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100-MeV proton beam intensity measurement by Au activation analysis using $^{197}Au(p, pn)^{196}Au$ and $^{197}Au(p, p3n)^{194}Au$ reactions

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ABSTRACT

The proton beam intensity of a 100-MeV proton linac at the Korea Multi-purpose Accelerator Complex (KOMAC) was measured by an Au activation analysis using $^{197}Au(p,pn)^{196}Au$ and $^{197}Au(p,p3n)^{194}Au$ reactions to determine the accuracy and precision of beam intensity measurement using Gafchromic film dosimetry method. The target, irradiated by 100-MeV protons, was arranged in a stack consisting of Au, Al foils and Pb plates. The yields of produced radio-nuclei in Au foils were obtained by gamma-ray spectroscopy. The FLUKA code was employed to calculate the energy spectrum of protons onto the front surface of Au foils located at three different depth points of the target and also to investigate the condition of incident beam on the target. A good agreement was found between the beam intensity measurements using the activation analysis method at three different depth points of the target. An excellent agreement was also observed between the beam intensity measurements using the Au activation analysis method and the dosimetry method using Gafchromic film.

1. Introduction

Korea Multi-purpose Accelerator Complex (KOMAC) [1] is a 100-MeV proton linac facility, which belongs to Korea Atomic Energy Research Institute (KAERI) for various applications including basic research and industrial utilizations. The method which is currently being used at proton target room to measure proton beam intensity is a Gafchromic film dosimetry. There is not enough information about precision of beam intensity measurement using this method. However, the beam intensity can be measured with a high precision by utilizing activation analysis method through the use of monitor reactions. The beam intensity may be monitored by well-known nuclear reactions if the reliable cross section data are determined. In case of proton beam, $^{27}Al(p,x)^{22,24}Na$, $^{65}Cu(p,n)^{65}Zn$, and $^{nat}Cu(p,x)^{56}Co$ nuclear reactions have been recommended as monitor reactions due to their well-known cross section data considering proton energy range [2–10]. Generally, for the proton energies of less than 50 MeV, copper is well suited as monitoring target element [10]. Aluminum, particularly, $^{27}Al(p,x)^{22,24}Na$ reaction, has been frequently used to monitor high-energy proton beam. Moreover, gold is recommended for monitoring the beam intensity due to well-defined and well-known gamma-ray emitters and existence of convenient nuclear reactions at the various ranges of proton energies [11,12]. Many studies have been directed toward investigating the excitation functions of proton reaction with gold [11–53]; a survey of those research works on Au element is given in Table 1.

The purpose of this work is to measure the intensity of 100-MeV proton beam using Au activation analysis via the yields of $^{197}Au(p,pn)^{196}Au$ and $^{197}Au(p,p3n)^{194}Au$ reactions to determine the accuracy and precision of beam intensity measured by Gafchromic film dosimetry method. The FLUKA Monte Carlo code was employed so as to calculate the energy spectrum of proton beam onto the surface of Au activation foils and also to investigate the condition of beam on the irradiated target. TALYS-1.6 and SRIM-2008 codes were used to evaluate the contributing reactions from 100-MeV protons on Au and range of protons on natural Pb, respectively. Subsequently, the proton beam intensity was measured using the well-known activation formula. The results derived from experimental and simulations have been presented and discussed in detail.

2. Material and methods

2.1. Experimental set-up

2.1.1. Target

Production of radio-nuclei by medium-energy protons irradiating thick and high-Z targets is extremely complicated. By reactions

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Table 1
A survey of research works on Au element.

Energy range or energies [MeV]	Authors	Measured nuclei	Reference
37–153	Albouy et al. (1963)	^{192}Ir	[13]
500	Asano et al. (1985)	Many radio-nuclei	[14]
12,000	Asano et al. (1988)	Many radio-nuclei	[15]
1000, 2200, 3000	Baker et al. (1958)	^{7}Be	[16]
28,000	Bächmann (1970)	Lanthanoides	[17]
1200–1900	Budzanowski et al. (2008)	Many radio-nuclei	[18]
1000–6000	Caretto et al. (1958)	^{18}F, ^{24}Na	[19]
7-15	Chodil et al. (1967)	^{197}Hg	[20]
320–880	Crespo et al. (1963)	^{18}F, ^{24}Na	[21]
450, 2050	Currie et al. (1956)	^{3}H	[22]
4.5–13.9	Elmaghraby et al. (2010)	^{197m,g}Hg	[23]
600, 30,000	Franz and Friedlander (1965)	^{149}Tb	[24]
32	G-Vidal and Wade (1960)	^{3}H	[25]
750	Green et al. (1988)	^{3,4}He	[26]
20–155	Gusakow et al. (1961)	^{196}Au	[27]
4–13	Hansen et al. (1962)	^{197}Au	[28]
18,200	Hagebo and Raw (1969)	Sc- and Sb-nuclei	[29]
3000, 10,000, 30,000	Hudis and Tanaka (1968)	^{7}Be, ^{22,24}Na	[30]
1000, 2000, 3000	Hudis (1968)	^{24}Ne, ^{24}Na	[31]
18–86	Kavanagh and Bell (1961)	^{194,195,196}Au	[32]
11.5–300,000	Kaufmann et al. (1979)	Many radio-nuclei	[33]
200–6000	Kaufmann and Steinberg (1980)	Many radio-nuclei	[34]
600, 800	Kelley et al. (2005)	Many radio-nuclei	[35]
400	Korteling and Caretto (1967)	^{22,24}Na	[36]
450	Kruger and Sugarmann (1955)	Fission products	[37]
120–660	Lavrukhina et al. (1959)	^{24}Na, ^{32}P	[38]
85	Lafleur et al. (1966)	^{7}Be	[39]
Threshold-2600	Michel et al. (1997)	Many radio-nuclei	[40]
12,000	Noguchi et al. (1991)	^{3}H	[41]
600, 10,500, 21,000	Simonoff et al. (1979)	^{83,84,85}Rb	[42]
40–155	Poffé et al. (1978)	(p, xn) reactions	[43]
198, 398, 547, 800	Porilc et al. (1978)	^{24}Na	[44]
18,000	Rudstam and Sorenden (1966)	^{118,124}I	[45]
8–20	Satheesh et al. (2012)	^{197m,g}Hg	[46]
12,000	Shibata et al. (1993)	^{10}Be, ^{26}Al	[47]
2600	Sümmerer et al. (1990)	Many radio-nuclei	[48]
6–20	Sudár and Qaim (2006)	^{197}Hg	[49]
4.7–18	Szelecsényi et al. (1997)	^{195,197}Hg, ^{196,194}Au	[11]
25–70	Szelecsényi et al. (2007)	^{195,197}Hg, ^{196,194}Au	[12]
1200, 2600	Scholten et al. (1994)	^{7}Be	[50]
8–60	Tilbury and Yaffe (1963)	^{196}Au, ^{195,197}Hg	[51]
82–426	Yule and Turkevrch (1960)	^{196}Au	[52]
11,500, 300,000	Yu and Porile (1975)	A = 131	[53]

of the primary proton beam, a variety of secondary particles is produced which themselves are responsible for most of the production of radio- nuclei while in the thin targets the contributions of secondary particles to nuclei production can mostly be neglected [54]. Therefore, thin Au foils were used in this experiment to provide the condition of $\mu \gg R$, in which R is a thickness parameter of target irradiated by protons and μ is a nuclear interaction length. The latter is obtained from Eq. (1) [54–56]:

$$\mu = A_l/N_L\sigma_l \approx 35\ \mathrm{g\ cm^{-2}} A_l^{1/3}, \quad (1)$$

where N_L is Avogadro's number, A_l is the atomic mass of the target element, and σ_l is thin target absorption cross section for the production of a radio-nuclide by protons on the target element l. The nuclear interaction length calculated by Eq. (1) is slightly larger than 35 g cm^{-2} for the numerical coefficient. The value of 35 g cm^{-2} is derived from the convention taken in the definition of hadronic interaction length. For protons, typical interaction length is $\mu(Au) \approx 203$ g cm^{-2} and thickness parameter (R) of Au foil irradiated in this experiment is 0.096 g cm^{-2}.

A layout of the experimental set-up, designed by simpleGeo 4.3 software [57], is illustrated in Fig. 1. High-purity Au foil was used as the activation foil to avoid additional production of nuclei by interaction of protons with elemental impurities. The weight and thickness of each target was measured before irradiation. Target was arranged in a stack consisting of Au (19.3 g cm^{-3}, 99.99% purity) and Al (2.69 g cm^{-3}, 99.999% purity) foils together with Pb plates in the form of Au-Pb-Al-Au-Al-Pb-Al-Au-Al-Pb-Pb array. The second and third Au foils were placed between Al foils to avoid cross contamination and recoil effects. The size of the target was about 5 × 5 cm, and the typical thickness of individual Au and Al foils was 50 and 100 μm, respectively. Natural Pb (11.35 g cm^{-3})

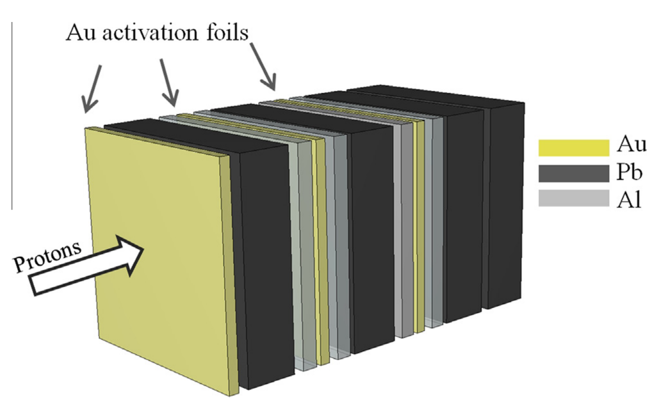

Fig. 1. A layout of experimental set-up designed by simpleGeo 4.3 software.