Nuclear Inst. and Methods in Physics Research B 434 (2018) 29–36

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research B

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

Measurement and calculation of thermal neutrons induced by the 24 GeV/c proton bombardment of a thick copper target

T. Oyama[a,*], M. Hagiwara[a], T. Sanami[a], H. Yashima[b], N. Nakao[c], E.J. Lee[d], E. Iliopoulou[e,f], R. Froeschl[e], A. Infantino[e], S. Roesler[e]

[a] High Energy Accelerator Research Organization-KEK, Oho, Tsukuba, Ibaraki 305-0801, Japan
[b] Institute for Integrated Radiation and Nuclear Science, Kyoto University 2-1010 Asashiro-nishi, Kumatori, Osaka 590-0494, Japan
[c] Shimizu Corporation, Etchujima 3-4-17, Koto-ku, Tokyo 135-8530, Japan
[d] Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 810-0395, Japan
[e] CERN, 1211 Geneva 23, 1211 Geneva 23, Switzerland
[f] Medical Physics Laboratory, School of Medicine, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

ARTICLE INFO

Keywords:
24 GeV/c proton
Activation
Benchmark
Thermal neutron
Monte Carlo

ABSTRACT

The CERN High-Energy AcceleRator Mixed field (CHARM) facility provides a secondary particle field, produced by irradiating a thick target with 24 GeV/c protons supplied by the proton synchrotron. In order to investigate the thermalization process of secondary neutrons in the CHARM facility, we measured the thermal neutrons using the gold foil activation method. Bare and Cd-covered gold foils were placed at 35 positions to deduce the thermal neutron distribution in the CHARM facility. The ^{197}Au(n, γ)^{198}Au reaction rates and thermal neutron fluxes measured in this study were compared with the Monte Carlo simulation codes, PHITS, FLUKA, and MARS. The comparison between the measured and simulated values gives an agreement better than a factor of two. Besides, we investigated the simple empirical formula to estimate a thermal neutron flux in the accelerator room, $\phi_{th} = CQ/S$, where Q is the neutron source intensity and S is the total surface area of a room. The coefficient C estimated in this study did not significantly depend on the incident proton beam energy.

1. Introduction

In constructing and operating high-energy, high-intensity proton accelerator facilities, the development of accurate computational methods for radiation shield design is essential to ensure the radiation safety of accelerator personnel and protect the surrounding environment. In particular, secondary neutrons are highly penetrative and act as sources of radioactivation, creating a need for the accurate characterization of their reactions and transport properties. Secondary neutrons produced inside an accelerator tunnel surrounded by concrete walls thermalize via multiple scattering processes. These thermal neutrons generate ^{41}Ar radioactive nuclides in the air through ^{40}Ar(n, γ) reactions. In comparison with other nuclides produced in the air of high-energy accelerator tunnels, ^{41}Ar significantly contributes to the radioactivity concentration in the exhaust air after a cooling time of about one hour. This is because argon, with a volume fraction of 0.93%, is the third most abundant element in the air after oxygen and nitrogen, and has a large cross section of 0.66 b, and ^{41}Ar has a relatively long half-life of 1.83 h. The ^{41}Ar concentration in air has significantly impacts on not only radiation exposure for personnel but also the facility management, because workers cannot access an accelerator tunnel until ^{41}Ar has sufficiently decayed. For these reasons, the accurate characterization of the amount of ^{41}Ar produced during beam operation is a crucial requirement for the design of high-energy accelerator facilities.

The accurate estimation of ^{41}Ar production requires the characterization of the thermal neutrons formed within the accelerator tunnel due to beam loss. Monte Carlo codes such as PHITS [1], FLUKA [2,3], and MARS [4] enable the simulation of the entire process from neutron production to thermalization and these methods are currently used in the design of many accelerator facilities. Evaluation using simple empirical formulas yields the safety analysis results more quickly than Monte Carlo methods, and offers the additional advantage of allowing the straightforward cross-checking of the results; for these reasons, this approach is also an effective method in radiation shielding design. Patterson et al. [5] derived the following formula characterizing the thermal neutron flux in an accelerator tunnel:

---

* Corresponding author.
E-mail address: takahiro.oyama@kek.jp (T. Oyama).

https://doi.org/10.1016/j.nimb.2018.08.016
Received 21 May 2018; Received in revised form 7 August 2018; Accepted 13 August 2018

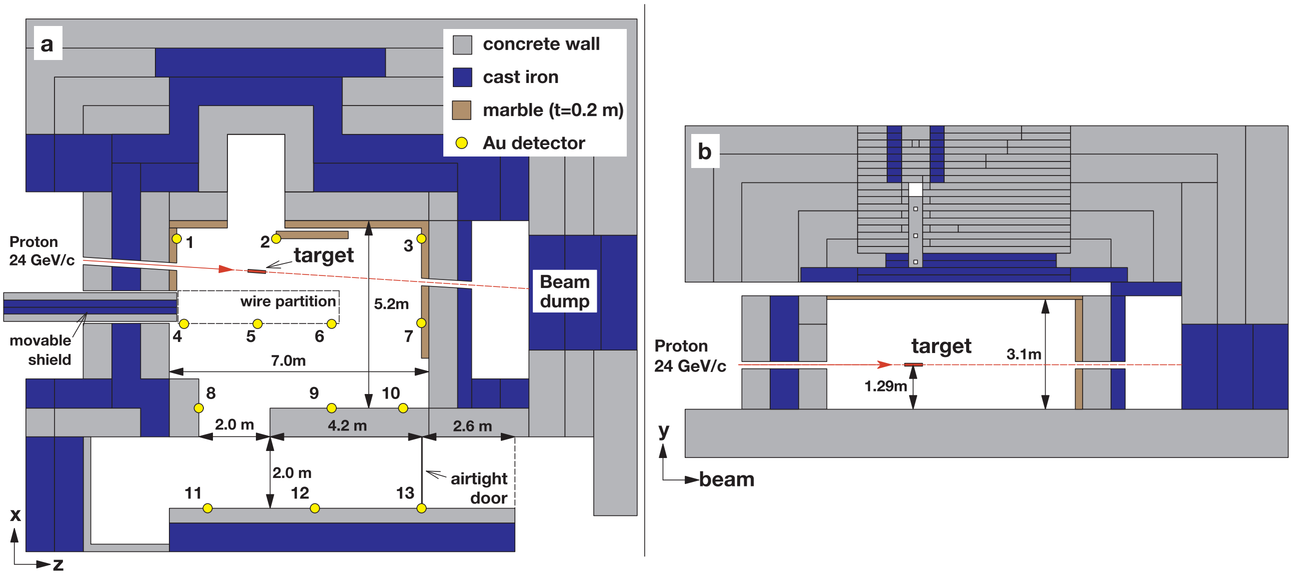

Fig. 1. Cross-sectional view (a) and longitudinal-sectional view (b) taken along the Cu target plane of the CHARM facility, together with important dimensions. The numbers 1–13 indicate the experimental location of the gold foils.

$$\phi_{th} = CQ/S \tag{1}$$

where ϕ_{th} ($cm^{-2}\ s^{-1}$) is the mean flux of thermal neutrons in the accelerator room, Q (neutron s^{-1}) is the neutron source intensity, S (cm^2) is the inner surface area of the room, and the coefficient C is a constant. Patterson et al. [5] recommended a C value of 1.25, but did not provide a theoretical basis for this recommendation. Ishikawa et al. [6] used calculations based on ANISN-W to show that C depends on the energy of the neutron source, and proposed a value of $C = 4$ for energies between 1 keV and 400 MeV. Lee et al. [7] used MCNPX to calculate C, and arrived at a value of 1.95 for the case of 20 MeV protons impinging on a carbon target. Both Ishikawa et al. and Lee et al. reported that C is essentially independent of the size of the accelerator room for similar geometric shape. However, appropriate values of C for high-energy proton accelerator facilities have not been reported in the literature. Consequently, it is important to accurately determine C using measurement data for high-energy protons for characterizing ^{41}Ar production.

The accuracy of the simple empirical formula and the Monte Carlo codes used for radiation shielding design must be tested against benchmark experimental data to ensure their consistency. However, high-energy proton accelerators are typically located inside a large tunnel, and the various instruments and shielding units, both large and small, present within the tunnel may affect the thermalization process of secondary neutrons. Moreover, accurately predicting beam losses during accelerator operation is difficult in many cases, except in situations in which the beam is entirely lost in the target or beam-dump. Few studies have attempted to measure the benchmark experimental data of the thermal neutron flux in high-energy proton accelerator facilities [8,9].

CHARM facility provides a secondary particle field, produced by a proton beam impacting on a cylindrical copper or aluminium target with 24 GeV/c beam momentum, for the investigation of radiation damage and the evaluation of the operational status of irradiated semiconductor devices. The target room of the CHARM facility is a rectangular cuboid and contains few structures that might affect neutron transport. Thus, the CHARM facility is available to measure the thermal neutron flux with a simple experimental system.

In this study, the distribution of the thermal neutron flux produced by 24 GeV/c proton losses at the CHARM facility was measured, and the experimental results were used to evaluate the accuracy of the predictions of PHITS, FLUKA, and MARS. This study is also crucial from the standpoint of providing measurement data for the facility design based on Monte Carlo simulation.

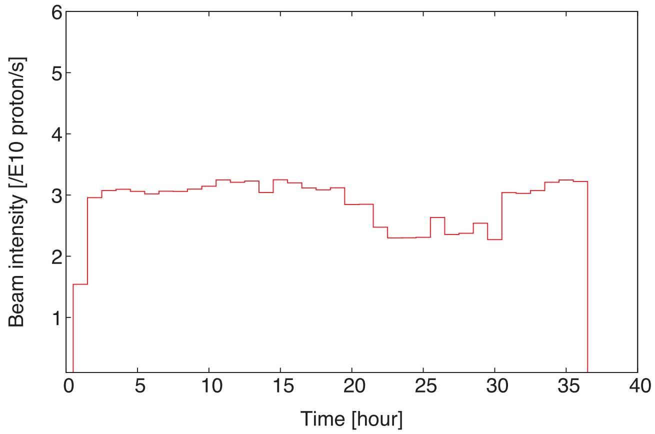

Fig. 2. Beam intensity of the CHARM facility during activation experiments averaged over 60 min binning intervals.

Table 1
Weight fractions and densities of concrete and iron used for the Monte Carlo calculations.

Element	Concrete (%)	Cast Iron (%)
H	0.561	
C	4.377	3.85
O	48.204	
Na	0.446	
Mg	1.512	0.3
Al	2.113	
Si	16.175	3.4
P		0.08
S	0.414	0.02
K	0.833	
Ca	23.929	
Ti	0.173	
Fe	1.263	92.3
Co		0.05
Density	2.4 g/cm^3	7.2 g/cm^3