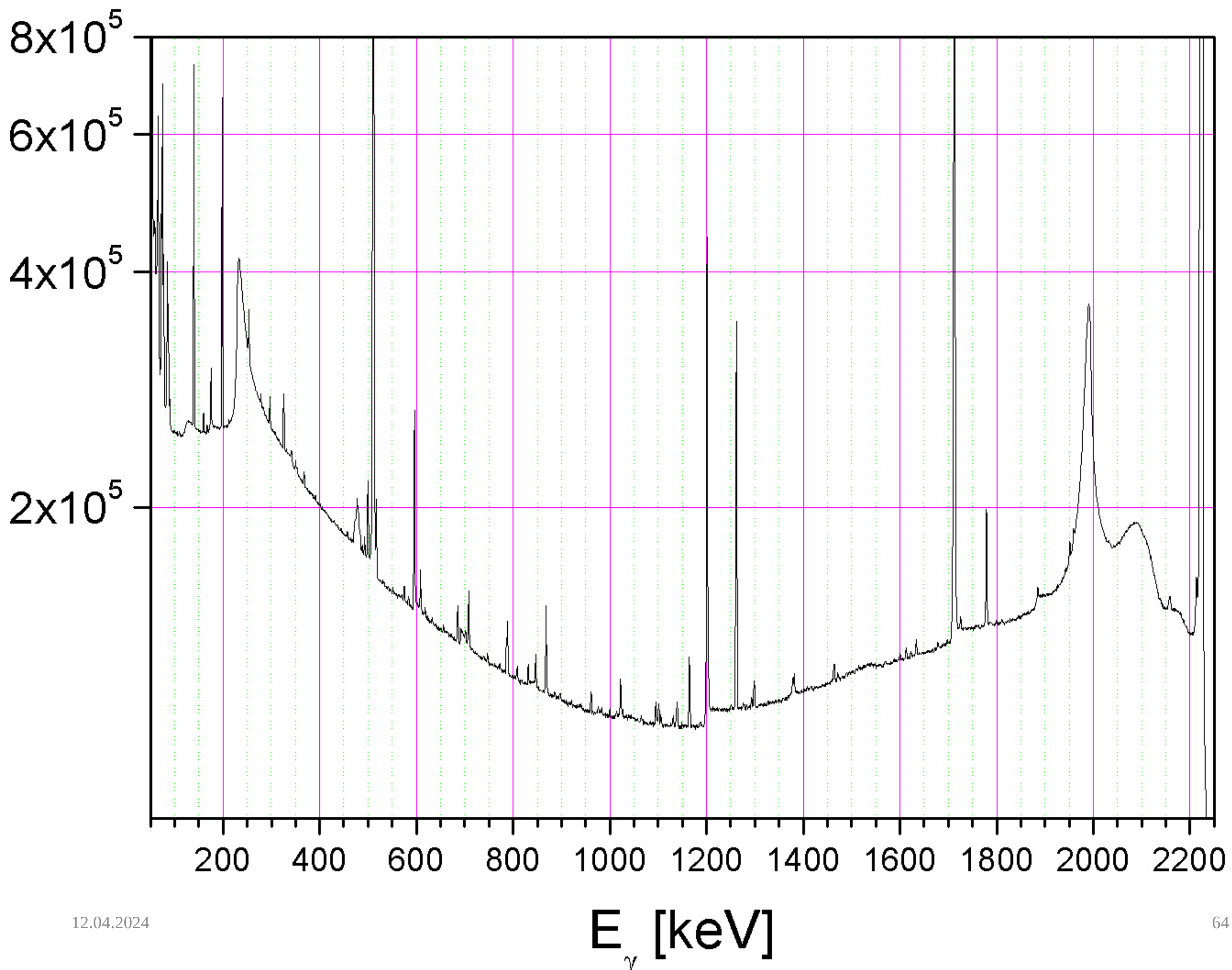
21. I.M. Kadenko, B. Biro, A. Fenyvesi, “Statistically significant observation of and cross sections for a new nuclear reaction channel on ^{197}Au with bound dineutron escape”, ArXiv 1906. 10755, 2020.

I. Kadenko, “Possible observation of the dineutron in the $^{159}Tb(n,{}^{2}n)^{158g}Tb$ nuclear reaction ”, Europhys. Lett., 114, 42001, 2016.

Light neutral nuclei.

- B.G. Novatski et al. observed the light neutral nuclei in fission reaction of ^{238}U by alpha particles with energy of 62 MeV. The sample of ^{88}Sr served as indicator. The authors supposed the transferring of 4 neutrons. The unstable nuclei of ^{92}Sr had been detected.

Polyethylene, 120 h



Low energy NN interaction.

Amplitude (two channels).

$$f = \frac{1}{-\frac{a+ib}{a^2+b^2}+\frac{1}{2}r_0 p^2 - i\cdot p} = \frac{(a^2+b^2)}{-a+\frac{1}{2}r_0 p^2(a^2+b^2) - ib - ip(a^2+b^2)} =$$

$$= \frac{(a^2+b^2)\left[-a+\frac{1}{2}r_0 p^2(a^2+b^2)+i(b+p(a^2+b^2))\right]}{\left[-a+\frac{1}{2}r_0 p^2(a^2+b^2)\right]^2+\left[b+p(a^2+b^2)\right]^2} =$$

$$= \frac{-a+\frac{1}{2}r_0 p^2(a^2+b^2)+i\left[p(a^2+b^2)+b\right]}{\frac{a^2}{a^2+b^2}+2bp-ar_0 p^2+(a^2+b^2)p^2+\frac{1}{4}r_0^2 p^4(a^2+b^2)+\frac{b^2}{a^2+b^2}}$$

$$\sigma_t = \frac{4\pi}{k}\mathrm{Im}\, f \approx \frac{4\pi\cdot a^2}{1+2bk+a^2k^2-a\cdot r_0 k^2+\frac{1}{4}r_0^2 k^4 a^2} + \frac{4\pi\cdot b}{k\cdot\left[1+2bk+(a^2-ar_0)k^2+\frac{1}{4}r_0^2 k^4 a^2\right]}$$