Contribution of the Direct Electronuclear Processes to Thin Target Activation*

SATIF-12

***P. Degtiarenko*, G. Kharashvili,** *Jefferson Lab, Newport News, VA 23606, U.S.A.*

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 obtained at JLab recently help to evaluate the contribution of the direct electronuclear processes to the 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.

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, and more.

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 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

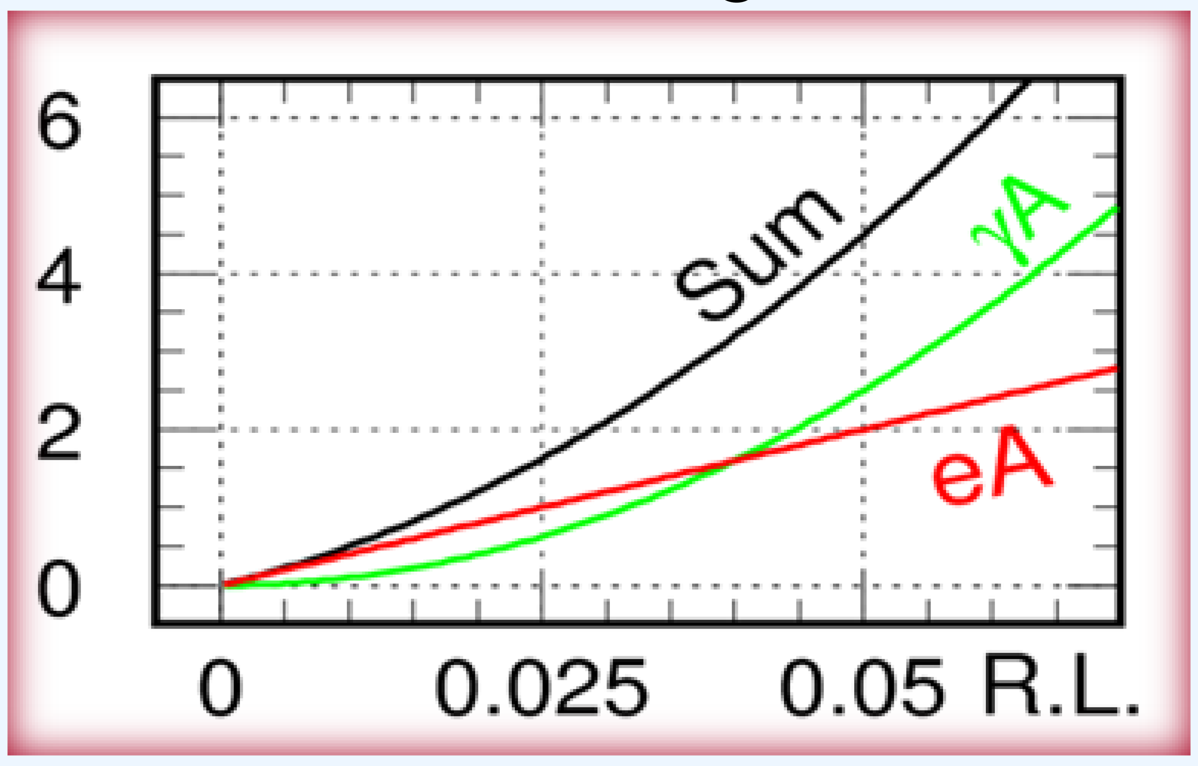
At sufficiently high energy and momentum transfers electrons can scatter off the parts of the target nucleus. In the processes of Quasielastic Electron Scattering electrons interact directly with weak-bound nucleons or nuclear fragments and may knock them out of the nucleus. The Deep Inelastic Scattering 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 the 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.

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

Neutron Yield vs. Target Thickness



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 is being successfully used at JLab in the radiation background calculations. The electronuclear processes were since implemented in geant4 (in 2000-2001) and in MARS (around 2003).

The algorithm is based on implementation of the Equivalent Photon Approximation method as described in ([3]).

$$d\sigma_{ep} = \sigma_\gamma(\omega)\,dn$$
$$(E - \omega \gg m_e)$$

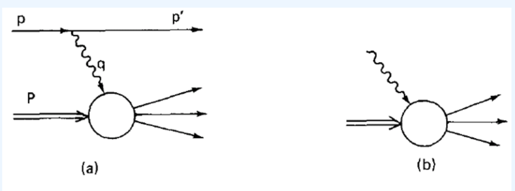


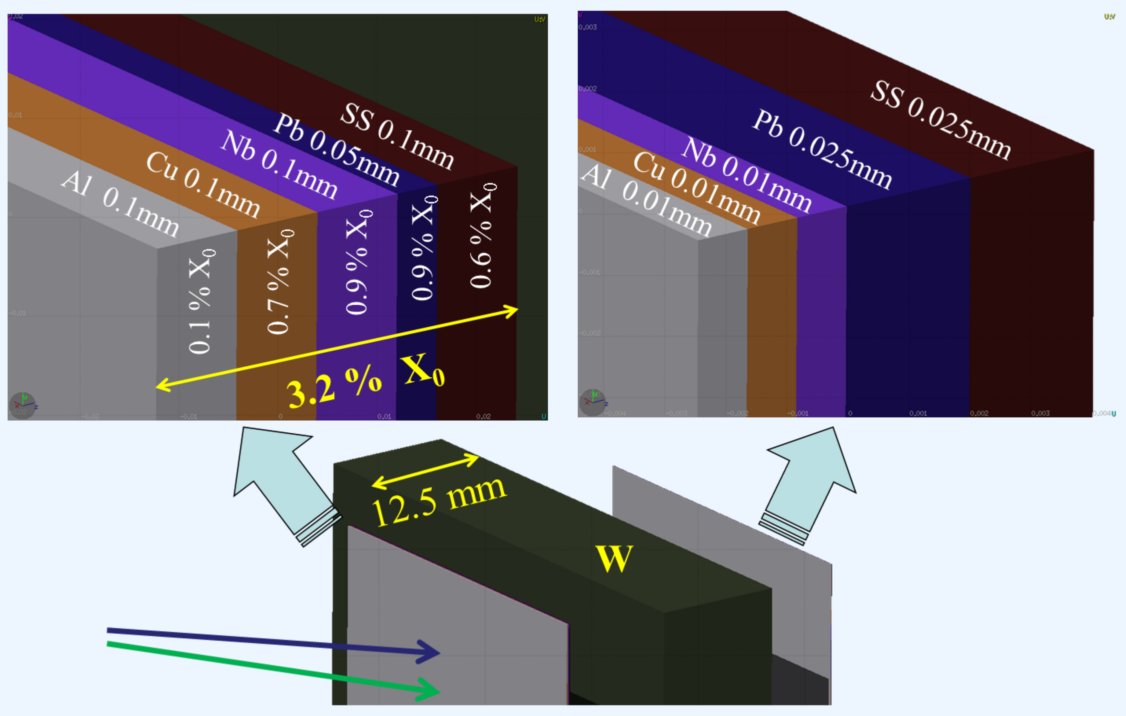
Fig. 35. Electroproduction and photo-absorption.

$$d\sigma = \sigma_\gamma(\omega)\,dn(\omega); \qquad (6.17a)$$
$$dn(\omega) = \int_{q^2_{min}}^{q^2_{max}} dn(\omega, q^2) = N(\omega)\,d\omega/\omega;$$
$$N(\omega) = \frac{\alpha}{\pi}\left[\left(1 - \frac{\omega}{E} + \frac{\omega^2}{2E^2}\right)\ln\frac{q^2_{max}}{q^2_{min}} - \left(1 - \frac{\omega}{2E}\right)^2 \ln\frac{\omega^2 + q^2_{max}}{\omega^2 + q^2_{min}} - \frac{m_e^2\omega^2}{E^2 q^2_{min}}\left(1 - \frac{q^2_{min}}{q^2_{max}}\right)\right]. \qquad (6.17b)$$

More details, discussion, and the description of algorithm can be found in ([4]).

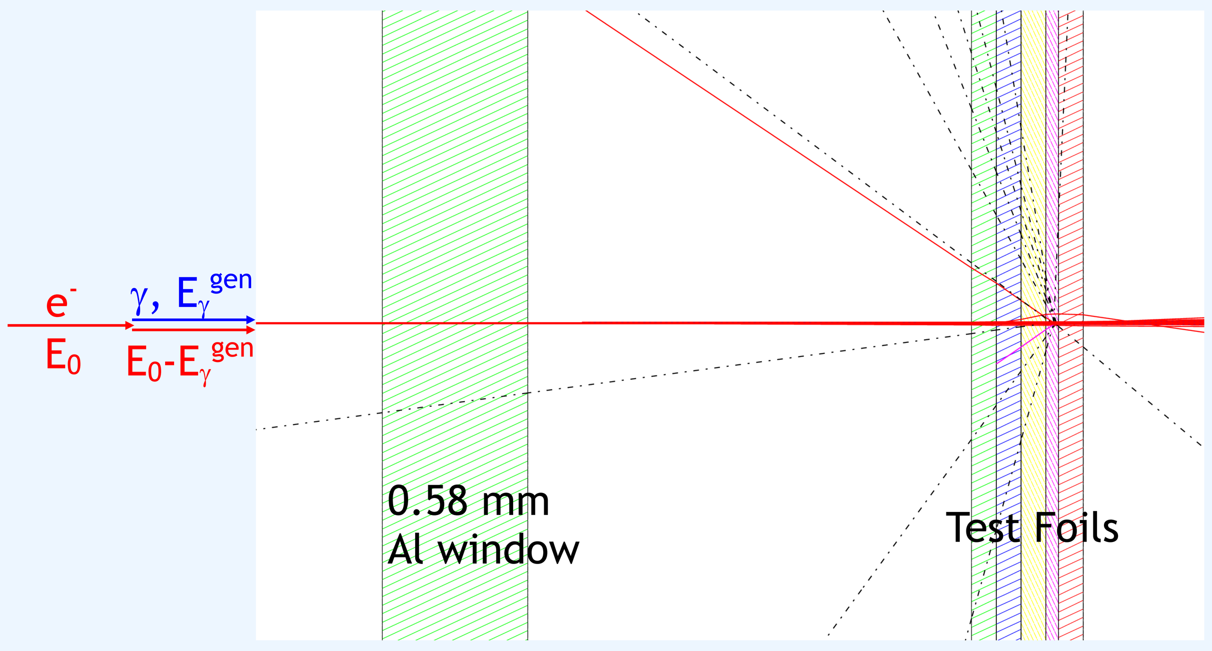
Foil Activation Experiment at JLab

To observe and characterize 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].

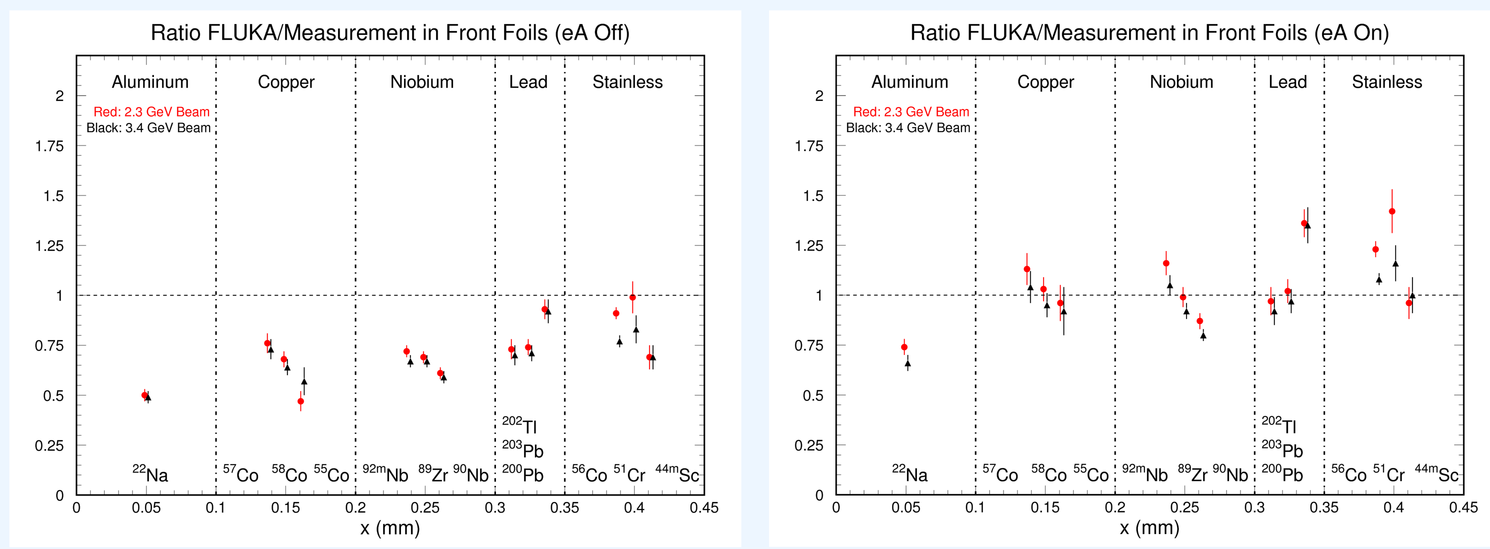


Simplified eA Algorithm for FLUKA[6]

We introduce the simplified model of direct interaction of beam electrons with target nuclei, implemented as a user routine. Equivalent gammas with correct energy spectrum are added to beam electrons in proportion, conserving energy.



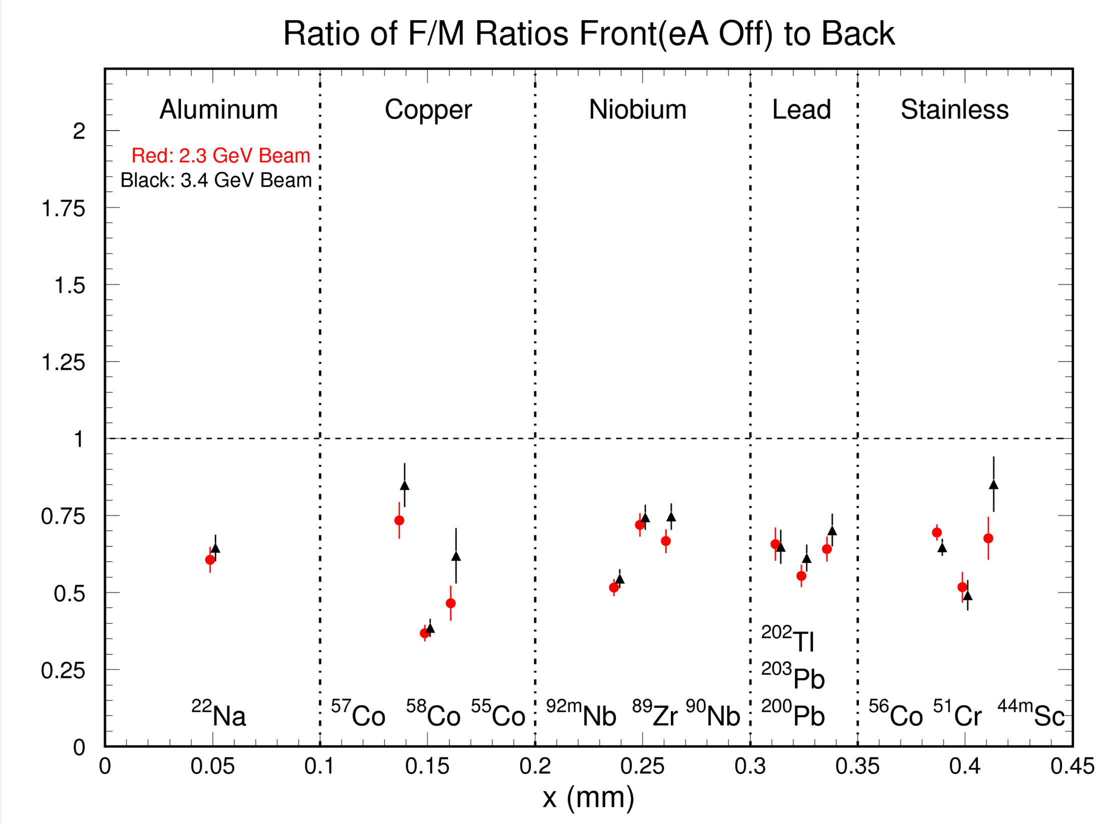
Selected Isotopes: FLUKA / Measurement Ratios

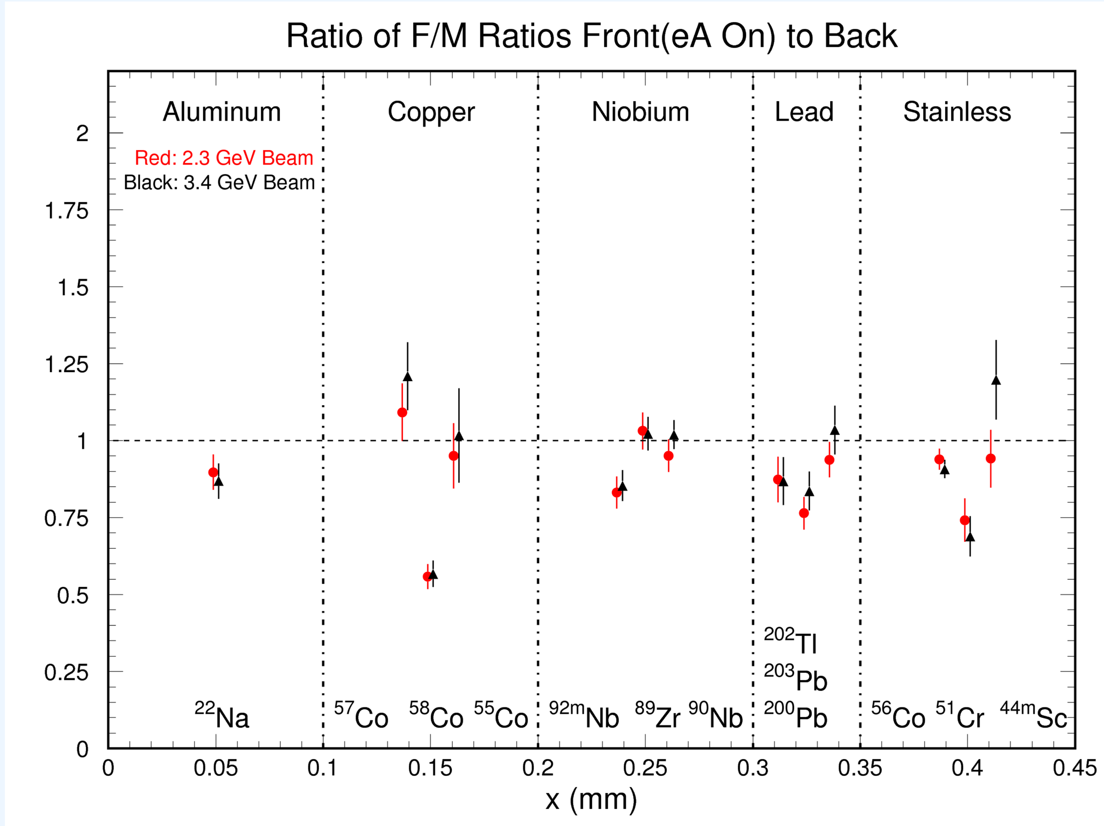


Abscissa corresponds to the foil placement in the assembly

Results

Direct electronuclear production of isotopes adds 25-50% to the activation of the front foils in this experiment.





Summary

Radioactive isotope production by 2.3 and 3.4 GeV electron beams in thin metal foils made of Aluminum, 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, and 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 is coming 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.

Conclusions

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. 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 the 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.

References

1. *X. Mao, K. R. Kase, and W. R. Nelson*, SLAC-PUB-6628, January 1996
2. *P. Degtyarenko and Geoff Stapleton*, SARE-2, CERN, 9-11 October 1995
3. *V.M. Budnev, I.F. Ginzburg, G.V. Meledin and V.G. Serbo*, Physics Reports 15, no.4 (1975) 181-282
4. *P. Degtiarenko, "Electronuclear Interactions in FLUKA"*, 2nd FLUKA Advanced Course and Workshop - Vancouver 2012 (*September 15-20, 2012*)
5. *G. Kharashvili*, Presentation at this conference
6. A. Ferrari, P.R. Sala, A. Fasso`, and J. Ranft, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773

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