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Measurements and calculations of air activation in the NuMI neutrino production facility at Fermilab with the 120-GeV proton beam on target

I.L. Rakhno*, J. Hylen, P. Kasper, N.V. Mokhov, M. Quinn, S.I. Striganov, K. Vaziri

Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

A R T I C L E I N F O

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A B S T R A C T

Measurements and calculations of the air activation at a high-energy proton accelerator are described. The quantity of radionuclides released outdoors depends on operation scenarios including details of the air exchange inside the facility. To improve the prediction of the air activation levels, the MARS15 Monte Carlo code radionuclide production model was modified to be used for these studies. Measurements were done to benchmark the new model and verify its use in optimization studies for the new DUNE experiment at the Long Baseline Neutrino Facility (LBNF) at Fermilab. The measured production rates for the most important radionuclides – ^{11}C, ^{13}N, ^{15}O and ^{41}Ar – are in a good agreement with those calculated with the improved MARS15 code.

1. Introduction

One of the most important radiation safety problems associated with the design and operation of high-power high-energy accelerators and their experiments is the release of radioactive gases into the atmosphere. In particular, ^{41}Ar with a relatively long half-life of 110 min is radiologically significant for off-site doses. One of the most challenging examples is neutrino experiments – planned (LBNF/DUNE) [1] and operational (NuMI/NOvA) [2] – with their 120-GeV proton, Megawatt scale beam power on target. To predict the air activation levels for a new facility, when direct measurements are not yet available, a combination of calculations and measurements from a similar existing facility are used. As an example, one can use measurements at the NuMI beam line, which has been operating at Fermilab for many years, to benchmark calculations used to predict air activation at future facilities. This paper describes measurements of the radionuclides production rates in the NuMI target chase and compares them with MARS15 calculations.

Once a beam line or experimental facility starts operations, the air composition at the release points is analyzed and quantified to get an actual release estimate. However, before the operation of a beam line starts, an estimate of the levels of radioactive gas emissions is needed as an input to the design of the facility. Contemporary Monte Carlo codes such as MARS15 [3] provide quite reliable predictions for a wide range of physical quantities. Benchmarking such code predictions against experimental data provides a very useful information on the range of reliability regarding the air activation calculations. This study presents such an effort to measure the production of ^{41}Ar and other important isotopes in the target chase at the NuMI beam line and compare the results with predictions by the MARS15 code.

When performing the air activation calculations, one faces the following problems: (i) primary and secondary particles of various types can contribute to the air activation; (ii) a very wide energy range should be taken into account (in our case spanning 14 decades, from 120 GeV down to thermal neutron energies); (iii) light target nuclei like oxygen, nitrogen and argon still represent a challenge for most of the cascade and evaporation modeling codes.

The general-purpose Monte Carlo code MARS15 allows modeling of particle and heavy ion interactions with matter from a multi-TeV region down to thermal neutron energies as well as spatial transport in arbitrary three-dimensional heterogeneous structures. To improve the quality of predictions for air activation levels, two upgrades were recently performed to MARS15 physics models: (i) production cross sections for a number of light target nuclei and most important projectiles were corrected in a very broad energy range; (ii) in the energy range from 1 up to 200 MeV, a completely new model of nuclear interactions, based on the TENDL library [4], was implemented for the most important projectiles.

The experimental and simulation procedures are described in the next two sections followed by comparisons between results of these measurements and MARS calculations.

2. Experimental setup and measurements

2.1. Experimental setup and air circulation model

Fig. 1 shows a drawing of the NuMI target chase with target and horns, where the air samples were taken. The experimental setup is

* Corresponding author.
E-mail address: rakhno@fnal.gov (I.L. Rakhno).

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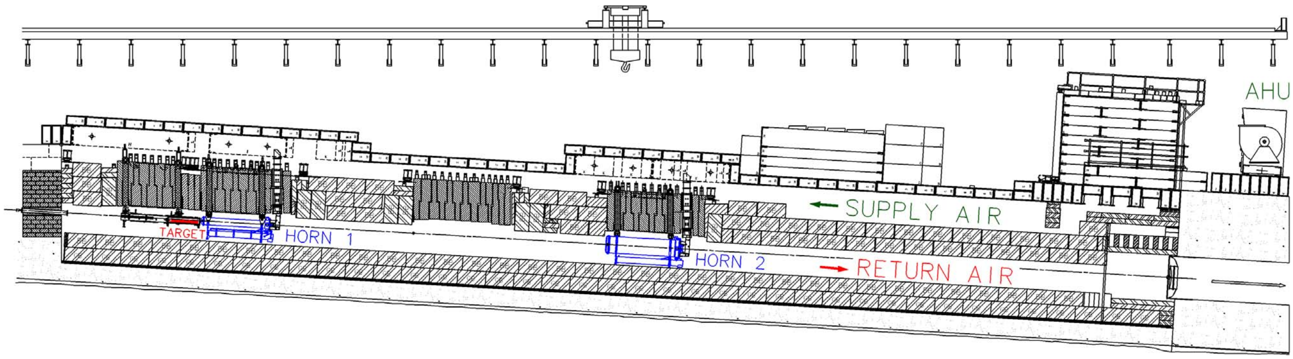

Fig. 1. A schematic diagram of the NuMI target pile showing the 120-cm long target and two focusing horns. This is the volume from which the air samples were taken. More detailed info on the target with its supporting structures, horns etc. is provided in Ref. [2] and in Fig. 3 below. The AHU refers to an air handling unit for recirculating air. The distance between upstream end of the target and AHU is approximately 50 m.

shown in Fig. 2. A corresponding fragment of the MARS model, that shows the carbon target and the magnetic focusing horn 1 filled with air, is shown in Fig. 3. Downstream of horn 1 there is another horn. The chase is surrounded by shielding, which altogether represents the NuMI target pile.

The activated air is circulated through the target chase by means of the target chase cooling system. A small amount of air continuously leaks out of the target chase air cooling loop. This leakage is taken into account by including an additional effective decay term, λ_L, which is the ratio of the air circulation rate and total air volume (see, e.g., [5,6]). For this analysis, a complete air mixing model [6] is used. According to this model, an activated nucleus has the same probability of being removed from the region where the air activation and complete mixing occurs, no matter where it is produced. The master equation for this model, which describes temporal dependence of the number of radionuclides in a region of interest, is the following:

$$\frac{dN_i}{dt} = P_i\nu_p-(\lambda_i + \lambda_L)N_i, \quad (1)$$

where N_i is the number of radionuclides of the certain type i in this

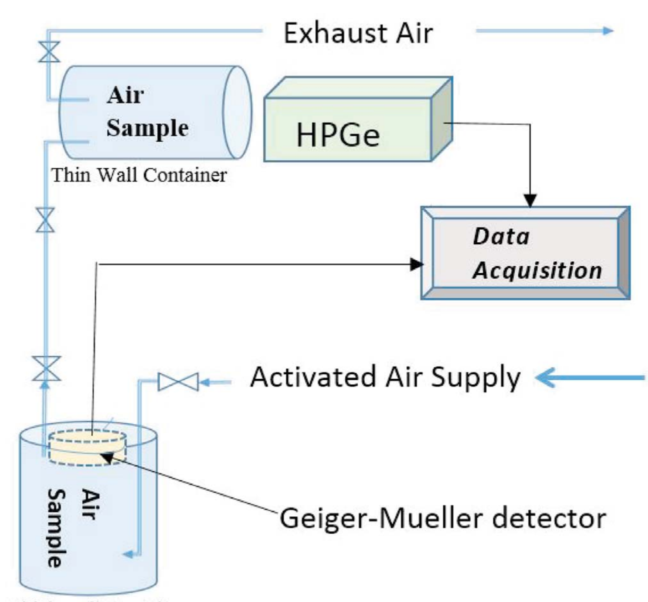

Fig. 2. A schematic drawing of the sampling and measuring configuration. Activated air from NuMI target chase was circulated through the sampling containers until the concentration levels reached an equilibrium. The valves shown in the supply and exhaust lines were then closed to isolate the samples before measuring their decay rates, "in situ," with the two different detector types: a High Purity Ge detector (HPGe), and a Geiger-Mueller counter (GM).

region, P_i is the radionuclide production per proton on target (POT), ν_p is the properly normalized incident proton rate, and λ_L is the correction to the decay constant, λ_i, due to the air leak described above.

2.2. Analytical description of radionuclides build-up and cool-down

To compare activation measurements and predictions, we will need to account for actual irradiation and cooling temporal profile. Here we will introduce the formulae that are used for this purpose. The build-up of radioactive isotopes per unit volume produced during a period of constant irradiation is described by the well-known formula:

$$N_b(t)/V = \varphi\rho\sigma\lambda^{-1}(1-e^{-\lambda t}) = P\lambda^{-1}(1-e^{-\lambda t}) \quad (2)$$

In Eq. (2) ϕ is the flux of particles produced by projectiles with energy above the corresponding threshold. In the standard methodology employed at Fermilab, this is defined as the flux of hadrons with kinetic energy above 30 MeV averaged over the target air volume, V. This is usually obtained from a MARS simulation in units of particles/cm^2/proton and is then scaled to the expected number of protons per second. The target density, ρ, is in units of atoms/cc and σ is the production cross section in cm^2. The variable λ is the isotope's decay constant in units of s^{-1}.

The first three terms in Eq. (2) define the normalized isotope production rate P that measures the number of isotopes produced per primary beam proton on target (POT). To calculate the total number of isotopes produced one need simply scale the result of the equation by the volume and beam rate. Note that if the irradiation time is large with respect to the isotope's lifetime, it reaches a saturation concentration of P/λ and a saturation activity per unit volume equal to the production rate, P.

The reduction during a cool-down period is simply given by the exponential decay formula:

$$N_c(t) = N_0e^{-\lambda t} \quad (3)$$

Eqs. (2) and (3) can be combined to determine the isotopes remaining after a sequence of irradiation or cool-down periods. This is done by simply adding the number of isotopes produced in each period from 1 to n weighted with cool-down terms for the earlier ones (with T_k being duration of the k_{th} period):

$$N_n(t) = N_1(T_1)e^{-\lambda(t-T_1)} + N_2(T_2)e^{-\lambda(t-T_1-T_2)} + \cdots + N_n(T_n) \quad (4)$$

The latter equation allows us to determine the isotope production resulting from arbitrarily complex irradiation scenarios. Of particular interest is the build-up resulting from cyclic irradiation with the possibility of some leakage loss during each cycle. If N_c represents the isotopes produced in a single cycle of length τ, and (1-f) is the fraction of the total air volume that leaks out each cycle then the result after n cycles is described by a geometric series: