

# The role of 14 MeV neutrons in light element nucleosynthesis

V. Valkovic, D. Sudac, and J. Obhodas

**Abstract**—The 14 MeV neutron induced nuclear reactions which might contribute to better understanding of so-called “cosmological lithium problem” have been discussed. The BBN theory predicted  ${}^7\text{Li}$  overestimated value could be lowered by  ${}^2\text{n}$  induced reactions on Li-isotopes and/or  ${}^7\text{Be}$  destruction via resonance in  $\text{d}+{}^7\text{Be}\rightarrow{}^9\text{B}$  process.

Proposals for  ${}^6\text{Li}+{}^2\text{n}$  and  ${}^7\text{Li}+{}^2\text{n}$  reactions cross section evaluations and measurements are discussed in some details.

We discuss also a preliminary measurements of n-n coincidences from the  ${}^{10}\text{B}(\text{n},2\text{n}){}^9\text{B}$  reaction with two neutron detectors placed outside the cone of 14 MeV tagged neutron beam. From the time-of-flight measurements and known geometry we deduce the neutron energies and calculate the  ${}^9\text{B}$  missing mass spectrum.

**Index Terms**—astrophysics, astrochemistry, boron, gamma-rays, neutrons, nuclear physics, scintillation counters.

## I. INTRODUCTION

THE 14 MeV neutrons are produced in the  ${}^2\text{H}+{}^3\text{H}\rightarrow{}^4\text{He}+\text{n}$  nuclear reaction, ( $Q=17.590$  MeV). In spite of large cross sections, both for their production and their interactions with light nuclei, their role in light element nucleosynthesis has not been studied in great many details.

By now it is accepted that the Big Bang nucleosynthesis, BBN, starts with the p-p chain with  ${}^1\text{H} + {}^1\text{H} \rightarrow {}^2\text{H} + e^+ + \nu_e$  nuclear reaction. According to the present model all neutrons end up bound in the most stable light element  ${}^4\text{He}$ . Heavier nuclei do not form in any significant quantity both because of the absence of stable nuclei with mass number 5 or 8. As a result Solar system shows very low relative abundance of Li, Be and B with respect to other elements.

One of the most important unresolved problem in nuclear astrophysics is so-called “cosmological lithium problem”. It refers to the large discrepancy between the abundance of primordial  ${}^7\text{Li}$  predicted by the standard BBN theory and the value inferred from the so called “Spite plateau” in halo stars. In fact, the predictions of the BBN theory reproduce successfully the observations of all primordial abundances except for  ${}^7\text{Li}$ , which is overestimated by more than a factor of three.

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Among the possible resolutions to this discrepancy are (i)  ${}^7\text{Li}$  depletion in the atmosphere of stars, (ii) systematic errors originating from the choice of stellar parameters – most notably the surface temperature and (iii) systematic errors in the nuclear cross sections used in the nucleosynthesis calculations.

We propose Li-isotopes destruction by the following series of nuclear reactions:

(i)  ${}^6\text{Li}+{}^2\text{n}\rightarrow{}^8\text{Li}\rightarrow{}^8\text{Be}+e+\bar{\nu}$  followed by  ${}^8\text{Be}\rightarrow 2\alpha$ .

(ii)  ${}^7\text{Li}+{}^2\text{n}\rightarrow{}^9\text{Li}\rightarrow{}^9\text{Be}+e+\bar{\nu}$  followed by  ${}^9\text{Be}\rightarrow\text{n}+2\alpha$ .

Where the  ${}^2\text{n}$  symbol represent neutron-neutron final state interaction (fsi) as observed in the  $\text{n}+\text{d}\rightarrow\text{p}+\text{n}+\text{n}$  reaction for  $E_n = 14$  MeV bombarding energy. (Nuclear reactions  ${}^1\text{H}+{}^2\text{H}\rightarrow{}^3\text{H}+e^++\nu_e$  and/or  ${}^2\text{H}+{}^2\text{H}\rightarrow{}^3\text{H}+{}^1\text{H}$  can than lead to 14 MeV neutron producing reaction  ${}^2\text{H}+{}^3\text{H}\rightarrow{}^4\text{He}+\text{n}$ ). During BBN, in the period of transition from quark-gluon plasma to baryonic matter, probability of  ${}^2\text{n}$  formation [n-n fsi or n-n bound state, if existed at that time] was increased. This would have led to Li distraction via reactions (i) and (ii).

Since the primordial  ${}^7\text{Li}$  is mainly produced by  $\beta$ -decay of  ${}^7\text{Be}$  ( $t_{1/2}=53.2$  days) the abundance of  ${}^7\text{Li}$  is essentially determined by the production and destruction of  ${}^7\text{Be}$ . The neutron induced reactions can also play a role in the destruction of  ${}^7\text{Be}$ , in particular the  ${}^7\text{Be}(\text{n},\alpha){}^4\text{He}$  reaction in the energy range of interest for BBN, in particular between 20 and 100 keV. Recent activity in solving the “lithium problem” in big bang nucleosynthesis has focused on the role that putative resonances may play in resonance-enhanced destruction of  ${}^7\text{Li}$ . Particular attention has been paid to the reactions involving  ${}^9\text{B}$  compound nuclear system  $\text{d}+{}^7\text{Be}\rightarrow{}^9\text{B}$ .

## II. THE ${}^2\text{N}$ -INDUCED NUCLEAR REACTIONS

The neutron-neutron scattering length of  $a_{nn} = -21.7$  F deduced from the measured proton spectrum from the  $\text{n}+\text{d}\rightarrow\text{p}+\text{n}+\text{n}$  reaction at  $E_n = 14$  MeV bombarding energy (as shown in Fig.1, from ref. [1]) allows the two neutrons to interact with target nucleus as a single projectile. Dominant contribution to “f” is coming from the  $-1/a_{nn}$  term in the effective range expansion. In the repeated measurement [2] the pure nuclear value for the neutron-neutron  ${}^1\text{S}_0$  scattering length is found to be  $a_{nn}=-22.5\pm 1$  fm. Scattering amplitude is a sum of partial wave amplitudes which are defined by scattering phase shifts. Let us remind that scattering length characterizes effective size of the target.

The support for this approach comes from the observed dineutron decay of halo nuclei and structure and decay correlations of the neutron systems beyond dripline. Nuclei

studied by Kohley et al. [3]:  $^{16}\text{Be}$ ,  $^{13}\text{Li}$ ,  $^{10}\text{He}$  and  $^{26}\text{O}$ . The correlations of the 3-body decay for the  $^{16}\text{Be}$  and  $^{13}\text{Li}$  were extracted and demonstrated a strong enhancement between two neutrons.  $^{16}\text{Be}$  and  $^{13}\text{Li}$  exhibit direct two-neutron decay since a sequential decay is energetically forbidden. Two-neutron radioactivity was observed in the case of  $^{26}\text{O}$  ground state.

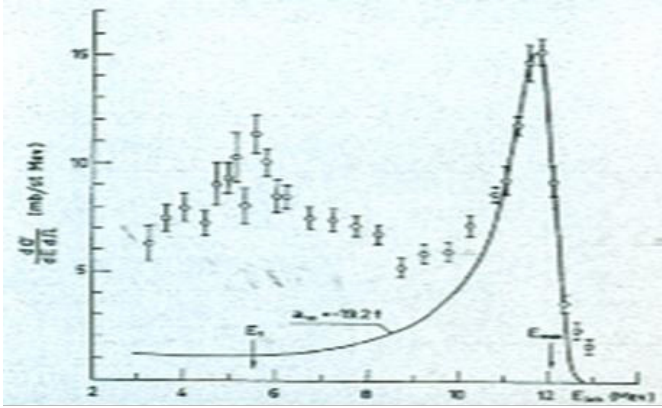


Fig 1: The experimental data for  $D(n,p)2n$  at 14.4 MeV at  $4^\circ$  in the laboratory system compared with the calculations for  $a_{nn} = -19.2$  fm after smearing and normalization [1]. This corresponds to the case when two neutrons are moving together with zero relative energy backwards in the center-of-mass system. E1 indicates the proton energy in the case where a neutron and proton are going together with zero relative energy in the forward direction in the center-of mass system.

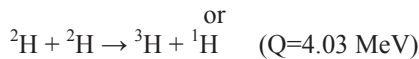
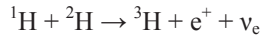
First observation of ground state dineutron decay:  $^{16}\text{Be}$ . In experiment [4]  $^{16}\text{Be}$  ground state was populated via single proton knockout reaction from  $^{17}\text{B}$ .  $^{16}\text{Be}$  is bound with respect to the emission of one neutron and unbound to two-neutron emission. The dineutron character of the decay is evident by a small emission angle between the two neutrons. The two-neutron separation energy of  $^{16}\text{Be}$  was measured to be 1.35 MeV – agreement with shell model calculations.  $^{16}\text{Be} \rightarrow ^{14}\text{Be}_{g.s.} + 2n$ . From the time reversal considerations dineutron induced reactions should be feasible.

### A. Experiment #1

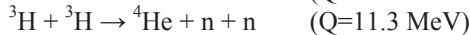
The neutron-neutron scattering length of  $a_{nn} = -21.7$  F deduced from the measured proton spectrum allows the two neutrons to interact with target nucleus as a single projectile.

Reactions of interest:

A step which might be of interest is



which can lead to one or more neutron producing reactions



Reaction  $^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} + n$  has peak in the total cross section ( $\sigma_T = 5$  b) at approximately deuteron energy of 100 KeV ( $T=1.16 \times 10^9$  K), while reaction  $^2\text{H} + ^2\text{H} \rightarrow ^3\text{He} + n$  total cross section is peaked at around deuteron energy of 2.0 MeV. During BBN, in the period of transition from quark-gluon plasma to baryonic matter, probability of 2n formation [n-n fsi

or n-n bound state (?) was increased. This would have led to Li distraction via reactions shown in Fig.2.

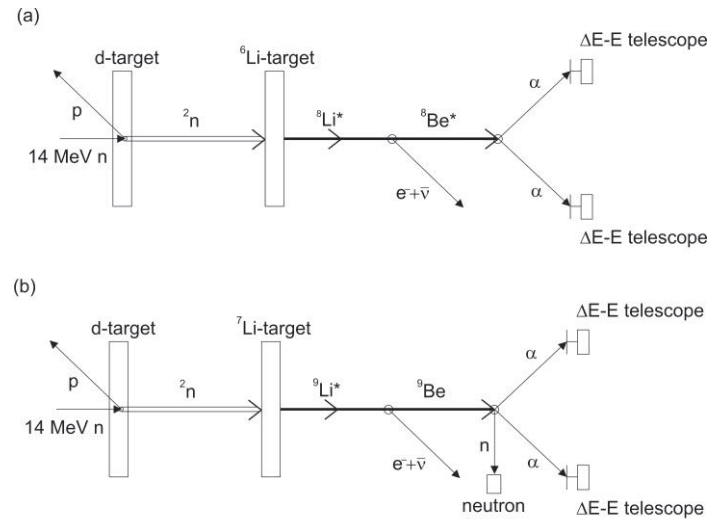


Fig.2: (i)  $^6\text{Li} + ^2n \rightarrow ^8\text{Li} \rightarrow ^8\text{Be} + e + \bar{\nu}$  followed by  $^8\text{Be} \rightarrow 2\alpha$ .  
(ii)  $^7\text{Li} + ^2n \rightarrow ^9\text{Li} \rightarrow ^9\text{Be} + e + \bar{\nu}$  followed by  $^9\text{Be} \rightarrow n + 2\alpha$ .

### B. Other Reactions

In real experiment one needs to bring  $^2\text{H}$  and Li targets / nuclei as close as possible. One possibility is using lithium hydrides  $^6\text{Li}^2\text{H}$  and  $^7\text{Li}^2\text{H}$ . Lithium hydride has chemical formula LiH and the crystal structure fcc (NaCl type) as shown in Fig. 3.

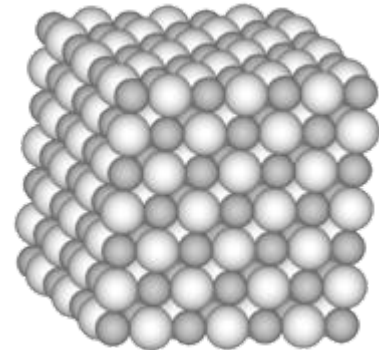


Fig.3: The crystal structure of lithium hydride with lattice constant  $a=0.40834$  nm..

Another possible target is  $^9\text{Be}$  as indicated in Fig.4.

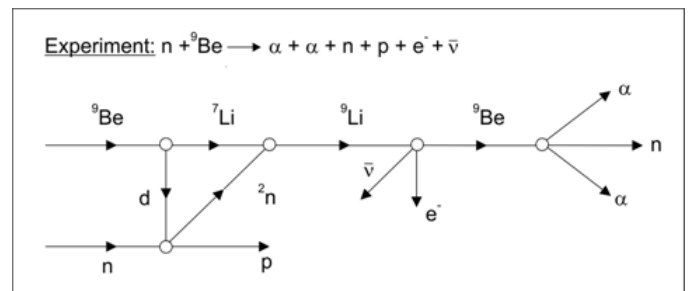


Fig. 4: Incoming neutron interacting with d in  $^9\text{Be}$  nucleus leading to  $^7\text{Li} + ^2n$  interaction and sequence of decays as indicated.

### III. $^{10}\text{B}(\text{n},2\text{n})^9\text{B}$ REACTION

Since the primordial  $^7\text{Li}$  is mainly produced by  $\beta$ -decay of  $^7\text{Be}$  ( $t_{1/2}=53.2$  days) the abundance of  $^7\text{Li}$  is essentially determined by the production and destruction of  $^7\text{Be}$ . The neutron induced reactions can also play a role in the destruction of  $^7\text{Be}$ , in particular the  $^7\text{Be}(\text{n},\alpha)^4\text{He}$  reaction in the energy range of interest for BBN, in particular between 20 and 100 keV. Recent activity in solving the "lithium problem" in Big bang nucleosynthesis has focused on the role that putative resonances may play in resonance-enhanced destruction of  $^7\text{Li}$ . Particular attention has been paid to the reactions involving  $^9\text{B}$  compound nuclear system  $\text{d}+^7\text{Be}\rightarrow^9\text{B}$ .

The concept of mirror nuclei is well established and mirror pairs like  $^7\text{Li}-^7\text{Be}$ ,  $^{13}\text{C}-^{13}\text{N}$ ,  $^{15}\text{N}-^{15}\text{O}$ ,  $^{17}\text{O}-^{17}\text{F}$  and  $^{19}\text{F}-^{19}\text{Ne}$  are known to have nearly identical energy level schemes. The properties of the mass-9 system, in which the  $^9\text{B}$  partner is particle unbound, even in the ground state, have been difficult to determine; the ground state is unbound to breakup into  $\text{p}+^8\text{Be}$  by 186 keV. There has been a large theoretical and experimental effort directed towards predicting and observing the low-lying states of  $^9\text{B}$ , especially the first excited  $1/2^+$  state (see Table I).

The unbound  $1/2^+$  state at 1.68 MeV in the mirror  $^9\text{Be}$  has been known for many years and yet the existence and

TABLE I  
EXPERIMENTAL DATA AND THEORETICAL CALCULATIONS OF 1<sup>ST</sup> EXCITED STATE IN  $^9\text{B}$

Reference	Reaction	First excited state in $^9\text{B}$	
		$E_x$ (MeV)	$\Gamma$ (MeV)
Marion and Levin	$^9\text{Be}(\text{p},\text{n})^9\text{B}$	1.4	1
Saji (1960)	$^9\text{Be}(\text{p},\text{n})^9\text{B}$	1.4	1
Spencer, Floyd and Young (1960)	$^{10}\text{B}(^3\text{He},\alpha)^9\text{B}$	Did not find	Did not find
Symons and Treacy (1962)	$^{12}\text{C}(\text{p},\alpha)^9\text{B}$	$1.7\pm 0.2$	1
Bauer, Anderson and Wong (1964)	$^9\text{Be}(\text{p},\text{n})^9\text{B}$	Did not find	Did not find
Teranishi and Furubayashi (1964)	$^9\text{Be}(\text{p},\text{n})^9\text{B}$	1.7	-
Farrow and Hay (1964)	$^{10}\text{Be}(\text{p},\text{d})^9\text{B}$	Did not find	Did not find
Islam and Tracy (1965)	$^{12}\text{C}(\text{p},\alpha)^9\text{B}$	$1.50\pm 0.05$	broad
Slobodrian et al. (1967)	$^9\text{Be}(\text{p},\text{n})^9\text{B}$	1.4	-
Kroepfl and Browne (1967)	$^9\text{Be}(^3\text{He},\text{t})^9\text{B}$	1.5	0.7
Anderson et al. (1970)	$^9\text{Be}(\text{p},\text{n})^9\text{B}$	1.4	0.0
Gul et al. (1970)	$^7\text{Li}(^3\text{He},\text{n})^9\text{B}$	Did not find	Did not find
Chou et al. (1978)	$^9\text{Be}(\text{p},\text{n})^9\text{B}$	Did not find	Did not find
Byrd et al. (1983)	$^9\text{Be}(\text{p},\text{n})^9\text{B}$	Did not find	Did not find
Sherr and Bertsch	calculation	0.9	1.4
Kadija et al. (1987)	$^9\text{Be}(^3\text{He},\text{t})^9\text{B}$	$1.16\pm 0.5$	$1.0\pm 0.2$
Burlein et al. (1988)	$^9\text{Be}(^6\text{Li},^6\text{He})^9\text{B}$	$1.32\pm 0.08$	$0.86\pm 0.26$
Arena et al. (1988)	$^{10}\text{B}(^3\text{He},\alpha)^9\text{B}$	$1.8\pm 0.2$	$0.9\pm 0.3$
Catford et al. (1992)	$^9\text{Be}(^6\text{Li},^6\text{He})^9\text{B}$	Did not find	Did not find
Efros and Bang (1999)	calculation	1.1	1.5
Akimune et al. (2001)	$^{10}\text{B}(^3\text{He},\alpha)^9\text{B}$	$1.8\pm 0.22$	$0.6\pm 0.3$
Scholl et al. (2011)	$^9\text{Be}(^3\text{He},\text{t})^9\text{B}$	$1.85\pm 0.13$	$0.7\pm 0.27$
Baldwin et al. (2012)	$^6\text{Li}(^6\text{Li},\text{t})^9\text{B}$	0.8-1.0	1.5
Karki (2013)	$^9\text{Be}(\text{p},\text{n})^9\text{B}$	Did not find	Did not find
Fortune and Sherr (2013)	$^9\text{Be}(^6\text{Li},^6\text{He})^9\text{B}$	$1.27(1.31)$	1.38

properties of the state in  $^9\text{B}$  are not clear. The state is hard to define because it is difficult to excite and very broad. Furthermore, it exists amongst much more intensely populated peaks with large widths [1-2]. Different nuclear reactions like  $^9\text{Be}(^6\text{Li},^6\text{He})^9\text{B}$ ,  $^9\text{Be}(^3\text{He},\text{t})^9\text{B}$  etc., were used to investigate the first-excited  $1/2^+$  state of  $^9\text{B}$ , but nevertheless the  $1/2^+$  state remains elusive.

Table II shows the first few excitation levels of  $^9\text{B}$ . A very broad the first excited level at 1.5 MeV (?) lies between two intensive peaks at 0 MeV and 2.345 MeV.

TABLE II  
THE FIRST FEW EXCITED STATE IN  $^9\text{B}$

$E_{\text{level}}$ (keV)	$J^\pi$	$T_{1/2}$
0	$3/2^-$	0.54 keV
1500 ?		$\approx 1.2$ MeV
2345	$5/2^-$	81 keV
2751	$5/2^+$	614 keV

Our approach to the problem consists using the experimental setup sketched in Fig.5. The 14 MeV neutron beam is produced in the  $^3\text{H}(\text{d},\text{n})^4\text{He}$  nuclear reaction. The n-n coincidences from the  $^{10}\text{B}(\text{n},2\text{n})^9\text{B}$  reaction are measured by two neutron detectors placed outside the cone of 14 MeV tagged neutron beam. From the time-of-flight measurements (n-detector start,  $\alpha$ -detector stop) and known geometry one can deduce the neutron energies and calculate the  $^9\text{B}$  missing mass spectrum. This could lead to much more precise information about the low lying states of  $^9\text{B}$ .

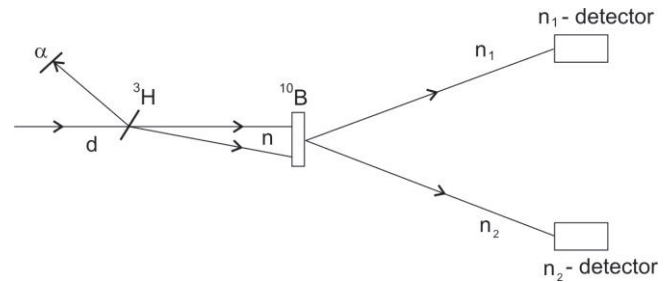


Fig.5: Sketch of experimental set-up for the measurement of  $^{10}\text{B}(\text{n},2\text{n})^9\text{B}$  reaction.

#### A. Experimental set-up

The used experimental set-up is shown on Fig. 6. Two plastic scintillator 10cmx10cmx10 cm were used as neutron detectors, equipped with adequate photomultiplier tubes (PMT). API120 neutron generator (NG) produced by ThermoFisher was used as a neutron source. NG is equipped with the YAP:Ce scintillator which serves as an alpha detector. YAP:Ce is connected to the Hamamatsu R1450 PMT. Boron target was boron carbide, CB4, 106 g in mass, volume  $\Phi 55$  mm x 50 mm, in plastic bottle. NG was tilted for  $8^\circ$  so that tagged neutron cone axis goes along the thick dashed line. Boron target center of mass was placed 22.5 cm from the NG tritium target inside the NG. Distance between the boron target center and neutron detector face was 50 cm. Exact position of the tagged neutron cone axis was found by  $3''\times 3''$  Ne213 neutron detector which was put in front of NG at two different distances from the tritium target. Ne213 was moved horizontally and vertically. For each position tagged

neutrons were counted and normalized to the same number of emitted alpha particles. Point at which maximum occurred was taken as a point on tagged neutron cone axis. Neutron detectors were placed outside the tagged neutron cone. Neutron beam intensity was kept fixed during the measurements and was around  $5 \times 10^6$  n/s.

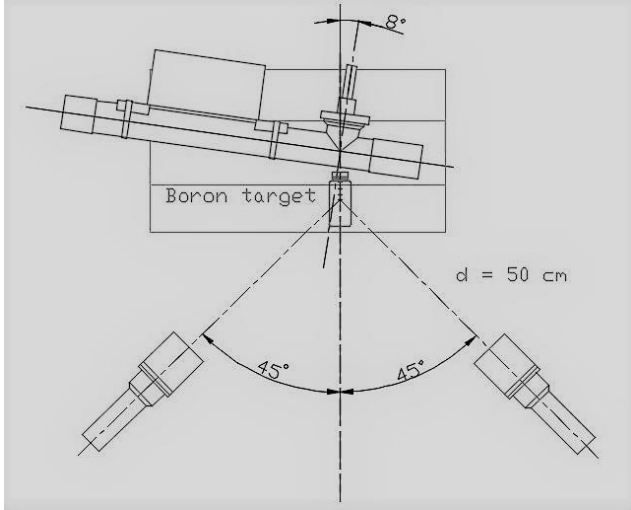


Fig. 6: Experimental set-up. As a neutron detectors two plastics scintillators 10 cm x 10 cm x 10 cm equipped with the available PMT (3"-12 stages 3M-P-E1-X-N) were used. Neutron detectors are called left and right from NG point of view.

Electronic set-up is shown on a Fig. 7. Fast output from the neutron detectors goes through Constant Fraction

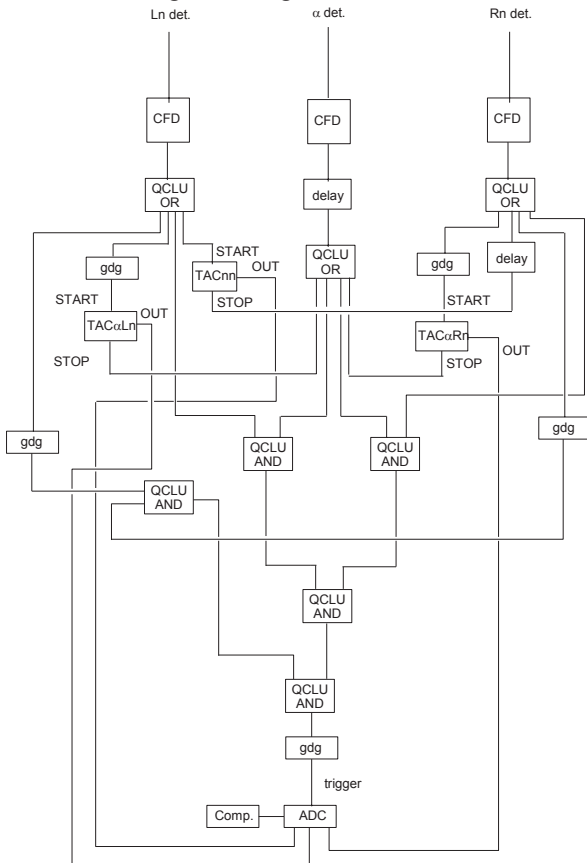


Fig. 7: Electronic set-up.

Discriminators (CFD) and splitting units to the START of the time-to-amplitude converters ( $TAC_{\alpha Ln}$ /  $TAC_{\alpha Rn}$ ), while STOP signal to the  $TAC_{\alpha Ln}$ /  $TAC_{\alpha Rn}$  comes from the alpha detector through associated CFD, splitting unit and delays. Left detector starts the  $TAC_{nn}$ , while right detector stops it. Outputs from all detectors were fed also to the Quad Coincidence Logic Units (QCLU) working in AND mode. There are three AND units for  $\alpha Ln$ ,  $\alpha Rn$  and  $nn$  coincidences, one AND unit for simultaneous  $\alpha Ln Rn$  coincidences and additional one for insurance. Output from the last AND unit serve as a trigger for Analog-to Digital Converter (ADC) which accepts outputs from all three TACs.

### B. Experimental results

In total, sixty hours of measurements were collected during the period of two weeks or ten days. Each day set of two measurements were done, one measurement lasting for three hours. Fig.8 shows the time spectra  $TAC_{\alpha Ln}$  (upper) and  $TAC_{\alpha Rn}$  (lower), while Fig. 9 shows the  $TAC_{nn}$  spectrum, respectively.

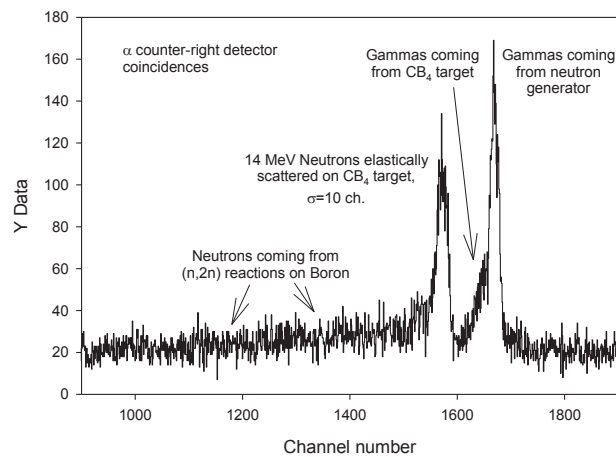
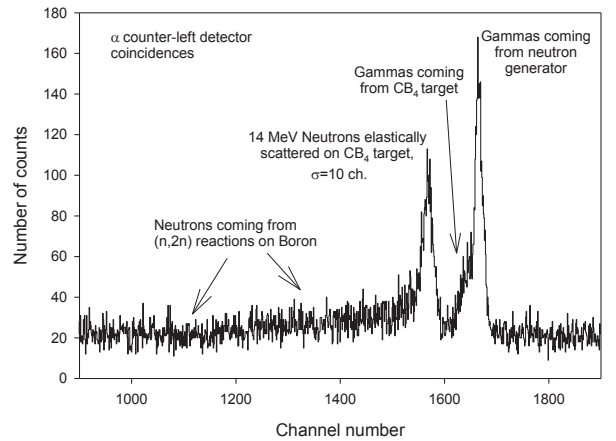


Fig.8: Coincidences between the alpha counter and neutron detectors (0.11 ns/ch). Scattered neutron peak has width  $FWHM = 2.34 \sigma = 23$  ch.

In both  $TAC_{\alpha Ln}$  and  $TAC_{\alpha Rn}$  spectra two peaks are clearly visible, one coming from the gamma rays induced in NG, and another one belonging to the 14 MeV neutrons elastically scattered on  $CB_4$  target (absent in target off configuration).



Time distance between this two peak correspond to the time difference between the time needed by gamma ray to travel the distance between the NG and neutron detector, and the time needed for 14 MeV neutron to travel the distance between the NG and the CB<sub>4</sub> target plus the time needed for 5.07 MeV neutron to travel the distance between the target and neutron detector. The second peak, the one belonging to the 5.07 MeV neutrons, is used for TACs calibration.

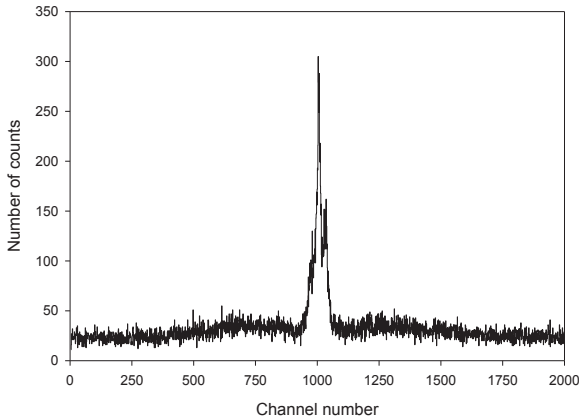


Fig. 9: Coincidences between two neutron detectors. Signal from the left detector is a START signal for time-to-amplitude converter.

Velocities,  $v_{Rn}$  and  $v_{Ln}$ , of the two outgoing neutrons are measured by t-o-f measurements using the associated alpha particle method and by knowing the position of the elastically scattered 14 MeV neutrons in t-o-f spectrum. Expression for excitation energy  $E$  in dependence on the output neutrons velocities  $v_{Rn}$ ,  $v_{Ln}$  is shown on Fig.10.

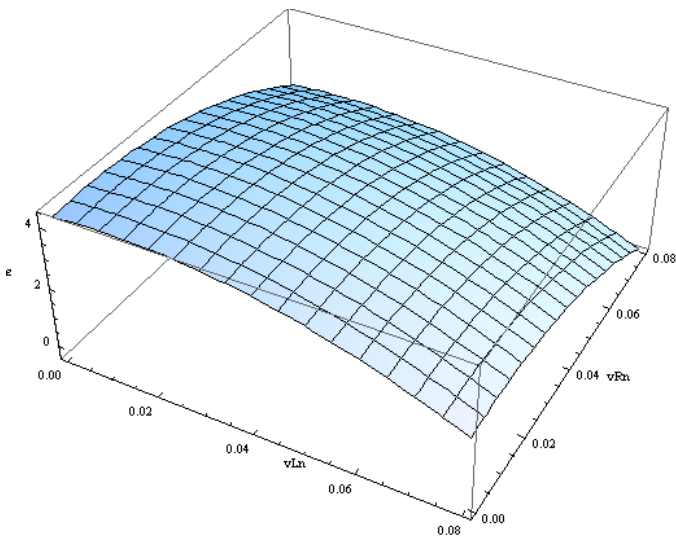


Fig. 10: Excitation energy of <sup>9</sup>B in dependence on neutron velocities.

The number of events for <sup>10</sup>B(n,2n)<sup>9</sup>B\* reaction was found by the following way:

By convention  $v_{Rn}$  was chosen to be the velocity of neutron coming to the right neutron detector. For a given  $ch_{Rn}$ ,  $v_{Rn}$  was calculated by following equation.

$$v_{Rn} = \frac{\frac{d}{s_0}}{a_{Rn}(-ch_{Rn} + ch_{oRn}) + \frac{d}{s_{0.7}}}, \quad v_{Ln} = \frac{\frac{d}{s_0}}{a_{Ln}(-ch_{Ln} + ch_{oLn}) + \frac{d}{s_{0.7}}}$$

The  $v_{Ln}$  velocity was calculated from corresponding channel number  $ch_{Ln}$ , see above.

The position of the above event in TAC<sub>nn</sub> spectrum is calculated by formula

$$ch_{nn} = ch_{nn0} + \frac{1}{30 a_{nn}} \left( \frac{d}{v_{Ln}} - \frac{d}{v_{Rn}} \right)$$

where  $ch_{nn0}$  correspond to simultaneously events recorded by neutron detectors. For  $ch_{nn} > ch_{nn0}$  signal came to the left detector was earlier in time than signal came to the right one. For  $ch_{nn} < ch_{nn0}$  the opposite is true. Only those events recorded in the channel windows  $(ch_{Rn} \pm 30)$  and  $(ch_{Ln} \pm 30)$  and  $(ch_{nn} \pm 30)$  are recorded as a true one.

Sixty channels windows were chosen as a compromise solution. In average around eight events were recorded during the 3 hours measurement which is not far from the theoretically estimated value. For narrower windows accepted events drops down, while broader windows includes more false events.

Fig.11 shows the excitation levels of <sup>9</sup>B found by procedure described above. Through the experimental data a curve was fitted described by eq. (6). Expected two peaks are found at 0 MeV (ground level) and 2 MeV (second excited level). The fitting parameters are peaks width (b and b1) and assumed flat background (y0). The second excited level has underestimated energy by 345 keV because the poor statistics and because the calibration problems described in the next chapter. Nevertheless, the peaks width is found to be  $b = (0.525 \pm 0.065)$  MeV for ground level and  $b1 = (0.37 \pm 0.04)$  MeV for second excited level, what should be compared with theoretical prediction 0.56 MeV and 0.4 MeV, respectively. Correlation factor was found to be  $R = 0.5318$ .

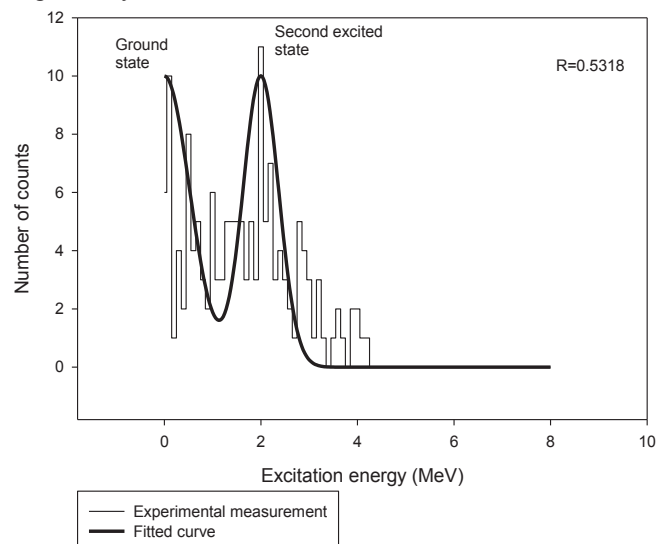


Fig. 11: Excitation levels of <sup>9</sup>B, fitted curve described below.

$$f(x) = y_0 + 10 e^{-0.5 \frac{(x)^2}{b^2}} + 10 e^{-0.5 \frac{(x-2)^2}{b1^2}}$$

Fitting parameters:  $b = (0.525 \pm 0.065)$  MeV  
 $b1 = (0.37 \pm 0.04)$  MeV  
 $y_0 = 2 \times 10^{-9} \pm 0.3$

Fig. 12 shows the same experimental results, but this time instead of two peaks, three peaks are fitted (centered at energies 0 MeV, x0 MeV and 2 MeV, eq. 7). Fitting parameters are position of the first excited level (x0), first excited level width (b2) and peak high (a). Since correlation factor is somewhat larger ( $R = 0.5707$ ), our data support existence of a peak between the ground level and second excited level, although data is insufficient for concluding statement.

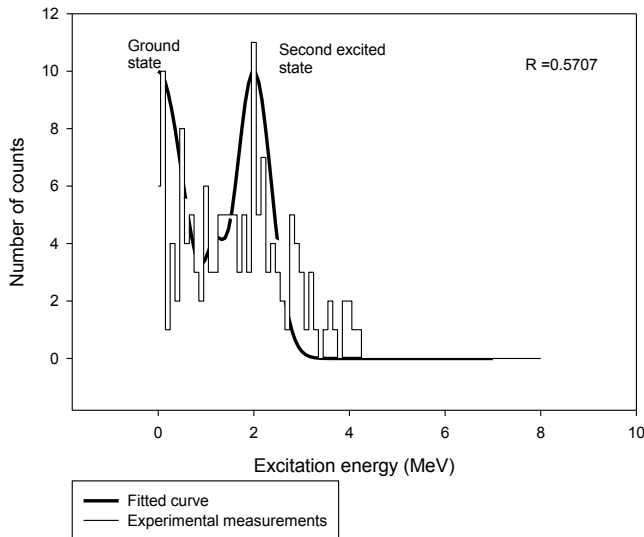


Fig. 12: Excitation level of  ${}^9\text{B}$ , fitted curve described below.  $R$  is correlation parameter.

$$f(x) = a e^{-0.5 \frac{(x-x_0)^2}{b^2}} + 10 e^{-0.5 \frac{(x)^2}{0.525^2}} + 10 e^{-0.5 \frac{(x-2)^2}{0.37^2}}$$

Fitting parameters:  $b_2 = 0.2 \pm 0.1$   
 $x_0 = 1.2 \pm 0.1$   
 $a = 2.5 \pm 1.4$

By calculating the area under the curve (7) and comparing it with the areas under the fitted curves on fig. 12, it is possible to roughly estimate the cross section for  ${}^{10}\text{B}(n,2n){}^9\text{B}^*$  nuclear reaction and particularly, cross section for excitation to first excitation level. Total cross section was found to be  $\sigma \sim 10$  mb which should be compared with 26 mb from [www.nndc.bnl.gov](http://www.nndc.bnl.gov). It should be noted that our rough estimation ignore the neutron detector efficiency dependence on neutron/gamma energy and all neutrons/gammas not detected because its signals did not pass the CFD. Total cross section for excitation to 1.2 MeV (first excitation level) is found to be 0.7 mb.

#### IV. CONCLUSION

According to the results presented above we can conclude that it is possible to check for the existence of the first excitation level of  ${}^9\text{B}$  nuclei and to measure its energy as well as width, by using the  ${}^{10}\text{B}(n,2n){}^9\text{B}^*$  nuclear reaction. In order to do it properly distance between the CB4 target and neutron detectors should be at least one meter. To compensate the lack of solid angle, pure  ${}^{10}\text{B}$  isotope should be used as well as several pairs of 10 cm x 10 cm x 10 cm neutron detectors (or equivalent). TACs calibration should be done at least once per day (every six hours) in full TACs range. Our preliminary

results support the existence of the first excitation level at  $(1.2 \pm 0.1)$  MeV, and with  $\text{FWHM} = 2.35 (0.2 \pm 0.1) \text{ MeV} = (0.47 \pm 0.235) \text{ MeV}$  which is in agreement with some of data presented in table 1. Total cross section for excitation to 1.2 MeV (first excitation level) is estimated to be 0.7 mb.

#### ACKNOWLEDGMENT

We would like to thank to dr. K. Nad from Rudjer Boskovic Institute, Zagreb, Croatia and mr. J. Jaegly from CEA Cadarache, France for assisting in  ${}^{10}\text{B}(n,2n){}^9\text{B}$  reaction data taking process.

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