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

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

Joint Institute for Nuclear Research

Low energy *NN* interaction.

Orbital momentum $L = 0$

Total momentum $\vec{J} = \vec{s}_1 + \vec{s}_2$

isospin

J = 0 – singlet state; T =1

J = 1 – triplet state; T =0

Elastic scattering $n + p \rightarrow n + p$

Total scattering cross-section: $\sigma_{sc,t} = \frac{1}{4}\sigma_S + \frac{3}{4}\sigma_t$

$$\sigma_S = \pi |F_S|^2 \qquad \sigma_t = \pi |F_t|^2$$

F_s and F_t - are Scattering amplitudes for singlet and triplet states.

Low energy *NN* interaction.

- Scattering amplitude

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

$$a - scattering \quad length$$

$$\rho - effective \quad range$$

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

Two channels: $A = a - ib \quad (b > 0)$

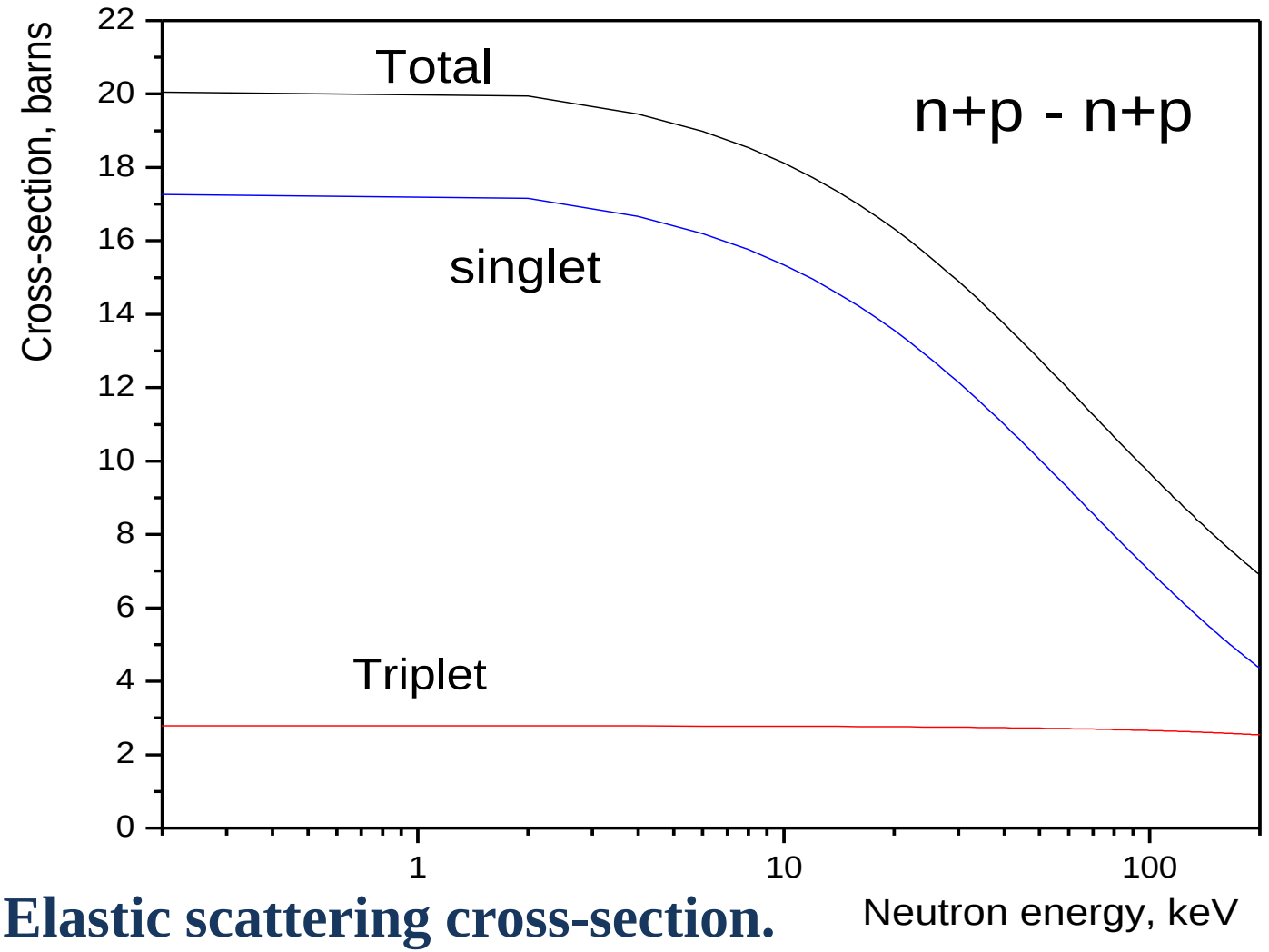
Capture cross-section: $\sigma_c = \frac{4\pi b}{k} \qquad E_n \to 0$

Low energy *NN* interaction

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(1S0)	-23,719 0,013	2,76 0,05		
nn	-18,7 0,6			
np(3S1)	5,414 0,005	1,75 0,05	0,13 0,09	

Low energy *NN* interaction.



Elastic scattering cross-section.

Low energy *NN* interaction.

Bound states. S-matrix $S = 1 + 2ikF$

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

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

Four poles:

$$\kappa_{1,2} = \frac{1}{\rho} \pm \sqrt{\frac{1}{\rho^2} - \frac{2}{a\rho}}$$

$^1S_0 \qquad a < 0$

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**	**?**

Low energy *NN* interaction.

Virtual level or Resonance with negative energy?

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

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

Resonance energy: $E_r = \frac{2}{ar}\frac{h^2}{2\mu}$ Neutron width: $\Gamma_n = \frac{4k}{\rho} \propto \sqrt{E_n}$

Radiative width: $\Gamma_\gamma = \frac{4b}{\rho a^2}$

S.T. Ma, Rev. Mod. Phys., v.25, p.853, 1953. (R - matrix)

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

Low energy *NN* interaction.

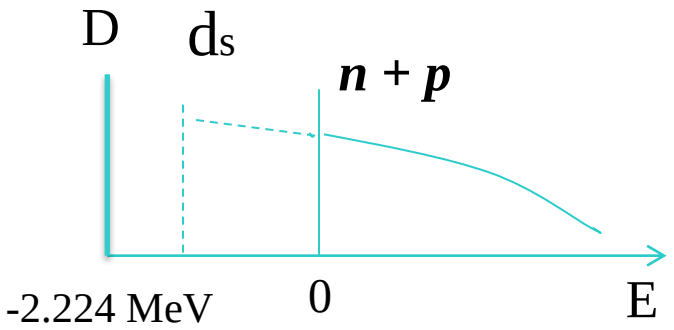
Virtual level or Resonance with negative energy?

$^1S_0$-state.

Resonance parameters: $E_r \approx$ -1,3 MeV; Γ_n (1 eV) = 10 keV; Γ_γ = 20 eV.

Resonance with negative energy is equivalent to the exited level of the Deuteron (singlet deuteron).

It is possible to observe the metastable singlet deuteron in the electromagnetic interactions.
Life time is approximately 10^(-17) sec.



Singlet Metastable Deuteron

- **I. Cohen B.L. et al., Phys. Rev. Lett., v. 18, No. 22, p.962, 1967.**

$$^{9}Be(p, d_S)^{8}Be$$

II. N.O. Gaither et al. Singlet Deuteron Production in the $^{4}He(d, p\alpha)n$ reaction at 7 MeV, Phys. Rev., C38 (1988) 1119.

III. O.V. Bochkarev et al., Physics of Atomic Nuclei, v. 46, No. 1(7), 1987.

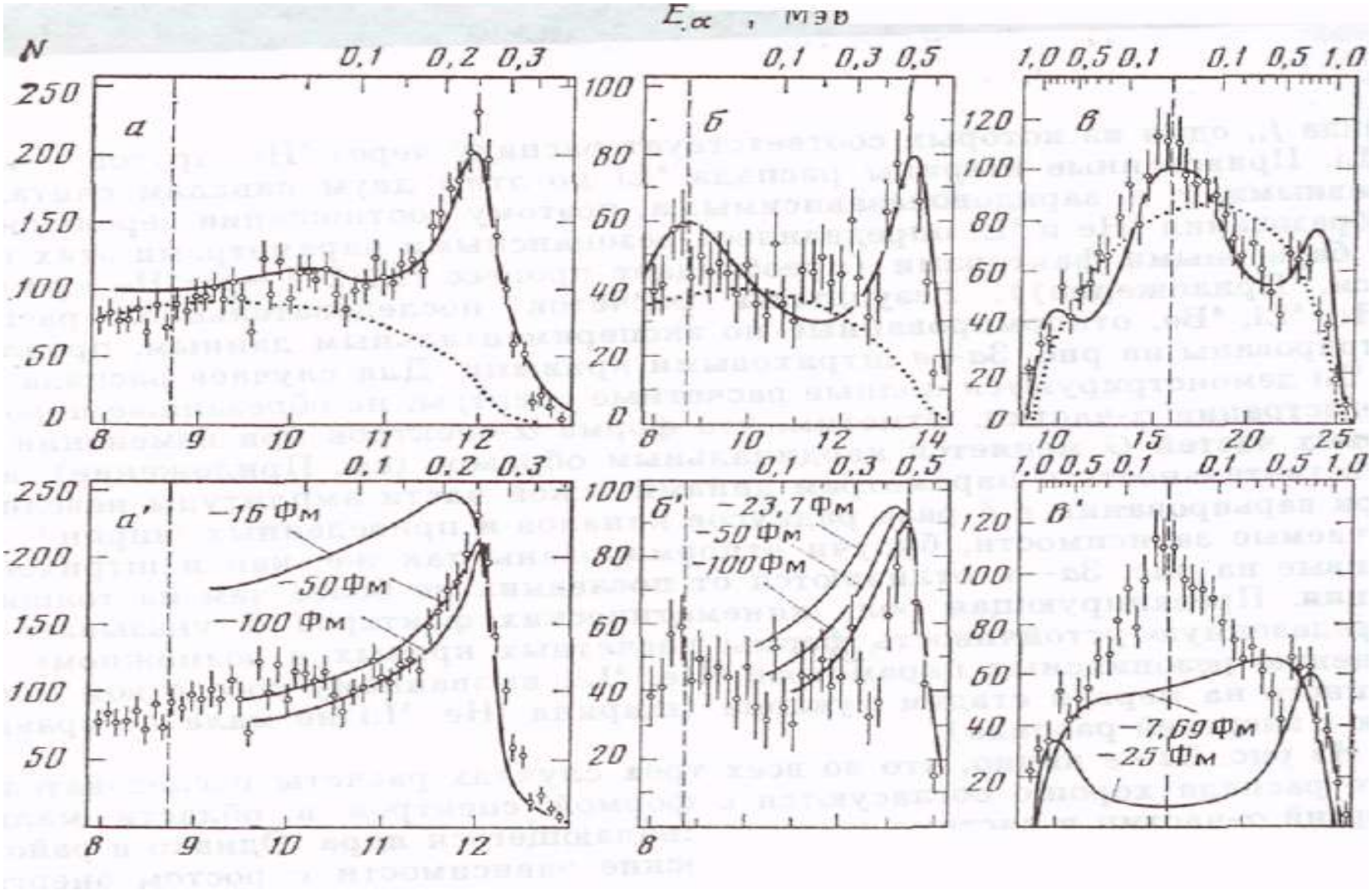
$$^{6}He(2^{+}) \rightarrow \alpha + 2n(^{1}S_{0})$$

$$^{6}Li(2^{+}) \rightarrow \alpha + np(^{1}S_{0})$$

$$^{6}Be(2^{+}) \rightarrow \alpha + 2p(^{1}S_{0})$$

The spectra of emitted alpha particles have been measured. The narrow peaks have been observed in the decay of the ^{6}He and ^{6}Li.

O.V. Bochkarev et al., Physics of Atomic Nuclei, v. 46, No. 1(7), 1987.
(ЯФ, т. 46, вып. 1(7), 1987 г.) Three body decay of the 2+ states 6He, 6Li and 6Be.



Alpha particles spectra.

Singlet Metastable Deuteron

Theoretical indications.

- **K. Maltman, N. Isgur, Phys. Rev., D29, No. 5, p. 952, 1984.** (6 quark states)

$B_d = 2.9$ МэВ $\qquad B(^1S_0) = 0.4$ МэВ

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

•"Quantum field theoretic model of metastable resonant spin-singlet state of the np-pair"

(Numbu – Iona-Lasinio model; NN treated as Cooper pair)

Binding energy $B_S = (79 \pm 12)$ keV

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

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

Eγ1 = 66 keV; Eγ2 = 2157 keV

Singlet Metastable Deuteron

T. Yamazaki, Y. Kuzamashi, A. Ukawa, Phys. Rev. D84, 054506, 2011. "Two Nucleon Bound States in Quenched Lattice QCD"

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.

$$-\Delta E_\infty = \begin{cases} 7.5(0.5)(0.9)\ \text{MeV} & \text{for } {}^3S_1 \\ 4.4(0.6)(1.0)\ \text{MeV} & \text{for } {}^1S_0 \end{cases},$$

Radiative capture

Method to Observe Singlet Metastable Deuteron.

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

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

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

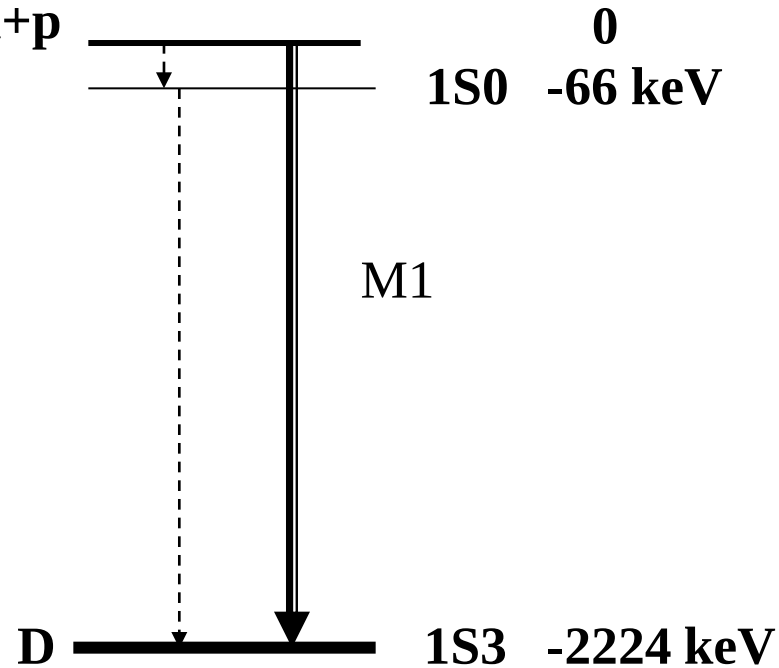
$$\hat{M}1 = \left(\frac{e\hbar}{2mc}\right)\left[\frac{1}{2}(\mu_p + \mu_n)\sum_i \vec{\sigma}_i + \frac{1}{2}(\mu_p - \mu_n)\sum_i \vec{\sigma}_i \vec{\tau}_{3i}\right]$$

$$\sigma_{n\gamma}(M1) = 2\pi\alpha \frac{c}{v_n}\left(\mu_n - \mu_p\right)^2 \left(\frac{B_d}{Mc^2}\right)^{5/2}\left(\gamma^{-1} - a_S\right)^2$$

$$\frac{\sigma_{2\gamma}}{\sigma_\gamma} = \frac{\left(\gamma_0 - a_t^{-1}\right)^2}{\left(\gamma - a_s^{-1}\right)^2}\left(\frac{a_t}{a_S}\right)^2\left(\frac{B_S}{B_d}\right)^{3/2}$$

$$\frac{\sigma_{2\gamma}}{\sigma_\gamma} = 10^{-5} - 10^{-4}$$

$$\sigma_\gamma = 334 \pm 0.5 mb$$



Singlet Metastable Deuteron

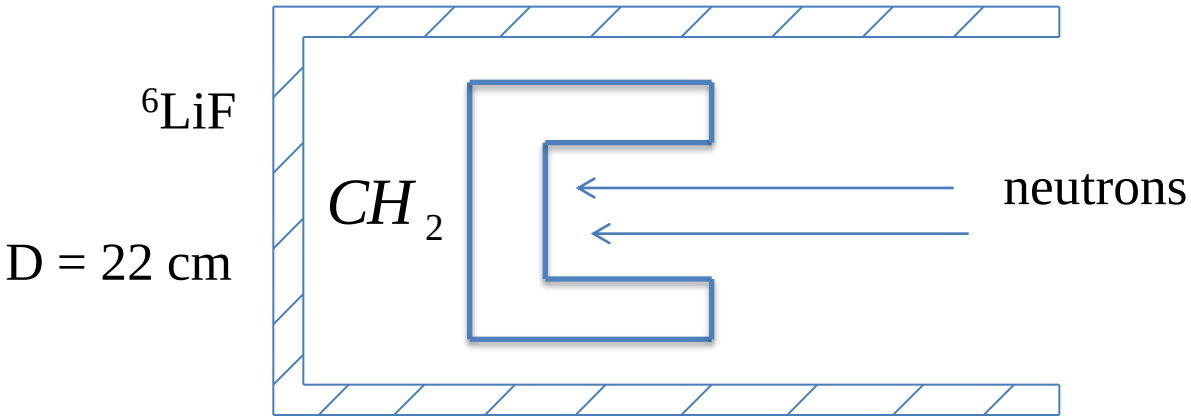
The experiment.

1. **Neutron source - pulsed reactor IBR-2M; W = 2 MW;**

2. **Mirror neutron guide; $\Phi_n \approx$ 6 10^5 n /(cm^2 sec);**

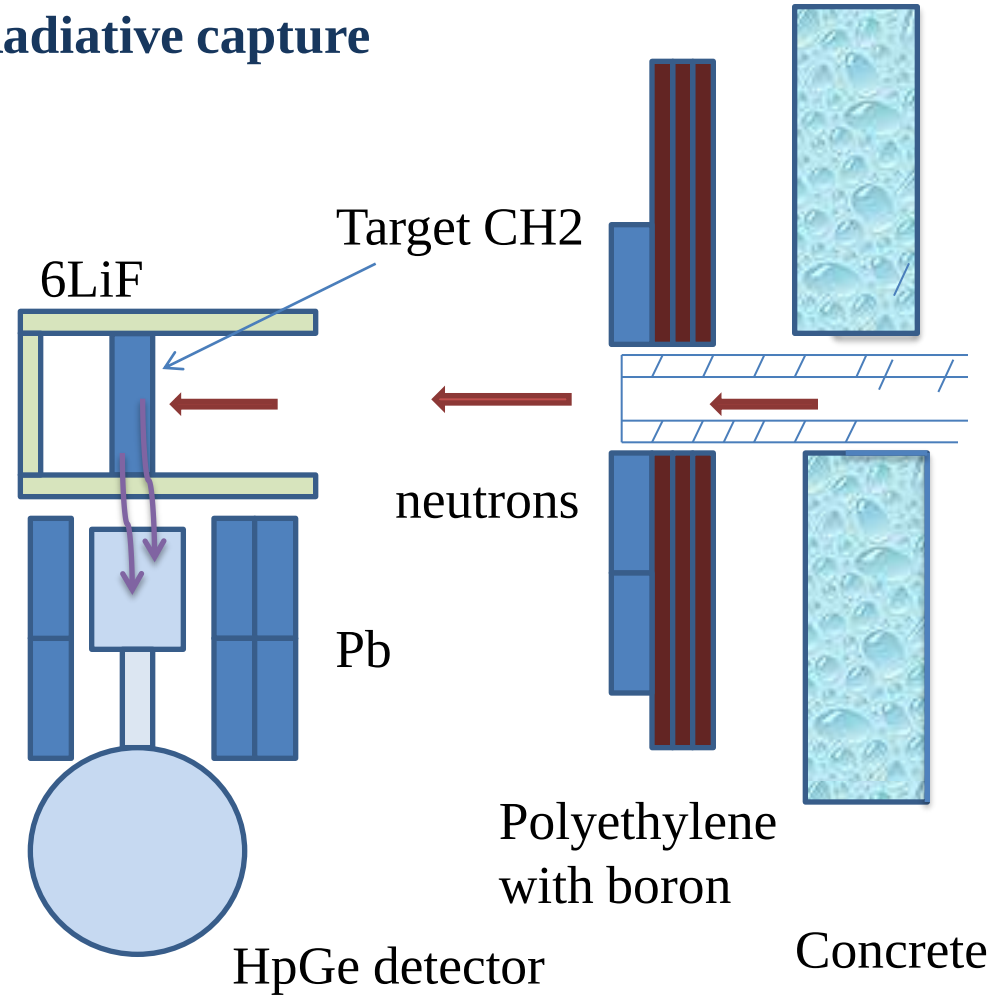
3. **HpGe detector $(\varepsilon_{rel.} \approx 35\%)$;**
   Energy resolution approximately 2.1 keV for lines 1173 and 1332 keV (Co60).

4. **Target – polyethylene into 6LiF shield.**



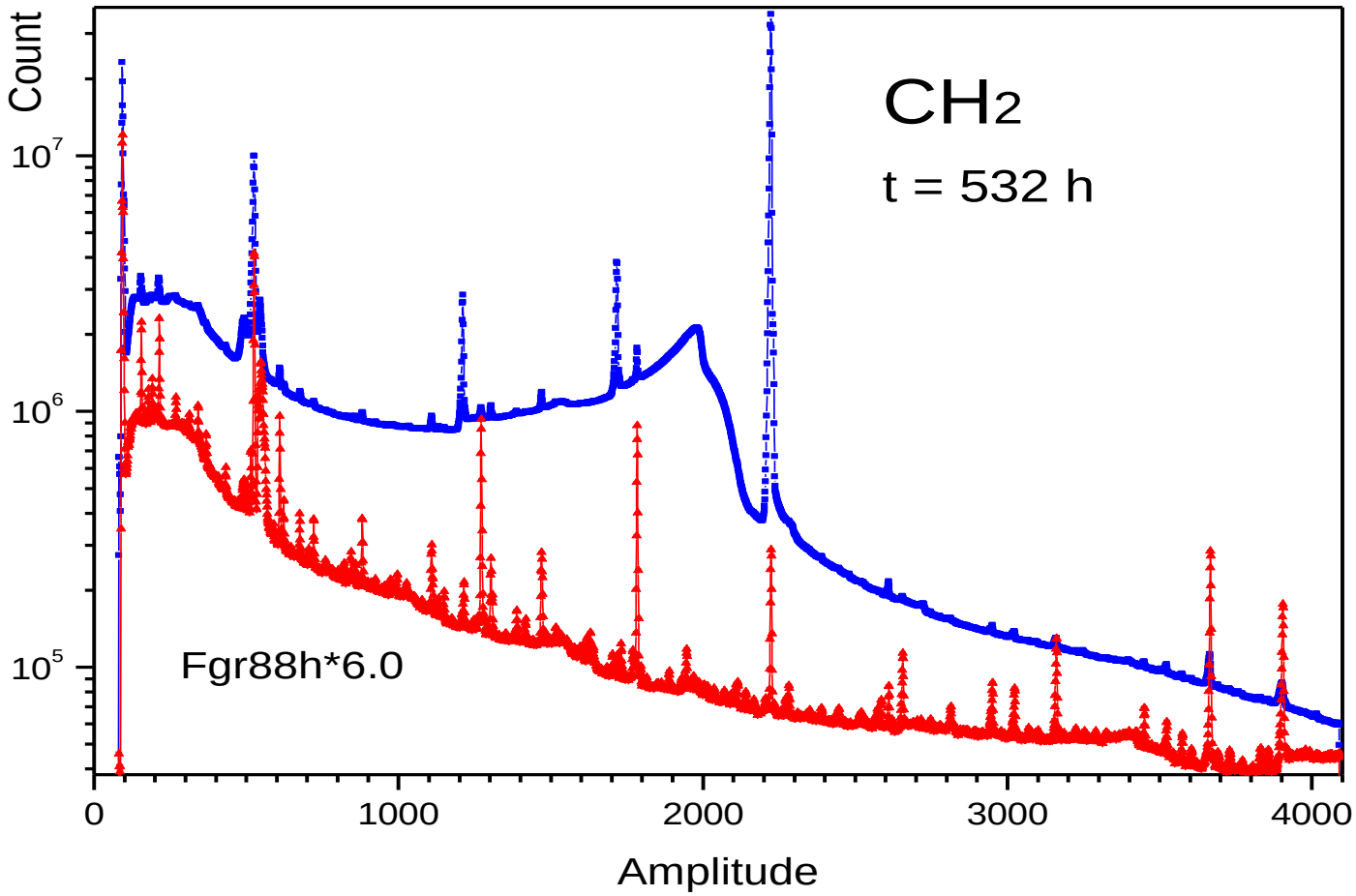
Singlet Metastable Deuteron

Radiative capture



Scheme of the experiment.

Singlet Metastable Deuteron.



Gamma ray spectrum measured with polyethylene (CH2) target.

Singlet Metastable Deuteron

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

Main transition $^1\widehat{S}_0 \rightarrow {}^3S_1 \quad E_{\gamma 0} = 2223$ keV

Peak area $S(2223) = 2.08 \cdot 10^8$ (t = 532 h)

According to R. Hackenburg $S(2157) \approx 15000$

Background:

Prompt gamma from ^{56}Fe ^{27}Al ^{nat}C ^{14}N etc.

Lines from activation ^{116m}In, ^{56}Mn, ^{28}Al

Natural background from U238, Th232.

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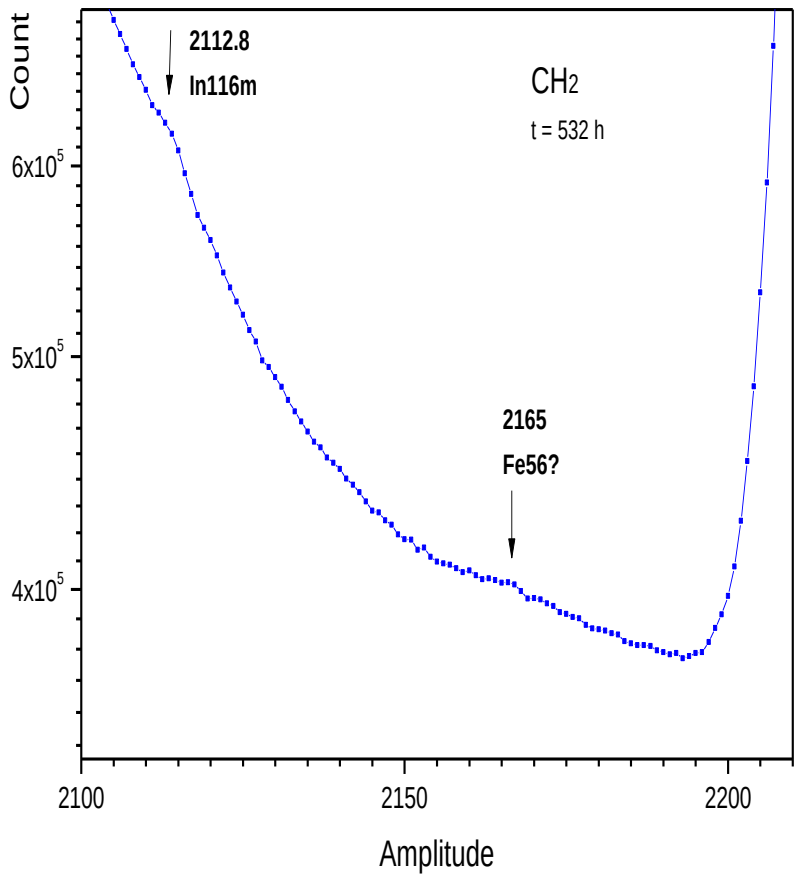

***Part of the amplitude spectrum in the interval* 2000 – 2200 keV.**

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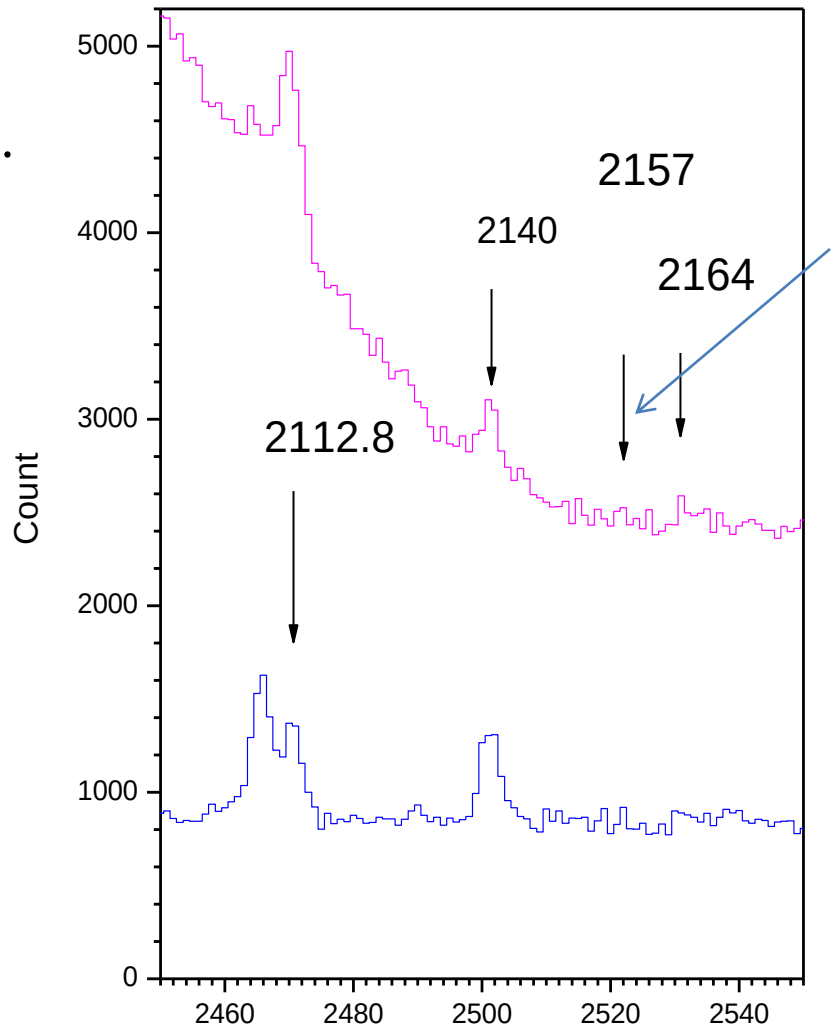
Preliminary measurements.



Singlet Metastable Deuteron.

- **2164 keV - ?**
- **65Cu 2163.2 (0.98) – no 543.85 (10.22); 1559.86 (13.66)**
- **120Sn 2163.7 (17.0) - no 925.7 (100); 942.9 (100); 966.0 (100)**
- **56Fe 2164.7 (0.69) - no 692.03 (16.38); 1612.78 (18.55); 1725.28 (21.72)**

Preliminary result $\sigma(n + p \rightarrow d + 2\gamma) = 46 \pm 25 \mu b$

The reported new result for this transition is 17 ± 6 μb which does not contradict to the preliminary result and needs additional measurements

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Singlet Metastable Deuteron

$$\sigma_{n,2\gamma} \leq \frac{3\sqrt{S}}{S(2223)} \frac{\varepsilon(E_{\gamma 0})}{\varepsilon(E_{\gamma 1})} \sigma_{n,\gamma 0}$$

E_γ , **keV**	$\sigma_{n,2\gamma}$, **μb**
2100 - 2130	< 15
2131 - 2160	< 12
2170 - 2200	< 13

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Conclusion.

1. **The gamma ray spectrum from polyethylene target have been measured with good statistics.**
2. **The upper limit for the value of $\sigma_{n,2\gamma}$ is obtained.**

3. **The peak 2165 keV needs further investigation.**
4. **Further measurements on stationary reactor with improved technique are needed.**

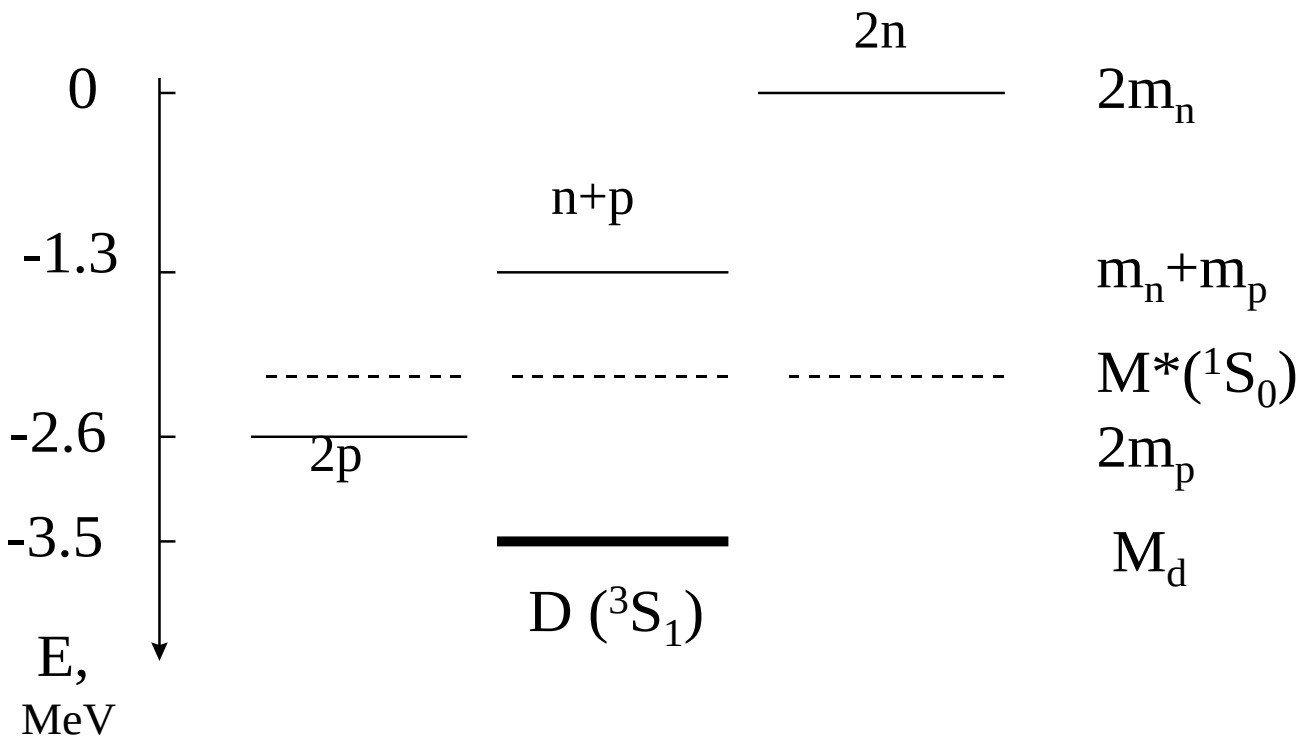
Singlet Metastable Deuteron.

Thank you for your attention !

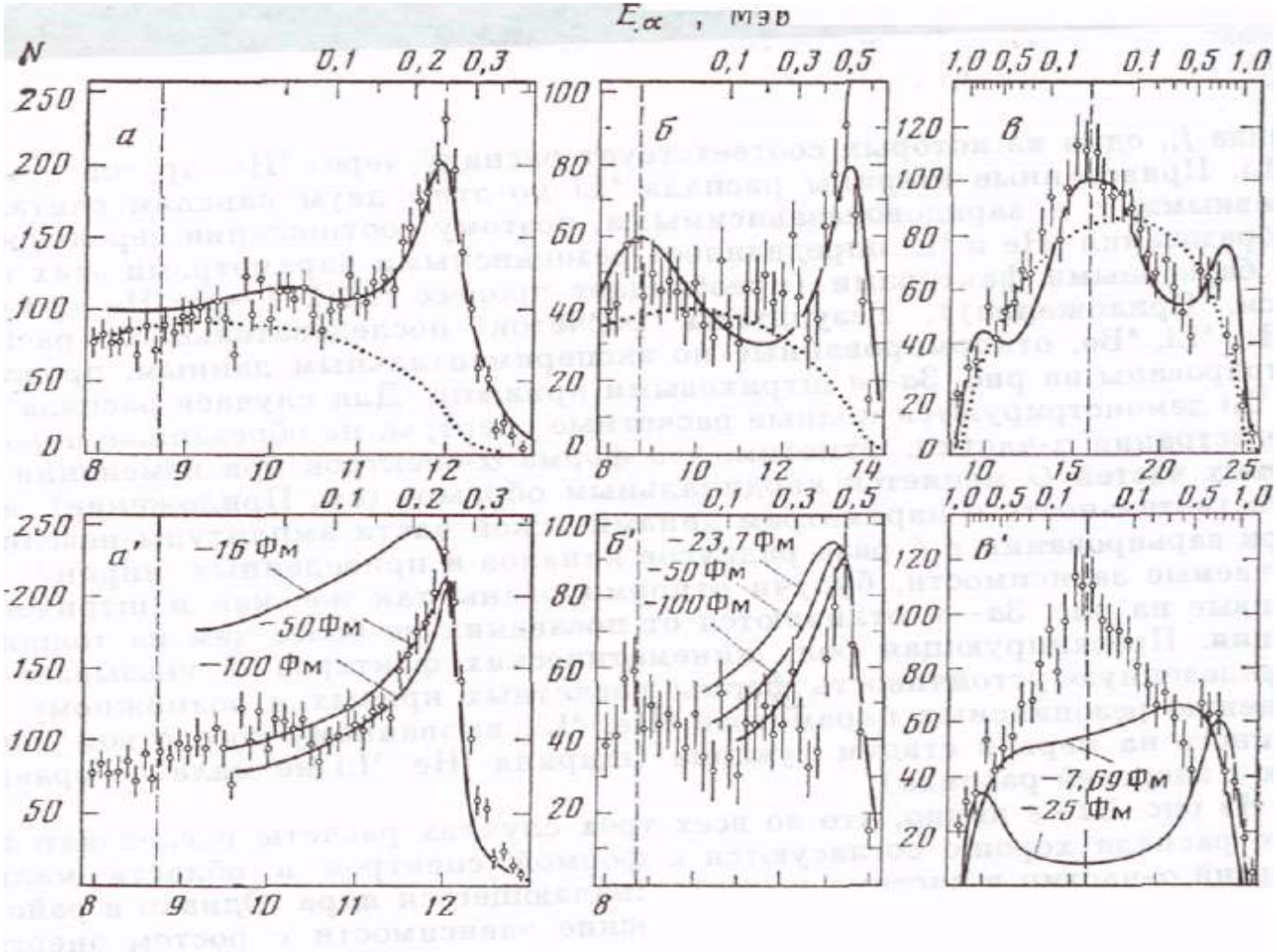
Energies and areas for observed gamma lines.

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	

Low energy *NN* interaction. Masses of the nucleon pairs.



Dineutron and Singlet Deuteron.



Singlet Metastable Deuteron.

Preliminary result.

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

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