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Estimate of production of medical isotopes by photo-neutron reaction at the Canadian Light Source

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ABSTRACT

In contrast to conventional bremsstrahlung photon beam sources, laser backscatter photon sources at electron synchrotrons provide the capability to selectively tune photons to energies of interest. This feature, coupled with the ubiquitous giant dipole resonance excitations of atomic nuclei, promises a fertile method of nuclear isotope production. In this article, we present the results of simulations of production of the medical/industrial isotopes ^{196}Au, ^{192}Ir and ^{99}Mo by (γ,n) reactions. We employ FLUKA Monte Carlo code along with the simulated photon flux for a beamline at the Canadian Light Source in conjunction with a CO_2 laser system.

1. Introduction

In recent years, there has been a growing interest in developing new methods of production of medical isotopes. This led to several proposals of new nuclear reactors and accelerator based isotope production facilities [1–3] in Canada as a possible replacement of NRU reactor that is planned to be decommissioned in 2016. It is to be noted that the early University of Saskatchewan proposal [1] called for a multipurpose reactor, which could take a few years before it is built and commissioned. Therefore currently alternative methods for production of medical and industrial isotopes are being employed at Canadian Light Source (CLS). Similar to the development in Sherbrooke, [2] proton beams from a cyclotron facility are used; however an isotope produced by this method, ^{99m}Tc by use of ^{100}Mo$(p,2n)$ reaction, has a short half-life $T_{1/2}=6.6$ h. Therefore other methods are being investigated for production of ^{99}Mo, a radionuclide with a half-life ten times longer (2.75 days), which decays to ^{99m}Tc.

1.1. Giant dipole resonance

A glance at the nuclear data tables will convince one that several medical isotopes can be produced using photon-nuclear reactions via the giant dipole resonance (GDR) [4] decay by emitting neutrons. In Fig. 1, the latest measured [5,6] cross sections for $(p,2n)$ reaction (^{100}Mo$\rightarrow$^{99m}Tc), are compared with cross sections for photo-nuclear (γ,n) reactions for ^{99}Mo (^{100}Mo$\rightarrow$^{99}Mo) [7], ^{192}Ir (^{193}Ir$\rightarrow$^{192}Ir) [8] and ^{196}Au (^{197}Au$\rightarrow$^{196}Au) [8]. Some earlier cross section data of ^{100}Mo$(p,2n)^{99m}$Tc differ from the data of Ref. [5,6] by a factor of two.

The noteworthy feature in Fig. 1 is a maximum cross section at around 14 MeV ($\approx 77_{*}A^{1/3}$ MeV [4], where A is atomic mass) excitation with a width (FWHM) of about 5 MeV ($\approx 23_{*}A^{-1/3}$ MeV [4]). Thus, one should expect enhanced probabilities for the respective (γ,n) photo-neutron reactions to occur and both photo-nuclear reactions could be used for production of the respective medical isotopes.

We presented some examples of calculations previously [10] to compare production of ^{99m}Tc isotope by proton beam with the application of a gamma ray beam for ^{99}Mo production. The production of Iridium-192, used for industrial applications, can be done by (γ,n) reaction with ^{193}Ir (natural abundance~63%) as the target material.

We explore here the modern photon beam facilities, such as the laser backscatter systems at the electron synchrotron sources at CLS, for possible use to produce photons at the required energy. The unique features of the resonant photo-nuclear isotope transmutations produced by laser photons scattered off GeV electrons have been well described before in Ref. [11]. Along the same lines, the Prairie Isotope Production Enterprise (PIPE) [3] called for a photon induced reaction, ^{100}Mo$(\gamma,n)^{99}$Mo, but propose using bremsstrahlung radiation from an electron linear accelerator. The idea is based on the work done at Idaho National Laboratory in the 1990s. Some comparison between these two methods is given in Section 2 using Monte Carlo simulations (FLUKA [12,13] code).

This article describes the preliminary Monte Carlo simulations (using FLUKA [12,13] code) for the production of ^{99}Mo, ^{196}Au and

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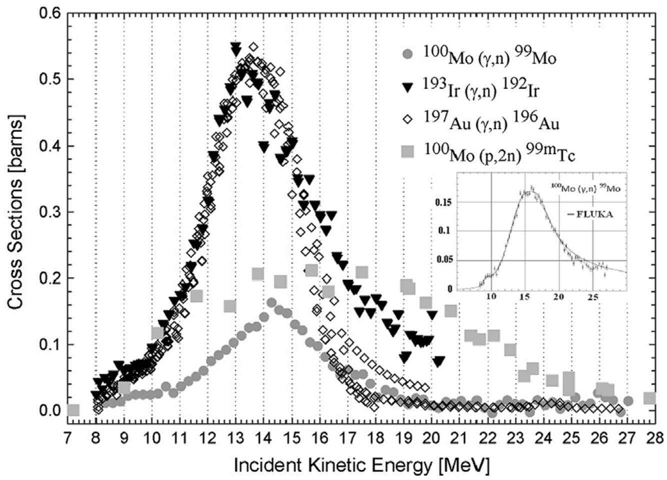

Fig. 1. Cross sections for ^{100}Mo (γ,n) [7], (p,2n) [5,6] and ^{193}Ir (γ,n) [8] ^{197}Au [9] reactions versus incident beam energy. Data are taken from http://www.nndc.bnl.gov. In the inset solid line represent used in FLUKA code the respective cross sections for ^{100}Mo (γ,n).

^{192}Ir isotopes, which find extensive applications in medicine. Also, simulations for proposed laser backscatter parameters in context with the Canadian Light Source are described on the example of production of ^{99}Mo, ^{192}Ir and ^{196}Au.

1.2. FLUKA simulation

FLUKA (FLUktuierende KAskade) is a fully integrated Monte Carlo simulation package for the interaction and transport of particles and nuclei in matter [12,13]. It is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications spanning from proton and electron accelerator shielding to target design, calorimetry, activation, dosimetry, detector design, accelerator driven systems, cosmic ray physics, neutrino physics, radiotherapy, etc.

FLUKA assumes that materials are static, homogeneous, isotropic and amorphous and their properties do not change. There is no interaction between cascade particles and photons following incident particles. Particles only interact with individual electrons, nucleons, atoms and molecules in the matter.

It uses well-tested models that are optimized by comparing with experimental data. It can be used in fully analog code or biased mode. In particular small photo-nuclear interaction probability is enhanced here through biasing. Double precision is used, with 10^{-10} energy fraction conservation. 60 particles are modeled (including polarized light). The photo-nuclear cross sections were implanted into Fluka by Alberto Fasso [14] and FLUKA became the first Monte Carlo particle transport code with photo-nuclear interactions in the MeV–TeV energy range implemented. In this work only the giant dipole resonance(GDR) interaction energy region (the lowest end of the energy range below 30 MeV) is explored as described above. The interactions take place based on nuclear cross section (as a function of photon energy and type of target nucleus) [14]. The outcome is modeled by an evaporation/fission module with basic physics described in [15]. FLUKA models are being updated constantly (see the documentation and release notes on http://www.fluka.org/fluka.php) and the new evaporation model was implanted in 1997. However, as noted in private communication [16] by Francesco Cerutti (and FLUKA release notes), the later model's enhancement of the energy dependence of the level density at the saddle point may lead to heavily underestimated photofission, induced by low energy photons.

2. Application of bremsstrahlung radiation for production of ^{99}Mo.

Preliminary experiments at NRC [17] show that a high-power 35 MeV electron accelerator could produce a significant amount of ^{99}Mo for Canada. In this work we did not intend to repeat simulation of this experiment. However for comparison we performed a simplified simulation of bremsstrahlung production of photons in a 0.7 cm thick, 7 cm diameter tungsten converter (Fig. 2). We used a 0.5 cm diameter pin electron beam with 35 MeV energy. In Fig. 2 we show simulated density of photons produced per electron. The black vertical lines indicate the possible ^{100}Mo target positions. They should be positioned very close to the tungsten converter (high photon density) but in a real experiment there are restrictions, since a cooling system is required to remove the excessive heat produced by the electron beam as shown in Fig. 3.

The higher the electron current the more heat is created in the converter and therefore an efficient cooling system is required. There are a large number of photons produced per electron as shown in Fig. 4, but only about 0.25 photons (ph) per electron for our parameters (35 MeV energy) are in the energy region (indicated by arrow) that can trigger directly GDR (compare Fig. 1) and cause the transmutation to ^{99}Mo. Pair positron-electrons and Compton scattered photons from higher energy photons (about 0.004 ph) may also excite GDR.

The energy of photons is dependent on the setup of the experiment (e.g. energy of electrons) and in this example there

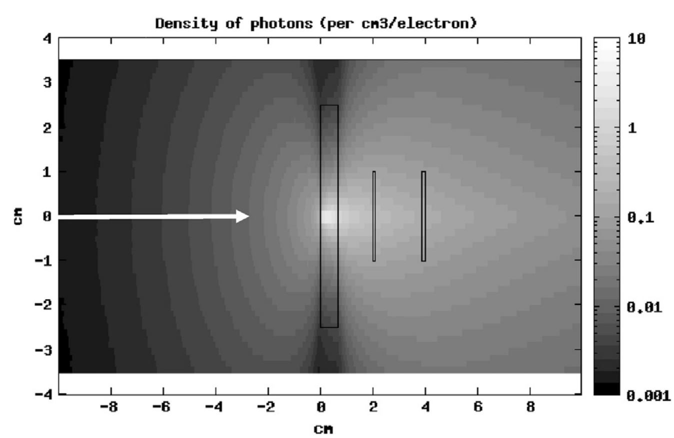

Fig. 2. FLUKA simulation (with 1 keV lowest transport limit for photons and electrons) of bremsstrahlung production of photons. in 0.7 cm thick, 7 cm diameter tungsten target by 0.5 cm diameter pin electron beam (35 MeV).

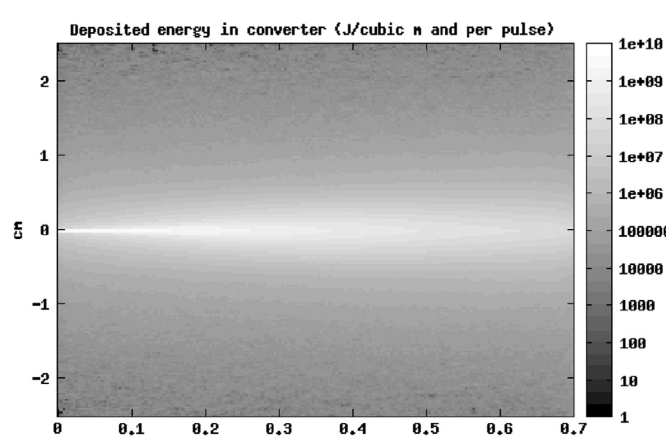

Fig. 3. FLUKA simulation of energy density deposited per pulse (7×10^{12} electrons).