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Study on the impact of pair production interaction on D-T controllable neutron density logging

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HIGHLIGHTS

- The effect of pair productions on D-T neutron gamma density logging is validated.
- The inelastic gamma spectrum above 2 MeV is sensitive to pair production.
- Mass attenuation coefficient due to pair production varies with lithology.
- The measurement precision can be effectively improved through lithology correction.

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ABSTRACT

This paper considers the effect of pair production on the precision of D-T controllable neutron source density logging. Firstly, the principle of the traditional density logging and pulsed neutron density logging are analyzed and then gamma ray cross sections as a function of energy for various minerals are compared. In addition, the advantageous areas of Compton scattering and pair production interactions on high-energy gamma ray pulse height spectrum and the errors of a controllable source density measurement are studied using a Monte Carlo simulation method. The results indicate that density logging mainly utilizes the Compton scattering of gamma rays, while the attenuation of neutron induced gamma rays and the precision of neutron gamma density measurements are affected by pair production interactions, particularly in the gamma rays with energy higher than 2 MeV. By selecting $0.2-2$ MeV energy range and performing proper lithology correction, the effect of pair production can be eliminated effectively and the density measurement error can be rendered close to the precision of chemical source density logging.

1. Introduction

To eliminate the hazard of radioactive chemical sources, controllable neutron induced gamma density logging (NGD) has attracted increasing interest. The traditional gamma-gamma density logging (GGD) utilizes a cesium-137 chemical source and measures the formation density by detecting the scattered gamma rays. In comparison, NGD utilizes the 14 MeV fast neutrons emitted by a D-T neutron generator and induced gamma rays in the formation, especially the gamma rays induced by inelastic scattering, to replace the traditional cesium sources (Wilson, 1995).

Wilson (1995) and Odom et al. (2001) proposed the method to measure formation density with gamma rays that are induced by the inelastic scattering of D-T neutrons. They believed that the precision of a density measurement is affected by the spatial distribution of the “induced gamma source” which is related to hydrogen index of the formation and presented the corresponding correction method utilizing a fast neutron or an epithermal detector (Quirein et al., 2005; Odom et al., 1999; Odom et al., 2001; Reichel et al., 2012). However, even after a series of corrections, the precision of a density measurement using induced gamma ray is still poorer than that of GGD and such an error has significant impact on the precision of formation evaluation (Yu, 2011). Unlike the gamma rays from chemical cesium source, the induced gamma rays have an energy level above 1.02 MeV, generating not only Compton scattering and the photoelectric effect, but also pair production. Previous study on the subject indicated that aside from the effect of Compton scattering of the induced high-energy gamma rays, pair production also has an impact on density measurement as its cross section varies with mineral type (Yu, 2011; Feyzi, 2014). Botto and Ellis (2011) discovered that the gamma ray signal whose energy is less than 3 MeV after attenuation mainly

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reflects the information from Compton scattering, while the gamma ray signal whose energy is higher than a few MeV reflects the information of formation lithology. Feyzi (2014) considered that the energy of induced gamma rays is on the MeV level and in addition, as the pair production effect is sensitive to mineral types, it introduces errors in density measurement (Committee on Radiation Source and Replacement, National Reserch Council, 2008). However, these studies have only recognized the existence of the pair production effect but have not analyzed the magnitude of density measurement errors resulting from pair production effect and have not proposed correction methods.

In this paper, the basic principles of GGD and NGD are introduced respectively first, then the rules reflecting how the cross section or mass attenuation coefficient of Compton scattering and pair production are subject to the change of formation properties are studied. Secondly, the advantageous energy areas of Compton scattering and pair production of neutron induced gamma ray are studied. Furthermore, the impact of pair production effect on the precision of formation density measurement with neutron induced gamma ray is analyzed and the magnitude of pair production interaction on different energy windows is compared. In addition, the lithology correction is performed based on the data of 0.2 – 2 MeV to further eliminate the impact of the pair production effect.

2. The principle of GGD logging

GGD logging is based on the exponential attenuation laws of narrow-beam gamma ray (Huang, 2000):

$$I = I_0 \cdot e^{-\mu x} \tag{1}$$

Where,

$$\mu = \sigma N_A \frac{Z}{A} \rho \tag{2}$$

where I_0 is the initial intensity of gamma ray, I is the intensity of attenuated gamma ray, μ is gamma ray cross section, ρ is bulk density of formation mineral, x is gamma ray transmission distance, Z is atomic number, A is mass number, N_A is Avogadro's number and σ is microscopic cross section.

Then the mass attenuation coefficient, μ_m, is:

$$\mu_m = \frac{\mu}{\rho} = \sigma N_A \frac{Z}{A} \tag{3}$$

In GGD logging, a cesium source with 0.662 MeV energy is used and the emitted gamma rays will only undergo Compton scattering and the photoelectric effect. For common rocks or minerals in the formation, except for water, the mass attenuation coefficients for Compton scattering, μ_{mcomp}, are almost identical. The XCOM code was used to calculate various cross sections and mass attenuation coefficients, and the results are shown in Fig. 1 (Berger and Hubbell, 1987; Yu et al., 2015). When the energy window selected for measuring starts above the energies of the photoelectric effect, the attenuation of gamma rays is generally only related to mineral density.

Then the attenuation of gamma intensity along with the variation of substance thickness x may be written as:

$$I = I_0 e^{-\rho \frac{Z}{A} N_A \sigma x} \tag{4}$$

The electron density index, ρ_e, is defined as $2(Z/A)\rho$. It can be obtained by measuring gamma flux before and after the attenuation during density logging and then converted into the bulk density of the formation using formula (5) (Berger and Hubbell, 1987). For a freshwater saturated limestone formation, the relationship between formation bulk density and electron density index can be expressed as:

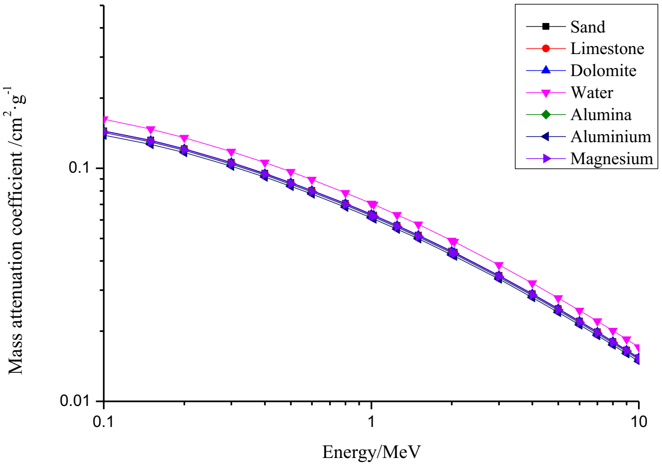

Fig. 1. Mass attenuation of Compton scattering.

$$\rho_b = 1.0704\rho_e - 0.1883 \tag{5}$$

For GGD logging, the electron density index is converted into bulk density considering the limestone formation as the standard, therefore, the measured density of sandstone and dolomite formation is not the true bulk density and is referred to as apparent density. For most formations, the apparent density may be approximately considered as the bulk density, and the precision of GGD logging is generally 0.015 g/cm^3.

3. The principle of NGD logging

The physics of the Neutron-Gamma density (NGD) measurement is similar to that of GGD logging. High-energy neutrons emitted from the pulsed neutron generator create an induced gamma source from inelastic reactions in the formation surrounding the source. This serves as the source of gamma rays for GGD, so the attenuation of gamma rays is related to the density of the formation.

The size of the induced gamma source will vary with formation physical properties. Fortunately, for a commercial tool, the size changes of the induced source can be corrected by using an epithermal detector at a distance (Quirein et al., 2005).

But, the induced gamma source of NGD is created in the formation, so collimation cannot be placed outside of the source. The gamma ray attenuation no longer conforms to the narrow beam model and the build-up factor should be considered. Therefore, the gamma ray attenuation Eq. (1) should be modified as Eq. (6).

$$I = B \cdot I_0 \cdot e^{-\mu x} \tag{6}$$

Where B is a build-up factor, which is approximate to $(1 + \mu x)$.

For D-T neutron induced high-energy gamma rays, the energy is much higher than that of cesium, i.e. 0.662 MeV. Gamma rays of 6.13 MV, 4.43 MeV, 1.78 MeV and 3.73 MeV are mainly emitted for inelastic scattering from oxygen, carbon, silicon and calcium respectively. The energy of all these gamma rays is higher than the energy threshold of pair production, i.e. 1.02 MeV, so not only Compton scattering but also pair production will occur.

Without regard for the photoelectric effect, the total cross section and mass attenuation coefficient are the sum of that of Compton scattering and pair production interactions.