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## Measurements of the $^{161}\text{Tb}$ production cross section for nuclear data and nuclear medicine

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► **To cite this version:**

Arnaud Guertin, Etienne Nigron, Alexandre Rintaud, Maxence Rayet, Lucas Granger, et al.. Measurements of the  $^{161}\text{Tb}$  production cross section for nuclear data and nuclear medicine. Fourth International Conference on Advances in Radioactive Isotope Science (ARIS), Jun 2023, Avignon, France. pp.92/491, 10.5281/zenodo.10655037 . hal-04521361

**HAL Id: hal-04521361**

**<https://hal.science/hal-04521361>**

Submitted on 26 Mar 2024

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The double Penning trap PIPERADE (Pièges de Penning pour les Radionucléides à DESIR) [1] for the DESIR facility has been advancing in its commissioning phase at the LP2i-Bordeaux laboratory. The traps were designed with the objective of performing high-precision mass measurements and high-resolution mass purification of strongly contaminated ion beams. The latter will be produced by the existing SPIRAL1 facility and the S3 spectrometer. In order to push the limits of existing devices, PIPERADE is equipped with a new type of high-capacity large trap that aims to separate up to  $10^4 - 10^5$  ions per bunch.

The purified samples will be re-injected in the main DESIR beam line for downstream setups to perform trap-assisted spectroscopy. Alternatively, the purified samples will be utilized to perform high-precision mass measurements. In this context, standard ion-beam manipulation techniques are now being routinely demonstrated, i.e. the sideband buffer gas cooling (BGC) [2] and the time-of-flight ion-cyclotron-resonance (ToF-ICR) [3], while others are being implemented - phase-imaging ion-cyclotron-resonance (PI-ICR) [4]. Last year, as part of the implementation process of PI-ICR, an imaging system consisting of a microchannel-plate detector coupled to an anode constructed of helical wire delay lines was installed. RoentDek Handels GmbH has developed the delay-line anode with a specific three-layer geometry ( “Hexanode” ) [5] to improve the ambiguity of multi-hit position and time encoding on the detector.

In this contribution, we will present the latest achievement from the BGC technique, the first mass measurement by using ToF-ICR and finally, the detector installation to allow the position encoding for future PI-ICR measurements.

[1] P. Ascher et al., Nucl. Instrum. Methods. Phys. Res. A 1019 (2021) 165857

[2] G. Savard, et al., Phys. Lett. A 158 (1991) 247

[3] M. Koenig, et al., Int. J. Mass Spectrom. 31 (1995) 95

[4] S. Eliseev et al., Phys. Rev. Lett. 110 082501 (2013)

[5] O. Jagutzki et al., IEEE Trans. Nuc. Sci. 49 (2002) 5

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## Measurements of the $^{161}\text{Tb}$ production cross section for nuclear data and nuclear medicine

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$^{161}\text{Tb}$  has interesting physical properties for therapeutic applications in nuclear medicine. It has a half-life of 6.88 days and it is a  $\beta^-$  emitter with a mean energy of 154 keV and a maximum energy between 42.85 and 593.1 keV. It corresponds to an electron range of 3 millimeters in water. Its coordination chemistry and energy range, comparable to that of  $^{177}\text{Lu}$  used in vectorized radiotherapy, allow a stable coordination with a DOTA chelator, a localized effect on targeted cells and limits the dose received by the surrounding healthy tissues. The therapeutic effect of  $^{161}\text{Tb}$  may be enhanced due to the co-emission of a larger number of conversion and Auger electrons as compared to  $^{177}\text{Lu}$ . In a theranostic approach, it could be coupled at another terbium isotope dedicated to diagnostic.

Production cross section of various  $\beta^-$ - and  $\alpha$  emitters dedicated to therapy were measured by the PRISMA team of the Subatech laboratory at the GIP ARRONAX using a multiparticle C70XP cyclotron, the stacked-foil technique and gamma spectroscopy. From irradiated stacks, composed of natGd foils, Ni monitors and Al degraders, we are able to obtain the natGd(d,x) $^{161}\text{Tb}$  cumulative production cross section coming from the reactions  $^{160}\text{Gd}(d,p)^{161}\text{Gd}$  and  $^{160}\text{Gd}(d,n)^{161}\text{Tb}$

between 6.69 and 16.47 MeV. Previous data sets published in the literature by Tarkanyi et al. [1] and Szelecsenyi et al. [2] are not in accordance, one objective of this work is to better define the shape and the maximum of the excitation function. Additional data have also been collected for the natGd(d,x)155Tb, 156Tb, 160Tb. Results are presented along with values extracted from TENDL-2019.

The only three series of published experimental data have been complemented in the energy region, near 12 MeV, of the maximum cross section, around 50 mb. This production cross section is of interest for nuclear models as it fixes the shape and the amplitude associated to this nuclear reaction and for nuclear medicine as it allows to defined optimized irradiation parameters to produce 161Tb that can be beneficial for vectorized radiotherapy to take advantage of its  $\beta^-$  and Auger electron emissions.

[1] Tarkanyi, F., Hermanne, A., Tackacs, S., Ditroi, F. Csikai, J. & Ignatyuk, A. V. (2013). Cross-section measurement of some deuteron induced reactions on 160 Gd for possible production of the therapeutic radionuclide 161 Tb. *Journal of Radioanalytical and Nuclear Chemistry*, 298(2), 1385-1392. <https://doi.org/10.1007/s10967-013-2507-x>

[2] Szelecsenyi, F., Kovacs, Z., Nagatsu, K., Zhang, M-R. & Suzuki, K. (2016). Investigation of deuteron-induced reactions on natGd up to 30 MeV: possibility of production of medically relevant 155Tb and 161Tb radioisotopes. *Journal of Radioanalytical and Nuclear Chemistry*, 307(3), 1877-1881. <https://doi.org/10.1007/s10967-013-2507-x>

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## Latest results from MARA

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A new vacuum-mode separator, MARA (Mass Analyzing Recoil Apparatus) [1, 2], has been completed and has extended the research possibilities whit the existing gas-filled recoil separator, RITU [3] at JYFL-ACCLAB. The ion-optical configuration of MARA is QQQDEDM, differing significantly from the other existing in-flight separators around the world. MARA has turned out be a very reliable separator and easy to operate. The studied nuclei of interest have been produced using fusion-evaporation reactions, mainly employing symmetric or inverse kinematics. In-beam studies, isomeric studies as well as production of new isotopes have been performed at and beyond the proton dripline starting from a mass number 66 up to a mass number 180. In this work some highlights of the latest results using the JYFL in-flight separator MARA will be given.

[1] J. Uusitalo et al., *Acta Physica Polonica B* 50 (2019) 319

[2] J. Sarén et al., *Research Report No. 7/2011*, University of Jyväskylä

[3] M. Leino et al., *NIMB* 99 (1995), 653

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## Isospin-symmetry breaking in the $B(E2)$ transitions of $T = 1$ isotriplets

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