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Examination of radioargon production by cosmic neutron interactions

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ABSTRACT

Radioargon isotopes, particularly ^{37}Ar, are currently being considered for use as an On-Site Inspection (OSI) relevant radionuclide within the context of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). In order to understand any soil air measurements taken during an OSI, the radioargon background due to cosmic ray induced activation along with other sources must be understood. An MCNP6 model was developed using the cosmic ray source feature within the code to examine the neutron flux at ground level as a function of various conditions: date during the solar magnetic activity cycle, latitude of sampling location, geology of the sampling location, and sampling depth. Once the cosmic neutron flux was obtained, calculations were performed to determine the rate of radioargon production for the main interactions. Radioargon production was shown to be highly dependent on the soil composition, and a range of ^{37}Ar production values at 1 m depth was found with a maximum production rate of 4.012 atoms/sec/m^3 in carbonate geologies and a minimum production rate of 0.070 atoms/sec/m^3 in low calcium granite. The sampling location latitude was also shown to have a measurable effect on the radioargon production rate, where the production of ^{37}Ar in an average continental crust is shown to vary by a factor of two between the equator and the poles. The sampling date's position within the solar magnetic activity cycle was also shown to cause a smaller change, less than a factor of 1.2, in activation between solar maxima and solar minima.

1. Background

Of the radioactive fission and activation products produced during an underground nuclear weapon's test, radioactive noble gases are the most likely to escape from the test chamber. This is of particular interest when conducting an On-Site Inspection (OSI) for verification of the Comprehensive Nuclear-Test-Ban Treaty (CTBTO Preparatory Commission, 1996). While radioxenon isotopes are the primary interest during an OSI, other isotopes are also being considered as potential OSI targets, particularly ^{37}Ar which has a half-life of 35.04 days (Haas et al., 2010; Riedmann and Purtschert, 2011).

With its longer half-life, ^{37}Ar will have a stronger signal than the radioxenons approximately 50 days post-detonation (Aalseth et al., 2011). This was confirmed in Project Gasbuggy, a 27-kt nuclear test, by sampling from wells drilled near the cavity (Smith, 1969). These measurements indicate that anywhere between 80 and 280 MBq of ^{37}Ar were produced per cubic meter of air. Models of argon transport from a fractured 1 kt detonation indicate that around 6 Bq/m^3 of ^{37}Ar should be detected in surface gas samples (Carrigan et al., 1996). In order to utilize radioargon as a nuclear weapons signature, the potential background sources of radioargon must be understood.

Previous work has shown that the anthropogenic background of ^{37}Ar produced in reactors is expected to be well below detection limits, however the ^{41}Ar production at reactors is significant enough to be commonly included in environmental reporting (Fay and Biegalski, 2012). Natural background sources of radioargon include the activation of lithospheric isotopes (particularly ^{40}Ca and K isotopes), and muon interactions with ^{39}K (Egnatuk and Biegalski, 2013; Riedmann and Purtschert, 2011; Lowrey, 2013). The previous work indicates that the dominant source is the $^{40}Ca(n,\alpha)^{37}Ar$ reaction, however, the $^{37+X}K(\mu,X\cdot N)^{37}Ar$ reaction may also be a major production mechanism (Lowrey, 2013). Only the neutron interactions were considered in this work.

The primary purpose of this work is to determine a range of values that describe the natural background of radioargon. While

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this is not a complete calculation of all possible background sources, the primary contributors are considered. This was a two part process. First, the production of neutrons from cosmic ray interactions and the resulting neutron flux at various soil depths was determined using a Monte Carlo neutron transport model using MCNP. The effects of various components of the cosmic ray flux intensity were considered as they impact the cosmic neutron flux at ground level. The components considered were latitude of the sampling location and date of the sample (as it relates to the solar cycle).

The calculated neutron fluxes were then used to determine the activities of radioargon produced by activation. This was calculated for a variety of soil compositions and for depths of 1–15 m below ground level.

1.1. Cosmic rays

The majority of cosmic rays incident on the Earth are of galactic origin, however the highest energy particles are thought to be extra-galactic in origin. The makeup of the primary particles is 86% protons, 11% alpha particles, 2% electrons, and 1% nuclei of heavier atoms up to uranium (Perkins, 2003). Virtually none of these primary particles reach the Earth's surface, rather, it is the secondary particles that reach the ground. These secondary particles consist primarily of pions, muons, nucleons, electrons, and photons. The most commonly produced particles are pions which decay to muons and neutrinos. However, 97% of the particles reaching sea level have been found to be neutrons (Perkins, 2003).

1.2. Effects of latitude on the cosmic ray flux

The Earth's magnetic field forms a barrier to charged particles everywhere except for at the poles where particles are able to travel vertically down the field lines. Primary charged particles that interact with the Earth's magnetic field are bent from their original trajectories and any secondary particles produced in a cosmic shower will also have their trajectories bent. This has a twofold effect, particles are more likely to be directed into space and the path length of the particles is lengthened. Both effects decrease the probability that a particle will reach sea level. The magnetic field of the Earth has been demonstrated to affect the cosmic rays reaching sea level by up to two times (Ziegler, 1996).

This flux variation occurs within a band approximately ±15° about 35° with little observable variation within approximately 20 degrees of the poles or the equator as illustrated in Fig. 1.

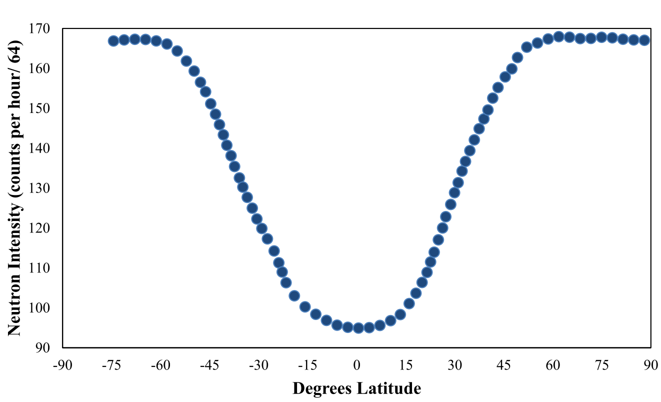

Fig. 1. Neutron intensity at sea level vs latitude. The neutron detector used in this experiment was not well characterized so the neutron energy being measured is unknown (Ziegler, 1996).

1.3. Temporal variation of the cosmic ray flux

The sun's magnetic field structure is driven by a hydromagnetic dynamo system, or the solar dynamo. At a solar minimum the sun's magnetic field is poroidal, however, due to the sun's differential rotation the field winds up and the field lines become more densely packed into a toroidal field. Convective motions within the sun further bunch the magnetic fields until some of the bunches, or tubes, burst from the surface of the sun. Sunspots are formed at regions where the magnetic field is very high (0.2–0.4 T) and orthogonal to the sun's surface. The high magnetic field prevents motion across the field lines and inhibits convection, reducing the surface temperature at that location and manifesting as visible dark spots. Solar activity is measured by counting the number of sunspots present on the sun's surface. This number waxes and wanes, with an average period of 11.4 years, and this cycle is known as the solar activity cycle. This 11 year activity cycle is actually just half of the 22 year magnetic period of the sun. The polar field of the sun also cycles, reversing every 11 years, so that the overall magnetic cycle has a 22 year period (Knipp, 2011).

The sun emits highly ionized plasma radially outward which is known as the solar wind. This outflow also serves to stretch the sun's magnetic field out into the surrounding space and forms the interplanetary magnetic field (IMF). This outflow also serves to redirect many incoming cosmic rays back out of the solar system without ever striking the Earth. The cosmic ray flux is therefore anti-correlated with the solar activity cycle. At the solar minimum the cosmic ray flux is increased and at solar maxima it is reduced. However, this cosmic ray reduction lags behind the maxima by 6–14 months.

The direction of the sun's polar field also affects the cosmic ray flux. When the sun's polar field is positive (directed outward), the cosmic ray flux is broadly peaked and the lag behind the solar minima is 10–14 months. When the polar field is negative (directed inward), the flux is sharply peaked and the lag is shorter, about 2 months. All of these patterns are evident in Fig. 2 where the cosmic ray flux, represented by the cosmic neutron flux, is plotted along with the smoothed sunspot number (SSN).

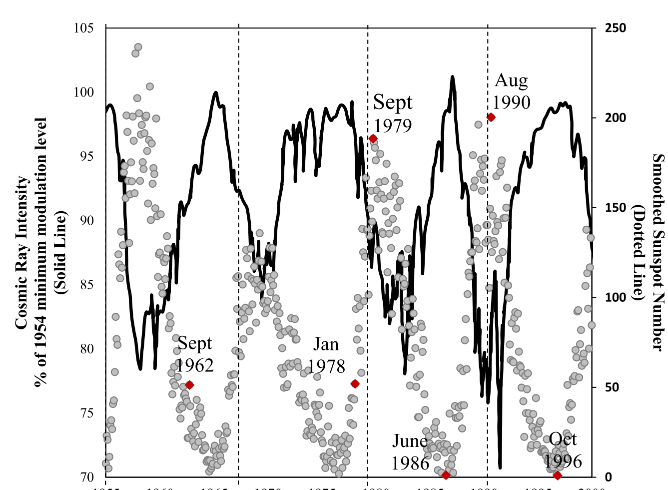

Fig. 2. The cosmic ray neutron flux at the Climax Neutron Monitor. The neutron flux is represented by the solid line (Duldig 2001) and the smoothed sunspot number (SSN) is represented by the dotted line (Royal Observatory of Belgium, 2013). The labeled points are the dates considered in this work.