ISSN: 2414-1895 DOI: 10.6919/ICJE.202503_11(3).0005

A Review of Research on Equipment Munitions Detection based on PGNAA Technology

Bohao Zhao[1], Yongtao Zhou[1], Chen Xie[1], Xiannian Zhang[1], Youcai Wang[1], Lei Song[2]

[1] Rocket Force University of Engineering, Xi'an, China

[2] China Shanxi Nuclear (Xi'an) Neutron Technology Co., Ltd., Xi'an, China

Abstract

The detection of equipment and ammunition is an important link in the military field, which is vital to ensure the safety and effectiveness of military operations. With the development of science and technology, the transient gamma-ray neutron activation analysis (PGNAA) technology gradually shows great potential in the detection of equipment and ammunition.As a non-destructive, multi-element nuclear analysis technology, the PGNAA technology generates specific transient gamma rays through the interaction between neutrons and the object under test, and then analyzes the elemental compositions and contents in the object. In equipment and ammunition detection, the use of PGNAA technology can realize the rapid and accurate identification of key elements in equipment and ammunition. In this paper, we will summarize the research on equipment ammunition detection based on PGNAA technology, and discuss the basic principle, equipment selection, application advantages and future development direction of this technology.

Keywords

Instantaneous Gamma-Ray Neutron Activation Analysis; Equipment and Munitions Detection; Transient Neutron Activation Analysis.

1. Introduction

PGNAA (transient neutron activation analysis) is a non-destructive, multi-element nuclear analysis technique that has been widely used in recent years in many fields, such as industry, environment and security. Compared with other neutron activation methods, it is less sensitive, but it is capable of detecting almost all elements on the periodic table, especially for light and metallic elements. In 1980, the U.S. has begun to use transient neutron activation technology for coal detection, selecting fission neutron sources with high-precision detectors to obtain the energy spectrum, and using the energy spectrum processing method to analyze the content of coal. However, the neutron energy of the fission neutron source is not high, which will make the radiation capture reaction stronger, and there is no way to obtain the characteristic rays of C and O. In 1999, Womble et al. used a pulsed neutron source for the transient neutron activation technique [1]; Chen Bohian et al. used this technique in the experiments of screening coal samples. In recent years, the application areas of this technique have become more and more diverse. For example, in cement detection, Naqvi et al. used a D-D neutron generator for analysis by the PGNAA technique [2] to determine the detection of cement samples. For soil detection, Galina Yakubova and other researchers used PGNAA technique to design a set of equipment for the detection of carbon content in soil [3], and for water quality detection, R. Khelifi et al. used the technique to detect and analyze heavy metal elements in water bodies, and the results showed good results [4].In 2009, Nuclear Chemistry of the Korea Atomic Energy Research Center

ISSN: 2414-1895 DOI: 10.6919/ICJE.202503_11(3).0005

Research Department utilized transient gamma spectra of materials as well as elemental component content data to identify a range of material samples, differentiating between explosives and non-explosives through the content of major elements [5].

This technology bombards the nuclei of various elements in the target samples by the neutron stream generated by the neutron source, and the nuclei undergo reactions such as radiation capture, inelastic scattering, etc., and release γ-rays by de-excitation in a very short period of time. By detecting these γ-rays through the detector, the elements can be analyzed qualitatively and quantitatively online according to the energy and intensity (peak area) of each characteristic γ-ray. In terms of equipment munitions detection, PGNAA technology has a unique advantage in accurately identifying key elements in munitions, such as C, H, O, N, etc., which are one of the characteristics that distinguish them from other substances. Overall, PGNAA technology can realize rapid and accurate identification of key elements in ammunition, and provides a powerful tool for quantitative analysis.

2. Realities of Equipment Munitions Testing

2.1 Limitations of Traditional Testing Methods

Traditional methods of munitions inspection often have many limitations. The scope of inspection is restricted, making it difficult to comprehensively cover the internal structure of the munition, the quality of the charge, and changes in the position of parts and components, and other key information, which leads to the fact that during the inspection process, some potential quality problems may be missed, thus increasing the risk of munitions in the process of using them. Traditional methods usually require destructive testing, i.e. opening or disassembling the ammunition casing, which not only wastes ammunition resources, but also poses safety risks, is relatively inefficient, requires a lot of time and manpower, and is a complicated testing process, which makes it difficult to meet the rapid testing needs of modern ammunition production and use. Due to the limitations of detection methods, traditional methods may not be able to accurately determine the quality of ammunition, and there is a risk of misjudgment or omission, which will have a serious impact on the safety and reliability of ammunition.

2.2 Advantages of PGNAA Technology

The advantage of PGNAA technology is that it enables rapid and accurate analysis of a wide range of elements in munitions without destroying the structure of the munition, thus ensuring the integrity and safety of the test. It has high sensitivity and accuracy, and can accurately measure the energy and intensity of gamma rays, so as to accurately identify the type of element and accurately determine its content, which is particularly important for the detection of trace elements and low concentration elements. In addition, PGNAA technology is widely adaptable to the inspection of different types of munitions, regardless of the shape, size or material of the munitions. This non-destructive detection method not only improves the accuracy of the detection, but also reduces the safety risk in the detection process, realizes the perfect combination of non-destructive and real-time, and at the same time enables real-time online monitoring, providing timely and accurate data support, which is of great significance for process control and quality control. In addition, the technology also has the ability of multi-element analysis, which can measure the content of multiple elements at the same time, greatly broadening the scope of its application in the fields of geological exploration, environmental monitoring, industrial process analysis, and equipment and ammunition detection[6].

3. Equipment Munitions Detection based on PGNAA Technology

3.1 Rationale for the PGNAA Technique

The core principle of neutron activation analysis is the detection and quantitative analysis of elemental composition through the nuclear interaction of a neutron beam with the nucleus of a target atom in the sample. The principle is shown in Figure 1.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202503_11(3).0005

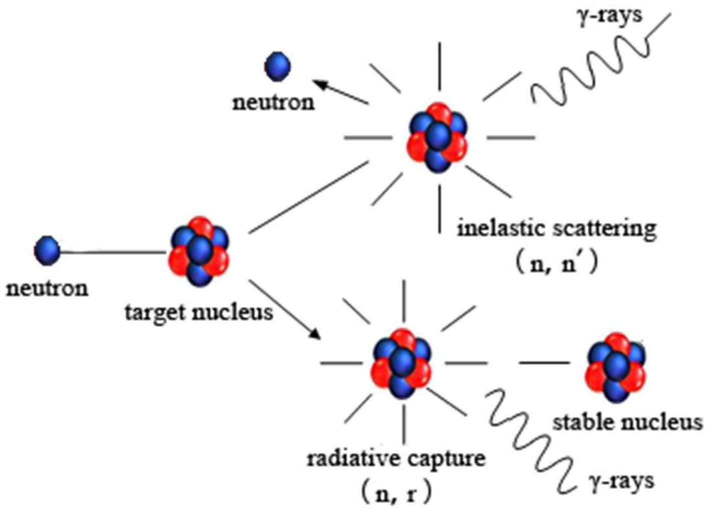

Figure 1. PGNAA schematic diagram

The target nucleus may become unstable after absorbing neutrons and then undergo a nuclear reaction, releasing characteristic transient γ-rays. By detecting and analyzing these γ-rays with high precision, accurate identification of nuclides can be performed based on the uniqueness of the characteristic γ-rays emitted by different nuclides under different reaction channels. Compared with the traditional Neutron Activation Analysis (NAA), the significant advantage of PGNAA is that it does not require a complex decay correction process, which makes PGNAA more straightforward and simpler in data processing and calculation. The technique focuses on the analysis of characteristic γ-rays, which are mainly produced by two types of reactions, one is inelastic scattering and the other is radiation capture. Specifically, thermal neutron capture reactions (n, γ) occur mainly in the thermal neutron energy range, and their product nuclei usually release multiple γ-rays during de-excitation to the ground state. Inelastic scattering reactions (n, n', γ), on the other hand, occur specifically under conditions where the fast neutron energy exceeds a specific excitation threshold. Most of the nuclides produced in a nuclear reaction are in the unstable first excited state, and they make the leap to the steady state by emitting a single energy γ-ray, a property that makes the ray directly desirable as a characteristic γ-ray without further screening or correction. For the counting of the characteristic γ-rays released by this process the following equation is satisfied:

$$C_r = Nt\gamma\varepsilon\alpha\int_0^{E_{max}}\sigma(E)\varphi(E)\,dE$$
$$= \frac{\mathrm{N_A}\theta\mathrm{W}}{\mathrm{M}}t\gamma\varepsilon\alpha\int_0^{E_{max}}\sigma(E)\varphi(E)\,dE$$

In addition, the neutron reaction cross-section distribution $\sigma(\mathrm{E})$ and the neutron injection rate distribution $\varphi(\mathrm{E})$ are also important factors that cannot be neglected in PGNAA analysis. The neutron reaction cross section determines the probability of a specific reaction of a neutron with a target nucleus, while the neutron injection rate describes the intensity and distribution of the neutron flow. Together, these two parameters influence the efficiency of neutron interaction with the nuclides in the sample and the production rate of characteristic γ-rays.

In the application of the PGNAA technique, when small samples of equipment and munitions are involved, the negligible variation of the neutron spectrum within the sample makes it possible to treat most of the parameters as constants, simplifying the calculation process. For this type of situation,

ISSN: 2414-1895 DOI: 10.6919/ICJE.202503_11(3).0005

the use of known material data and the formula for each parameter, calculate the intensity counts of the characteristic rays, and finally through the detector broadening can be obtained with the experimental situation similar to the spectral data, so as to decompose the spectrum and calculate the nuclide content. Because the actual measurement is often interfered by a variety of factors, it is difficult to obtain accurate results directly. To overcome this challenge, the parameters of the neutron source and the detector are usually set in practice and calibrated by measuring a sample with a known nuclide content and determining certain parameters related to the properties of the nuclide itself.

3.2 Selection of Key Equipment

The main equipment used in PGNAA technology includes neutron generators, γ detectors and related auxiliary equipment, the geometric configuration and specific parameters of the device will have an impact on data collection, in which the selection of neutron sources and γ detectors is crucial, directly affecting the measurement and analysis of the equipment and ammunition.

3.2.1 Neutron Sources

Neutron sources are used to produce neutrons, and choosing the right neutron source is crucial. There are three main categories:

The reactor neutron source produces neutrons continuously through the reaction process of chain fission. It is operated by mechanical control. The neutron source in a reactor has a complex spectral structure and generally consists of three types of neutrons: fast neutrons, thermal neutrons and slow neutrons. To break them down into neutron beams of different energy ranges, external equipment is required. The Reactor Neutron Source is not suitable for on-site detection in industry, as it is not easy to move and has a complex structure.

The use of charged particles accelerated in the gas pedal to obtain sufficient energy, when the charged particles bombard the target nucleus, the nuclear reaction between the two has the ability to release neutrons, based on this mechanism to create the device is named gas pedal neutron source. At present, many types of neutron sources have been developed, and the intensity of the gas pedal neutron source is significantly higher than the isotope neutron source, and the nuclear reaction is not only limited to (α, n) and (γ, n) the two types; there are no special requirements for the environment, etc., which is a new type of new high-energy nuclear material with great development prospects. The gas pedal neutron source is also capable of pulse modulation, thus controlling the output of neutron energy and enabling better detection of certain elements. It is an electrically controllable device and once it stops working, the neutron generation also stops, thus providing a higher level of security. Currently the most commonly used are proton beams and energetic particle streams.

The isotope neutron source is the optimal choice for the experimental environment, which has the advantages of compactness, easy to carry, and simple to make, etc. In this thesis, the isotope neutron source is chosen as the setting of the neutron source. However, the neutron source is usually radioactive, so it is more important to store it properly, which requires professionals to operate.An isotope neutron source works on the principle that for the spontaneous decay of a radioactive isotope to produce rays that interact with its equipped target material to produce neutrons. The rays emitted by their spontaneous decay are all high-energy rays, and there are two main types of reactions that can be induced by the rays produced, one being (α, n) and the other (γ, n).

3.2.2 Gamma Detectors

The principle of γ detector is through the process of γ-ray and material interaction, γ-ray is a kind of high-energy electromagnetic radiation, when passing through the detector material will produce several different reactions, it is based on these reactions to measure the intensity of γ-ray. Common γ detectors are scintillator detectors, semiconductor detectors, and gas detectors.

Scintillator detectors in the experimental process usually need to be detected with photomultiplier tubes and other equipment to form a set of detection system, the crystal has luminescent properties, can be divided into organic and inorganic properties, Table 1 lists the specific parameters of several common inorganic scintillators.

DOI: 10.6919/ICJE.202503_11(3).0005

Table 1. Properties of common scintillators

norm	NaI	BGO	LaBr3(Ce)
Density (g/cm^3)	3.67	7.13	5.2
deliquescent	deliquesce	non-dampening	deliquesce
Light decay time (ns)	230	300	16
Maximum emission wavelength (nm)	415	650	380
Light output relative to NaI	100%	10%-14%	130%
energy resolution	About 7.5%	About 2.6%	About 3%

NaI (Tl) has a high light yield, can respond quickly, and has a high detection ability for γ-rays. However, it is prone to deliquescence and its resolution is not high, and its shortcomings need to be compensated by other work in the need for high precision requirements and in harsh environments.

Lanthanum bromide (LaBr3) belongs to the recently introduced scintillator materials, which are now widely used in experimental as well as industrial detection processes, and it has a higher light output efficiency than sodium iodide, with an energy resolution of about 3%, and a small nonlinear response [7].

Bismuth germanate (BGO) is a type of inorganic crystal that is not susceptible to deliquescence and can effectively resist and absorb high-energy rays from a variety of radiation sources. In addition, BGO also has high scintillation efficiency, can quickly and efficiently release visible light scintillation under the action of high-energy rays, and also exhibits excellent energy resolution, which can accurately distinguish between rays or particles of different energies.

In selecting γ detectors for research, the main focus is on energy resolution and detection efficiency. For pure γ detectors, the main detector applications are still focused on NaI (Tl) and lanthanum bromide (LaBr3).

4. Future Prospects

The application of PGNAA technology in equipment and ammunition inspection research has shown unprecedented potential and broad prospects.PGNAA technology stands out in complex equipment and ammunition inspection by virtue of its non-destructive, high-precision and multi-element simultaneous analysis capabilities, effectively making up for the shortcomings of traditional inspection methods. It is not only able to penetrate into the interior of equipment and ammunition, accurately identify and quantify key components, but also realize comprehensive quality and safety assessment without destroying the structure of ammunition, which is of great significance for the maintenance and safety of modern military equipment. However, despite its many advantages, PGNAA technology faces some challenges that cannot be ignored. Instrument performance and stability are the key factors restricting its application. The performance and stability of key links such as neutron sources, detectors, data acquisition and processing systems have an important impact on the analysis results, so it is necessary to continuously research and develop and improve the instrumentation to improve its performance and stability. The difficulty of data analysis and resolution is also a major challenge. Since the measured substance may contain multiple elements and the characteristic peaks between different elements may overlap or interfere, which increases the complexity and difficulty of data analysis, how to effectively resolve these data and establish accurate mathematical models to assess the performance of the equipment and munitions is a problem that needs to be solved at present. Looking ahead, the continued advancement of PGNAA technology and interdisciplinary integration will be the key forces driving its development. With the integration of Internet of Things (IoT), cloud computing, and advanced sensor technologies, the level of intelligence and networking of the PGNAA inspection system will be significantly improved, enabling remote monitoring and instant data analysis, and dramatically improving inspection efficiency and accuracy. At the same time, combined with Deep Learning and advanced statistical analysis methods, PGNAA technology will be able to mine deeper ammunition performance information, through the big data-driven prediction model for equipment and ammunition life assessment, failure warning and performance optimization to provide a scientific basis. Especially important is that the cross research between PGNAA technology and material science, explosion mechanics and other fields will continue to expand the boundaries of its application, promoting the development of new equipment and ammunition materials and upgrading the performance of existing equipment and ammunition. In this process, the establishment of a standardized and systematic testing process and database plays an irreplaceable role in promoting the popularization of the technology and upgrading the testing standards. In the face of challenges, future research should focus on technological innovation and transformation of results, and continuously optimize the portability, detection speed and cost-effectiveness of PGNAA equipment to adapt to different battlefield environments and operational needs. With the continuous progress of science and technology and the deepening of related research, PGNAA technology will provide strong technical support for the safety management, performance evaluation and modernization and upgrading of military equipment and ammunition.

References

[1] Belbot D M, Vourvopoulos G, Womble C P, et al. Elemental online coal analysis using pulsed neutrons[C]. Western Kentucky Univ. (United States), 1999: 45-52.Wells K ,Bradley D .A review of X-ray explosives detection techniques for checked baggage[J]. Wells K ,Bradley D .A review of X-ray explosives detection techniques for checked baggage[J].

[2] Naqvi,,AA.A Monte Carlo comparison of PGNAA system performance using ²⁵²Cf neutrons, 2.8-MeV neutrons and 14-MeV neutrons [J].NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT,2003,511(3). 400-407.

[3] Yakubova G, Kavetskiy A, Prior A S, et al. Application of Geant4 simulation for analysis of soil carbon inelastic neutron scattering measurements[J]. Applied Radiation and Isotopes, 2016, 113: 33-39.

[4] Khelifi R, Bode P. Monte Carlo study of a flexible device for in situ PGNAA using 241Am-Be source: application to total chlorine determination[J]. Journal of Radioanalytical and Nuclear Chemistry, 2016, 309(1): 189-193.

[5] Im,,Hee-Jung et al.Classification of materials for explosives from prompt gamma spectra by using principal component analysis[J].APPLIED RADIATION AND isotopes,2009,67(7-8):1458-1462.

[6] Abdullah A T .Developing a PGNAA setup for heavy metal detection in solid samples[J].Journal of Radioanalytical and Nuclear Chemistry,2024,333(7). 3523-3528.

[7] A. Favalli, H-C. Mehner, V. Ciriello, B. Pedersen, Investigation of the PGNAA using the LaBr3 scintillation detector, Applied Radiation and Isotopes, Volume 68, Issues 4-5, 2010. Volume 68, Issues 4-5, 2010, 901-904. ISSN 0969-8043.