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

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Low energy *NN* interaction.

"Effective range theory".

- Scattering amplitude:

$$F = \frac{1}{-\frac{1}{a} + \frac{1}{2}\rho k^2 - ik} = \frac{1}{g(k) - ik}$$

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

- neutron impulse.

$a - scattering \quad length$

$\rho - effective \quad range$

$$g(k) = -\frac{1}{a} + \frac{1}{2}\rho k^2 + Pk^4 + Qk^6$$

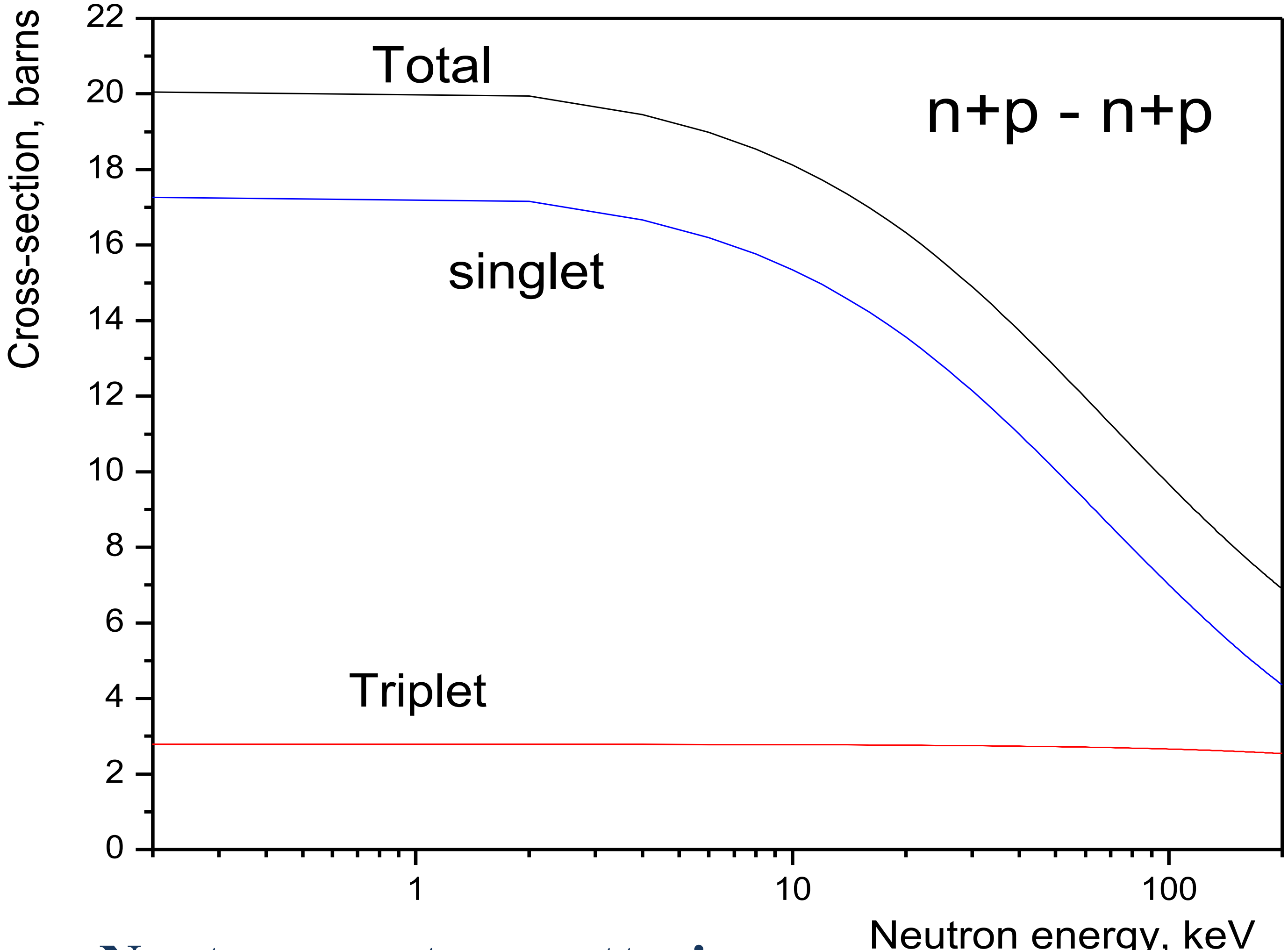
Two channels: $A = a - ib$

Capture cross-section: $\sigma_c = \frac{4\pi b}{k}$

Scattering parameters

	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	-18,7 ± 0,6			
$np(^3S_1)$	5,414 ± 0,005	1,75 ± 0,05	0,13 ± 0,09	

Low energy *NN* interaction.



Neutron-proton scattering cross-section.

Low energy *NN* interaction.

S-matrix $S = 1 + 2ikF$

$E \langle 0 \quad \Rightarrow \quad k = i\kappa$

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

Four poles:

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

$^1S_0 \qquad a < 0$

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

”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.

Low energy *NN* interaction.

Virtual level or resonanse?

$$F = \frac{1}{-\frac{1}{a-ib} + \frac{1}{2}\rho k^2 - ik} = \frac{1}{2k}\frac{\frac{4}{\rho}k}{k^2 - \frac{2}{\rho a} - i\frac{1}{2}(\frac{4k}{\rho} + \frac{4b}{\rho a^2})}$$

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

$$E_r = \frac{2}{ar}\frac{h^2}{2\mu} \qquad \Gamma_n = \frac{4k}{\rho} \propto \sqrt{E_n} \qquad \Gamma_\gamma = \frac{4b}{\rho a^2}$$

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

S.B. Borzakov, Physics of Atomic Nuclei, v. 57, p. 517, 1994.
(С. Б. Борзаков, Ядерная физика, т. 57, с. 517, 1994).

Singlet deuteron

- K. Maltman, N. Isgur, Phys. Rev., D29, No. 5, p.952, 1984.

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

- A.N. Ivanov et al., e-Arxiv: nucl-th/0407079, 2004.

$E_S = -79 +/- 12$ кэВ

- 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

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

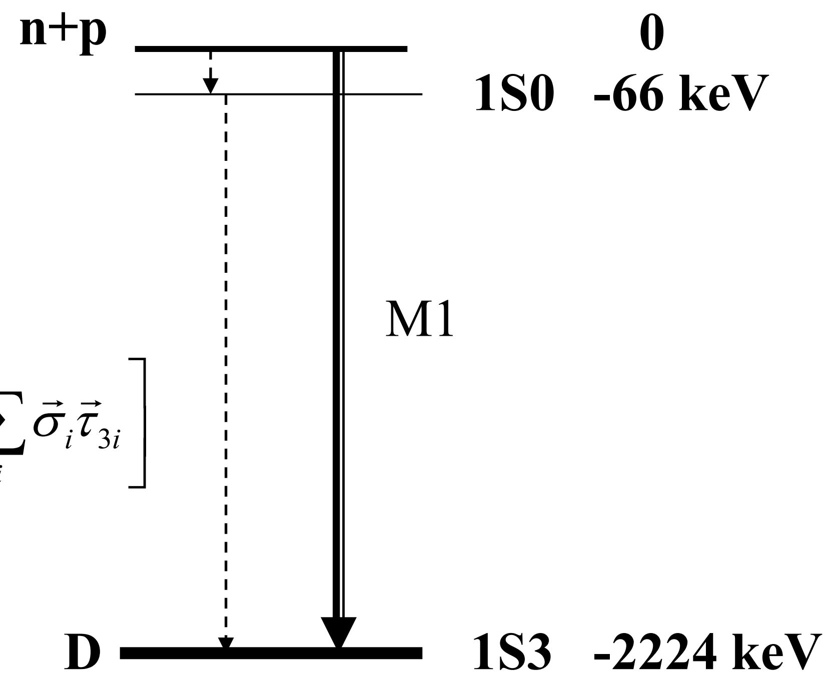
Radiative capture

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

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

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

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



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

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

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

Singlet deuteron

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.

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

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

Idea of the experiment:

Search for the two-step γ-ray transition

$$^3S_1 \text{ (continuum)} \rightarrow {}^1S_0 \text{ (metastable)} \rightarrow {}^3S_1 \text{ (ground state)}$$

in addition to the direct one

$$^1S_0 \rightarrow {}^3S_1 \text{ with energy 2223 keV}$$

Cold neutron prompt gamma activation analysis facility of the Budapest Neutron Center;
Neutron flux 10^7 n/(sec $\cdot$ cm^2);
Target – polyethylene (diameter 2 cm);
HPGe detector with anticompton shield.

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

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Nuclear Instruments and Methods in Physics Research B 213 (2004) 385–388

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Cold neutron PGAA facility at Budapest

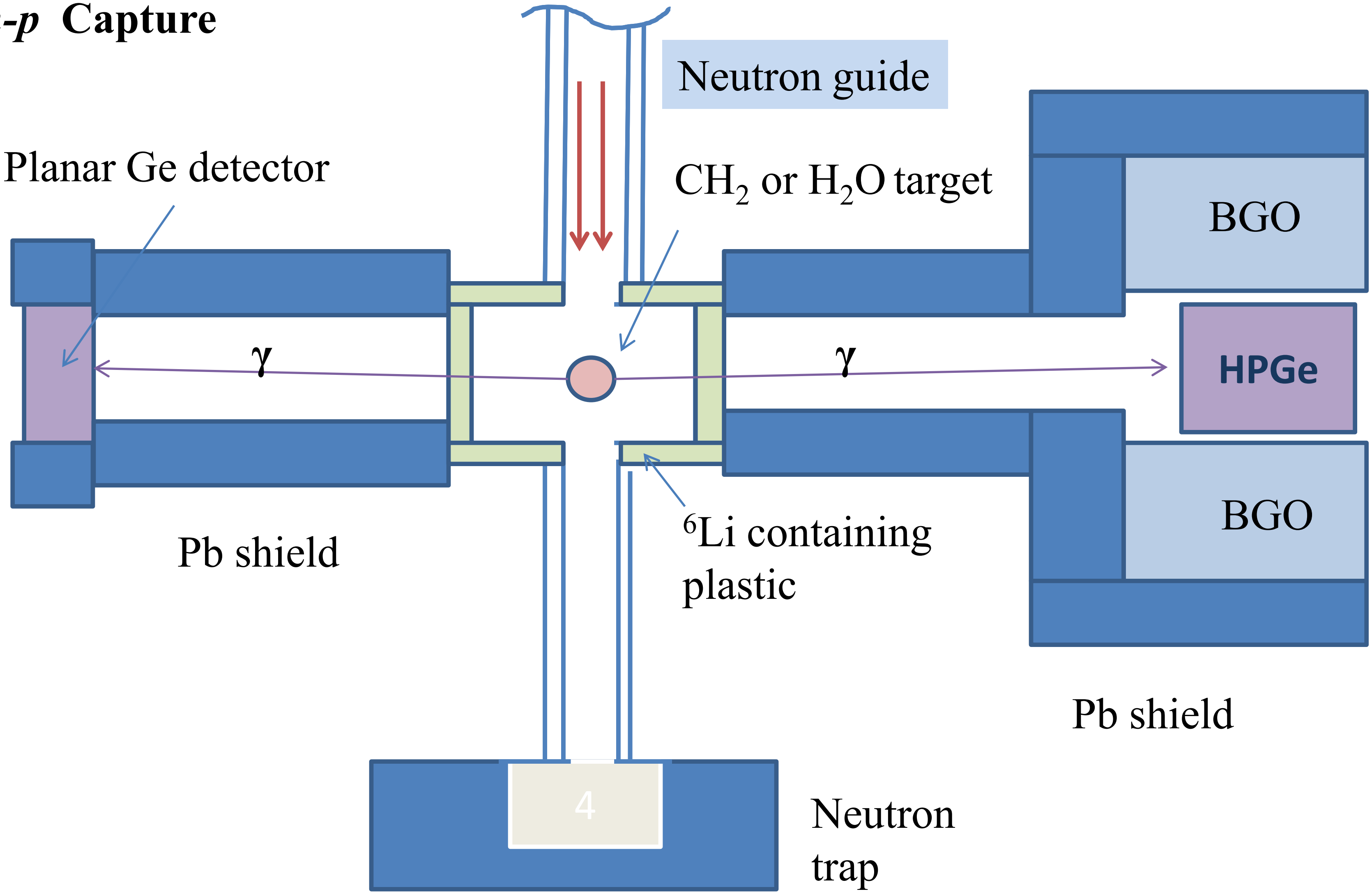
Zs. Révay *, T. Belgya, Zs. Kasztovszky, J.L. Weil, G.L. Molnár

Institute of Isotope and Surface Chemistry, CRC HAS, H-1525 Budapest, P.O.Box 77, Hungary

Abstract

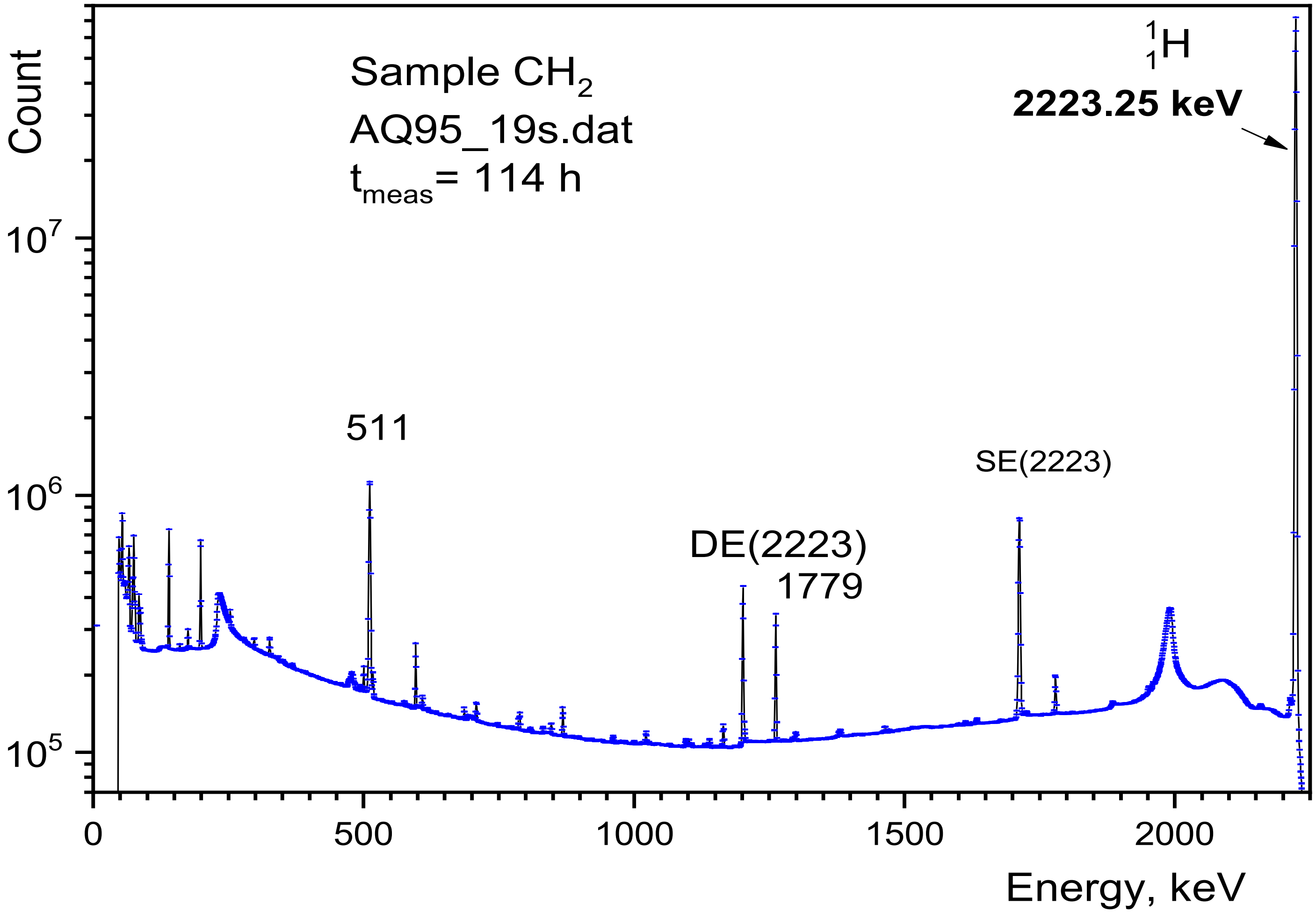
The new cold neutron prompt gamma activation analysis (PGAA) facility provides improved capabilities for routine prompt gamma analysis and for the investigation of radiative neutron capture. The versatile beam chopper makes possible time-of-flight measurements and the acquisition of prompt and decay spectra simultaneously. The chopped beam PGAA technique combines the advantages of the in-beam measurement and the greater simplicity of decay gamma spectra.

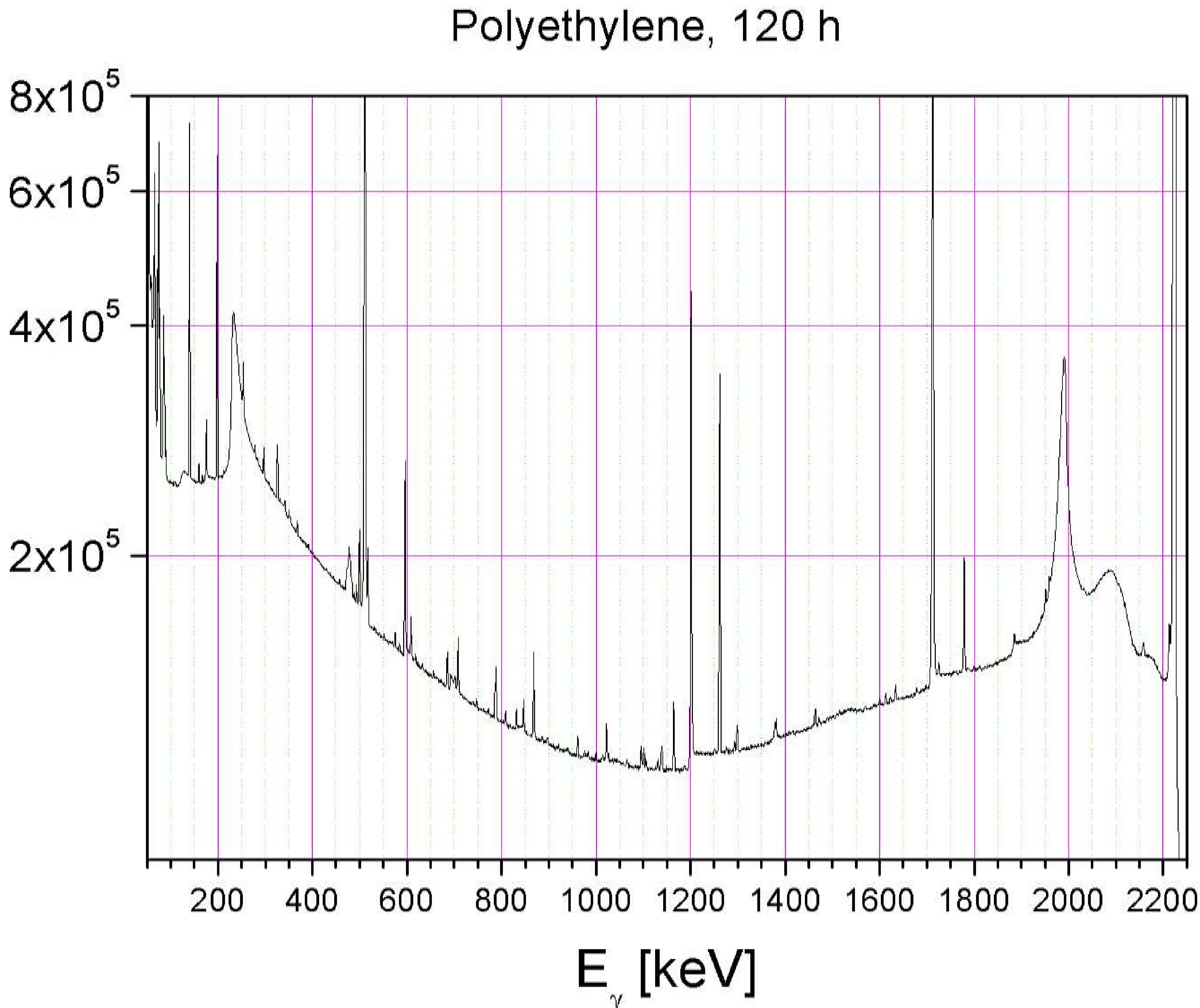
Experimental Search for the Bound State Singlet Deuteron in the Radiative *n-p* Capture



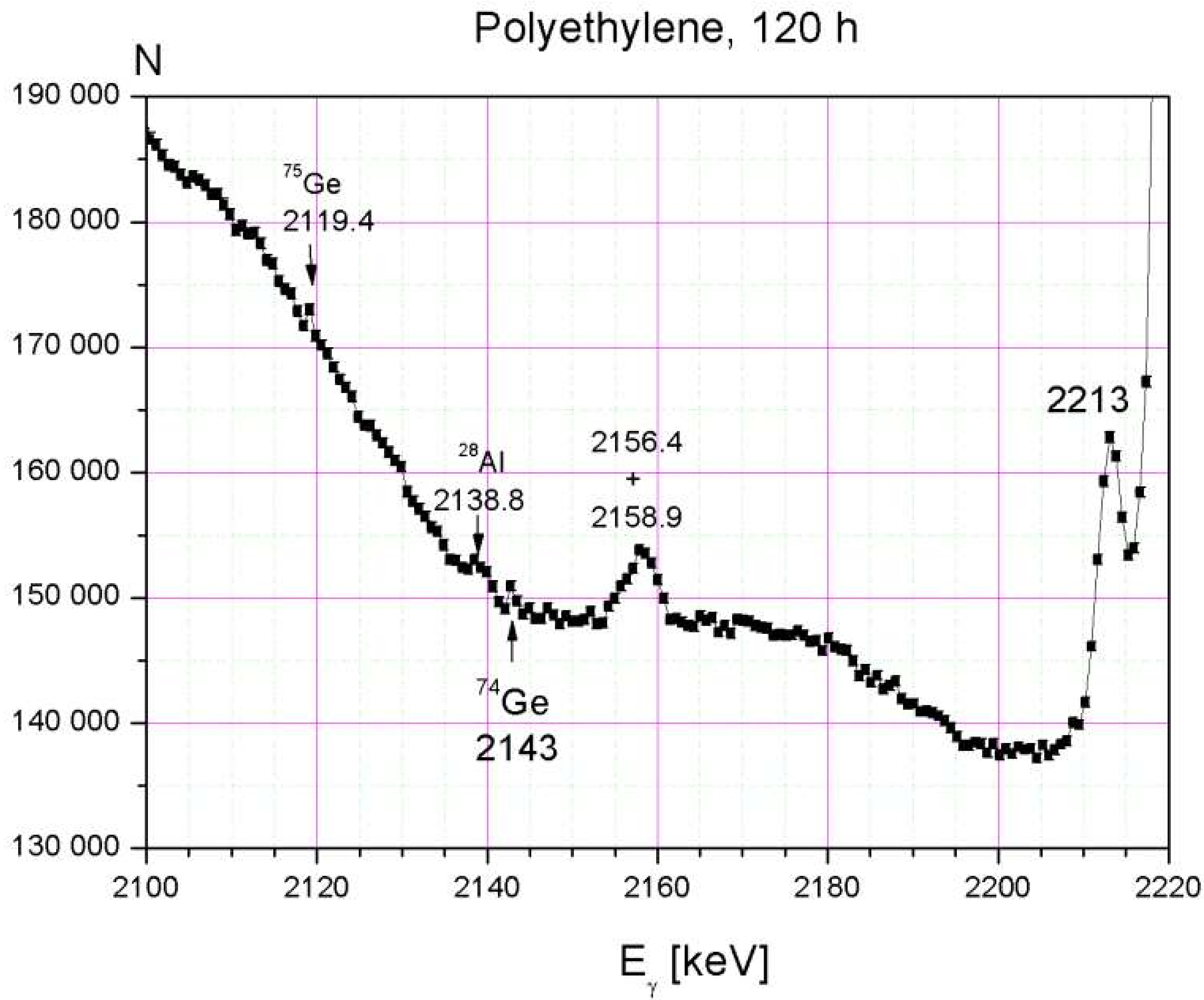
Principal scheme of the experiment.

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

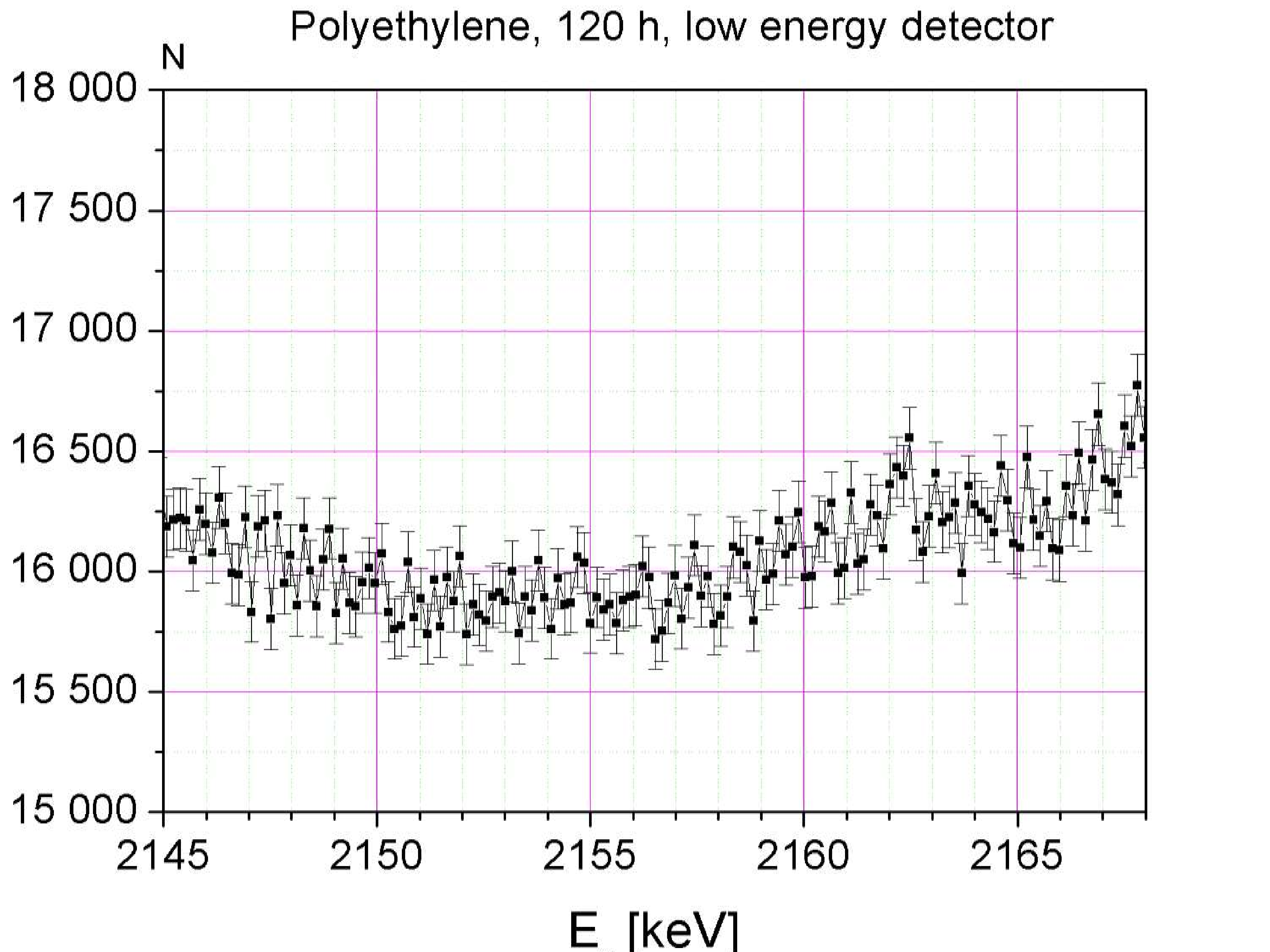




Polyethylene, 120 h
8x10^5
6x10^5
4x10^5
2x10^5
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
E_γ [keV]



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


Polyethylene, 120 h, low energy detector
N
18 000
17 500
17 000
16 500
16 000
15 500
15 000
2145
2150
2155
2160
2165
E [keV]

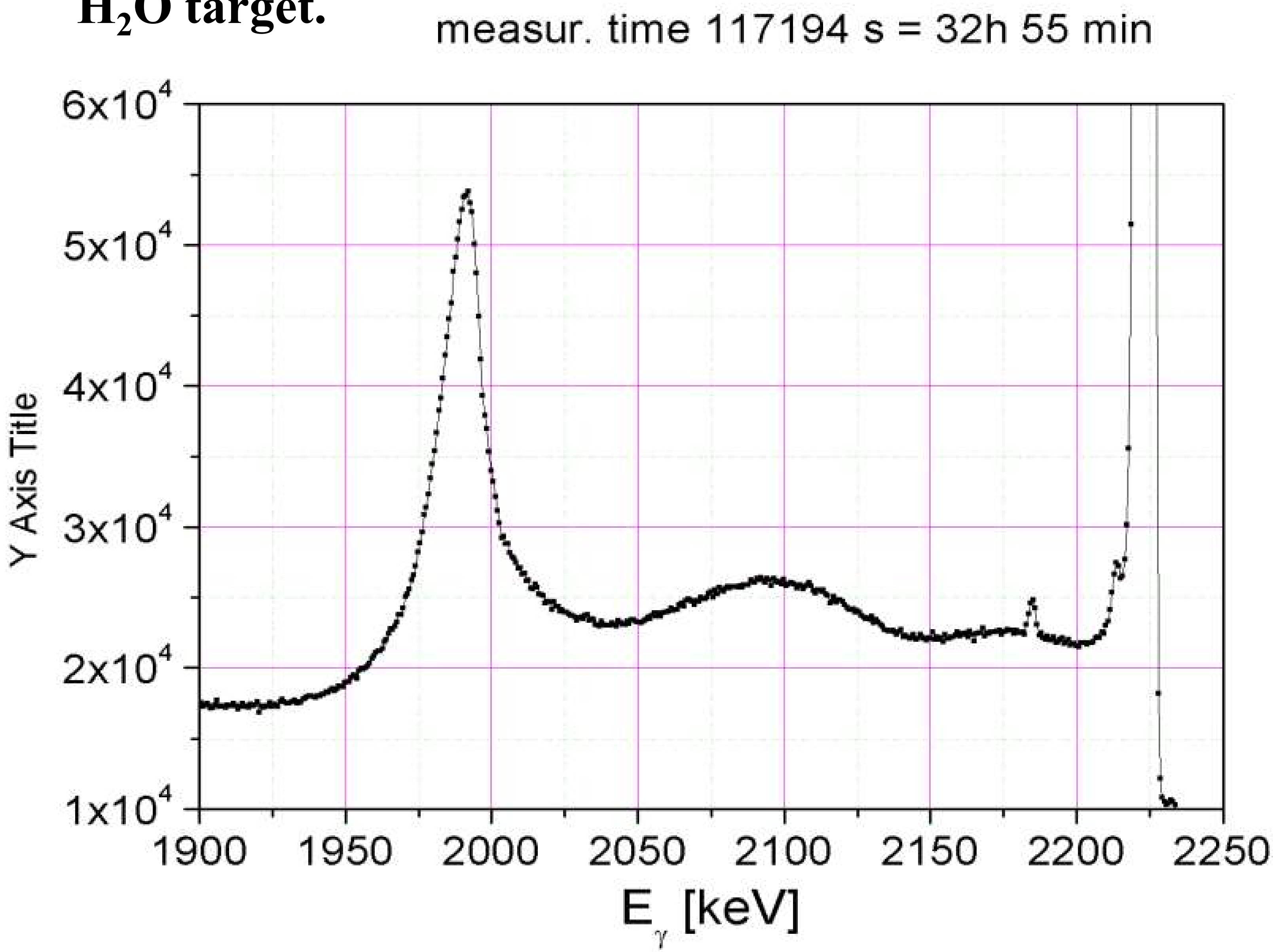
Energy calibration using 22 γ-peaks
arising from neutron capture by hydrogen and nuclei of isotopes
of Ge, ^{35}Cl, ^{12}C, ^{14}N, ^{27}Al, ^{207}Pb

Estimated shielding of Ge detectors by the ^{6}Li-containing plastic
from neutrons scattered by the target was about 10^5,
nevertheless we observed about 250 photopeaks.

Nuclear data:
Nndc.bnl.gov

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

H_2O target.



$$n(^6Li, \alpha)t \quad (E_t = 2.73MeV)$$

$$t(^6Li,^8Be)n, \quad Q = 16.02MeV$$

$$t(^6Li, 2\alpha)n, \quad Q = 16.15MeV$$

Estimated fluence of fast ($E_n \approx 14MeV$) on HPGe detector was about $10^6\,cm^{-2}$

(n,n$'$), (n,p), (n,α), (n,2n)

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}.

Conclusions

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)

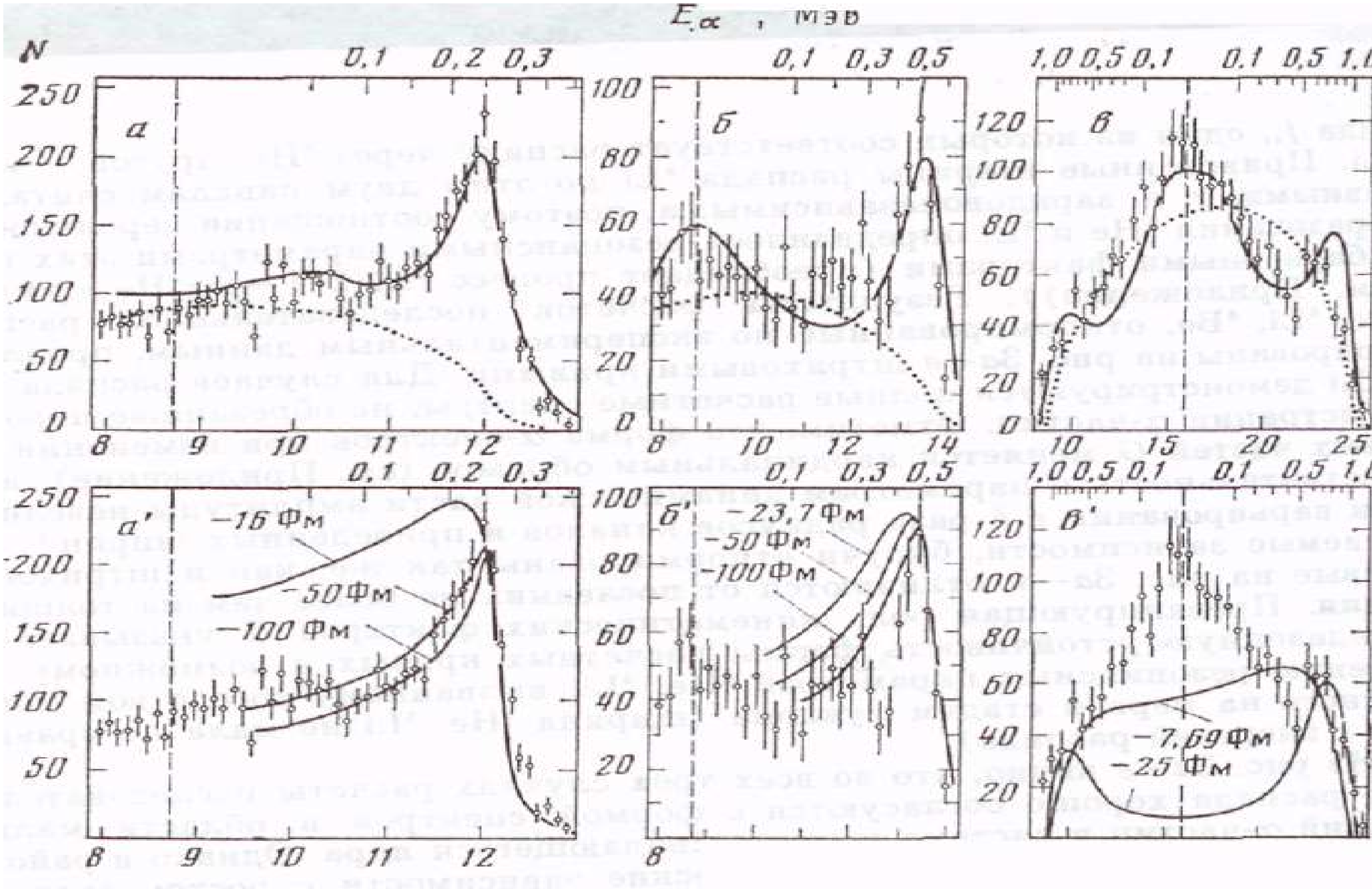
There is no nuclide which gives the gamma quanta with the energy 2212.9

keV! Probably this line is from hydrogen.

We must find second line with the energy approximately 10 keV.

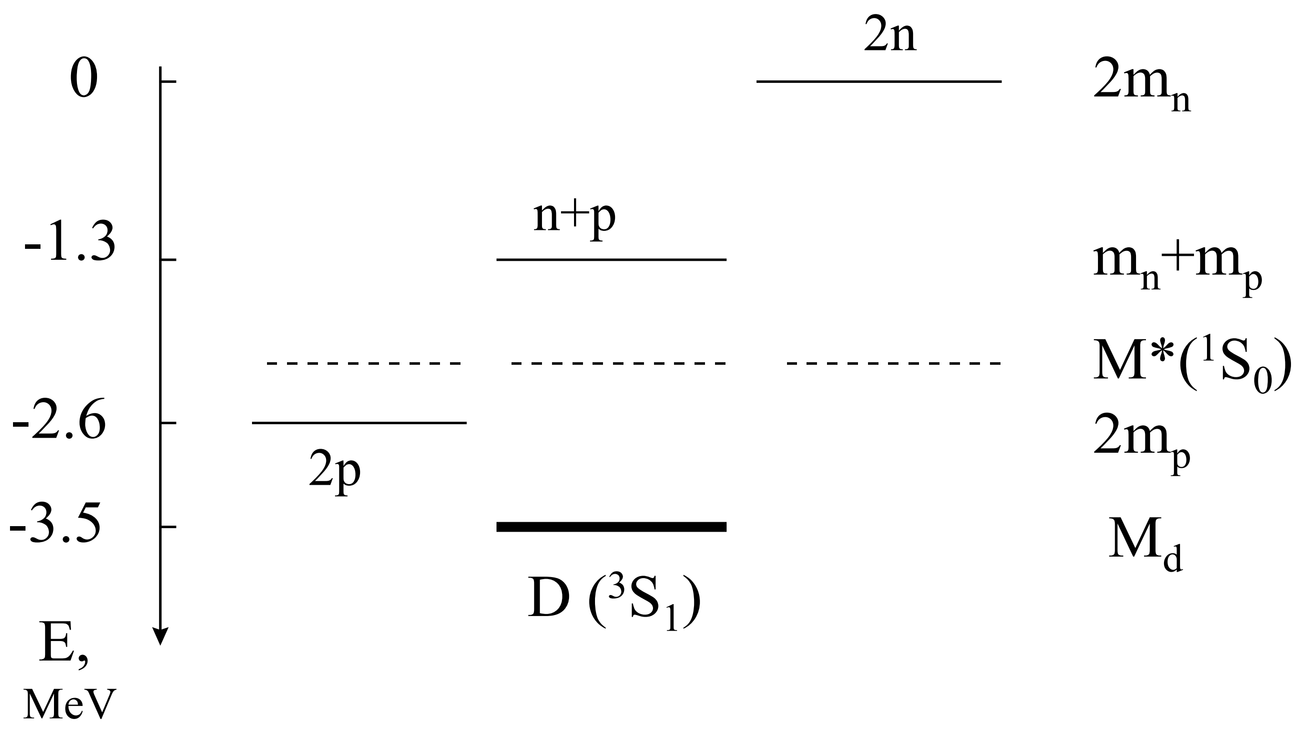
Thank you for your attention!

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.,



Low energy *NN* interaction.

The masses of the nucleon pairs.



Neutron Radiative Capture.

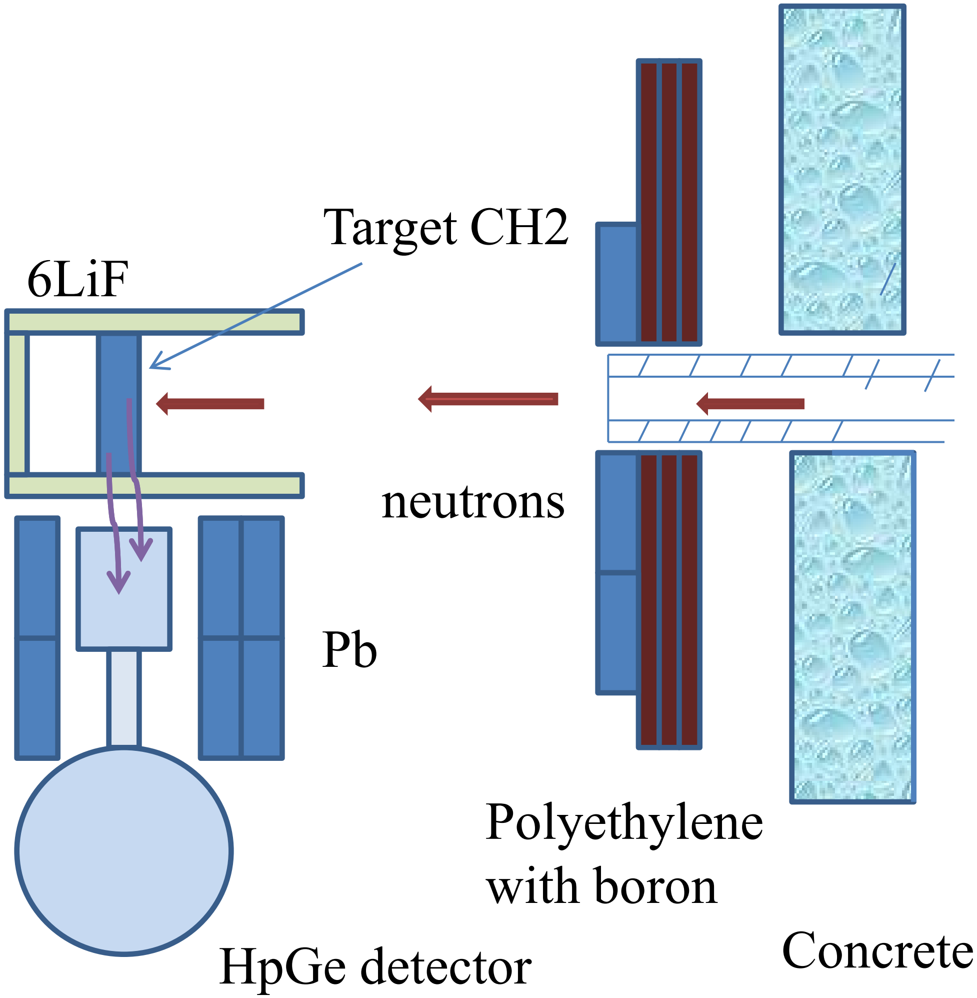


Схема установки на ИБР-2М.

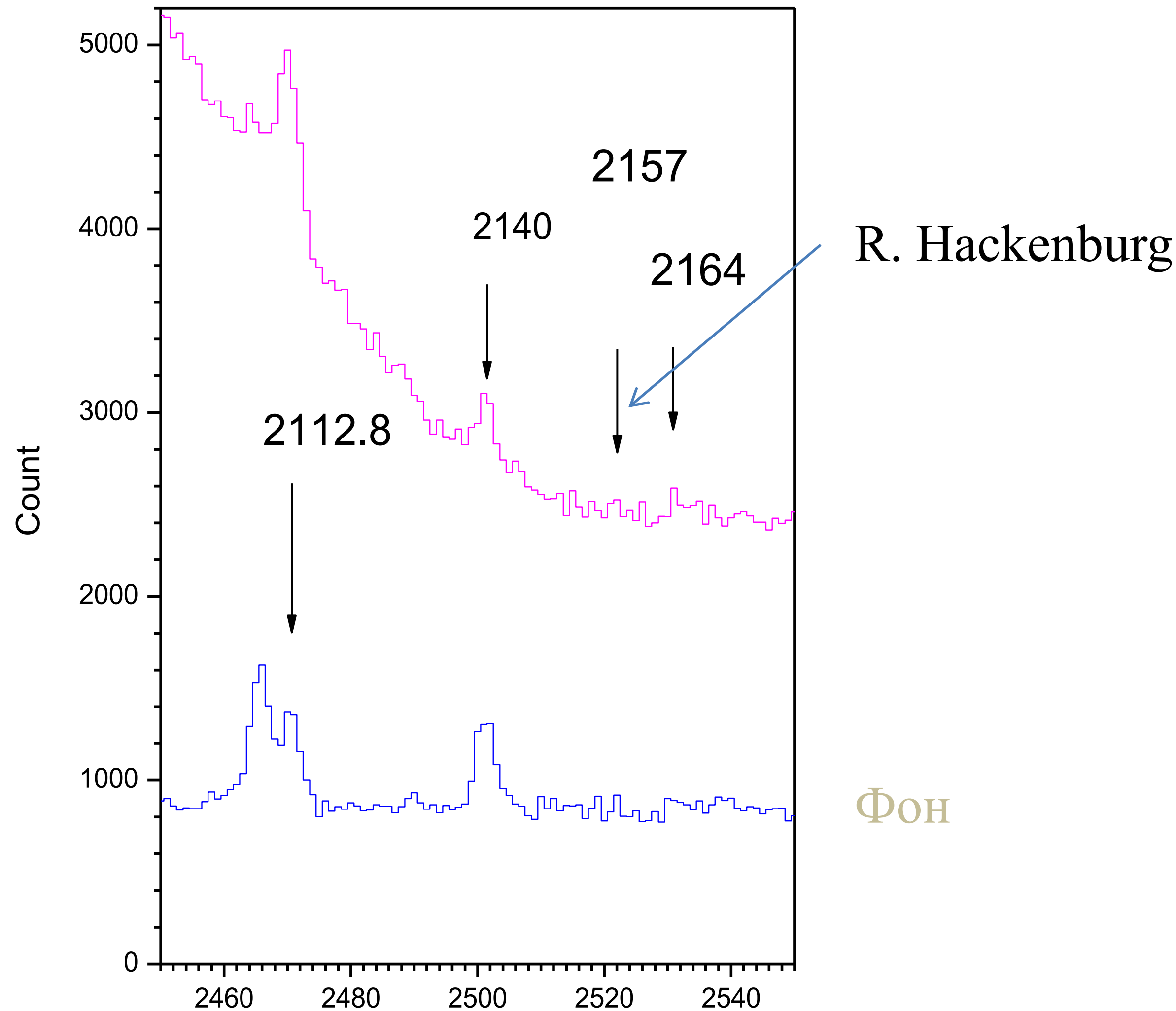
$$n + p \longrightarrow d + \gamma$$

Амплитудный спектр гамма-квантов.

Энергии и площади гамма линий.

Channel	E, keV	S +/- dS	Element	comment
621	511..0			Annig.
718.5	595.4	30321 +/- 716	Ge	
1006	844	14472 +/- 434	56Mn	Act.
1163.5	984.0	1541 +/- 255	27Al	
1296	1099	12939 +/- 354	59Fe	
1384	1171.5	1015 +/-740	60Co	
1417	1201.3	24211 +/- 419	DE(H)	
1567	1332	1091 +/-257	60Co	
1902.4	1622.5	2117 +/-188	27Al	
2005.4	1712.3		SE(H)	
2083	1778.9	53176 +/- 485	27Al	Act.
2120	1810.6	1894 +/- 340	56Mn	
2470	2112.8	600 +/- 200	56Mn	Act.
2598.6	2223.3	1817211 +/- 5278	1H	

Singlet deuteron



Singlet deuteron.

S.B. Borzakov, N.A. Gundorin, L.B. Pikelner, N. V. Rebrova, K.V. Zhdanova, ISINN-16, Dubna, June 11-14, 2008.

$$\sigma(n+p \to d+2\gamma)\langle 75\mu b$$

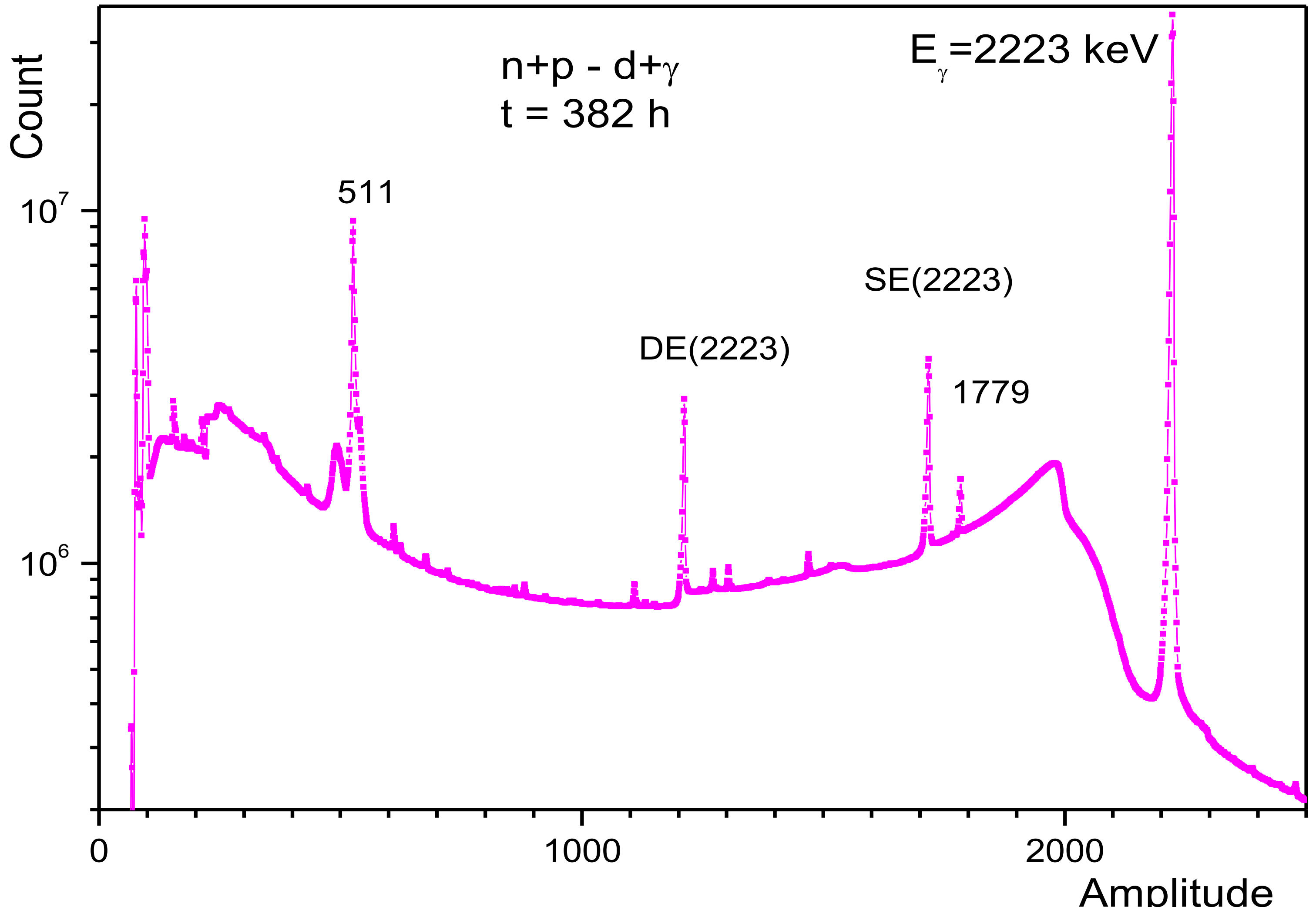
Our preliminary result on the bound state singlet deuteron, obtained in the experiment at the pulsed reactor IBR-2:

$\sigma_{singl} = (17 \pm 6)\ \mu$b at $E_\gamma = 2165$ keV, E_b=58 keV ?

S.B. Borzakov, N.B. Gundorin, Yu.N. Pokotilovski

Phys. Part. & Nucl. Lett. **12** (2015) 536.

Singlet deuteron.



Spectrum of the gamma quanta measured with the CH2 target.

Dineutron and Singlet Deuteron.

Sakisaka M., Tomita M. - J. Phys. Soc. Japan, 1961, 16, p. 2597.

Агеев Ю.А. и др. - Препринт КИЯИ 85-4, АН УССР, Киев, 1985.

Detraz C. - Phys. Lett., 1977, 66B, p. 333.

.

$^{2}n + ^{70}Zn \rightarrow ^{72}Zn$ $^{28}Mg \rightarrow ^{28}Al \rightarrow ^{28}Si$ $^{26}Mg(^{k}n, ^{k-2}n)^{28}Mg$

$^{92}Sr \rightarrow ^{92}Y$

Dineutron and Singlet Deuteron.

Д.В. Александров и др. [18] изучали испускание нейтральных ядер в спонтанном делении.

Они использовали в качестве источника ^{252}Cf интенсивностью 10^7 делений в секунду. Активатором служили образцы ^{26}Mg весом от 0.1 до 6 г, располагавшиеся на расстоянии 3 мм от источника.

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

2.71 часа. Спектр гамма квантов измерялся с помощью HPGe детектора объемом 120 см^3. Была обнаружена линия с энергией 1384 keV.

Dineutron and Singlet Deuteron.

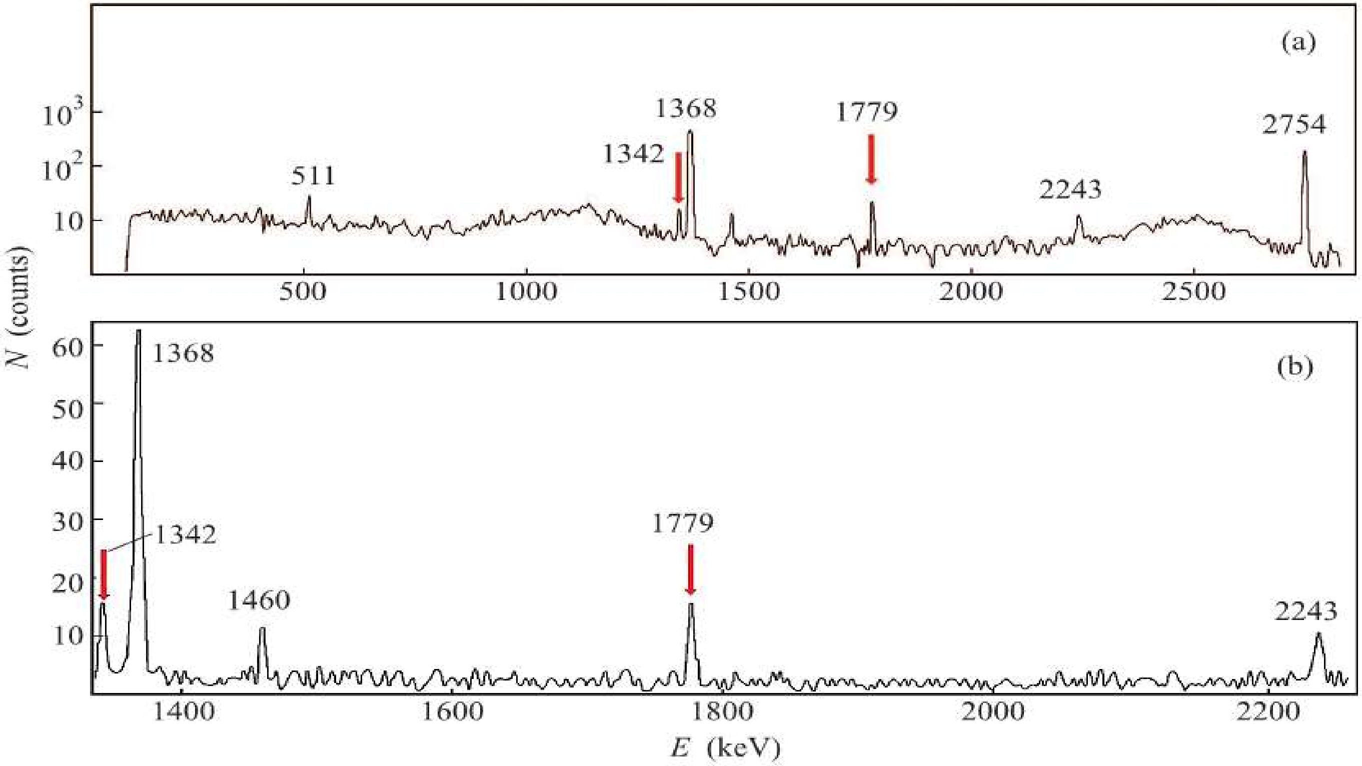


Рис. 2. (a) – Энергетический спектр γ-квантов активируемого образца ^{27}Al, облученного продуктами вынужденного деления ^{238}U α-частицами. (b) – Выделенный участок γ-спектра в диапазоне энергий 1330–2250 кэВ. Стрелками отмечены γ-линии, сопровождающие β-распад ядер ^{28}Mg (1342 кэВ) и ^{28}Al (1779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

Dineutron and Singlet Deuteron.

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

Первая попытка поиска динейтрона в реакции взаимодействия нейтронов с дейтронами была предпринята Глазго и Фостером. Они измерили сечение рассеяния нейтронов дейтронами для 241 значений энергии в интервале 2.25-15 МэВ (в лабораторной системе) с точностью 1.2-5.6% и получили верхний предел сечения реакции с вылетом динейтрона 100-1000 мкб.

В последнее время широким фронтом ведутся измерения с пучками нестабильных ядер. Ф.М. Маркуш с соавторами наблюдали 6 событий появления тетранейтронов. В этом эксперименте пучок ядер ^{14}Be.

А. Спироу с соавторами наблюдали распад ^{16}Be с одновременным вылетом двух нейтронов. Аналогичный процесс наблюдался в реакции

^{26}O – ^{24}O +2n .

Б.Г. Новацкий с соавторами обнаружили легкие нейтральные ядра в делении ^{238}U альфа частицами с энергией 62 МэВ. Индикатором служил образец, содержащий ^{88}Sr, причём предполагалось, что осуществлялась реакция передачи 4-х нейтронов. В результате появлялись нестабильные ядра ^{92}Sr.

Dineutron and Singlet Deuteron.

Оригинальный подход осуществлён в работе группы из Томского Политехнического института. Они исследовали продукты распада ^{252}Cf и обнаружили ^{232}U, который мог появиться **только** в результате испускания октонейтронов.

TABLE II. Summary of the results of the present measurements on the two-quantum radiative thermal neutron capture cross section $\sigma_{\gamma\gamma}$ of ^1H and the partial thermal neutron capture cross section σ_p of ^{16}O [1088–2184]–871 keV γ cascade].

Detectors	Time resolution[a] (ns)	Measuring time (d)	^1H: $\sigma_{\gamma\gamma}$ (μb)[c] 330–1890 keV	^1H: $\sigma_{\gamma\gamma}$ (μb)[c] 700–1500 keV	^{16}O: σ_p (μb)[c]
Ge(Li) 56 cm^3/Ge(Li) 42 cm^3	12	24	6 ± 32[b]		171 ± 22
NaI(Tl) 7.6 × 7.6 cm/NaI(Tl) 10.2 × 10.2 cm	4	28	−2.7 ± 9.8	−4.0 ± 4.0	152 ± 8
Ge(Li) 120 cm^3/Ge(Li) 127 cm^3	9	20	−5 ± 16	10.6 ± 5.6	160 ± 16
Ge(Li) 120 cm^3/Ge(Li) 127 cm^3	11	40	−10.8 ± 10.8	3.2 ± 5.3	140 ± 18
Weighted averages			−5.2 ± 6.4	−0.4 ± 3.0	152 ± 6

[a] FWHM obtained with ^{22}Na source. During the measurements, events were accepted in a time window of 1.2 × FWHM. In the last run with the big Ge(Li) detectors lower energy thresholds were used which results in a slightly worse time resolution.

[b] Experiment already reported (Ref. 18), improved value from reevaluation.

[c] The given errors include those from the coincidence peak determination and errors of the absolute coincidence efficiencies.

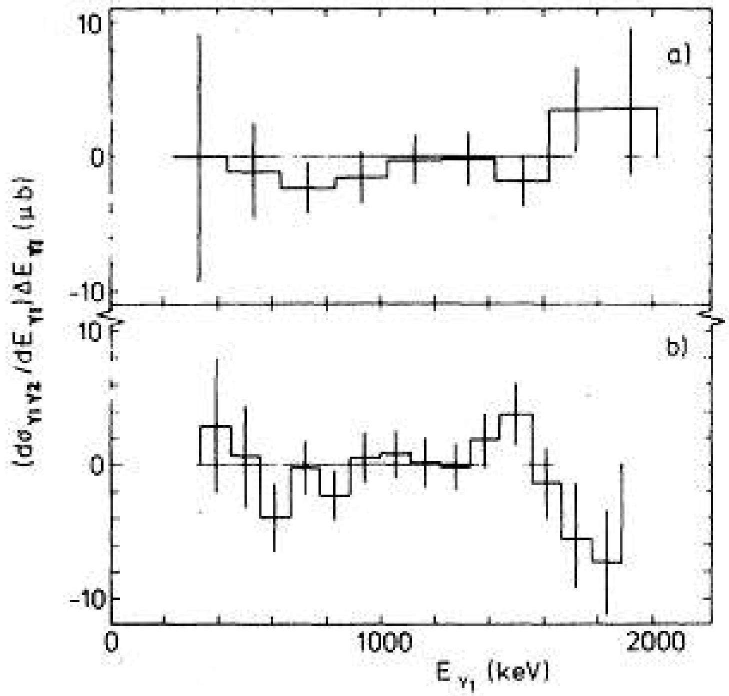


FIG. 6. Differential cross section for the $^{1}H(n,\gamma\gamma)^{2}H$ reaction [(a) is from the NaI(Tl) measurement, (b) is from the second measurement with the big Ge(Li) detectors].