Thick lead target exposed to 660 MeV protons: benchmark model on radioactive nuclides production and heat generation, and beyond

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Abstract. The benchmark is proposed on the basis of the first axial residue production distributions measurements in the thick Pb target irradiated with 660 MeV protons. Heating calculation during irradiation and decay heat assessment is foreseen as well. First benchmarking results with MCNPX2.5.0 and FLUKA2006.3 of residue production are presented. These new data from thick targets allow a consistent check of physics models with the predictions coming from microscopic residue cross sections (in thin lead target) over a wide energy range and the use of particle spectra simulations. Results obtained for thin targets data are consistent with this experiment and a combination of both sets of data could more constrain the INC models especially on the excitation energy of the nucleus before deexcitation. The main difficulties, data accuracy and contribution of emitted particles to residue production, are analysed and discussed in this work.

1 Introduction

One of the essential parts of ADS (or RIB) is the spallation target serving as the subcritical system external neutron source (or radioactive ion source). The study of ADS operation and maintenance includes also the analysis of the build-up and decay of the target radioactivity and heating. The heating resulting both from the beam particles and radioactive nuclides decay. This can be calculated partially with the use of standard computational tools such as MCNPX, FLUKA and others. However benchmarks on particle and residue production are needed to know efficiency of the different codes. Also the proper calculation of the spallation target heating, both during its exposition to the beam and after its switch off, is of importance for the designing of the XT-ADS and EFIT systems. With the above-mentioned objectives, some experiments were done and more are proposed, in the frame of EUROTRANS. The present proposed benchmark model is based on the earlier experiment done within the projects MUSE and SAD, in the Joint Institute of Nuclear Research in Dubna (Russia). In the experiment absolute activities of several long-lived radionuclides, generated in lead target during its irradiation with 660 MeV proton beam, were determined in 32 pieces of Pb samples distributed inside the target. Thus, the benchmark is oriented to compare simulation predictions based on different available codes and physical models with the experimental data. In the case of the target heating there are not yet available the respective experimental data and the benchmark will serve only for comparison of results from different calculation methods. Moreover, these new data from thick targets allow a consistent check of physics models with the predictions coming from microscopic residue cross sections (in thin lead target) over a wide energy range and the use of particle spectra simulations, known to be reliable. In practice, integration over the whole energy range of the product of the microscopic

Fig. 1. The experiment simplified geometry.

cross sections by the particle flux leads to residue activity predictions in the thick target. Also the combination of the data from thin and thick target should show if the number of energetic particles emitted by the models is good or not. The main difficulties, data accuracy and contribution of emitted particles to residue production, will be analysed and discussed in this work.

2 Benchmark description

2.1 Experiment description

The experiment described earlier in details in [1] was devoted to the measurement of axial distributions of radionuclide activity induced in Pb target. It was conducted at the Dzhelapov Laboratory of Nuclear Problems in JINR Dubna (Russia). For assessing this distribution the spallation target was built of several pieces of 0.5 cm to 5 cm thick cylindrical parts and of 32 pieces of 1 mm thick lead samples, all 80 mm in diameter (fig. 1). The Pb samples were placed along the target in such a way that to best reproduce the characteristic distribution of proton induced activity of Bi radionuclides (evaluated earlier with the use of LAHET code). The total length of the target was 308 mm.

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Fig. 2. (a), (b) Example of ^{207}Bi experimental and simulated results.

The following values of the parameters were applied in the experiment:

- Proton energy: $E_p = 660 \pm 4$ MeV
- Max. proton yield: $I_{p,\max} = 3 \times 10^{10}$ p/s
- Irradiation time: $t_i = 530$ min
- Total number of protons: $2.6 \pm 0.2 \cdot 10^{14}$ (the proton beam time walk in 10 minutes intervals is available)
- End of irradiation: 24th Nov. 2001, 6:00 hrs GMT.

2.2 Benchmark goals

2.2.1 Radioactive nuclides production rate and particles spectra calculations

Production rates of ^{46}Sc , ^{59}Fe , ^{60}Co , ^{65}Zn , ^{75}Se , ^{83}Rb , ^{85}Sr , ^{88}Y , ^{88}Zr , ^{95}Nb , ^{95}Zr , ^{102m}Rh , ^{102}Rh , ^{110m}Ag , ^{121m}Te , ^{121}Te , ^{139}Ce , ^{172}Hf , ^{172}Lu , ^{173}Lu , ^{175}Hf , ^{183}Re , ^{185}Os , ^{194}Au , $^{194m2}\text{Ir}$, ^{195}Au , ^{203}Hg and ^{207}Bi in individual samples and for the whole target will be simulated and compared with experimental results. Exemplary results for ^{207}Bi from LAHET [2] and FLUKA [3,4] are shown on figures 2(a), (b). Flux and spectra calculation of protons, neutrons, alpha particles and negative pions, average for a 1 mm thick slice, along the Pb target in 1 cm steps, starting from the front surface of the target are requested as well.

2.2.2 Heat generation rate

There was no experiment conducted within this research resulting in respective measurement of heat generation or temperature distribution in the target. Therefore the conditions are purely assumed from the point of view of convenient modelling and calculations. The axially directed constant 1 mA beam has a gaussian distribution. The FWHM of the proton current gaussian density distribution is equal to 10 mm. The target is exposed for 10^7 s. The pure lead target of 11.34 g/cm³ density and $\Phi 80 \times 350$ mm dimensions is divided into a number of parts to demonstrate the distributions of calculated variables. This division will be defined in the MCNPX input supplied with benchmark description. The power density of the released heat [W/cm³] averaged over the whole target and its distribution in the cells defined in the input should be calculated. Contribution to these values from the main participating particles i.e. protons, photons, alphas, for protons also differentiated between primary and secondary ones will be requested. Also the power density of the released decay heat [W/cm³] averaged over the whole target for the cooling times equal to: 10^2 s, 10^3 s, 10^4 s, 10^5 s, 10^6 s, 10^7 s and 10^8 s will be of interest as well.

3 Comparison between calculations and data

Spallation models available in MCNPX2.5.0 [5] have been already benchmarked on particle production (thin and thick targets) [6] and residue production [7], but only with thin targets. This experiment [1] is the first one which allows to test these models on residue production in thick target according to deepness. Calculations performed to reproduce the specific activities have been done with MCNPX2.5.0 followed by the evolution code CINDER'90 [8]. Bertini-Dresner, INCL4-Abla, Isabel-Abla and CEM2k are the spallation models used in MCNPX. For each model 20 millions events have been run.

We show with the figures 3–8 some typical results we obtained for: a fission fragment (^{95}Nb – fig. 3), two nuclei produced after evaporation, one far from the target (^{172}Lu – fig. 5) and the other one closer (^{183}Re – fig. 4), and finally a nucleus with a mass similar to the target (^{207}Bi – fig. 6).

A shadow appears in the region where the number of nuclei responsible of the specific activity for the studied nucleus is lower than ~ 100 . These nuclei are the nucleus itself and its parents.

Neutron rich fission fragments (fig. 3) are quite well reproduced by INCL4-Abla and Isabel-Abla whereas CEM2k and Bertini-Dresner underestimate them. This is still true for Bertini-Dresner with the neutron poor fission fragments (figure not shown), but less for CEM2k. If Isabel-Abla gives still the same good results, INCL4-Abla has a rate a little bit too low.

Isabel-Abla is the best model to reproduce the nuclei obtained after evaporation. If INCL4-Abla is very good also when the evaporation chain is short (fig. 4), the quality decreases when the chain becomes longer and longer (fig. 5). Bertini-Dresner always overestimates and CEM2k is a rather good candidate.

Fig. 3. Specific activities of a fission fragment (^{95}Nb) inside a lead target. Four spallation models within MCNPX2.5.0 (INCL4-Abla, Isabel-Abla, Bertini-Dresner and CEM2k) are compared to data.

Fig. 6. Specific activities of a residue with a mass similar to the target (^{207}Bi). For details see figure 1.

Fig. 4. Specific activities of an evaporation residue far from the target (^{183}Re). For details see figure 1.

Fig. 5. Specific activities of an evaporation residue far from the target (^{172}Lu). For details see figure 1.

For ^{207}Bi (fig. 6) the results depend strongly which region is considered: before the Bragg peak or the Bragg peak itself. All models give very good results before the peak, especially INCL4-Abla and Isabel-Abla, but concerning the peak, these two models could give much better results than CEM2k and Bertini-Dresner, if the four models did not show this peak ~ 5 mm beyond the one given by the data.

Figure 7 summarizes the calculation/data ratios for the nuclei where the statistics is good enough. Isabel-Abla is the best model within a factor of ~ 2 . INCL4-Abla gives almost the same results except for the nuclei far from the target and obtained by evaporation (factor ~ 3) and for the rather neutron

Fig. 7. Summary of the calculation/data ratios inside the target for the nuclei where the statistics obtained by the models is good enough (better than ~ 100 events). Models shown are INCL4-Abla, Isabel-Abla, Bertini-Dresner and CEM2k.

Fig. 8. Total amounts of ^{95}Zr are plotted from two sets of data. In red results come from this experiment in thick target and in blue the results are the convolution of microscopic residue production cross sections over a wide energy range, obtained by R. Michel in thin targets, with particle spectra from INCL4-Abla calculations. Different contributions for this latter case have been extracted.

poor fission products (but still within a factor of 2). If Bertini-Dresner overestimates every time fission products (factor of 3 and even worse), CEM2k is better for the neutron poor fission fragments (similar results as INCL4-Abla) than for the neutron rich ones (factor of 4).

4 Consistency between thin and thick data sets and beyond...

Residue production cross sections on a thin lead target were measured over a wide projectile energy range with proton beams [9] and also with neutron beams, but over a smaller range and for very few residues [10]. So we show below (fig. 8) the quantity of ^{95}Zr nuclei produced within the conditions of the experiment done at Dubna with a thick lead target (red points and curves), and the same quantity obtained via the residue production cross sections with a convolution by the particle spectra calculated with a spallation model (here INCL4/Abla).

In an ideal world (*experimentally speaking*), the differences between the two data sets should be due to the not exact numbers of emitted particles computed (for the associated spectra). Then, fitting these numbers on the “thick target” data, the energy released during the intra-nuclear cascade would be corrected and the excitation energy of the nucleus undergoing evaporation and/or fission also.

To reach this goal one needs, first, to reduce the uncertainties concerning the microscopic cross sections, principally $\sigma_n(E)$, and to get more data, and secondly, to increase the role of the secondary particles (radial measurements could be the solution and fortunately an experiment has been done, for others purposes, at Dubna and is being analyzed).

5 Summary, discussion of results, conclusions

The benchmark is proposed on the basis of the first axial residue production distributions measurements in the thick Pb target irradiated with 660 MeV protons. Heating calculation during irradiation and decay heat assessment is foreseen as well. First benchmarking results with MCNPX2.5.0 and FLUKA2006.3 of residue production are presented. These new data from thick targets allow a consistent check of physics models with the predictions coming from microscopic residue cross sections (in thin lead target) over a wide energy range and the use of particle spectra simulations. Results obtained for thin targets data are consistent with this experiment and a combination of both sets of data could more constrain the

INC models especially on the excitation energy of the nucleus before deexcitation. To achieve this goal we need much accuracy on microscopic residue production cross sections and data from an experiment where the contribution of the secondary particles is much more important.

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