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**A Method to Estimate the Fast-Neutron Fluence
for the Hiroshima Atomic Bomb**

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A new method to estimate the fast-neutron fluence of the Hiroshima atomic bomb is proposed. ^{63}Ni produced by the $^{63}\text{Cu}(\text{n,p})^{63}\text{Ni}$ reaction provides a unique measure by which to estimate the fast-neutron fluence of the Hiroshima/Nagasaki atomic bombs, because the half-life of ^{63}Ni is 100 years and 70 % of the ^{63}Ni produced in a copper piece presently exists after 50 years.

Using the neutron spectrum given in DS86 and the estimated cross section, we found that a piece of copper of about 10 g which was exposed at a point around 100 m from the hypocenter gives a measurable amount of ^{63}Ni using a low-background liquid scintillation counter. For the measurement of ^{63}Ni , accelerator mass spectrometry also seems to be applicable.

KEYWORDS: Hiroshima, DS86, atomic bomb, neutrons

The neutron spectra correlated to the distance from the hypocenter are given in the Dosimetry System 1986, DS86.¹⁾ So far no experimental results for the fast neutrons has been reported for the Hiroshima atomic bomb except for the early measurement of ^{32}P .¹⁾ The detailed analysis²⁾ of several nuclei produced by the thermal-neutron capture reaction suggests that the derived neutron spectrum for the Hiroshima atomic bomb is much harder than the spectrum given in DS86. The measurement³⁾ of ^{152}Eu and ^{60}Co also suggests that systematic errors exist in the DS86 neutron spectrum. The recent measurements of ^{36}Cl for Hiroshima, Nagasaki and the reactor experiment⁴⁾ have shown that the source neutrons for the Hiroshima atomic bomb could be different from the one given in DS86. Thus the direct measurement of the fast neutrons for the Hiroshima atomic bomb is particularly desirable.

^{63}Ni provides a unique measure by which to estimate the fast-neutron fluence of the atomic bomb. Since the half-life of ^{63}Ni is 100 years, 70% of the ^{63}Ni nuclei produced in a copper piece due to the Hiroshima atomic bomb presently exists in the piece 50 years after the explosion. The Q-value of the $^{63}\text{Cu}(\text{n,p})^{63}\text{Ni}$ reaction is 0.7 MeV; the reaction is exothermic. The cross section for thermal

neutrons is, however, negligible because of the Coulomb barrier of the $p+^{63}\text{Ni}$ system.⁵⁾

The decay rate of ^{63}Ni in a one-gram copper piece is given by

$$-\frac{dn}{dt} = \lambda N_0 \exp(-\lambda T), \quad (1)$$

where λ denotes the decay constant for ^{63}Ni , N_0 is the number of ^{63}Ni atoms produced in a one-gram copper piece due to the explosion, and T represents the time elapsed since the explosion. N_0 is given by

$$N_0 = \int N \frac{d\phi}{dE} \sigma(E) dE, \quad (2)$$

where N represents the number of ^{63}Cu atoms in a one-gram copper piece, $d\phi/dE$ denotes the neutron fluence at a certain distance from the hypocenter, and $\sigma(E)$ is the cross section for the $^{63}\text{Cu}(n,p)^{63}\text{Ni}$ reaction at neutron energy E . Using the values of $d\phi/dE$ at 100 m from the hypocenter given in ref.1 and $\sigma(E)$ given in ref.5, we get the number of ^{63}Ni atoms to be 1.3×10^7 and the ^{63}Ni activity to be 2.8×10^{-3} Bq in a one-gram copper piece after 50-year decay correction.

The thermal-neutron capture cross section of ^{62}Ni is 14.2 b and the effective thermal-neutron fluence is about 10^{13} n/cm², as given in ref.2. Therefore the nickel impurity of 300 ppm in the copper piece produces the same amount of ^{63}Ni . The nickel impurity in copper used for ordinary electric wire is usually less

the 1 ppm. Therefore the contribution due to the thermal neutrons for such material is negligible.

The fast-neutron flux in cosmic rays is of the order of 0.004 n/(cm².s) at the ground surface, giving a fluence of 10^7 n/cm² for 50 years. This value is far below the expected fast-neutron fluence at the point around 100 m from the hypocenter of the Hiroshima atomic bomb. Therefore the cosmic-ray contribution is also negligible.

A small amount of ^{63}Ni can be separated from copper⁶⁾ with high efficiency (> 95 %) and purified, very specifically, by extracting nickel-dimethylglyoximate complex into chloroform.

A recent measurement of ^{63}Ni using our low-background liquid scintillation counter shows that the background rate for an energy window adjusted for ^{63}Ni β -rays is 3.4 cpm and that the detection efficiency is 55 % for ^{63}Ni β -rays. The measurement of a sample for a 1000-min period gives the standard deviation (σ) of 58 counts for the background. If we set 3σ as the minimum value for the signal of ^{63}Ni , we require 5.6×10^{-3} Bq of ^{63}Ni which can be extracted from a 2 g copper piece. Therefore if a 10 g specimen of copper exposed at 100 m from the hypocenter is available, we will be able to obtain crucial information of the fast neutron fluence of the Hiroshima atomic bomb.

Accelerator mass spectrometry (AMS) can also detect ultra-trace amounts of specific nuclei. If we assume that AMS can detect 10^7 atoms, a few-gram copper piece will enable us to obtain similar information.

We should note that there has been no report on the experimental cross section data of the $^{63}\text{Cu}(n,p)^{63}\text{Ni}$ reaction except for those on the 14 MeV neutron. The measurement of the

excitation function for the $^{63}\text{Cu}(n,p)^{63}\text{Ni}$ reaction is under progress.⁷⁾

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