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SOME POSSIBLE APPLICATIONS OF MEASUREMENTS ON MU MESONS TO NUCLEAR SAFEGUARDS, NONPROLIFERATION, AND ARMS CONTROL ACTIVITIES

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SOME POSSIBLE APPLICATIONS OF MEASUREMENTS ON MU MESONS TO NUCLEAR SAFEGUARDS, NONPROLIFERATION, AND ARMS CONTROL ACTIVITIES

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ABSTRACT

In the nuclear safeguards and arms control areas, well-developed methodologies exist for determining the properties of nuclear materials via measurements of the gamma rays and neutrons emitted from these materials, or in the arms control area, by the use of radiography. In certain favorable instances, it may by feasible to perform comparable measurements with the use of a ubiquitous, naturally-occurring radiation - cosmic ray mu mesons (muons). At the earth's surface these charged particles have a broad energy distribution peaking at about 500 MeV with a flux of approximately 10^{-2}/cm^2-sec-steradian. In traversing matter, muons lose energy at a rate of approximately 2 MeV/gram almost independent of atomic number. Muons can readily be detected by either plastic scintillators or wire planes. While the flux is small, a scintillator of one meter area, for example, will register about 20,000 events/min. These particles should have utility in the detection and imaging of objects with sectional densities of a few hundred grams/cm^2. The degree of intrusiveness of the imaging can be controlled through the detector configuration. Some possible applications include: 1. Mass measurements on large UF_6 cylinders, 2. Determination of the size of treaty-limited objects, e.g., missiles, in rail cars or other containment, 3. Verification of single or multiple warheads or components, 4. The detection of concealed, underground cavities. Examples will be presented.

INTRODUCTION

In recent years considerable efforts have been devoted to developing methodologies which employ radiation detection for the verification of treaty-limited objects. These utilize either the neutron and gamma radiation emitted from, for example, warheads or other items containing fissile material, or, alternatively, employing an external source of radiation specifically an x-ray generator or radioisotope such as ^{60}Co to radiograph and distinguish between objects of interest, in particular, missiles (SS-20 or SS-25). While external radiation sources are admittedly effective for this purpose, their use is inevitably burdened with stringent requirements involving the safety of personnel and regulations that must be complied with concerning the transportation and utilization of such items. The purpose of this note is to point out that a naturally occurring type of radiation, the flux of cosmic ray mu mesons reaching the earth's surface that is continually produced in the upper atmosphere by primary cosmic rays entering the earth's atmosphere, may be useful for some of these applications. The utilization of this type of radiation for measurements in the safeguards, arms control, and non-proliferation areas can be carried out without any real or perceived hazards to personnel or the public and, by comparison, with minimal safety or regulatory requirements.

PROPERTIES OF MU MESONS (MUONS)

Mu mesons reaching the earth's surface have the following properties which are relevant to possible measurement systems:

- Mass The muon has a mass 215 times more than the electron, but smaller than nucleons (neutrons or protons). Physically it is essentially a heavy electron, interacting only very weakly with nucleons.

- Charge As in the case of electrons, muons have both positive and negative charge. Most of those reaching the earth's surface have positive charge.

- Flux The muon flux at sea level is 10^{-2}/sec-ster. The flux increases both with latitude and altitude.

- Angular Distribution While muons arrive at all angles above the horizon, more arrive at nearly vertical angles since they will have suffered less absorption in the atmosphere than those traveling at shallower angles. The angular distribution, with respect to the zenith, is given by the expression $(\cos\theta)^{3.2}$.

- Energy Muons reaching the earth's surface have a broad distribution of energies peaking at about 500 MeV. This is shown in Figure 1.

- Energy Loss in Matter In traversing matter, most muons deposit approximately 2 MeV per g/cm^2 traversed. Since the mean energy is in the vicinity of 500 MeV, a significant fraction will thus have a range of several hundred g/cm^2.

- Penetration in the Earth As muons penetrate the earth, the half-thickness for their absorption is of the order of a meter. The muon flux at any depth underground is thus related to the depth of overburden they have penetrated.

POSSIBLE APPLICATIONS

1. Determination of The Mass of UF_6 in a Large Cylinder It may be necessary, under international obligations to verify the mass of UF_6 stored in large, 4-foot diameter cylinders. These cylinders are often stacked three-high, and their unstacking and weighing would impose an expensive burden on the facility operator. A more cost-effective alternative to this approach would be to determine the mass of UF_6 by measuring the attenuation of muons traversing the cylinder. The sectional density (radial) of a 4-foot cylinder will be of the order of 500 g/cm^2, which will stop more than half of the muons impinging on it from above. If scintillator "paddles" with a few hundred cm^2 area are placed above and below the cylinder and coincidences measured between them, a statistically significant measurement of the attenuation, and consequently, the mass, can be made in a few minutes. The calibration of the system can readily be accomplished by measurements with "bare" scintillators and on cylinders with known quantities of UF_6.

A "mock-up" measurement of this type has been performed at Brookhaven National Laboratory. The results of this measurement are shown in Figure 2. Coincidences were measured between muon-initiated events in two scintillators, approximately 100 and 200 cm^2 in area respectively placed 25 cm apart. Various amounts of lead shielding, ranging up to 16 cm in thickness (180 g/cm^2) were interposed between the two scintillators. The coincidence rate is seen to decrease by approximately a factor of 2 for the full amount of lead, as expected.

2. Determination of the Size of Treaty-Limited Objects There are sometimes requirements under various treaties or agreements to determine the size or shape of a treaty-limited object. As an example, under the Intermediate Nuclear Forces Treaty, it was necessary to distinguish between two Russian missiles, the SS-20

(treaty-limited), and the SS-25 (permitted), by the diameter of the second stage. For the two missiles, the difference in diameter was 8 cm. This problem was addressed through the use of radiography at the missile production center at Votkhinsk, and a radiographic method utilizing a ^{60}Co source was developed independently by Argonne National Laboratory. With a properly designed array of scintillators placed above and below such a treaty-limited object, it should be possible to delineate its "muon shadow", and thus obtain the required information on its size and shape.

3. Verification of Single or Multiple Warheads or Components While detection and imaging of such items by measurements on the intrinsic radiations emitted (neutrons and gamma rays), the detection of muons could also play a role in the verification process. Specifically, the attenuation in the muon flux observed (between detectors) will provide a direct measurement of the intervening mass. Thus, the use of heavy shielding to mask the presence or transfer of warheads or other items containing substantial quantities of nuclear materials would be readily apparent. In this connection, it is worth noting that the energy deposition of 2 MeV per g/cm^2 in the scintillators is large enough so that detection thresholds for muon initiated events can be set high enough to exclude background from the gamma rays emitted from nuclear materials.

4. Detection of Underground Cavities Several decades ago, the physicist Luis Alvarez carried out a search for hidden cavities in an Egyptian pyramid by measuring the muon flux at various points in its interior. This suggests that this approach might be followed in locating undisclosed underground installations or parts of known installations. Since the half-thickness for the attenuation of muons as they penetrate the earth is of the order of a meter, a rapid decrease in the muon flux with depth is normally observed, although some especially energetic muons can still be observed at depths of up to several thousand feet. Since this expected attenuation will not occur for a cavity, a higher than expected muon flux will be measured. Clearly, the most effective method for detecting such cavities would be through measurements with detectors situated below their expected location, for example, in a borehole, but measurements made adjacent to the expected location of the cavity would also be expected to show a departure from the expected muon flux. These effects can be modeled with Monte Carlo calculations, and more practically, direct measurements can be made at appropriately selected sites.

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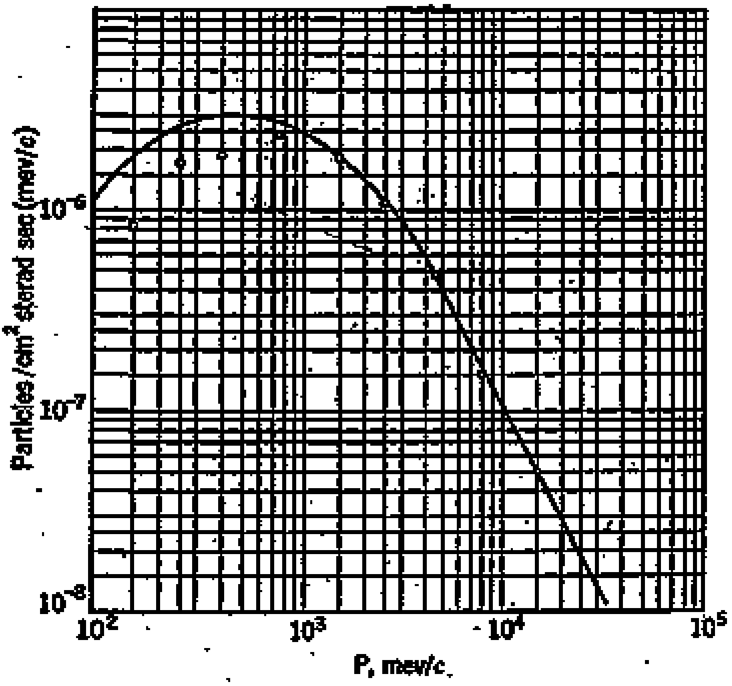

Figure 1. The Number of Mesons at Sea Level per Unit Area, Time, Solid Angle, and Momentum Interval for Various Momenta.

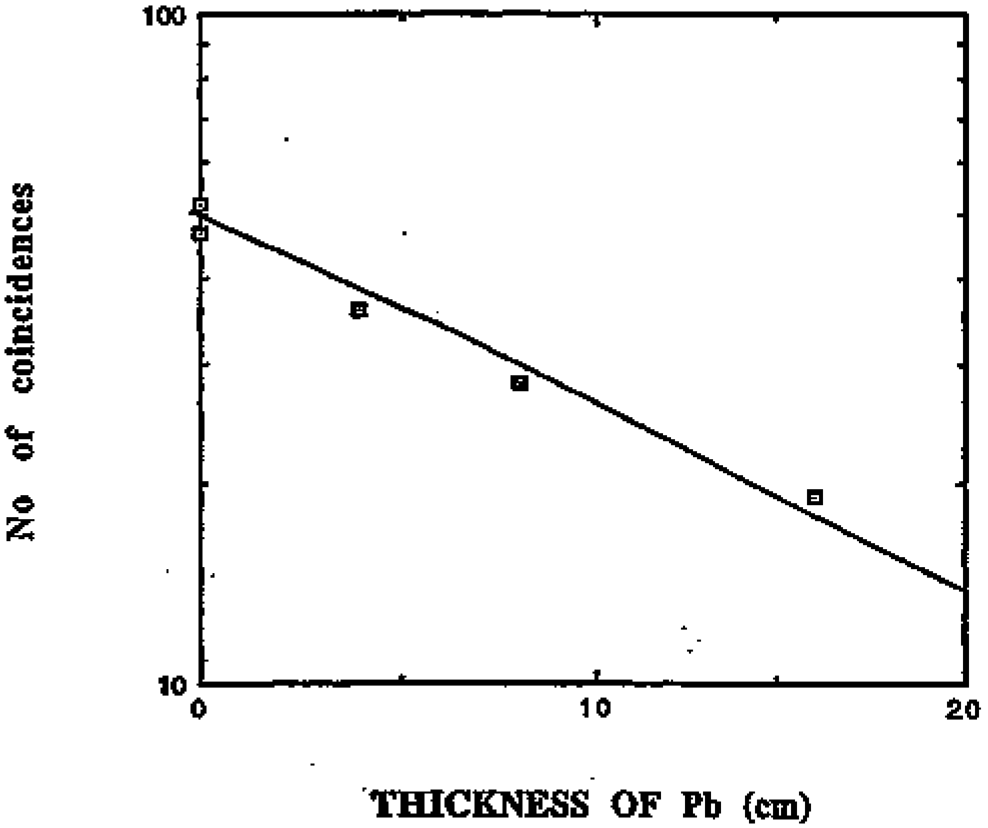

Figure 2. Coincidences of Muon-Initiated Events in Two Plastic Scintillators versus The Thickness of Intervening Lead Shielding.