Colloquia: EuNPC 2018

Nuclear data program for Neutron Capture Therapy at the n_TOF facility at CERN

F. Ogállar(1)(2), M. Sabaté-Gilarte(2)(3)(*), P. Torres-Sánchez(1),
I. Porras(1), J. Praena(1), J. M. Quesada(3), T. Wright(4), S. Bennett(4),
C. Lederer-Woods(5), S. J. Lonsdale(5), R. Garg(5)
and The n_TOF Collaboration

(1) Dpto. de Física Atómica, Molecular y Nuclear, Universidad de Granada - Granada, Spain
(2) European Organization for Nuclear Research (CERN) - Geneva, Switzerland
(3) Dpto. de Física Atómica, Molecular y Nuclear, Universidad de Sevilla - Sevilla, Spain
(4) Dpt. of Physics and Astronomy, University of Manchester - Manchester, UK
(5) Sch. of Physics and Astronomy, University of Edinburgh - Edinburgh, UK

Summary. — Few cross section measurements have been performed at the n_TOF facility at CERN with the aim of supplying nuclear data for some neutron-induced reactions of importance in Neutron Capture Therapy. In this paper, a brief introduction to the topic will be presented as well as a discussion on the status of the nuclear data available prior to the executions of the experiments.

1. – Introduction

1˙1. *Neutron Capture Therapy.* – NCT is a selective binary experimental radiotherapy based on the neutron irradiation of a tumour previously loaded with a suitable stable isotope. Incoming neutrons induce a high Q-value nuclear reaction in the isotope, causing the emission of high LET (*Linear Energy Transfer*) radiation with an energy deposition range of 5 to 9 μm, which is comparable to the cancerous cell size. As a result of the energy deposition, the cancer cell is damaged. ^{10}B is the isotope that is normally used in this radiotherapy, and $^{10}B(n,\alpha)^7Li$ the reaction induced by neutrons reaching the tumour. In the past, patients were taken to nuclear reactors to receive the necessary neutron irradiation, this posed logistical problems that significantly limited the potential of this therapy. Nowadays, the development of accelerator-based neutron sources for NCT opens the possibility to implement this therapy in hospitals [1], taking advantage of more versatile and safe neutron beams. This paradigm shift inaugurates a new era

---

(*) E-mail: marta.sabate.gilarte@cern.ch

for NCT, therefore, many aspects of this therapy must be studied in detail in order to improve its therapeutic outcome. The use of ^{33}S as a cooperative target to ^{10}B was proposed in 2008 [2,3]. The most probable neutron-induced reaction channel of this stable isotope is $^{33}S(n, \alpha)$, presenting important resonances above 10 keV. These resonances can be used to increase the delivered dose to the tumour loaded with ^{33}S, especially when using accelerator based neutron sources, which provide neutrons in the epithermal range of energy. Regarding the dosimetry specifications, the International Commission on Radiation Units and Measurements (ICRU) recommends that the delivered dose should have less than 5% deviation from the prescribed dose [4]. Therefore, a good knowledge of the nuclear reactions involved is required; what will lead to a better control of the released dose through more accurate estimation of the therapy safety margins. Moreover, chlorine is present in human body tissue, especially in the brain where it represents a fraction of 0.3% in mass. Accordingly, neutron-induced reactions on chlorine may play an important role. Using Monte Carlo simulations, it was concluded that $^{35}Cl(n, p)^{35}S$ and $^{35}Cl(n, \gamma)^{36}Cl$ reactions should be included accurately in NCT dosimetry studies [5, 6], due to their cross section resonances in the epithermal region, the high LET of the released proton in the first reaction and the high Q-value of the $^{35}Cl(n, \gamma)^{36}Cl$ reaction (approximately 8.58 MeV).

In order to improve the dosimetry studies of this therapy and to explore the potential of ^{33}S as a cooperative target to ^{10}B, several cross section measurements were performed at the neutron time of flight facility (n_TOF) at the European Organization for Nuclear Research (CERN), since the status of the available nuclear data was not optimal according to the recommendations of the ICRU.

1˙2. *Neutron Time Of Flight facility at CERN*. – n_TOF is a spallation neutron source based on a 20 GeV/c proton beam impinging on a lead target [7, 8]. n_TOF is a unique facility in the world due to the state of the art of its detectors, the data acquisition system and the characteristics of its neutron beam, *i.e.*, high instantaneous flux in a wide energy range —from few meV to several GeV—, high energy resolution which allows resolving resonances and low repetition rate of the primary pulsed proton beam. The facility is in operation since 2001 and features two experimental areas: n_TOF-EAR1 [9], located at 185 m from the spallation target along the horizontal direction of the incoming proton beam, and n_TOF-EAR2 [10], along the vertical direction at 20 m from the target, which was built in 2014. n_TOF is mainly dedicated to measure neutron-induced cross sections for nuclear technology, astrophysics, basic nuclear physics and medical physics.

2. – Nuclear data status before the n_TOF measurements

The $^{33}S(n, \alpha)^{30}Si$ cross section data available showed important deficiencies, as discussed in [11], with no experimental data between thermal (25 meV) and 10 keV, and major discrepancies at the thermal point. There was only one (n, α) experiment resolving resonances [12]. An important discrepancy was found between such experiment and the description of the most important resonance by means of the unique transmission measurement [13]. With respect to the evaluated nuclear data files, only EAF-2010 includes the resonance, but with a lower average cross section than the one reported in ref. [12].

For the $^{35}Cl(n, p)^{35}S$ reaction, the cross section data showed significant discrepancies among existing data sets in both the resonance region and the thermal point, leading to some complications in the nuclear data evaluation [14], as it is widely discussed in ref. [5].

The reaction $^{14}N(n,p)^{14}C$ is of great importance in NCT, with the biggest contribution to the energy deposition in brain tissue for neutrons with energies below 50 eV, in absence of ^{10}B [15]. However, as explained in ref. [5], some discrepancies with potentially crucial consequences for NCT were identified in the available nuclear data.

The quality of the data available for the $^{35}Cl(n,\gamma)^{36}Cl$ reaction in the resonance region limited the accuracy of the cross section determination. This has led to discrepancies in the cross section evaluations across the major libraries, evidenced in ref. [6]. The only measurement in the resonance region was performed using natural Chlorine [16], and the measurements of the cross section at the thermal point showed too large discrepancies for NCT dosimetry calculations, as shown in ref. [6].

3. – Experiments

3`1. $^{33}S(n,\alpha)^{30}Si$. – The measurement of the cross section was performed at n_TOF-EAR1 for the resonance region [17] and at n_TOF-EAR2 for neutron energies down to 0.01 eV [11]. In both cases, a setup of in-beam gaseous micromegas detectors [18] was used. Two important results were found: the $1/v$ behaviour below 10 keV, and a much higher area of the resonance at 13.5 keV than the one obtained in ref. [12], in agreement with the transmission measurement [13]. Fig. 1 (left) shows the combination of the data obtained in both experiments for the cross section measurement. The potential of ^{33}S as a cooperative target for NCT was evaluated in ref. [19] using the new n_TOF cross section data, where it can be seen that adding sulfur could be very appropriate for treating superficial tumors.

3`2. $^{14}N(n,p)^{14}C$ and $^{35}Cl(n,p)^{35}S$. – A combination of in-beam micromegas detectors and off-beam DSSSD detectors was used in our experimental setup [5] at n_TOF-EAR2. With the micromegas detectors collecting most of the statistics, the DSSSDs were used to study any possible anisotropy of the emitted protons in the most important resonances. The analysis of the data is an ongoing work; preliminary results of the yield are shown in fig. 1 (right), where cross sections are shown up to 100 keV. Our goal is to extend the neutron energy range up to 500 keV or even 1 MeV. In this experiment, the micromegas setup has proved to be suitable for measuring (n,cp) reaction cross sections for low energy charged particles (approximately 400 keV) in the neutron energy range which extends from thermal up to 100 keV.
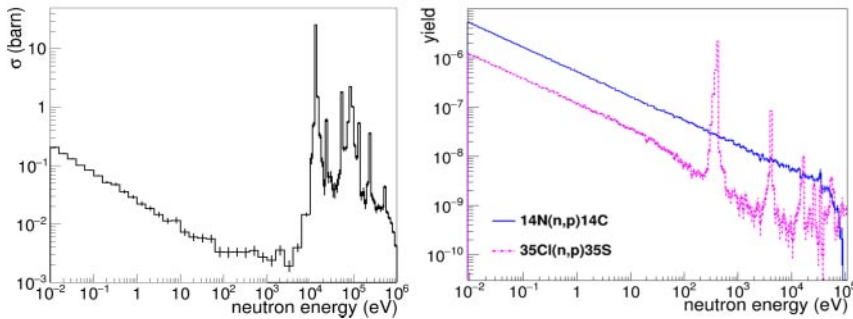

Fig. 1. – Differential cross sections obtained at n_TOF using micromegas detectors: $^{33}S(n,\alpha)^{30}Si$ reaction (left); preliminary results for the $^{14}N(n,p)^{14}C$ and $^{35}Cl(n,p)^{35}S$ reactions (right).

3˙3. $^{35}Cl(n,\gamma)^{36}Cl$. – In order to measure the $^{35}Cl(n,\gamma)^{36}Cl$ cross section, four C_6D_6 liquid scintillators [20], widely used for capture measurements at n_TOF, were employed at n_TOF-EAR1. The data analysis of this experiment is at an early stage, but some of the $^{35}Cl(n,\gamma)^{36}Cl$ resonances have been already identified.

4. – Conclusions

NCT faces a new era due to the development of accelerator-based NCT facilities. There is room to improve its therapeutic outcome from many different perspectives, such as the investigation of alternative and cooperative isotopes to ^{10}B, or the improvement of dosimetric calculations, which requires accurate nuclear data that is not always available. For this reason, in recent years, important efforts have been made by the n_TOF Collaboration seeking to solve this lack of data by conducting experiments aimed to obtain the cross section of those reactions of interest for this therapy. Four reactions have been studied so far and the data analysis of some of them is a work in progress. The resulting nuclear data will, ideally, allow the NCT community to plan treatments capable of increasing the dose delivered to tumours, improving the chances of patient survival.

$$* * *$$

REFERENCES

[1]   KREINER A.J. *et al.*, Rep. Pract. Oncol. Radiother. **21** 95-111 (2016).
[2]   PORRAS I., Phys. Med. Biol. **53** L1 (2008).
[3]   PORRAS I. *et al.*, Appl. Radiat. Isot. **69** 1838-41.3 (2011).
[4]   ICRU Rep. **46** (1992).
[5]   PRAENA J. *et al.*, CERN Reports **CERN-INTC-2017-039** INTC-P-510 (2017).
[6]   PORRAS I. *et al.*, CERN Reports **CERN-INTC-2018-010** INTC-P-541 (2018).
[7]   RUBBIA C. *et al.*, CERN/LHC/98-02 (EET) (1998).
[8]   GUNSING F. *et al.*, Eur. Phys. J. Plus **131:37** (2016).
[9]   GUERRERO C. *et al.*, Eur. Phys. J. A **49**: 27 (2013).
[10] WEISS C. *et al.*, NIM A **799** (2015).
[11] SABATÉ-GILARTE M. *et al.*, EPJ Web of Conferences **146** 08004 (2017).
[12] WAGEMANS C. *et al.*, Nucl. Phys. A **469** 497-506 (1987).
[13] CODDENS G.P. *et al.*, Nucl. Phys. A **469** 480-96 (1987).
[14] SAYER R.O. *et al.*, Phys. Rev. C **73** 044603 (2006).
[15] GOORLEY J.T. *et al.*, Med. Phys. **29** 145-56 (2002).
[16] GUBER K. H. *et al.*, Phys. Rev. C **65** 058801 (2002).
[17] PRAENA J. *et al.*, Phys. Rev. C **97** 064603 (2018).
[18] CHARPAK G. *et al.*, Nucl. Instr. Meth. Phys. Res. A **478** 26-36 (2002).
[19] SABATÉ-GILARTE M. *et al.*, Rad. Prot. Dos. pp. 1-4 (2017).
[20] PLAG R. *et al.*, Nucl. Instrum. and Meth. A **496** 425-436 (2003).