HORIZON 2020

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D.2.11 Report on the production cross sections of beta+ emitters used for range verification in proton therapy (Carlos Guerrero, U. Sevilla)

Project: H2020 SANDA: Supplying Accurate Nuclear DAta for energy and non-energy applications
Work Package 2. New nuclear measurements for non-energy applications
Task 2.6. New data measurements for energy and non-energy applications
Task description: The task comprises three different measurements, all aimed at providing new data on production yields of β+ emitters of interest for range verification in proton therapy: production of long-lived emitters up to 18 MeV, production of long-lived emitters up to 200 MeV, and production of short-lived emitters up to 200 MeV.

1. Production of long-lived emitters up to 18 MeV

The measurements were carried out at the CNA (Seville, Spain) 18 MeV cyclotron. Thin targets of polyethylene, PMMA and Nylon were irradiated and the corresponding activity from ^{11}C and ^{13}N, both β^+ emitters, measured with a clinical PET scanner. The production yields were validated against the IAEA standard $^{63}Cu(p,n)^{53}Zn$ cross section. The data analysis was finalized within the first 18 months of SANDA. The results consist of the cross sections of 5 reactions at 14 energy values, between 4 and 18 MeV, each. The highlights of this work can be summarized as:

- Development of a new method to measure the production yield of β+ emitters induced by a beam of charged particles.
- Combination of multi-foil activation with detection of the annihilation radiation with a clinical PET scanner.
- Reactions studied up to 18 MeV: $^{14}N(p,\alpha)^{11}C$, $^{12}C(p,\gamma)^{13}N$, $^{16}O(p,\alpha)^{13}N$ and $^{16}O(p,3p3n)^{11}C$.

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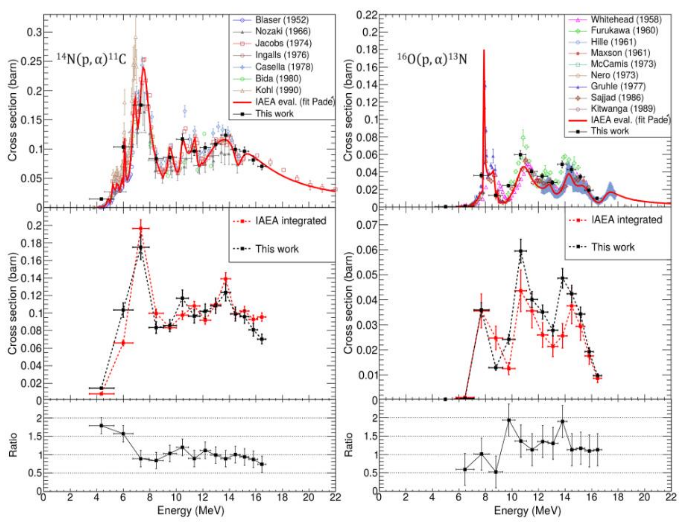

Fig. 9. Top: Selected data for the IAEA evaluation and recommended parametrization (fit Padé) for $^{14}N(p,\alpha)^{11}C$ (left) and $^{16}O(p,\alpha)^{13}N$ (right) reactions. Middle: Experimental and evaluated data integrated in the energy intervals of our measurement for $^{14}N(p,\alpha)^{11}C$ (left) and $^{16}O(p,\alpha)^{13}N$ (right). Bottom: Ratios of the obtained data sets with respect the evaluation for $^{14}N(p,\alpha)^{11}C$ (left) and $^{16}O(p,\alpha)^{13}N$ (right).

Figure 1. Top: selected data for the IAEA evaluation and recommended parametrisation (fit. Padé) for $^{14}N(p,\alpha)^{11}C$ (left) and $^{18}O(p,\alpha)^{13}N$ (right) reactions. Middle: experimental and evaluated data integrated in the energy intervals of the measurement for $^{14}N(p,\alpha)^{11}C$ (left) and $^{18}O(p,\alpha)^{13}N$ (right). Bottom: ratios of the obtained data sets with respect to the evaluation for $^{14}N(p,\alpha)^{11}C$ (left) and $^{18}O(p,\alpha)^{13}N$ (right).

The results have been published as: T. Rodríguez-González, C. Guerrero et al., "*Production yields at the distal fall-off of the β^+ emitters ^{11}C and ^{13}N for in-vivo range verification in proton therapy*", Radiation Physics and Chemistry 190 (2022) 109759 (DOI: 10.1016/j.radphyschem.2021.109759)

2. Production of long-lived emitters up to 200 MeV

The measurement up to 200 MeV require the use of a clinical beam, which is not available for research in Spain. Hence the researchers from Universidad de Sevilla established a collaboration with the WPE proton therapy center in Essen Germany. A first experiment was carried out in July 2020, using again targets of polyethylene, PMMA and Nylon that were irradiated with a pencil beam and then analyzed with a clinical PET scanner; a second one with improved targets took place in 2021. Overall, the results represent, to date, the most complete and accurate set of excitation functions for the production of light-positron emitters ^{11}C, ^{13}N and ^{15}O in proton induced reactions on human tissue up to 200 MeV. Seven excitation functions have been measured: ^{12}C(p,x)^{11}C, ^{14}N(p,x)^{11}C, ^{14}N(p,x)^{13}N, ^{14}N(p,γ)^{15}O, ^{16}O(p,x)^{11}C, ^{16}O(p,x)13N and ^{16}O(p,x)^{15}O up to 200 MeV of proton incident energy.

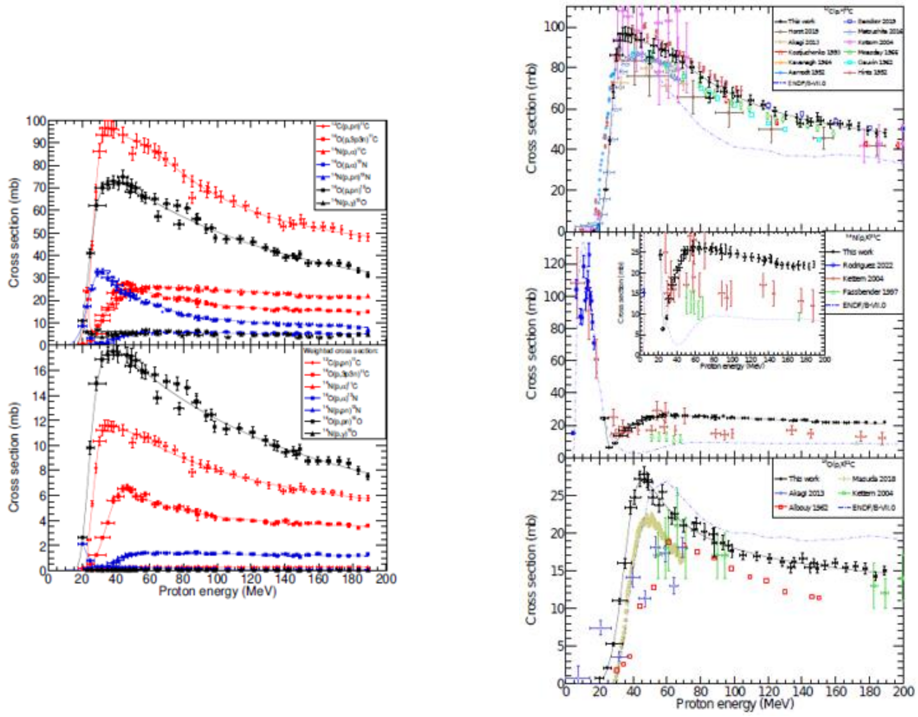

Figure 2.Left panel. Top: proton induced reaction cross section to produce ^{11}C, ^{13}N and ^{15}O in C, N and O. Bottom: proton induced reaction cross section to produce ^{11}C, ^{13}N and ^{15}O weighted by the C, N and O composition in the human body. Right panel. cross sections for the production of ^{11}C, ^{13}N and ^{15}O on C, N and O. Note that, although the original evaluated data correspond to the ENDF/B-VII.0 library, in order to cover the full energy range, the ICRU63 extrapolation has been included, which originates the change of style above 150 MeV.

The results have been accepted for publication in Nuclear Data Sheets: T. Rodríguez-González, C. Guerrero et al., "*Production of ^{11}C, 13N and ^{15}O in proton-induced nuclear reactions up to 200 MeV*", accepted for publication in Nuclear Data Sheet (Sept. 2022)

3. Production of short-lived (^{12}N, ^{29}P and ^{38m}K) up to 230 MeV

The measurement of short-lived ($t_{1/2}$<4s) isotopes requires measuring with a clinical beam but having the detection system in-situ. An added difficulty compared to the measurement on longer-lived ones, is that the material used as converter for the emitted positrons is also activated by the beam and hence produced a non-desirable background. The measurements to produce ^{12}N, ^{29}P and ^{38m}K from C, P and Ca targets took place in Fall 2021 at the Heidelberg proton therapy center (HIT) in Germany, with funding for Transnational Access via the H2020 HITRIplus project. The detection set-up consisted in two LaBr3 scintillators that looked at individual thin targets placed in the proton beam, which was pulsed in beam-on/beam-off intervals adjusted to the half-life of the corresponding isotope of interest (from milliseconds to a few seconds), as illustrated in Figure 3.

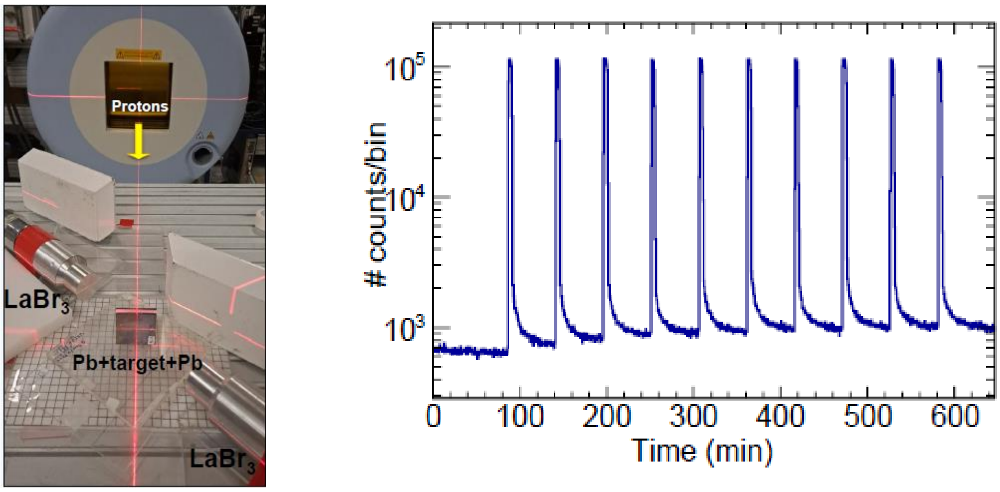

Figure 3.Left panel: photo of the setup. Right panel: time structure of the decays of the isotopes produced by the pulsed proton beam.

The experimental campaign was successful and the data analysis is currently ongoing. The expected results include the cross section corresponding to $^{12}C(p,n)12N$, $^{31}P(p,pnn)^{29}P$ and $^{40}Ca(p,ppn)^{38m}K$ from the reaction threshold up to 200 MeV.