Cross sections for a new nuclear reaction channel on $^{197}$Au with a bound dineutron in the outgoing channel

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A new nuclear reaction channel on $^{197}$Au with neutron in the incident channel and a bound dineutron ($^2n$) in the output channel is considered based on available experimental observations. The dineutron is assumed to be formed as a particle-satellite, separated from the volume but not from the potential well of $^{196}$Au residual nucleus provided the energy of incident neutron is about 2 MeV below the threshold of corresponding ($n,^2n$) reaction. The dineutron was identified by statistically significant radioactivity detection due to decay of $^{196}$gAu nuclei. Cross sections for the $^{197}$Au ($n,^2n$)$^{196}$gAu reaction are determined as $180 \pm 60 \mu$b and $37 \pm 8 \mu$b for $[6.09-6.39]$ MeV and $[6.175-6.455]$ MeV energy ranges, correspondingly.

Key words: gold; neutron induced nuclear reaction; dineutron; cross section

Introduction - The purpose of this letter is discussion of the dineutron as a bound particle, or two-nucleon nucleus, consisting of the two neutrons only without any nucleus charge and formed in the outgoing channel on neutron induced nuclear reaction on $^{197}$Au near the $^{196}$Au nucleus surface. Such a configuration is different from the classical description of nuclear reactions at low energies and described in details in [1]. The dineutron was predicted by A.Migdal [2] to be formed as a bound particle under certain circumstances when an additional bound state appears, not existing in the perturbation theory. This bound state is interpreted as a single particle state for the two neutrons, or bound dineutron, located near the surface of some nucleus, beyond its volume but within its potential wells. This bound state corresponds to single-particle level at an additional energy branch, which concludes at $\varepsilon_c \sim 0.4$ MeV. As it is well known, as a minimum, only 0.066 MeV is necessary to bind the two neutrons in the dineutron and this mechanism could make a possible formation of a bound dineutron in the output channel of nuclear reaction. First observation of this phenomenon was described in [3], but statistical significance of detection of $^{158}$Tb induced activity as a product of the $^{157}$Tb ($n,^2n$) nuclear reaction was not good enough due to 180 years half-life of $^{158}$gTb residual nucleus. Thus, we decided to search for another nucleus with a reasonable half-life to make sure the statistical significance of its detection will meet $5\sigma$ criteria. Another requirement to select a proper nucleus should be a very high purity of a sample for neutron irradiation to exclude any interferences due to unexpected nuclear reactions on impurities. As a result, our selection procedure get us to $^{197}$Au as a nucleus-candidate for statistically significant search of a bound dineutron. Then the presence of the dineutron in the outgoing channel of the $^{197}$Au ($n,^2n$)$^{196}$gAu nuclear reaction would be greatly facilitated when the residual nucleus $^{196}$gAu decays with emission of corresponding gamma-lines, that can then be reliably detected. Finally, our goal was to succeed with dineutron observation in a configuration, similar to presented in Fig.I, and to make cross-section estimates for the $^{197}$Au ($n,^2n$)$^{196}$gAu reaction introducing a new nuclear reaction channel with a bound dineutron escape.

Experimental observations. - To obtain expected results, golden foil samples were selected for neutron irradiation followed by subsequent gamma-ray counting.

Irradiations of Au foil samples at Atomki. - Two irradiation experiments were carried out at Atomki. Fig. II shows the sketch of the arrangement of the irradiations. The quasi-monoenergetic $d+D$ neutrons were produced via bombarding a $D_2$-gas target [4] with deuterons accelerated by the MGC-20E cyclotron of Atomki. The energies of the deuterons were $E_d = 3.459$ MeV and $E_d = 3.523$ MeV. The energy spread of the analyzed deuteron beam was $\delta E_d/E_d = 0.1\%$. The diameter of the bombarding deuteron beam was 4 mm and a window of the gas cell was a 5 µm thick Nb foil.
FIG. I Schematical representation of \(^{196}\text{Au}\) and the dineutron in the outgoing channel of the \(^{197}\text{Au}(n, 2n)^{196}\text{Au}\) reaction.

The pressure of the \(D_2\)-gas was kept in the \(p = (1.94 - 1.80)\) bar range and a pressure loss \(dp/dt = -0.04\) bar/hour was compensated by re-filling the gas cell periodically each 1.5 hours. The beam stop of the gas cell was a 200 µm thick tungsten plate. The distance between the window foil and the beam stop and, thus, the length of the bombarded gas volume was 39.4 mm. The beam stop was cooled by an air jet. Typically \(I_{\text{coll,1}} = 400\) nA current was measured on the dia. 8 mm collimator and the \(I_{\text{coll,2}} \leq 50\) nA current on the dia. 6 mm collimator was in the range of the leakage current of the system. For the experiment done at \(E_d = 3.459\) MeV deuteron energy 100 µm thick and 1.3 cm diameter foil samples made of 99.99% purity Au were prepared. Of them 3 pieces of Au foils (Au-I, Au-2 and Au-3) were put in a closed cadmium cover of 0.51 mm wall thickness to reduce intensity of 411.8 keV gamma line due to \(^{198}\text{Au}\) decay because of scattered neutrons and possible yield enhancement for \(^{197}\text{Au} (n, g)\) \(^{198}\text{Au}\) nuclear reaction. Such sample configuration ensured us to avoid a situation when gamma-peaks of our interest with 333 and 355 keV energies will not be hidden in the Compton distribution. The internal diameter of the cover was 13 mm. The quasi-monoenergetic peak of the spectrum of the \(d+D\) neutrons covered the \([6.09 - 6.39]\) MeV neutron energy range. The average current of the deuteron beam was \(I_d = 1.92\) µA and the total amount of the charge of deuterons delivered to the target was \(Q_d = 2.73 \times 10^{22}\) C. The neutron fluence was \(\Phi_{\text{total}} = 1.33 \times 10^{11}\) cm\(^{-2}\) delivered at \(<\Phi_{\text{neutron}}>/dt = 9.5 \times 10^{6}\) cm\(^{-2}\)s\(^{-1}\) average neutron fluence rate.

For the experiment done at \(E_d = 3.523\) MeV deuteron energy Au foils of 12.2 mm diameter and 150 µm thickness (Au-I and Au-II) and one more Au foil of the same diameter and 200 µm thickness (Au-III) were stacked and covered by 1 mm thick cadmium shielding. Then the stack was irradiated with quasi-monoenergetic neutrons for 7,809 s. The energy spectrum of the \(d+D\) neutrons covered the \([6.175-6.455]\) MeV energy range. The average current of the deuteron beam was \(I_d = 1.92\) µA and the total amount of the charge of deuterons delivered to the target was \(Q_d = 1.51 \times 10^{22}\) C. The neutron fluence was \(\Phi_{\text{total}} = 7.5 \times 10^{10}\) cm\(^{-2}\) and it was delivered at \(<\Phi_{\text{neutron}}>/dt = 9.6 \times 10^{6}\) cm\(^{-2}\)s\(^{-1}\) average neutron fluence rate to the samples.

FIG. II Sketch of the arrangements for irradiations

The NeuSDesc code [5] was used for calculation of the spectra of the \(d+D\) neutrons and the neutron fluence rates for the positions of the geometry centers of the foil stacks. The obtained neutron spectra are shown in Fig. III that are below the \(E_{th}(n, 2n) = 8.11372\) MeV threshold energy of the \(^{197}\text{Au}(n, 2n)^{196}\text{Au}\) nuclear reaction.

FIG. III The spectra of the \(d+D\) neutrons for the geometry centers of the foil stacks
Results of the instrumental gamma-spectra acquisition. - The gamma activities of the neutron activated Au samples were counted with HPGe gamma spectrometers. The $^{198}$Au ($T_{1/2} = 2.69517$ d.) and the $^{198m}$Au ($T_{1/2} = 2.27$ d.) radioisotopes from the $^{197}$Au($n,\gamma$)$^{198}$Au nuclear reaction were present in all Au samples irradiated. The measurements focused on counting the $E_\gamma = 332.983$ keV ($I_\gamma = 22.9\%$) and $E_\gamma = 355.684$ keV ($I_\gamma = 87\%$) energy gamma photons emitted due to decay of the $^{196g}$Au ($T_{1/2} = 6.183$ d.) radioisotope that might be produced via dineutron emission in the $^{197}$Au($n,2n$)$^{196}$Au nuclear process. At Atomki the three Au samples (Au-1, Au-2 and Au-3) irradiated in cadmium cover were counted together on the surface of a vertical HPGe detector (Model: GC1520-7935.7, Canberra Industries, Inc., Meiden, Connecticut, USA). The arrangement of the measurement is shown in Fig. IV.

![FIG. IV. The counting arrangement at the HPGe detector used at Atomki (Debrecen, Hungary)](image)

The gamma lines at $E_\gamma = 332.983$ keV and $E_\gamma = 355.684$ keV in the gamma spectrum measured for the group are shown in Fig. V together with fits to the background and to the peaks. The live time and the real time of the counting were $T_{LIVE} = 271,494$ s and $T_{REAL} = 271,640$ s, respectively.

In the case of counting the Au-1, Au-2 and Au-3 samples together at Atomki the statistical significances for the peaks were 3.3 $\sigma$ from the $E_\gamma = 355.684$ keV gamma photons and 9.3 $\sigma$ for the $E_\gamma = 355.684$ keV gamma photons.

Second set of Au foils was counted at INSCU/Department of Nuclear Physics, Taras Shevchenko National University of Kyiv, Ukraine with application of HPGe spectrometer, described in [3]. In the case of counting the Au-I, Au-II and Au-III samples together at INSCU in Kyiv, the best statistical significance was 6.4 $\sigma$ for the peak that corresponds to the $E_\gamma = 355.684$ keV gamma photons.

![FIG. V The channel contents (yellow line) of the gamma spectrum measured at Atomki for the gamma lines at $E_\gamma = 332.983$ keV and $E_\gamma = 355.684$ keV. The fitted peaks (red line) and the background fit (green line) are also shown](image)

Cross-section estimates. - After counting the gamma activity of the samples the $A_{sat}$ saturation activity of $^{196}$Au was calculated. Then, on the basis of the results of the two irradiations, cross sections were estimated for a bound dineutron emission in the outgoing channel of the $^{197}$Au ($n,2n$)$^{196}$Au nuclear process. The cross section averaged for the $(E_n;\text{min}, E_n;\text{max})$ neutron energy interval was obtained as

$$
\frac{\int_{E_n;\text{min}}^{E_n;\text{max}} \phi(E_n) \sigma(E_n) dE_n}{\int_{E_n;\text{min}}^{E_n;\text{max}} \phi(E_n) dE_n} = A_{sat}
$$

where $E_n$, $\phi(E_n)$ and $\sigma(E_n)$ are the neutron energy, the energy distribution of the neutron fluence rate and the excitation function of the nuclear reaction, respectively. The estimates are summarized in Table I. The main contributors for the total uncertainty were:

- positioning of the stacks in front of the $D_2$-gas target, $< 10\%$;
- limited knowledge on the possible contribution of the neutrons generated by the bombarding deuteron beam impinged on the Ta collimators, the Nb window foil and the W beam stop, $< 5\%$;
- counting statistics, 22\%;
- uncertainty of the detection efficiencies estimated for the counting geometry used at the HPGe detector at Atomki, 17\%.


Discussion. - Still being self-criticized, additional 11 countings were conducted by us at INSCU to check whether a half-life estimate for $^{196}$Au did not vary due to possible cosmic burst. Based on measurement results, no indications were found within experimental uncertainties that $^{196}$Au activity was induced by a cosmogenic activation. This activity dropped below detection level within 1 month since irradiation was completed. Thus, statistically significant observation of a bound dineutron in the $^{197}$Au($^2n$,2$n$)$^{196}$Au nuclear reaction, and in addition true conclusion about a manifestation of dineutron escape in the $^{159}$Tb ($^2n$)$^{158}$Tb nuclear reaction in [3], both demonstrated, that Migdal’s prediction about possible formation and existence of a bound dineutron in the outgoing channel of nuclear reaction is absolutely correct nowadays even it was made 45 plus years ago with some obsolete values like $n$-$n$ scattering lengths within and beyond the nucleus, etc. Based on two cross-section estimates, available as those of major results in this research, one can assume, that the dependence of cross section versus energy for the $^{197}$Au($^2n$,2$n$)$^{196}$Au nuclear reaction may start from zero in the vicinity of the energy $E_\gamma$ and reach the maximum within $[2.2-2.8]$ MeV, then decrease after $6.17$ MeV reaching zero value near the $E_{dn,scattering}$ energy, where ($n,2n$) reaction channel opens up. Here $B_{dn}$ is the binding energy of the dineutron, and according to current interval estimate, $B_{dn}$ stays within $[2.2-2.8]$ MeV [1]. In other words, the cross section versus energy dependence has a resonant character, to some extent reminding the pumping between levels in a laser system. By analogy, let’s call this phenomenon as “the dineutron pumping”. Then thorough study of such cross section vs energy dependence with application of VdG accelerators, targeted to precisely identify a maximum position and corresponding cross section value, could enable us to deeply understand between which levels in and beyond of residual nucleus this dineutron pumping takes place. Also we can note the mass interval, for which dineutron generation seems to be possible now is as follows: 159-197. This interval is in a full agreement with what was predicted in [1] and [3].

Summary. - Results of this study shed some light on the process of reliably generating such unique particles as bound dineutrons, which were considered as non-existent for very long time since the first mentioning by Colby and Little in [6]. While the theoretical description of dineutron formation in the vicinity of much heavier nucleus is for now not that much comprehensive, our statistically significant experimental results, exceeding 5 $\sigma$ criteria, confirmed observation of the dineutron, which since now is not just hypothesized to exist, but certainly existing. We also were capable of deriving cross-section estimates $180 \pm 60$ and $37 \pm 8$ $\mu$b for the two energy intervals of incident neutrons $[6.09 \div 6.39]$ and $[6.175-6.455]$, respectively. Thus, based on our experimental facts, this research opens up a new exciting direction in nuclear physics, appealing for much more efforts to explore new low energy physics. Then our observations allow us to raise a reasonably justified question about introduction of a new nuclear reaction channel ($n$, $^2n$) into available nuclear libraries. Moreover, this initiative is in a full conformance with the following statement from [7]: “TENDL takes a rather extreme point of view here: every nuclear reaction process which is expected to take place in reality should be present in a nuclear data library, measured or not measured. In short, that means, all projectiles, all nuclides, all reaction channels and all energies”.

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\begin{table}
\centering
\caption{The results of the counting of the full energy photopeaks of $^{196}$Au and the estimated cross sections for the dineutron emission in the $^{197}$Au($^2n$,2$n$)$^{196}$Au nuclear process.}
\begin{tabular}{cccccc}
$E_{\gamma}$ & $E_{\gamma,min}$ & $E_{\gamma,average}$ & $E_{\gamma,max}$ & The gamma peaks used for CS estimation & Cross section (CS) \\
Mev & MeV & MeV & MeV & & (mbarn) \\
\hline
3.459 & 6.09 & 6.19 & 6.39 & $E_\gamma = 332.983$ keV & 0.18 $\pm$ 0.06 \\
3.523 & 6.17 & 6.27 & 6.46 & $E_\gamma = 355.684$ keV & 0.037$\pm$0.008 \\
\end{tabular}
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