FNAL の NuMI ビームライン中の Al 及び Cu 標的上で速ミューオンによって誘起される核反応

Nuclear reactions induced by fast muons on Al and Cu targets in the NuMI beam course of FNAL

The JUSMIN collaboration (KEK, JAEA, KUR, Kyusyu Univ, Shimizu Co, RIST, FNAL)

It is important for nuclear physics and earth sciences to understand fast muon interactions with nuclei. In order to enhance our understanding of the interactions, we measured the yields of spallation nuclides produced by fast muons on Al and Cu targets in the NuMI secondary beam course [1] of the Fermi National Accelerator Laboratory (FNAL).

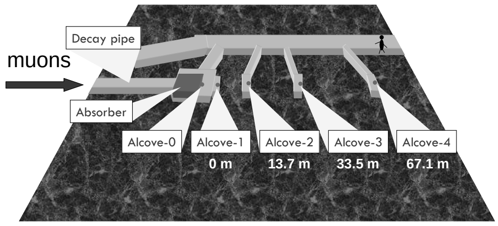

Fig. 1 Downstream view of the decay pipe of the NuMI beam course

Figure 1 shows a downstream view of the decay pipe of the course. Behind the hadron absorber, there are four rooms at depths of 0, 13.7, 33.5, and 67.1 m from the rock surface; they are referred to as “Alcove-1,” “Alcove-2,” “Alcove-3,” and “Alcove-4,” respectively. The Al and Cu targets were installed in every room along the beam axis and were irradiated by the muons that were produced as a result of the bombardment of 120-GeV protons with a graphite target for 22.8 h. After irradiation, γ-ray spectrometry was performed with HPGe detectors in order to determine the spallation yields.

The yields of ^{24}Na on Al and 18 nuclides (^{64}Cu, ^{57}Ni, ^{58}Co, ^{57}Co, ^{56}Co, ^{55}Co, ^{59}Fe, ^{54}Mn, ^{52}Mn, ^{51}Cr, ^{48}V, ^{48}Sc, ^{47}Sc, ^{46}Sc, ^{44m}Sc, ^{43}K, ^{42}K, and ^{24}Na) on Cu were obtained in this study. The measured yields on Cu were fitted to Rudstam’s empirical charge distribution and mass distribution (MD) formula for estimating spallation yields. The MD of the Cu target at Alcove-2 is plotted in Fig. 2 together with a MD that was calculated using the MARS15 Monte Carlo particle transport simulation code [2, 3]. The experimental MD displayed a steep exponential decrease with the mass number of the product and they agreed with the calculated MD well. Figure 3 shows the energy dependence of the slope parameter of the mass yield curve, *P*, in the Rudstam’s formula. The *P*s for the muon reaction obtained at Alcove-1 and Alcove-2 are similar to that for a photonuclear reaction in which the energy transfer to a target nucleus is saturated.

The relative variations in the yield up to a depth of ~70 m in rock were almost the same, regardless of the products. This indicates that the effective energy of the nuclear reaction is independent of the depth of the rock. Furthermore, long attenuation of muons in the rock could be indirectly observed in a depth profile of the yields.

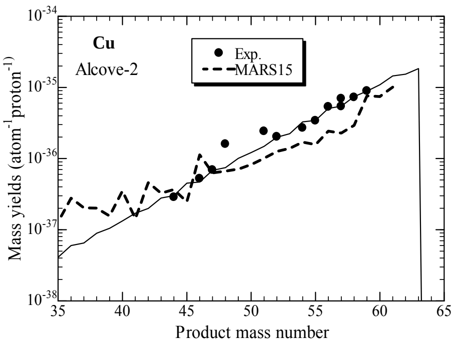

Fig. 2 MDs on Cu at Alcove-2. The closed circles indicate the experimental mass yields and the solid line indicates the MD estimated from Rudstam’s empirical formula. The broken line indicates MD calculated by MARS15.

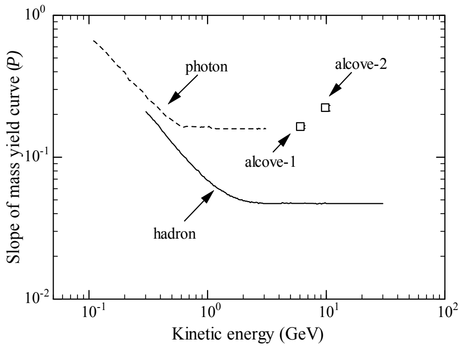

Fig. 3 Energy dependences of Rudstam’s parameter *P* in hadron-induced (solid line, summarized in [4]), photon-induced (broken line, [4]), and muon-induced (square, in this study) nuclear reactions.

REFERENCES [1] J. Hylen, et al., Conception design for the technical components of the neutrino beam for the main injector (NuMI), Fermilab-TM-2018, 1997. [2] N. V. Mokhov, “The Mars Code System User's Guide", Fermilab-FN-628 (1995). [3] N. V. Mokhov *el al.*, Radiat. Prot. Dosim., **116**, 99 (2005). [4] S. Shibata *et al.*, Phys. Rev. **C35**, 254 (1987).