Contribution of the direct electronuclear processes to thin target activation*

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Abstract

Contribution of the direct inelastic interactions of electrons with nuclei to the neutron production and to the material activation radiation source terms may become significant or even critical in certain conditions at high-energy electron accelerators. At Jefferson Lab's CEBAF accelerator, these processes are often responsible for the significant portion of the radiation source terms in the experimental Halls. New experimental data on thin nuclear target activation by the few-GeV electron beams recently obtained at JLab help to evaluate the contribution of the direct electronuclear processes to thin target activation. A model description of the process based on the Equivalent Photon Approximation method, the corresponding Monte Carlo simulation algorithm, and the (limited and simplified) method of implementing these processes in the FLUKA code are presented.

Introduction: Thin targets in electron beams

The ability to evaluate material activation by the electron beams at High Energy Electron Accelerators is a practical necessity serving the purposes of evaluating radiation environment, planning work, decommissioning efforts.

Thin targets present a special class in such evaluations, due to the need to take into account not only nuclear interactions of real photons, but also the direct electronuclear interactions. Impact of these processes may be considered negligible in descriptions and simulations of fully developed electromagnetic or hadronic particle cascades in thick targets and beam dumps. However, in the cases of electron beam interactions in targets thinner than a few percent of a radiation length, the direct electronuclear processes become significant.

Beam interactions in vacuum windows, experimental targets, air gaps, residual gasses in the beam lines – all serve as examples in which electronuclear processes may dominate.

Electronuclear processes

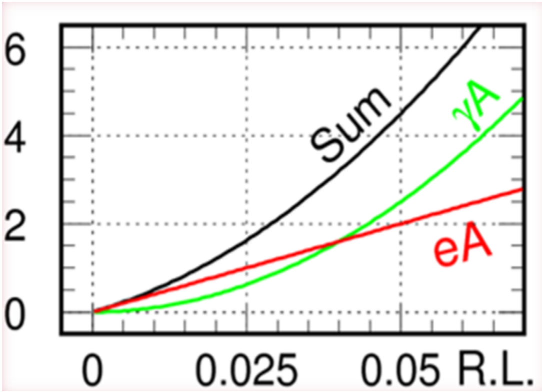
At transfers of sufficiently high-energy and momentum electrons can scatter off parts of the target nucleus. In the processes of quasielastic electron scattering electrons interact directly with weak-bound nucleons or nuclear fragments and may knock them out of the nucleus. The deep inelastic scattering processes generally leave enough excitation energy to break up the target nucleus.

In direct electronuclear processes, electrons break up the nucleus without the need to produce real bremsstrahlung photons to invoke subsequent photonuclear reactions.

The electronuclear reactions are therefore direct one-stage reactions with their rates linearly dependent on the target thickness as opposed to the two-stage photonuclear reactions, dependent on the target thickness quadratically. For sufficiently thin targets the electronuclear reactions will therefore constitute a dominating term in hadron production.

Figure 1 illustrates the relative importance of the electro- and photoproduction in thin targets, as a function of the target thickness. Electroproduction starts to dominate neutron production in thin targets at thicknesses below approximately 4% radiation length.

Figure 1. Neutron yields or target activation by the high-energy electron beams, in arbitrary units, as a function of target thickness in radiation lengths



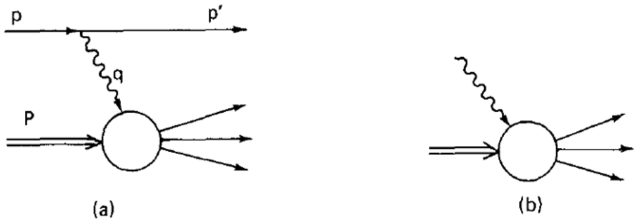
The relative importance of electronuclear and photonuclear (bremss.) contributions to the GDR neutron yield was evaluated as Y_{total}/Y_{bremss} = (1 + 0.04/T) in [1] (T is the target thickness in Radiation Lengths).

Simulation tools

The algorithm for Monte Carlo simulation of the electronuclear reactions was first implemented in 1995 [2]. Since that time the simulation tool based on GEANT3 has been successfully used at JLab in the radiation background calculations. The electronuclear processes have since been implemented in Geant4 (in 2000-2001) and in MARS (around 2003).

The algorithm is based on implementation of the equivalent photon approximation (EPA) method as described in [3]. More details, discussion, and the description of the algorithm can be found in [4]. The electromagnetic interaction of fast charged particles with nuclei can be reduced to the effective interaction of equivalent flux of photons distributed with density $n(\omega)$ on a frequency spectrum. Figure 2 illustrates the connection between the two processes, showing in (a) the interaction of the incident charged particle (for example, electron) with the target nucleus via the dominating one-photon exchange mechanism, which can be related with (b) the interaction of real photons of the same energy with the same target.

Figure 2. Diagrams for electroproduction (a) and photo-absorption (b)



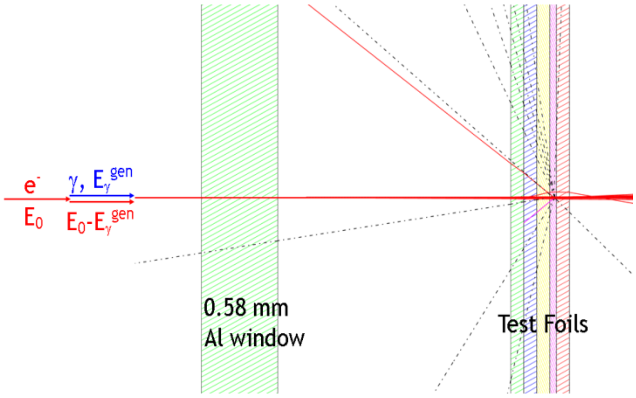
The brief description of the EPA algorithm for electrons as originally implemented within the GEANT3 Monte Carlo Simulation code is as follows:

- At each step of the simulated cascade, the electron is represented as carrying a collinear flux of equivalent photons distributed according to dn(ω) (Equation 6.17b of [3]) in the range of ω from the threshold energy E_{thr} up to the electron energy E_e.
- One "virtual" equivalent photon is generated with an energy ω_v in accordance with the spectrum dn(ω).
- The distance to the next nuclear interaction point of this photon (considered as real) is generated according to its photonuclear cross section, multiplied by the flux factor (the total flux is obtained by integrating dn(ω) from E_{thr} to E_e).
- If this generated point happens to be the closest among all of the electron interaction candidates at the step, then the photon interaction is generated, producing secondary particles and the electron is continuing in the cascade with decreased energy. If other electron interaction process wins, then the virtual equivalent photon is discarded.

Foil activation experiment at JLab

To observe and characterise the contribution of the direct electronuclear processes we have conducted the experiment on foil activation by high-energy electron beams at 2.3 and 3.4 GeV [5]. The schematic of the foil activation set-up is shown in Figure 3. After passing through the experimental target, the electron beam was bent in magnetic field, crossed thin aluminum exit window and was then directed into the set of test metal foils of different materials: aluminum, copper, niobium, lead, and stainless steel. These front foils were subject to mostly direct electron beam, with a small addition of gammas produced in the exit aluminum window. As a reference point to these measurements, we used a symmetric set of back test foils positioned downstream of the first set, and after a thick (1.25 cm) tungsten plate. All parameters of the irradiation were recorded, and after the runs all test foils were analysed using methods of gamma spectroscopy to measure amounts of the various radioactive isotopes produced. Detailed data on multiple isotopes are presented in [5]. For the pupose of this work, only a few representative and most reliably measured isotopes are used.

Figure 3. Schematic of the thin foil activation experiment at JLab, together with the diagram for the simplified model of equivalent photon approximation describing the electronuclear interaction contribution to foil activation



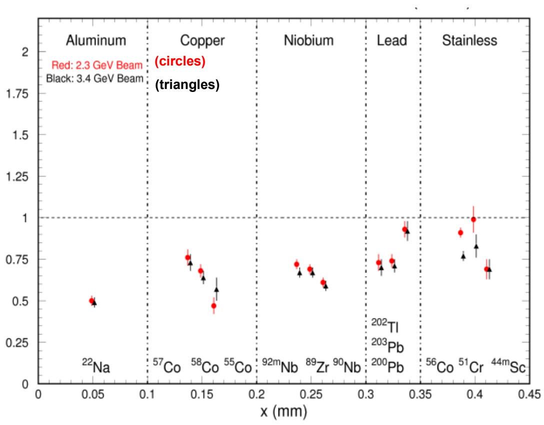
Comparison between the front set of foils and the back set of foils allows evaluating the contribution of the direct electronuclear mechanism of isotope production. The front set is irradiated directly by the beam electrons, and also by the small number of real photons produced in the aluminum exit window, plus by the photons returning from the tungsten block. The foils in the back set are placed inside a well-developed electromagnetic cascade in tungsten, where the real photonuclear reactions dominate.

Simplified electronuclear algorithm for FLUKA

The mechanism of real photonuclear reactions is implemented in FLUKA [6], thus the irradiation of the back foils can be simulated using the code, and can be used as a reference. To model the activation of the front set of foils, we have introduced the simplified model of direct interaction of beam electrons with target nuclei, implemented as a FLUKA user routine.

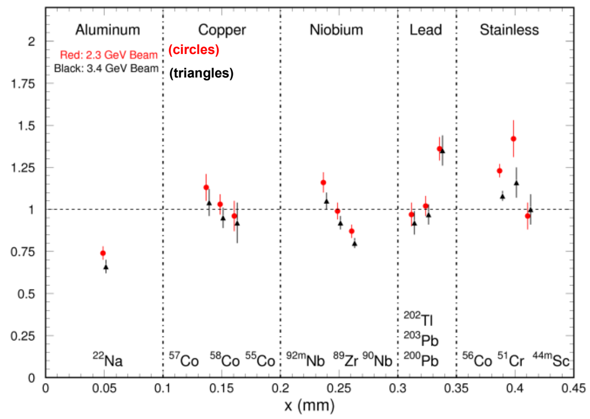
In this method, equivalent photons with correct energy spectrum are added as real photons to the beam electrons in proportion, conserving energy, as illustrated in Figure 3. The method approximates the general EPA algorithm for Monte Carlo simulations in the simple case of a thin target set at the beam entry point. Because of the energy conservation, the subsequent electromagnetic cascade is practically not disturbed.

Figure 4. FLUKA/Measurement ratios in the front foil set with eA *Off*



Figures 4 through 7 present the results of comparison between the measurements of the selected isotopes' production in different materials, and the FLUKA model simulations, both without („eA Off") the electronuclear algorithm, and with it ("eA On"). The results are presented as ratios FLUKA/Measurement (Figures 4,5), and the "ratios of ratios" (Figures 6,7), that is the ratios of the FLUKA/Measurement values between the front and the back set of foils. The abscissa is shown as the cumulative thickness of the five foils in mm as they were installed in the set. The radioactive isotopes selected for comparison are indicated at the bottom of the plot, corresponding to the foil placement. The 2.3 and 3.4 GeV data sets are distinguished by the symbols and colours.

Figure 5. FLUKA/Measurement ratios in the front foil set with eA *On*



Overall comparison of the measurements with FLUKA simulations for the selected isotopes generally shows a very good agreement (within 25%) for the back foil set as discussed in [5], both in "eA Off" and "eA On" simulations. In the front foils, without the direct electronuclear production contribution the simulation is systematically lower than measurements by 25-50%. Adding the direct electronuclear production removes this systematic difference.

"Ratio of Ratios" plots (see Figures 6,7) allow removing part of a systematic difference between the FLUKA model and the measured data, which might be expected to be the same for the front and the back set of foils, demonstrating more clearly the necessity to introduce direct electroproduction mechanism in the Monte Carlo simulation code.

Figure 6. Ratio of FLUKA/Measurement ratios in the front foil set to the back foil set, with eA *Off*

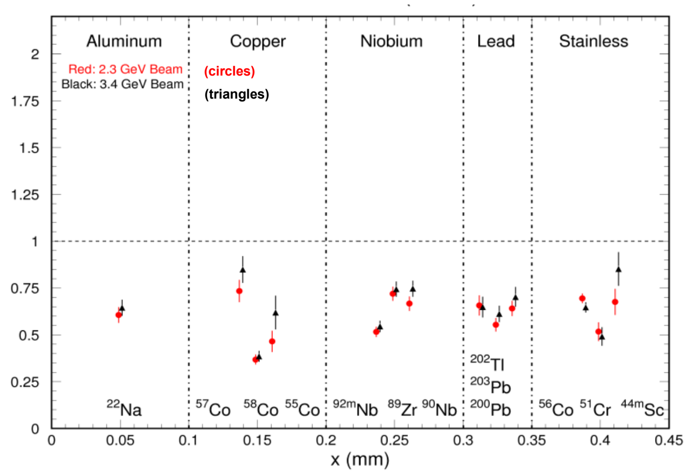
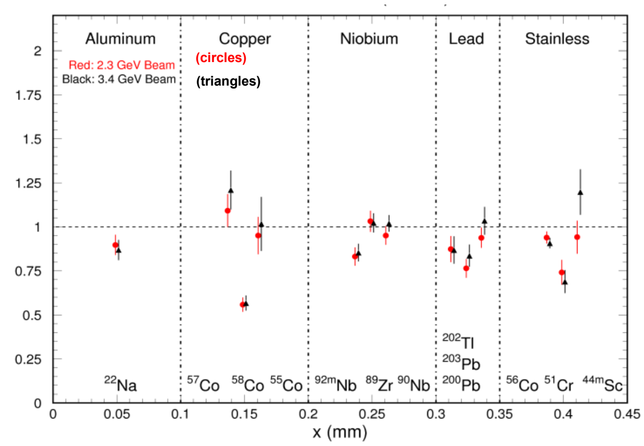


Figure 7. Ratio of FLUKA/Measurement ratios in the front foil set to the back foil set, with eA *On*



Summary and conclusions

Radioactive isotope production by 2.3 and 3.4 GeV electron beams in thin metal foils made of aluminium, copper, niobium, lead, and stainless steel has been measured in two characteristic placements of the foils near the beam dump absorber. One set of the foils was placed directly on the beam at the dump entrance, in an attempt to observe activation processes due to the direct interactions of high-energy electrons with nuclei. The second set was placed around the maximum of the E-M shower in the body of the dump as a reference point, where the dominant contribution to the nuclear disintegration processes comes from the real photons in the well-developed electromagnetic cascade. The concentration of the radioactive isotopes after irradiation was measured using the methods of gamma spectroscopy, and then compared with the results of realistic simulation of the setup using FLUKA Monte Carlo.

The comparison indicated that FLUKA in the standard configuration reproduces well radioisotope production in the second set of the foils in the maximum of E-M cascade. At the same time, it underestimates by 25-50% the production in the first set, which is subject to the direct electron beam impact. By introducing the simplified model of direct interaction of beam electrons with the target nuclei, we were able to reproduce the observed increase in the isotope production. Thus we report strong experimental evidence for the need to include the direct electronuclear production model in the standard set of Monte Carlo simulation tools. Important applications of such calculation tool would include material activation and neutron source term evaluations in high-energy electron beam interactions with thin vacuum windows, experimental targets, air gaps in the beam lines, etc.

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References

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