# ACTIVATION OF $^{165}$Dy ISOMER STATES BY NEUTRONS FROM THE PHOTODISINTEGRATION OF $^{164}$Dy NUCLEI

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RAD CONFERENCE 2025

Abstract No.
RAD 13-128

## Motivation

▪ According to cosmic nucleosynthesis models, abundances of most elements heavier than iron depend on the number of free neutrons available fo capture reactions. Equilibrium between (n,γ) and (γ,n) reactions plays important role while nuclear isomer states serve as β-decay waiting points [1]. Photonuclear reactions can give considerable contribution for abundances of some nuclides neighbouring with the seven stable dysprosium isotopes in the 150≤A≤190 region (Fig.1).

▪.Lantanides, such as gadolinium, terbium, holmium and dysprosium are widely used as dopants to modify properties of various materials of which many find their application in environments subjected to high γ-ray fluences.

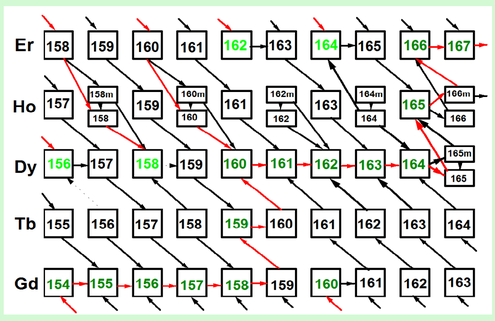


**Figure 1.** Stable dysprosium nuclides and their neighbours. Arrows depict experimentally observed capture and decay processes linking these nuclei. Red arrows show main nucleosynthesis process route. Stable nuclides are shown with green colour (p-nuclei are shown with somewhat lighter green). Decay and capture processes prominent during $^{164}$Dy activation are shown with bolder lines.

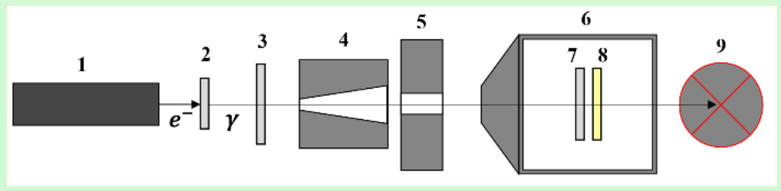


**Figure 2.** Experimental set-up:.1 – Microtron; 2 - Convertor (with two W targets 1.5 and 3 mm and one Sn foil 0.2 mm); 3 - Target with combined Al-Cu scattering foils; 4 - Primary conical stainless steel collimator; 5 - Secondary square W-steel collimator; 6 - Water-cooled chamber; 7 - Sample target; 8 –Reference monitor target (Au, or Cu, at $E_e$>14 MeV); 9 - Absorber.

## Experiment

Experimental photoactivation measurements were performed at the microtron MT-25 of the **Nuclear Physics Institute of the Czech Academy of Sciences (Prague)**. The targets made of $Dy_2O_3$ – 0.198 mg enriched to (97.8% of $^{164}$Dy, and 0.368 mg of natural Dy were irradiated for 15-20 min with bremsstrahlung photons at several electron energies $E_e$ ranging from 7.11 up to 22.82 MeV. Fig.2 shows scheme of the experimental set-up. Deactivation γ-spectra were measured after different cooling times with a HPGe detector (efficiency 78%, and energy resolution FWHM 1.8 keV for 1332 keV γ-line of $^{60}$Co.

## Results

Most of γ-lines observed in the spectra of enriched and natural dysprosium targets activated at $E_e$>16 MeV (see, e.g., Fig.4) were assigned to the β- decay ($T_{1/2}$=19.5 min) of $^{163}$Tb following the reaction $^{164}$Dy(γ,p)$^{163}$Tb (see Ref. [2]), as well as to the β- decay ($T_{1/2}$=7.60 min) of $^{162}$Tb following the reaction $^{163}$Dy(γ,p)$^{162}$Tb. Below $E_e$<16 MeV, observation of the (γ,p) reaction products is hindered by the exit Coulomb barrier.

The products of (γ,xn) reactions on the most abundant Dy isotopes are stable and one cannot see corresponding decay lines in activation experiments. However, our experimental results show that capture reactions of thermal and epithermal photoneutrons produced during irradiation process give notable contribution to the total measured activity. Starting with $E_e$=9.75 MeV, we observe in our spectra (see, e.g., Figs.3 and 4) the most intense $^{165}$Dy decay lines to $^{165}$Ho ($T_{1/2}$=2.33 h). In the decay spectra registered after cooling times less than 4 min, we observe also the 108.2 keV line of the $^{165m}$Dy isomer decay ($T_{1/2}$=1.257 min) [3] in the case of both $^{nat}$Dy and enriched $^{164}$Dy targets.

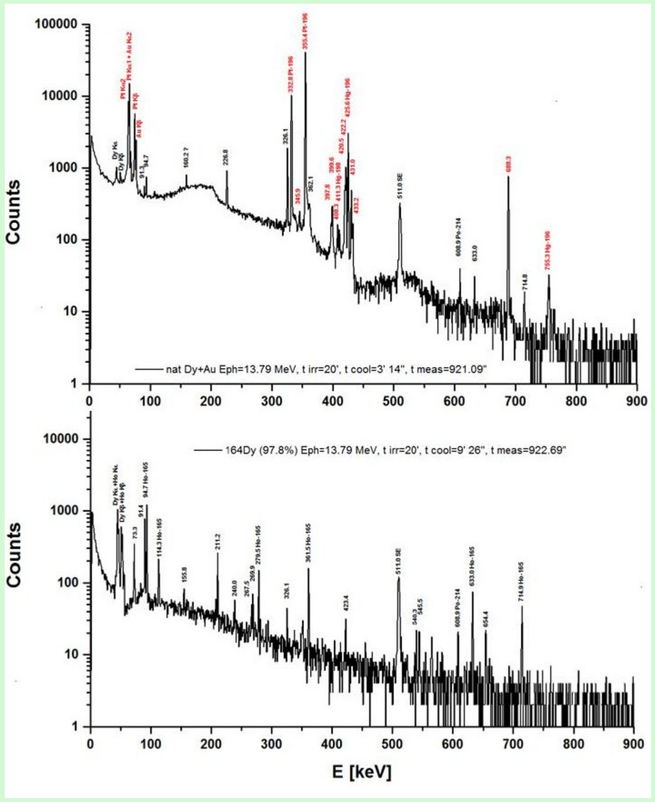


**Figure 3**. Portions of γ-ray spectra measured after the activation of enriched $^{164}$Dy and $^{nat}$Dy targets with $E_e$=13.79 MeV bremsstrahlung photons. The lines marked with red colour are originating from the pure $^{197}$Au monitor target irradiated and measured together with $^{nat}$Dy target. The rest of intense γ-lines belongs mostly to the $^{165}$Dy decay. Note, that due to relatively short cooling times between Dy target irradiations, spectra contain also some of the most intense lines originating from the decay of the longer living (γ,n) reaction products: $^{157}$Dy, $^{155}$Dy.

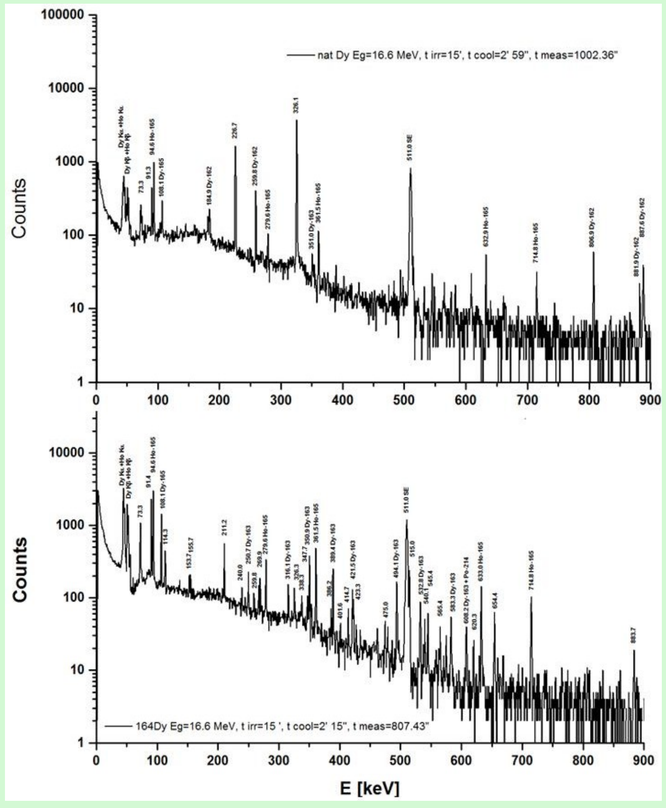


**Figure 4**. Portions of γ-ray spectra measured after the activation of enriched $^{164}$Dy and $^{nat}$Dy targets with $E_e$=16.6 MeV bremsstrahlung photons. The most of intense γ-lines belongs to $^{162}$Tb, $^{163}$Tb, and $^{165}$Dy decay products. Since spectra have been measured after relatively short cooling times (2-3 min), one can see the 108.2 keV line of the $^{165m}$Dy ($T_{1/2}$=1.257 min) isomer decay.

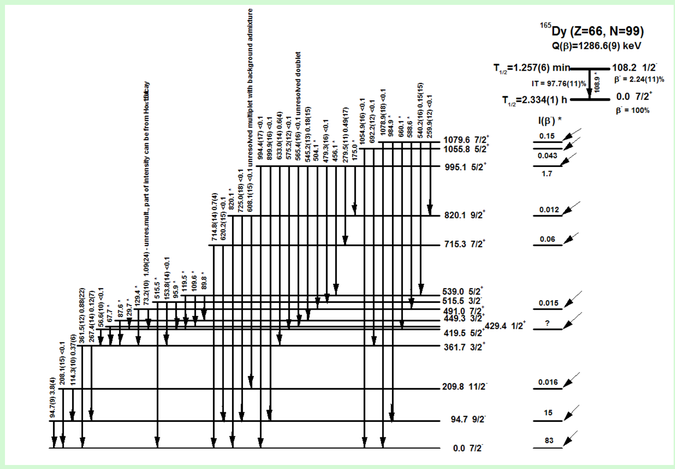


**Figure 5**. Levels of $^{165}$Ho (Z=67, N=98) populated in the β- decay of $^{165}$Dy. Transitions unobserved in present measurements are marked with asterix.

**Table 1**. Activation yields $Y(E_e)$ of the $^{164}$Dy(n,γ)$^{165}$Dy reaction assessed using reference yield of the $^{197}$Au(n,γ)$^{198}$Au reaction in the case of enriched $^{164}$Dy, and natural Dy target irradiation with bremsstrahlung photons. In the second column, we show the evaluated values of the $^{164}$Dy(γ,n) reaction cross-sections from the TENDL-2023 files [4].

| $E_e$ [MeV] | σ ($E_e$) for $^{164}$Dy(γ,n) [barn] | $Y(E_e)_{enrich}$ [barn·MeV] | $Y(E_e)_{nat}$ [barn·MeV] |
|---|---|---|---|
| 9.75 | | 0.39(9) | 0.21(10) |
| 10 | 0.1012 | | |
| 12 | 0.2144 | | |
| 12.12 | | 1.74(27) | 0.95(21) |
| 13 | 0.2279 | | |
| 13.79 | | 3.0(4) | 1.6(4) |
| 14 | 0.2629 | | |

The experimental activation yields $Y(E_e)$ of the $^{164}$Dy(n,γ)$^{165}$Dy reaction at microtron energy $E_e$ were determined from the measured intensities of several strong γ-transitions following the $^{165}$Dy decay to $^{165}$Ho (Fig. 5). The most intense 94.7 keV γ-line was observed in all measured spectra starting with $E_e$=9.75 MeV end-point energy bremsstrahlung irradiation. Table 1 presents values evaluated using the simple activation equation

$$Y(E_e) = \frac{N_\gamma(E_e)\cdot\lambda}{\varepsilon\cdot I_\gamma\cdot n\cdot\Phi(E_e)\cdot(1-e^{-\lambda\cdot t_{irr}})\cdot e^{-\lambda\cdot t_{cool}}\cdot(1-e^{-\lambda\cdot t_{meas}})},$$

where $N_\gamma(E_e)$ - the measured full peak count from which background and other possible admixtures are subtracted; $\lambda$ – the radioactive decay constant, $n$ - the number of nuclei in the irradiated target, $\varepsilon$ - the full energy peak detection efficiency, $I_\gamma$ - the absolute γ-ray intensity, $\Phi(E_e)$ – photoneutron flux, while $t_{irr}$, $t_{cool}$, and $t_{meas}$ – the irradiation, cooling, and measuring times, correspondingly.

Since experimental photoneutron flux Φ($E_e$) and spectrum are unknown, the $Y(E_e)$ values were assessed relative to the $^{197}$Au(n,γ)$^{198}$Au reaction yields determined from the measured intensities of the 411.8 keV reference line from the $^{198}$Au decay to $^{198}$Hg. This line is observed in all spectra of Au targets irradiated together with dysprosium as photon flux monitors. It indicates that photoneutron capture takes place both in Dy and Au targets.

## Discussion and Conclusions.

Importance of measured intensity corrections due to photoneutron capture has been noted earlier. In [5], the admixture of (n,γ), and (n,n'γ) reaction product activities was studied in the case of $^{115}$In bremsstrahlung irradiation. Since $^{164}$Dy has even higher neutron capture cross-section than $^{115}$In, the observed enhancement of the total activity is more prominent.

The activation of $^{165}$Dy increases with $E_e$ due to growing number of photoneutrons via opening of the (γ,2n) reaction channels. Unfortunately, we could not assess corresponding values since Cu used as photon flux monitor has small neutron capture cross-section, contrary to Au. Therefore, additional studies are required including separate irradiations of Dy and Au targets.

The enhanced activation due to photoneutron capture should be taken into account both in cosmic nucleosynthesis models and in isotope applications.

Also, one should always take great care when planning photonuclear experiments in the energy range above neutron separation energy. It regards also the usual practice of sandwiching several targets during irradiation.

## References

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