A new type nuclear reaction considering observation of a bound dineutron in the outgoing channel

Prof. I.M. Kadenko
Head, Department of Nuclear Physics
Faculty of Physics, Taras Shevchenko National University of Kyiv

French-Ukrainian Workshop, 26-28 September, LAL, France, 2018
Outline

- Ukraine-France cooperation: INSC of Ukraine - IRSN
- Experimental results
- Hypothesis on a bound dineutron existence
- Theoretical prerequisites
- Last years researches
- Latest results
- Conclusions
Ukraine-France cooperation: INSCU-IRSN

Pattern source of mono energetic neutrons for energy range 2 keV - 20 MeV
Ukraine-France cooperation: INSCU-IRSN

- AMANDE – neutron generation facility for neutron irradiation: Cadarache, IRSN, France
- Outstanding conditions for \((n,\gamma)\) cross-section measurements
- Utilization of \((D,D)\) reaction with fixed target to irradiate Tb samples with 3 - 7 MeV neutrons

Target

Detector

Experimental Room

(20 x 20 x 16 m³)

Incident Beam

Bras mobiles

French-Ukrainian Workshop, 26-28 September, LAL, France, 2018
Published: N. Dzysiuk, I. Kadenko, V. Gressier, A. J. Koning. Cross section measurement of the $^{159}$Tb(n,γ)$^{160}$Tb nuclear reaction. Nucl. Phys. A 936 (2015), pp. 6-16

French-Ukrainian Workshop, 26-28 September, LAL, France, 2018
Cross section measurement of the $^{159}\text{Tb}(n, \gamma)\text{Tb}^{160}$ nuclear reaction

N. Dzysiuk, I. Kadenko, V. Gressier, A.J. Koning

Abstract

The cross section of the $^{159}\text{Tb}(n, \gamma)\text{Tb}^{160}$ reaction was measured in four mono-energetic neutron fields of energy 3.7, 4.3, 5.4, and 6.85 MeV, respectively, with the activation technique applied to metal discs of natural composition. To ensure an acceptable precision of the results all major sources of uncertainties were taken into account. Calculations of detector efficiency, incident neutron spectrum and correction factors were performed with the Monte Carlo code (MCNPX), whereas theoretical excitation functions were calculated with the TALYS-1.2 code and compared to the experimental cross section values. This paper presents both measurements and calculations leading to the cross section values.

French-Ukrainian Workshop, 26-28 September, LAL, France, 2018
Ukraine-France cooperation: INSCU-IRSN

Table 3
Measured and calculated cross sections for the $^{150}$Tb$(n, \gamma)^{160}$Tb.

<table>
<thead>
<tr>
<th>Neutron energy (Δ) (MeV)</th>
<th>Cross section (Δ) (mb)</th>
<th>TALYS</th>
<th>Prior data (mb), the energy of incident neutron is in parenthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6700 (0.0008)</td>
<td>30.8 (2.2)</td>
<td>29.54</td>
<td>49.2 ± 7.0 (3 MeV) [19]</td>
</tr>
<tr>
<td>4.2800 (0.0010)</td>
<td>21.78 (1.80)</td>
<td>22.38</td>
<td>31.3 ± 3.2 (3.5 MeV) [18]</td>
</tr>
<tr>
<td>5.3900 (0.0015)</td>
<td>6.13 (0.55)</td>
<td>8.20</td>
<td>23.5 ± 2.6 (4.0 MeV) [18]</td>
</tr>
<tr>
<td>6.850 (0.002)</td>
<td>2.14 (0.83)</td>
<td>2.2</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. Excitation function for the $^{150}$Tb$(n, \gamma)^{160}$Tb nuclear reaction. The data are given with the statistical error bars only.
Experimental results

- In one plus year after irradiation complete: counting of Tb big sample with HPGe spectrometer (GC 2019 detector)
Experimental results – background
Experimental results – Tb sample measurements

French-Ukrainian Workshop, 26-28 September, LAL, France, 2018
Experimental results

- Peak like structure is fixed for 944.2 keV energy of gamma-rays, possible candidates:
  - $^{48}$V: $T_{1/2} = 15.97$ days, stronger line of 983.5 keV is missing;
  - $^{156}$Eu: $T_{1/2} = 15.19$ days, stronger line of 811.8 keV is missing;
  - $^{158}$gTb: $T_{1/2} = 180$ years, reaction product from $^{158}$Dy $(n,p)$; $^{158}$Dy isotope content is 0.1% in natural Dy abundance; experimental data in EXFOR are absent; TENDL-2017 evaluation $\Rightarrow$ mass of Tb sample should be inadequate;
  - $^{158}$gTb from the $^{159}$Tb $(n,2n)$ nuclear reaction.

- Low cps in gamma peak - $(1.4\div1.8)\cdot10^{-4}$ 1/s:
  - background: $17 \pm 324.56\%$ for $1,730,000.93$ seconds measurement;
  - peak area: $74 \pm 36.19\%$ for $408,165.48$ seconds measurement.
Experimental results

- 1.5 years of sample and background measurements;
- Very good results repeatability relating to the:
  - presence of 944.2 keV peak in instrumental gamma-spectra with the sample;
  - absence of 944.2 keV peak in background spectra.
- Appearance of peak-like structure with 944.2 keV energy for measurements from 400,000.00 s and up to 1,150,000.00 s.
- Value of neutron energy in Tb sample – 6.85 MeV.
- Gamma line with the biggest yield is fixed for decay of $^{158g}\text{Tb}$.
- **BUT:** reaction threshold for $^{159}\text{Tb}(n,2n)$: 8.18 MeV or 1.3 MeV above the energy of neutrons in Tb sample!!!
Experimental results

Fig. 2: ROI with 944.2 keV \((I_\gamma = 0.439)\) peak of \(^{158}\text{Gd}\).

- Experimental set up to execute the measurements

*Taras Shevchenko National University of Kyiv*

*French-Ukrainian Workshop, 26-28 September, LAL, France, 2018*
Hypothesis on a bound dineutron existence

- Analogously to the threshold of \((n,d)\) reaction, which is 2.225 MeV lower of \((n,np)\) reaction threshold due to the binding energy of the deuteron

- Interval estimate of the binding energy for the dineutron: 
  \[ 1.3 \text{ MeV} < B_{dn} < 2.8 \text{ MeV} \]

- Published in: Igor Kadenko. Possible observation of the dineutron in the \(^{159}\text{Tb}(n, ^2n)^{158}\text{Tb}\) nuclear reaction. EPL, 114 (2016) 42001
Hypothesis on a bound dineutron existence

Possible observation of the dineutron in the $^{159}$Tb ($n,^2n$) $^{158}$Tb nuclear reaction

IGOR KADENKO

International Nuclear Safety Center of Ukraine; Department of Nuclear Physics
Taras Shevchenko National University of Kyiv – St. Volodymyrska 60, 01601, Kyiv, Ukraine

PACS 21.10. -k - Properties of nuclei, nuclear energy levels
PACS 21.10. Dr' - Binding energies and masses
PACS 27.10. +h - $A \leq 5$

Abstract – Experimental observation of the $^{159}$Tb($n,^2n$) reaction product was performed with application of the activation technique. Tb specimen of natural composition was irradiated with $(d,d)$ neutrons of 5.39 and 7 MeV energies. Instrumental spectra of Tb specimen were measured with HPGe spectrometer. An unexpected 944.2 keV $\gamma$-ray peak was observed. Other $\gamma$-ray lines due to $^{158}$Tb decay were identified as well. A bonded dineutron emission with the binding energy ($B_{nn}$) within limits $1.3$ MeV $< B_{nn} < 2.8$ MeV is evidenced by the energy of incident neutrons and by $^{158}$Tb presence in output channel. The specific nuclear properties of $^{158}$Tb as deformed nucleus were discussed to explain a bonded dineutron formation based on theoretical assumptions and calculations, using standard parameters for this mass region.

Introduction. The purpose of this Letter is to point out that the dineutron may exist as a bonded particle in the vicinity of the heavy nucleus in output channel of nuclear reaction. The field of nuclear physics knows long history of searching for dineutron bound states. Numerous attempts had been made to channels with expected low activities in output channel, the neutron activation technique is among the most suited ones. In order to understand the behaviour of new neutron induced reactions on Tb, the irradiations of specimen were made with incident neutrons at the AMANDE facility (the Institute for...
Hypothesis on a bound dineutron existence
Hypothesis on a bound dineutron existence (in cooperation with ATOMKI, Hungary: Dr. A. Fenyvesi, Mr. B. Biró)
Hypothesis on a bound dineutron existence

Possible Results of a New Reaction

M. Y. Colby and R. N. Little, Jr.
Department of Physics, University of Texas, Austin, Texas
August 8, 1946

We would like to point out some interesting possibilities in a new reaction. With the availability of tritium in fairly large quantities, the reaction of deuterium on tritium should be possible. There are several possible ways for the reaction to go. If the following occurs:

\[ {^1}H^3 + {^1}H^2 \rightarrow {^2}He^4 + 0n^1, \]

the reaction may be a source of high energy neutrons all of the same energy. From rough mass difference values the expected Q value would be about 17.6 Mev.

Published in: M. Y. Colby and R. N. Little. Phys. Rev. 70, 437 (1946)
Hypothesis on a bound dineutron existence

A second possible reaction is

\[ ^1H^3 + ^1H^2 \rightarrow ^2He^3 + 2^n, \]

with either the creation of three particles with a continuous neutron energy range up to a maximum or the possible emission of a “di-neutron,” \( ^0n^2 \). The existence of the di-neutron has been discussed but no evidence for their existence has been found. If they do exist, then important knowledge concerning the binding energies can be obtained from this reaction.

Published in: M. Y. Colby and R. N. Little. Phys. Rev. 70, 437 (1946)
Theoretical prerequisites

- Hundreds of publications:
  - The dineutron was the subject to search since 1946 including reactions with light nuclei of Borromean type (\(^6\text{He}, \; ^8\text{He}, \; ^7\text{Li}, \; ^{11}\text{Li}, \; ^{11}\text{Be}, \; ^{14}\text{Be}, \; ^{17}\text{B}, \; ^{19}\text{B}, \; ^{22}\text{C}\)) as well in reactions on and in fission of heavy nuclei (A≥209)
  - Up-to-date research direction: dineutron correlations: “The di-neutron correlation is a spatial correlation with which two valence neutrons are located at similar position inside a nucleus”
  - Different estimates of dineutron binding energies: from dozens keV up to 3 MeV
Theoretical prerequisites


- “In a related development, Migdal (1972) has proved that a potential containing two interacting unbound particles allows many bound states if the particles are sufficiently close to the threshold. When this principle is applied to two neutrons loosely bound to a nucleus, the resulting states can be interpreted as dineutrons at the nuclear surface” (A.S. Jensen et. al., REVIEWS OF MODERN PHYSICS, Vol. 76, January 2004)
Actually in this paper of A.B. Migdal:

- “It is shown that under certain circumstances there appears an additional bound state, which does not exist in perturbation theory. Possible applications to nuclear theory are discussed, in particular the possible existence of a dineutron near the surface of some nuclei.”

- “It is shown that in the case when the potential well is produced by a nucleus, there appears a state which has to be interpreted as a bound state of two neutrons near the nuclear surface.”
Theoretical prerequisites

- The energy range of additional states to bind the two neutrons in the dineutron according to Migdal:
  \[0 \div 0.4\text{ MeV}\]

- The mass range:
  “The problem, solved in the present paper is a special case of the three-body problem, when one of the three particles has a considerably larger mass than the other two, so that the action of the heavier particle on the lighter ones can be considered as an external field.”

- Is this condition met for \( ^6\text{He}, ^8\text{He}, ^7\text{Li} \ldots \) ???
Theoretical prerequisites

- "The physical nature of this additional level consists in the following. The particles form a bound state even in the case when their attraction is insufficient for the formation of a bound state outside the well."

- The dependence of the binding energy $\varepsilon$ of two particles ($\varepsilon = \lambda^2$) on the binding energy $\varepsilon_0$ of the one-particle level in the well ($\varepsilon_0 = \lambda_0^2/2$). For $\lambda_c > \lambda_0 > 0$ there are two branches for the two-particle energy.
Last years research

  
  - The well-known stack-foil technique was employed for measurements of the $^{159}$Tb $(p,3n)$ $^{157}$Dy reaction cross-sections within 14 - 66 MeV with 66 MeV initial energy of proton beam
  
  - Cross-section: $\sigma_1 = 1.17 \pm 0.11$ mb for $E_{p_1} = 15.47 \pm 1.78$ MeV while the reaction threshold is: 17.14 MeV (only 0.11 MeV overlapping)
Last years research

  - The same stack-foil technique, reaction: $^{159}\text{Tb} (p, 3n) ^{157}\text{Dy}$, the proton energy range: 5.5 - 34 MeV for incident proton beam energy 34 MeV
  - Cross-section: $\sigma_2 = 90\pm10 \mu$b for $E_{p_2} = 14.86\pm0.85$ MeV (without any overlapping!!!).
  - The most likely explanation: a new nuclear reaction type and channel:
    $^{159}\text{Tb} (p, 2n+n) ^{157}\text{Dy}$

- Statistical significance of a dineutron detection: the condition \( S_p = S_b + 5 \Delta S_p \) is met for number of counts 153 and more in a gamma-peak due to \(^{157}\text{Dy}\) decay \((T_{1/2}=8.14\text{ hours}; E_\gamma=326.33\text{ keV}; k_\gamma=93\%\)

- Dineutron decay: \(^2n \rightarrow d + e^- + \bar{\nu}_e\), this transition is superallowed

- New interval limits for the binding energy of the dineutron: \(2.2\text{ MeV} < B_{dn} < 2.8\text{ MeV}\)
Last years research

- Interval assessment of a dineutron radius:
- From these energy limits and a very well known theoretical expression

\[ r_{dn}^2 = \frac{\hbar^2}{(m_n \cdot B_{dn})} \]

where \( m_n \) is a neutron mass, an interval estimate of a dineutron radius \( r_{dn} \) may be obtained.
Last years research

- For upper value of the binding energy ($B_{dn} = 2.8 \text{ MeV}$) this gives the lower estimate of a dineutron radius $r_{dn,l} = 3.85 \text{ fm}$, while for lower value of the binding energy ($B_{dn} = 2.2 \text{ MeV}$) the upper estimate of a dineutron radius $r_{dn,u}$ equals 4.34 fm.

- Then $3.85 \text{ fm} < r_{dn} < 4.34 \text{ fm}$ and the dineutron by spatial structure is similar to a "friable" deuteron with it's $r_d = 4.3 \text{ fm}$. 

Taras Shevchenko National University of Kyiv

French-Ukrainian Workshop, 26-28 September, LAL, France, 2018
Last years research

\[
\log f_{dn} = 4.0 \cdot \log E_{\text{max}-dn} + 0.78 + 0.02 A_d \\
- 0.005(A_d - 1) \cdot \log E_{\text{max}-dn}
\]

<table>
<thead>
<tr>
<th>( E_{\text{max}-dn}, \text{MeV} )</th>
<th>Interval estimate of a dineutron half-life:</th>
<th>( \log (f_{dn} \cdot t_{1/2 \ dn}) )</th>
<th>( t_{1/2 \ dn} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>( 2.5 \text{ s} &lt; t_{1/2 \ dn} &lt; 20.5 \text{ s} )</td>
<td>2.8</td>
<td>2.5 \text{ s}</td>
</tr>
<tr>
<td>3.0</td>
<td>( f_{dn} \cdot t_{1/2 \ dn} ) - comparative half-life; Sargento’s rule</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.5 s</td>
<td>( t_{1/2 \ dn} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.5 s</td>
<td>( t_{1/2 \ dn} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.8 s</td>
<td>( t_{1/2 \ dn} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
NEW DIRECTION IN NUCLEAR PHYSICS ORIGINATED FROM THE NEUTRON ACTIVATION TECHNIQUE APPLICATION

I.M. KADENKO
International Nuclear Safety Center of Ukraine, Kyiv, Ukraine and
Department of Nuclear Physics, Taras Shevchenko National University of Kyiv
Kyiv, Ukraine
imkadenko@univ.kiev.ua
(Received August 17, 2017)

The neutron activation technique is utilized to determine activation cross-section values for neutron-induced reactions on Lu, Tb, Dy, Er and Yb isotopes with application of in-home designed and manufactured neutron generator NG-300 and AMANDE facility within 3.5±14.7 MeV energy range of incident neutrons. Observation of the dineutron in the output channel of nuclear reaction on Tb is discussed. The cross-section estimate for the reaction with a dineutron escape for 6.85 MeV equals 75 ± 30 mb and is presented for the first time.

- For development of idea to measure cross-section values in the outgoing channel:
- \( \sigma_3 = 75 \pm 30 \text{ mb} \) for nuclear reaction \( ^{159}\text{Tb} (n,^2n) ^{158}\text{gTb} \) and neutron energy \( 6.850 \pm 0.002 \text{ MeV} \)
Last years research – in cooperation with ATOMKI, Hungary

This summer the following experiment was conducted:

- Three foils made of 0.9999 Au were irradiated in a neutron field generated with MGC-20 cyclotron
- Subject of the study: $^{197}$Au $(n,^2n)^{196}$Au nuclear reaction
- Reaction threshold: 8.114 MeV, neutron energy: 2 MeV below the threshold
- Expected results: availability of the following most intensive gamma peaks due to $^{196m,g}$Au decay in the instrumental spectrum:
  - $E_\gamma=355.73$ keV; $k_\gamma=87\%$
  - $E_\gamma=333.03$ keV; $k_\gamma=22.9\%$
  - $E_\gamma=426.10$ keV; $k_\gamma=6.6\%$
Last years research – in cooperation with ATOMKI, Hungary

- $E_\gamma = 355.73$ keV; $k_\gamma = 87\%$, statistical significance: 6.2 $\sigma$
Last years research – in cooperation with ATOMKI, Hungary

- $E_\gamma = 333.03$ keV; $k_\gamma = 22.9\%$, statistical significance: $4.7 \sigma$
Last years research – in cooperation with ATOMKI, Hungary

- $E_\gamma = 426.10$ keV; $k_\gamma = 6.6\%$, statistical significance: 3.8 $\sigma$
Features of the outgoing channels in some nuclear reactions

- Classical representation of nuclear reaction:
The dineutron is trapped in one of several level within (66÷400) keV energy range.

This level keeps the two neutrons in a bound state during some time as a single particle: the dineutron.

The dineutron is allowed to beta minus decay with an electron and the deuteron escape.
Features of the outgoing channels in some nuclear reactions

- $^{158\text{g}}$Tb as a nuclear reaction $^{159}$Tb ($n,^2n$) product is EC and $\beta^+$- decaying in 83%, $\beta^-$ - in 17% of total decays

- Possible reaction: $^{158\text{g}}$Tb + $e^-$ $\rightarrow$ $^{158}$Gd (stable):

$$\left\{ \begin{array}{l}
\frac{dN_{dn}(t)}{dt} = -\lambda_{dn} \cdot N_{dn}(t) \\
\frac{dN_{Tb}(t)}{dt} = -\lambda_{Tb} \cdot N_{Tb}(t) - \lambda_{dn} \cdot P \cdot N_{dn}(t)
\end{array} \right.$$

$$N_{dn}(t) = N_0 e^{-\lambda_{dn} t} \quad N_{Tb}(t) = \frac{P \lambda_{dn}}{\lambda_{dn} - \lambda_{Tb}} N_{dn}(t) + N_0 \frac{\lambda_{dn} (1 - P) - \lambda_{Tb}}{\lambda_{dn} - \lambda_{Tb}} e^{-\lambda_{Tb} t}$$

- For a dineutron half-life it is possible, that during first $\sim$100 s:

$$N_{Tb}(t) \approx N_{dn}(t) \Rightarrow A_{Tb}(t) = \lambda_{Tb} N_0 \exp (-\lambda_{dn} t)$$
Observation of $^{157}$Dy as a product of the $^{159}$Tb ($p,3n$) $^{157}$Dy nuclear reaction for proton energies below the reaction threshold does not exclude the possibility for existence of the following reaction channel: $^{159}$Tb ($p,3n$) $^{157}$Dy

Search for the trineutron could be justified in the following energy range provided the binding energies for the dineutron and the trineutron are known:

$$E_{th}^{3n} - B_{tn} < E < E_{th}^{3n} - B_{dn}$$

Some conclusive remarks from Migdal’s paper: “One might think that an analogous mechanism leads to bound states which are more complicated than the dineutron...”
Conclusions

- Experimentally proved the possibility of dineutron existence in a bound state as a particle-satellite of recoil nucleus in the outgoing channel of nuclear reactions on $^{159}$Tb with protons and neutrons in the input channel
- Independently observed the dineutron in the outgoing channel of the $^{197}$Au ($n,^2n$) $^{196}$Au nuclear reaction
- The interval estimates are obtained for the binding energy, half-life and radius of the dineutron as well as cross-sections for generation of the dineutron
- Assumption is made about a possible interaction of dineutron decay products with the heavy nucleus in the outgoing channel to fostering it’s “faster decay”
Many thanks for your attention and questions!