POSSIBLE LENR OBSERVATION DUE TO DINEUTRON FORMATION AS A PRODUCT OF THE ^{159}Tb$(n, 2n)^{158}$Tb NUCLEAR REACTION*

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Possibility of low-energy nuclear reactions (LENR) occurrence is considered due to dineutron formation in the outgoing channel of a neutron-induced nuclear reaction on ^{159}Tb. In the instrumental gamma-ray spectra of Tb sample irradiated with 6.85 MeV neutrons, we observed the surplus-induced activity of ^{160}Tb/^{160}Dy in addition to ^{160}Tb activity, originated from the ^{159}Tb$(n,\gamma)^{160}$Tb nuclear reaction. We assumed that accumulation of ^{160}Tb/^{160}Dy activity results from strong processes via nuclear reactions at room temperature. The cross section for ^{158}Tb$(d,\gamma)^{160}$Dy is estimated as 44.5 b.

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1. Introduction

This work is a continuation of series of papers dedicated to research a formation of a bound dineutron in the outgoing channel of a neutron-induced nuclear reaction on ^{159}Tb [1–3]. The bound dineutron is an unstable nucleus, therefore, it might decay via the beta-minus mode, creating three particles instead of one. Possible interaction of an electron with a residual nucleus was considered in [3], in which we conjectured about probable much faster reduction of number of ^{158g}Tb nuclei, and not only due to decay with 180 years half-life into ^{158}Gd (EC/β^+ mode, 83.4%) or into ^{158}Dy (β^- mode, 16.6%) [4]. This hypothesis is now under research and some experimental results will be reported soon. The electron antineutrino is not a likely candidate to observe any results of its interaction with ^{158}Tb nuclei. Then

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the third particle, namely the deuteron, could be an interesting neighbor of ^{158}Tb nucleus provided this configuration of the two nuclei, located at few fm distance, for which the strong interaction prevails over the Coulomb repulsion, may exist for a long enough time. As it is well-known from the beta-decay theory, if an electron and an electron antineutrino are emitted with their intrinsic spins being antiparallel (singlet state), the nuclear spin change ΔI equals zero, and this process follows the Fermi selection rule. Then the deuteron must be formed in an unbound by 0.066 MeV s-state, and may be kept at one of the single-particle levels, predicted by Migdal [5] for the dineutron. Should this configuration exist, then it would be possible to keep a bound deuteron in the s-state in the potential well of ^{158}Tb or ^{158}Gd for a long time. If electron and antineutrino spins are parallel (triplet state is realized), then $\Delta I = -1, 0, +1$ with forbidden $0 \to 0$ transitions, and the Gamov–Teller selection rule must be applied. In this case, the deuteron will be formed in a bound triplet state and, most likely, a configuration, consisting of ^{158}Tb/^{158}Gd and the deuteron, will vanish shortly. Now, it would be reasonable to ask: what about the further destiny of the deuteron being kept in the s-state in the potential well of ^{158}Tb/^{158}Gd? Answering this question we could suggest two options: (1) no interaction between both nuclei will take place and then we must observe the induced activity of ^{160}Tb [6] decaying into ^{160}Dy with 72.3 days half-life [4], or (2) the strong interaction between these two nuclei will occur and we might then observe additional induced activity, assigned to ^{160}Dy and accompanied by burnout of ^{158}Tb nuclei.

Therefore, the subject of our paper is to observe whether in the instrumental gamma-spectra some extra radioactivity could be detected and assigned to ^{160}Tb decay into ^{160}Dy or directly to ^{160}Dy formation due to the nuclear reaction between ^{158}Tb and the deuteron at room temperature conditions.

2. Measurements of Tb sample instrumental spectra

All measurements in this paper are considered for the same Tb sample, which was used to determine the $^{159}\mathrm{Tb}(n,\gamma)^{160}\mathrm{Tb}$ nuclear reaction cross section for 6.85 MeV incident neutrons [6]. Irradiations for this neutron energy at IRSN facility AMANDE, Cadarache, were completed on December 6, 2013. Then irradiated Tb sample of 28.89 g mass was measured several times. All the measurements are summarized in Table I. In the instrumental gamma spectrum due to ^{160}Tb decay into ^{160}Dy, two strong gamma peaks were observed with energies 298.58 keV (26.1%) and 879.38 keV (30.1%). We selected 879.38 keV peak for our consideration because of absence of any unexpected overlapping with other peaks, first of all, of the background origin.

Two CANBERRA spectrometers were utilized for gamma-spectra counting, namely HPGe detectors GC1212 at IRSN, Cadarache, France, and GC2020 at the Department of Nuclear Physics, Faculty of Physics, Taras Shevchenko National University of Kyiv (NUK), Ukraine. The first gamma spectrum was measured within first 9 hours after completion of Tb sample neutron irradiation, the last one — about 2.3 years later. In our background measurement during 420,043.12 s with GC2020 spectrometer in April 2016 just prior the very last counting, zero counts of peak area were detected within $875 \div 885$ keV energy region of interest.

TABLE I

Counting data for Tb sample. $T_{\rm cool}$ is cooling time before measurements; $T_{\rm count}$ refers to live/real counting time of Tb sample; $S_{\rm p}$ corresponds to 879.38 keV gamma-line peak area detected in a current instrumental spectrum; $\Delta S_{\rm p}$ — gamma-line peak area uncertainty.

No. of meas.	HPGe spectrometer/ location	$T_{\rm cools}$, days	Start date of meas.	$T_{\rm count}$,days live/real	$S_{\rm p}$, counts	$\Delta S_{\rm p}$, [%]	$T_{\rm cool}+$ $T_{\rm count}$, real, days
1.	GC1212/IRSN	0.23576	06 Dec 2013	0.142751/0.14288	518	4.6	0.37864
2.	GC2020/NUK	523.10524	13 May 2015	2.0627/2.0631	275	11.2	525.16834
3.	GC2020/NUK	625.29787	22 Aug 2015	5.7753/5.7767	303	13.4	631.07457
4.	GC2020/NUK	864.3324	18 Apr 2016	2.72438/2.7249	58	37.7	867.05730

3. Induced activities calculations

We consider the possibility to observe a result of fusion as extra ^{160}Dy prompt gammas detected directly or due to ^{160}Tb as a function of time from the following nuclear reactions: $^{158}{\rm Tb}(d,\gamma)^{160}{\rm Dy}$ or $^{158}{\rm Gd}(d,\gamma)^{160}{\rm Tb}$.

3.1. Accumulation of ^{160}Tb nuclei in Tb-irradiated sample

For all countings from Table I, the activity $A(t)$ was calculated for the 879.38 keV gamma line. This activity was assigned to the ending points of corresponding spectrum counting (last column in Table I). For comparison, we also calculated the reference values of ^{160}Tb activity $A^{\rm r}(t)$ by the following equation:

$$A^{\rm r}(t) = A_0 \times \exp\left[-\frac{\ln 2}{T_{1/2}t}\right] ,$$

where $T_{1/2}$ is as half-life of ^{160}Tb and A_0 was derived from the expression as follows:

$$A_0 = \ln 2/T_{1/2} \times \sigma_{n\gamma} \times \varphi \times N_{\rm Tb} \times T_{\rm irr} \,, \quad (1)$$

where $\sigma_{n\gamma}$ — cross section for the ^{159}Tb$(n,\gamma)^{160}$Tb nuclear reaction with incident neutrons of 6.85 MeV energy; φ — neutron flux density; $T_{\rm irr}$ — total time of Tb sample irradiations in neutron fields; $N_{\rm Tb}$ — number of Tb nuclei in terbium sample. All these data were taken from [6]. According to our calculations, $A_0 = 19.7 \pm 7.7$ Bq. The results of $A_i(t)$ and $A_i^{\rm r}(t)$ calculations along with their ratios (R_i) and corresponding uncertainties (ΔR_i) are given in Table II.

TABLE II

Results of ^{160}Tb-induced activity measurements and calculations. Last two columns present net activities $A_{{\rm n},i}(t)$ and their uncertainties $\Delta A_{{\rm n},i}(t)$.

i	$A_i(t)$, [Bq], $i = 1 \div 4$	$\Delta A_i(t)$, [Bq]	$A_i^{\rm r}(t)$, [Bq]	$\Delta A_i^{\rm r}(t)$, [Bq]	$R_i = A_i(t)/A_i^{\rm r}(t)$	ΔR_i	$A_{{\rm n},i}(t) = A_i(t) - A_i^{\rm r}(t)$, [Bq]	$\Delta A_{{\rm n},i}(t)$, [Bq]
1.	19.4	1.1	19.7	7.7	0.99	0.39	0	0.076
2.	0.41	0.06	0.13	0.05	3.20	1.35	0.279	0.083
3.	0.16	0.03	0.05	0.02	3.48	1.48	0.112	0.033
4.	0.07	0.03	0.005	0.002	13.5	7.5	0.061	0.026

Then the first set of measured data was fitted with linear function as presented in Fig. 1. From the fit, we can derive an estimate of ^{160}Tb half-life from the following equation:

$$T_{1/2} = \frac{\ln 2}{0.00717} = 96.67^{+16}_{-12}\ \text{days}\,,$$

which is quite different from an expected value of ^{160}Tb half-life.

Then we calculated net values of the activities $A_{\rm n}(t)$, which must be assigned to additional activity generated in our sample (Table II) and fitted them with a parabola $A_{\rm n}(t) = a_1 \times t^2 + a_2 t + a_3$. We got the following results of approximation: $\chi^2 = 0.76$; $a_1 = -(1.1 \pm 0.5) \times 10^{-6}$; $a_2 = (9.7 \pm 4.6) \times 10^{-4}$; $a_3 = (0.0 \pm 0.1)$, and calculated the maximum of net activity as 0.28 ± 0.18 Bq, being reached within 440 ± 280 days from the Tb sample end of irradiation and dropping to about zero value of net activity at ~ 3 years since irradiation completion date.

3.2. Fusion parameter estimations

Let us assume that no interaction between an electron and ^{158}Tb takes place to convert the latter into ^{158}Gd [3], and ^{158}Gd amount of nuclei within 2 years is negligible due to ^{158g}Tb decay. Then due to a nuclear interaction at a few fm distance between the deuteron and ^{158}Tb, only the reaction of

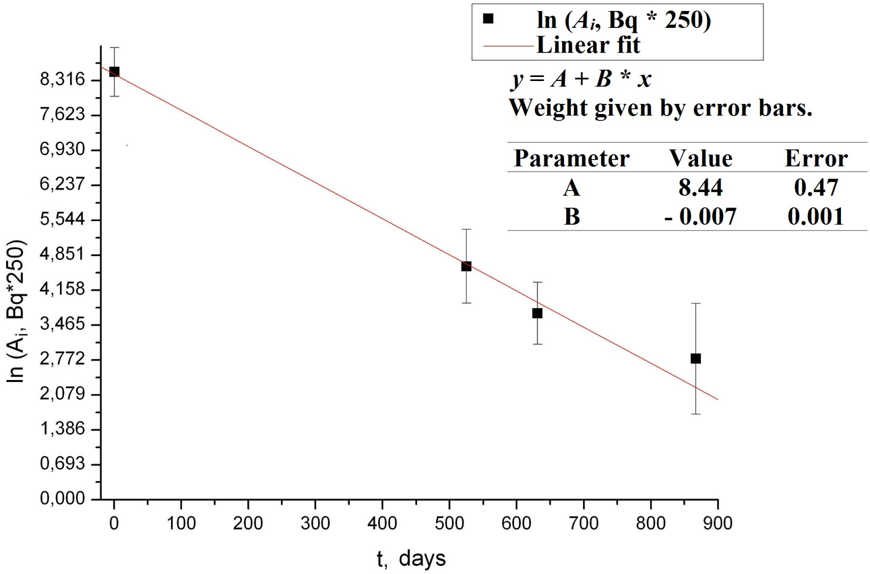

Fig. 1. Results of the activity $A_i(t)$ measurements together with a fit results.

fusion may take place. Now, we can write the following expression describing the dependence of ^{160}Dy activity *versus* time:

$$A_{\rm n}(t) = r(t) + A_{\rm cosmic} = A_{\rm fus}(t) + A_{\rm cosmic}\,,$$

where r is a reaction rate for the ^{158}Tb(d,γ) fusion reaction with accumulation of ^{160}Dy; $A_{\rm cosmic}$ — the activity of Tb sample due to cosmogenic activation with thermal neutrons. The fusion activity thus can be presented in the following manner: $A_{\rm fus}(t) = r(t)$. Because our Tb sample may be additionally exposed with neutron irradiation of cosmogenic origin, we made an assessment of the ^{160}Tb-induced activity due to thermal neutron absorption with application of the following expression: $A_{\rm cosmic} = N_{\rm Tb} \times \sigma_{\rm th} \times \varphi_{\rm th}$, where $N_{\rm Tb}$ is defined above; $\sigma_{\rm th}$ — cross section for thermal neutron absorption by ^{159}Tb nuclei (according to [7] $\sigma_{\rm th} = 23.9 \pm 0.2$ b). Thermal neutrons flux for our latitude was precisely determined in [8]: $\varphi_{\rm th} = 2.53 \times 10^{-4} ({\rm cm}^2\,{\rm s})^{-1}$. Then $A_{\rm cosmic} = 6.5 \times 10^{-4}$ Bq. We also considered some additional contributions to ^{160}Tb/^{160}Dy activity due to contamination of our Tb sample with Dy (20 ppm) and Gd (39 ppm) isotopes by the following nuclear reactions with fast neutrons and protons:

— ^{161}Dy$(n,2n)^{160}$Dy (18.91% of ^{161}Dy in natural abundance);
— ^{160}Dy$(n,p)^{160}$Tb (2.34% of ^{160}Dy in natural abundance);
— ^{160}Gd$(p,n)^{160}$Tb (28.89% of ^{160}Gd in natural abundance).

These estimates resulted in 8–10 orders of magnitude smaller reaction rate or induced activity values of what was observed in our measurements, therefore, they were neglected.

Let us make an estimate of ^{160}Dy activity due to low-energy fusion. In Table II, from pre-last column data, we can calculate the activity A_{fus} of ^{160}Dy due to the fusion between ^{158}Tb and d: $r_i = A_{\mathrm{fus},i}(t) = A_{\mathrm{n},i}(t) - A_{\mathrm{cosmic}}$, giving us the following numerical values:

$$\begin{aligned} A_{\mathrm{fus},2}\ (t = 525.168\ \text{days}) &= 0.279 \pm 0.083\ \text{Bq}\,, \\ A_{\mathrm{fus},3}\ (t = 631.075\ \text{days}) &= 0.112 \pm 0.033\ \text{Bq}\,, \\ A_{\mathrm{fus},4}\ (t = 867.057\ \text{days}) &= 0.06 \pm 0.03\ \text{Bq}\,. \end{aligned}$$

Our Tb sample was kept under room temperature conditions, therefore, the projectile (d) and target nuclei (^{158}Tb) are in thermal equilibrium and must follow a Maxwell–Boltzmann relative velocity distribution

$$\Phi(v) = 4\pi \times \left(\frac{\mu_{\mathrm{Tb}-d}}{2\pi \times k \times T_{\mathrm{R}}}\right)^{3/2} \times v^2 \times \exp\left(-\frac{\mu_{\mathrm{Tb}-d} \times v^2}{2k \times T_{\mathrm{R}}}\right)\,,$$

where $\mu_{\mathrm{Tb}-d}$ is the reduced mass: $\mu_{\mathrm{Tb}-d} = (m_d \times M_{\mathrm{Tb}})/(m_d + M_{\mathrm{Tb}})$; k is the Boltzmann constant and T_{R} is a room temperature. Then a reaction rate r for fusion is as follows:

$$r = N_{\mathrm{Tb}} \times N_d/V \times \int_0^\infty \Phi(v) \times \sigma_{\mathrm{fus}}(v)dv = N_{\mathrm{Tb}} \times N_d \times \langle\sigma_{\mathrm{fus}} \times v_{\mathrm{th}}\rangle/V\,,$$

where $N_{\mathrm{Tb}} = N_d$ are numbers of Tb and d — paired nuclei in our sample; V — volume of Tb sample; $\langle\sigma_{\mathrm{fus}}\rangle$ and $\langle v_{\mathrm{th}}\rangle$ — averaged fusion cross section and thermal velocity, accordingly. For calculations of $N_{\mathrm{Tb}} = N_d$, we used data from [1, 2] and the expression analogical to (1). We got an initial amount of paired up ^{158}Tb and d nuclei $N_{\mathrm{Tb},0} \approx 2.2 \times 10^8$. Provided some nuclei of ^{158}Tb were disintegrated/converted during $\sim$ 500 days since the irradiation date, we took for our estimates $N_{\mathrm{Tb},1} = 2.0 \times 10^8$ nuclei for $A_{\mathrm{fus},1}$ calculation. Numbers of nuclei for measurements 3 and 4 decreased as square root of ratios between $A_{\mathrm{fus},3}/A_{\mathrm{fus},2}$ and $A_{\mathrm{fus},4}/A_{\mathrm{fus},2}$, accordingly.

Then we calculated an averaged relative thermal velocity with the following parameters: $T_{\mathrm{R}} = 293.6$ K; $\mu_{\mathrm{Tb}-d} = 3.3 \times 10^{-27}$ kg; $\langle v_{\mathrm{th}}\rangle = \sqrt{\frac{2k\times T_{\mathrm{R}}}{\mu_{\mathrm{Tb}-d}}} = 1.567$ m/s $= 1.567 \times 10^5$ cm/s.

Thus, knowing $A_{\mathrm{fus},i}$, $N_{\mathrm{Tb},i}$ and $N_{d,i}$, and assuming that $\langle\sigma_{\mathrm{fus}} \times v_{\mathrm{th}}\rangle$ is constant for all 3 measurements, we can make an estimate $\sim$ 44.5 b as an expected cross section for the fusion reaction $^{158}\mathrm{Tb} + d \to {}^{160}\mathrm{Dy}$.

4. Conclusion

In this work, we presented results of our observations dealing with fusion reactions between ^{158}Tb and the deuteron at room temperature conditions. The basis for this observation was discovered in countings of Tb sample and in identification of the significant surplus between accumulated and expected activity of ^{160}Tb. This effect is based on a configuration of reaction products, including originally the ^{158}Tb nucleus with a bound dineutron located within the potential well of this heavy nucleus at distances up to 2 fm from its surface. After dineutron decay, such paired nuclei, ^{158}Tb and the deuteron, might have been fused to increase the number of ^{160}Dy nuclei in time what is equivalent to "enhancing" half-life of ^{160}Tb. For fusion processes we considered our cross-section estimate to be ~ 44.5 b.

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