Nuclear Instruments and Methods in Physics Research A 745 (2014) 133–137

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Studying photonuclear reactions using the activation technique

S.S. Belyshev [a,b], A.N. Ermakov [b], B.S. Ishkhanov [a,b], V.V. Khankin [b], A.S. Kurilik [a,b], A.A. Kuznetsov [b], V.I. Shvedunov [b], K.A. Stopani [b,*]

[a] *Lomonosov Moscow State University, Faculty of Physics, Moscow 119991, Russia*
[b] *Lomonosov Moscow State University, Skobeltsyn Institute of Nuclear Physics, Moscow 119991, Russia*

ARTICLE INFO

Article history:
Received 17 September 2013
Received in revised form
8 January 2014
Accepted 28 January 2014
Available online 7 February 2014

Keywords:
Photonuclear reactions
Gamma-ray spectroscopy
Induced activity technique

ABSTRACT

The experimental setup that is used at the Skobeltsyn Institute of Nuclear Physics of the Moscow State University to study photonuclear reactions using the activation technique is described. The system is based on two modern compact race track microtrons with maximum energy of electrons of up to 55 and 67.7 MeV. A low-background HPGe detector is used to measure the induced gamma activity. The data acquisition and analysis system, used to process the measured spectra, is described. The described system is used to study multiparticle photonuclear reactions and production of nuclei far from the beta stability region.

1. Introduction

Nuclear reactions triggered by photons, or photonuclear reactions, are an important subject of studies in nuclear physics. Experimental studies of photonuclear reactions have started in 1950s but some major questions still remain open:

- Although numerous systematic measurements have already been made, the existing datasets are still incomplete. In the June 2013 version of the EXFOR [1] database there are as many as 1350 reaction entries for the (γ,n) reaction, 313 entries for the (γ,2n) reactions, 64 for (γ,3n), and only 14 for (γ,4n). There are 789 entries for the (γ,p) reaction and just 7 for the (γ,2p) reaction. Another experimental database, the IAEA Photonuclear Data Library [2] contains 146 evaluated total photoproduction cross-sections, 21 entries for (γ,2n) reactions, 12 entries for (γ,p) reactions, and 8 for (γ,2p) reactions (the IAEA library omits duplicated and redundant datasets, hence the large difference in numbers). A number of practical applications of photonuclear interactions depend on availability of as full datasets as possible, yet properties of the reactions are measured only for a limited range of nuclei. It can be seen that very little data is available on reactions with high multiplicities.
- A widely recognized problem of existing data is the problem of data validation that needs to be performed for at least some results of past large-scale programs to measure photonuclear cross-sections. There are known systematic discrepancies in existing measurements and independent experiments are needed to resolve the discrepancies and to elaborate reliable data evaluations [3–5].
- The purely electromagnetic character of the interaction between photons and nuclei also means that accurate experimental data are required for refinement and further development of theoretical models and computation packages [6,7].
- Photodisintegrations play a fundamental role in actively studied phenomena like the astrophysical p-process. There are 32 so-called p-nuclei which depend on photonuclear reactions during stellar nucleosynthesis. Current theoretical calculations cannot accurately predict their abundances [8]. Experimental laboratory studies of photonuclear reactions are required to refine the calculations.
- Finally, applications, like transport security scanners [9], photon activation analysis (refer to bibliography in Ref. [10]), production of radioisotopes, and so on require high quality experimental and evaluated data for specific photonuclear reactions that they depend on.

There is a strong need for systematic measurement of photonuclear reactions on different nuclei. To perform these measurements and to obtain accurate and reliable data a specialized system specifically tailored for this kind of systematic measurements is needed. This paper describes the setup built for this purpose at the Skobeltsyn Institute of Nuclear Physics of the Moscow State University (SINP MSU).

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* Corresponding author.
E-mail address: hatta@depni.sinp.msu.ru (K.A. Stopani).

http://dx.doi.org/10.1016/j.nima.2014.01.057
0168-9002

2. Experimental technique

There are established techniques of experimental measurements of photonuclear reaction properties which rely on different types of sources of incident photons and different ways of detection of occurring reactions. The measurements described in this work are based on the activation technique, that is, the experiments are split into two stages: the irradiation stage and the residual activity measurement stage.

Since the cross-sections of photonuclear reactions are typically of the order of 0.1 b or smaller, a high intensity photon source is required to collect reasonable statistics. We use bremsstrahlung radiation as the source of photons. The general view of the bremsstrahlung production setup is shown in Fig. 1. Depending on the required energy either the 67.7 MeV racetrack microtron [11] or the 55 MeV racetrack microtron [12] is used, both of which are modern compact electron accelerators developed and operated by a collaboration at the SINP MSU. The main parameters of the accelerators are listed in Table 1.

The accelerators are installed in a radiation-shielded room within the experimental hall. A modular digital control system is used to operate the accelerators. Variations of the beam current are measured with a calibrated ionization chamber in the beamline and a Faraday cup and are recorded in a web-accessible database for use during analysis via an analog-to-digital converter card and a LabView program. An example of recorded beam current is shown in Fig. 2.

To produce gamma radiation a radiator target made of tungsten or lead is used. Tungsten is a common convertor material and using lead as a bremsstrahlung production material has the advantage that the target thickness can be easily adjusted. We use thick (2.3 mm tungsten and 2–5 mm lead) targets to maximize the number of photons in the energy range of the giant dipole resonance which dominates the photonuclear cross-section from the nucleon separation threshold to 20–30 MeV. An optional aluminum absorber can be placed behind the radiator to remove remaining electrons from the bremsstrahlung beam. To simulate the angular and energy distribution of the bremsstrahlung radiation produced in a thick radiator, an absorber, and the studied target itself a GEANT4 [13] model of the irradiation geometry from Fig. 1 is used later during analysis of results. Electric charge collected on the target is also digitized and used to measure the beam current in addition to the ionization chamber and the Faraday cup. No specialized cooling systems are installed as even long (several hours) irradiations do not result in significant overheating of radiators or targets.

The generated bremsstrahlung irradiates targets made of the isotopes to be measured. The radiator, the ionization chamber, the electron absorber and the target are mounted in the beamline in a special rigid frame in order to ensure reproducible geometry in all experiments. A web camera is used to monitor position of the beam with the help of a fluorescent screen and to correct placement of targets.

The duration of irradiation is typically 0.5–10 h and depends on the cross-section of the reaction to be studied and on the properties of the reaction products. We use the so-called activation technique to determine the rate of photonuclear reactions in the target. This technique relies on the presence of relatively long-lived unstable nuclei with identifiable gamma lines in their decay spectra among the products of the reaction. As soon as the irradiation ends and radiation levels in the experimental hall become safe the target is transported to a high-purity germanium spectrometer (HPGe) which measures photon spectra of residual activity. We use the Canberra GC 3019 HPGe detector with 30% relative efficiency and an energy resolution of 0.9 keV at 122 keV and 1.8 keV at 1.332 MeV. The detector enclosed in a radiation shielding chamber is located in a dedicated room, which allows us to decrease the natural background by ≈ 3 orders of magnitude. A procedure of routine energy and efficiency calibrations of the detector is established. To obtain the detector efficiency in different geometries and to calculate correction coefficients for coincidence summing of photons a GEANT4 model of the detector cryostat and the measurement chamber is used. The Livermore electromagnetic package option is used in the model as it leads to the most precise reproduction of the detector response function. The model is matched against the real detector and its environment using the standard sources ^{137}Cs, ^{60}Co, ^{152}Eu, ^{133}Ba, ^{241}Am. To

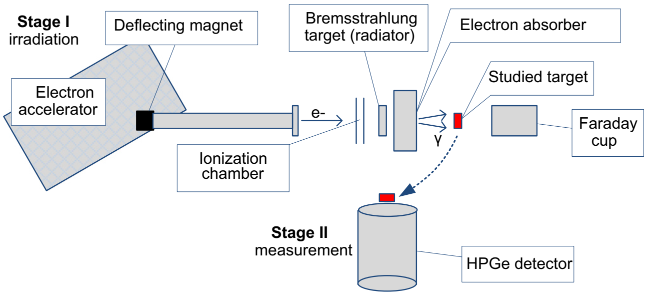

Fig. 1. Schematic view of the setup that is used to irradiate targets with bremsstrahlung radiation.

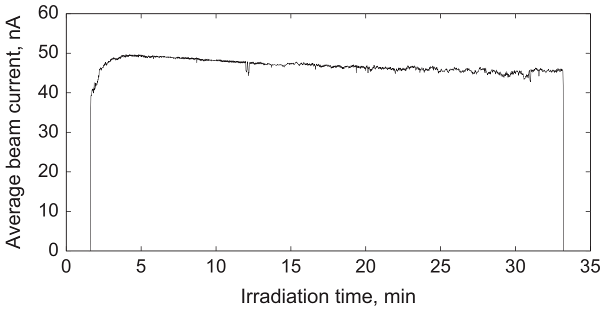

Fig. 2. Time dependence of the beam current during a 30 min irradiation measured using the ionization chamber.

Table 1
Parameters of the race-track microtrons [11,12].

Parameter	67.7 MeV microtron	55 MeV microtron
Output energy	14.8–67.7 MeV	55.5 MeV
Beam energy spread	0.1 MeV at 67.7 MeV (from beam dynamics simulation)	1.1 MeV at 10 MeV (measured at 2nd orbit)
Output current at max. energy	5 mA	10 mA
Pulse duration	5–40 μs	5 μs
Orbits	14	11
Energy gain	4.8 MeV/orbit	5 MeV/orbit
Max duty factor	0.4%	0.025%
RTM dimensions	2.2 × 1.8 × 0.9 m	2.7 × 1.7 × 0.8 m