X-ray Production by Cosmic-ray Muons

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Abstract—**Cosmic-ray muons contribute significantly to the spectra of heavily shielded HPGe detectors, even in deep underground laboratories. Production of X-rays in tungsten, gold and lead by CR muons on the ground level is studied by means of a coincidence system consisting of a plastic scintillation detector and an extended range HPGe detector. X-rays that originate from direct interactions of muons with the target material, the yield of which may be reliably estimated by Monte Carlo simulations, are excluded by this arrangement, and only X-rays produced by all secondaries from muon interactions with the lead shield are present in the HPGe spectrum. Production rate of K_α X-rays per unit mass of all the elements studied (74<Z<82) is found to be close to 7 x 10^{-4} $g^{-1}s^{-1}$. This corresponds to an unexpectedly high and Z independent effective cross-section for this production of about 40(5) barns.**

I. Introduction

APPLICATION of high-resolution gamma-ray spectrometry with HPGe detectors to the study of rare nuclear or particle fundamental processes, like the neutrinoless double beta decay, the search for dark matter particles and the like, requires the knowledge and control over all components of background. Cosmic-ray muons contribute a number of components to background spectra of these detectors, even deep underground, and detailed studies of these contributions lead to better understanding and improvement of low-background experiments. There are four main types of background components of heavily shielded Ge detectors that are attributed to CR muons. These are:

1. *Neutrons*, in typical lead shields of Ge detectors, studied for instance in [1],
2. *Annihilation* radiation, as studied in [2],
3. *Characteristic X-rays* of materials close to the Ge crystal, produced either in direct ionizations by muons or indirectly, by particles from stopped muon capture and other secondary particles from muon interactions, as preliminarily studied in this work
4. *Bremsstrahlung* continuum from muon and electron electromagnetic interactions [not yet evaluated, difficult]

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II. Experiment

Our experiment is designed to measure the production of fluorescence characteristic X-rays of materials in the vicinity of a Ge detector by secondary particles that emerge from interactions of CR muons with heavy lead shields of low-background Ge detectors. It is designed to be insensitive to the X-rays directly produced by CR muons in the target material, since these production rates are easily evaluated by contemporary simulation codes, GEANT4 for instance, and there is little interest to determine this yield experimentally. Production by the secondaries, however, is a complex process involving many different low-energy cascades, and is much more difficult to evaluate. Figure 1 illustrates the geometry of the experiment and explains why the direct production of X-rays by muons does not contribute to the X-ray lines.

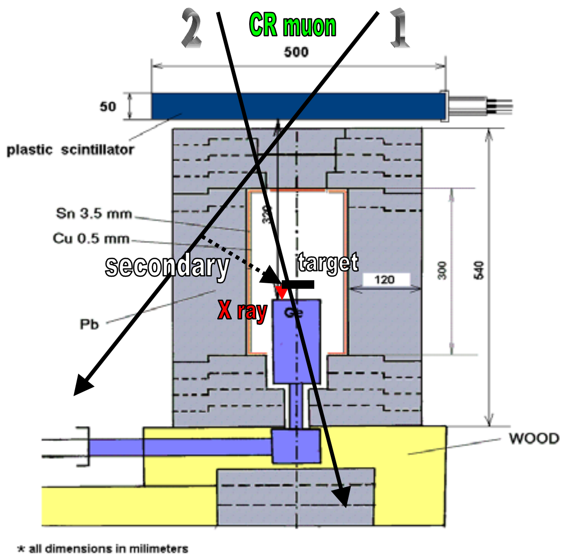

Fig.1. Arrangement of detectors and materials in the experiment. CR muon passes through the plastic scintillation detector and triggers the HPGe detector. The muon marked “1” then produces a secondary (dotted line) in the heavy lead shield which is in turn stopped in the target where it induces the emission of the X-ray, which is registered by the HPGe detector in the X-ray peak. If the muon (marked “2”) hits the target and produces the X-ray which is detected by the Ge detector, it also passes through the Ge detector and its energy loss is summed with the X-ray, which is then registered ouitside the X-ray peak.

To single-out the contributions of the muon-produced secondaries to the X-ray peaks the extended range HPGe detector (32%) spectrum is taken in coincidence with the energy-loss muon spectrum from the plastic scintillation detector situated above the Ge detector. In order to minimize the number of accidental coincidences the fast-slow coincidence circuit is employed. The threshold on the constant fraction discriminator in the plastic scintillation detector branch is set at about 6 MeV, so as to cut-off the low-energy environmental radiations while to let through the muon energy-loss peak which is situated at around 10 MeV. The threshold in the HPGe branch is set lowest possible, when it cuts-off the radiations with energies below some 35 keV, what corresponds to X-rays of elements with atomic numbers around 60. The target materials were all of the diameter equal or smaller to that of the base of the HPGe detector, and were placed directly on the front base of its casing.

III. Results

The coincident spectra of the HPGe detector containing the X-ray lines of interest are presented in Figure 2. It is seen that except of these no other lines appear in the spectra. When no target material is present in front of the detector only the continuous background spectrum remains.

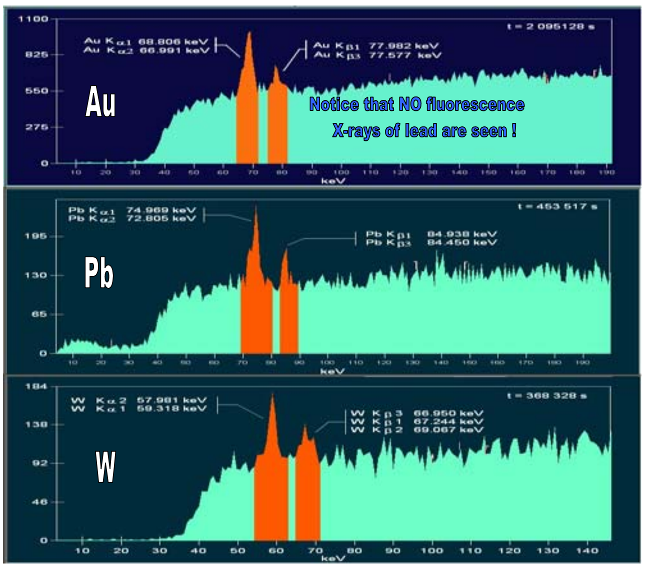

Fig.2. The coincidence spectra of the HPGe detector when gold, lead and tunsten targets are positioned in front of the detector. Only K_α and K_β lines of the corresponding element are seen in the spectra.

Values of the effective cross sections σ for the production of K_α X-rays are estimated from the corresponding spectral intensity I_α via the expression $\sigma=R/(N\Phi)$, where the X-ray production rate $R=I_\alpha/(\varepsilon t)$ (ε=total detection efficiency for the detection of the corresponding X-ray and t is the total live measurement time), N is the number of given atoms in the target and Φ is the rate of gates from the plastic scintillation detector. The difficult part here is to estimate the total detection efficiency ε minding that the thickness of our samples is a saturation one for the low-energy X-rays we are interested in. We estimated this quantity by using the well known semi-empirical program ANGLE [3]. Minding that in this energy range this estimate may have substantial systematic error, ranging perhaps even up to 30%, our results for the effective cross sections for the production of X-rays in tunsten, gold and lead by the secondaries produced by cosmic-ray muons in heavy lead shields, cited with their statistical errors only, are listed in Table 1:

TABLE I
Values of the Effective Cross Sections

Element	Atomic number	cross section [barn]
W	74	49(7)
Au	79	43(3)
Pb	82	46(4)

It is seen that the values of the cross sections are unexpectedly high, and that the dependence of the cross sections on atomic number is, within our statistical accuracy, practically absent.

References

[1] G. P. Škoro, et al. NIM **A316**(1992)333

[2] J. M. Puzović and I. V. Aničin, NIM **A480**(2002)565]

[3] S.Jovanovic, A. Dlabac, N.Mihaljevic and P.Vukotic, in *Proceedings of the 19th Yougoslav Symposium for the Radiation Protection, Golubac, Serbia and Montenegro, 1997*, edited by M.Ninkovic, G.Joksic, M.Orlic and R.Kljajic; Belgrade, 1997 p.127