Nuclear Instruments and Methods in Physics Research A 797 (2015) 182–187

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Uranium mass and neutron multiplication factor estimates from time-correlation coincidence counts

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ARTICLE INFO

Article history:
Received 9 January 2015
Received in revised form
3 March 2015
Accepted 26 May 2015
Available online 6 July 2015

Keywords:
Time-correlation coincidence count
Uranium component
Mass
Multiplication measurement
Neutron TOF

ABSTRACT

Time-correlation coincidence counts of neutrons are an important means to measure attributes of nuclear material. The main deficiency in the analysis is that an attribute of an unknown component can only be assessed by comparing it with similar known components. There is a lack of a universal method of measurement suitable for the different attributes of the components. This paper presents a new method that uses universal relations to estimate the mass and neutron multiplication factor of any uranium component with known enrichment. Based on numerical simulations and analyses of 64 highly enriched uranium components with different thicknesses and average radii, the relations between mass, multiplication and coincidence spectral features have been obtained by linear regression analysis. To examine the validity of the method in estimating the mass of uranium components with different sizes, shapes, enrichment, and shielding, the features of time-correlation coincidence-count spectra for other objects with similar attributes are simulated. Most of the masses and multiplications for these objects could also be derived by the formulation. Experimental measurements of highly enriched uranium castings have also been used to verify the formulation. The results show that for a well-designed time-dependent coincidence-count measuring system of a uranium attribute, there are a set of relations dependent on the uranium enrichment by which the mass and multiplication of the measured uranium components of any shape and size can be estimated from the features of the source-detector coincidence-count spectrum.

1. Introduction

Time-correlation coincidence-count measurements are an important means in verifying attributes of nuclear components. The studies on applications of the method in technology verification of nuclear reduction reflects many ingenious relationships between features of neutron coincidence spectra and attributes of the nuclear component that reveal some intrinsic connection existing between the spectrum, the configuration of the nuclear component, and the experimental setting. Based on this, Oak Ridge National Laboratory has developed a nuclear material identification system for verifying fissile materials [1,2].

Whereas time-dependent coincidence-count analysis has provided some success in plutonium and depleted uranium measurements, for other important nuclear materials, applications have encountered some difficulties [3,4]. Because of low efficiency, the emission rates for neutrons and gamma rays following spontaneous fission of uranium, active detection of radiation sources is required but brings in more complications and difficulties than passive plutonium measurements [5,6].

(1) Several theoretical and experimental works are carried out to establish the relation between the characteristic of the time spectrums and the features of the uranium object. In 2004, the neutron imaging is introduced in to the nuclear material identification system and applied to determine nuclear material and object in Oak Ridge National Laboratory to give more constraint to the estimation process [7,8]. With the geometry information acquired by imaging system, the enrichment of uranium is estimated by comparing the detection result with the simulated results [10]. There are other efforts to improve the time coincident measurement system, such as adding high resolution gamma ray spectrometry. By the improvement, the system could be used to detect the explosive and some chemical agents [9].

By a series of numerical simulations and experimental measurements, the research at the China Academy of Engineering Physics (CAEP) on measuring uranium component attributes with time-correlation-coincidence analysis has made some progress [11,12]. Uranium castings with similar mass and shape but different enrichments can be effectively distinguished by their coincidence spectra and specific features, in much the same

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http://dx.doi.org/10.1016/j.nima.2015.05.066
0168-9002/

Table 1
(a) Mass of the 90%-uranium-enriched fitted group.

Thickness (cm)	Average radius (cm)							
	2	3	4	5	6	7	8	9
0.4	0.377	0.847	1.504	2.350	3.383	4.604	6.013	7.610
0.8	0.761	1.701	3.016	4.707	6.773	9.215	12.033	15.227
1.2	1.161	2.570	4.543	7.079	10.179	13.842	18.069	22.859
1.6	1.583	3.462	6.092	9.473	13.606	18.491	24.127	30.514
2.0	2.035	4.384	7.671	11.898	17.064	23.170	30.215	38.199
2.4	2.525	5.343	9.288	14.360	20.560	27.887	36.341	45.922
2.8	3.060	6.347	10.950	16.868	24.101	32.648	42.511	53.689
3.2	3.647	7.404	12.665	19.428	27.694	37.463	48.735	61.510

(b) Multiplication of the 90%-uranium-enriched fitted group

Thickness (cm)	Average radius (cm)							
	2	3	4	5	6	7	8	9
0.4	1.124	1.137	1.147	1.154	1.160	1.164	1.168	1.172
0.8	1.222	1.256	1.280	1.298	1.313	1.325	1.335	1.344
1.2	1.314	1.375	1.420	1.455	1.483	1.507	1.526	1.543
1.6	1.401	1.498	1.571	1.629	1.678	1.718	1.753	1.784
2.0	1.485	1.625	1.736	1.827	1.905	1.971	2.029	2.081
2.4	1.564	1.756	1.916	2.054	2.173	2.279	2.374	2.458
2.8	1.641	1.892	2.115	2.314	2.497	2.665	2.817	2.956
3.2	1.716	2.032	2.334	2.620	2.892	3.157	3.407	3.643

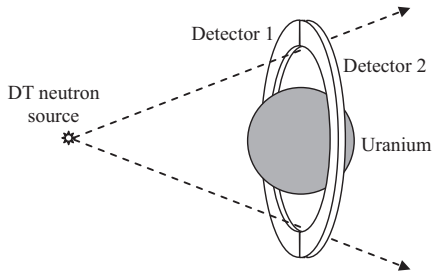

Fig. 1. The configuration of detection system used in the simulation.

manner as castings with similar enrichment and shape but different mass. However, according to all the published data, the current technology used in time-correlation coincidence-count measurements of component attributes has an obvious drawback in that only the uranium components with a single variable attribute can be distinguished. To measure the enrichment/mass of an unknown component, known components of the same type need to have been studied to establish a template for the comparison so that the attribute of the unknown component can be distinguished in the different coincidence spectra. Because of a lack of a universal method of measurement suitable for the different attributes of the components, further development and application of the time-correlation coincidence-count analysis is greatly restricted.

Researchers at Oak Ridge National Laboratory have produced estimates of plutonium attributes by passive time-correlation coincidence-count measurements [13, 14], but active uranium measurements are much more complex and difficult. This paper presents a new method to estimate the mass and multiplication of any uranium component with known enrichment using universal relations. We numerically simulated and analyzed 64 highly enriched uranium (HEU) components with different thicknesses and average radii, and developed empirical relations between mass, multiplication, and coincidence spectrum features by fits to the data. The attributes of six other HEU components with different sizes and shapes are simulated. The result indicates that the relations and the parameters remain constant for all components. Furthermore, the applicability of this method is also discussed in regard to the measurement of uranium components with different enrichment factors placed in metal containers of different thicknesses. Results from experimental measurements of six HEU castings support the validity of the formulation.

2. Simulation and analysis of 90% uranium components

In measuring an unknown uranium component, generally the enrichment and mass are acknowledged as important attributes of interest. Generally, the uranium enrichment factor can be obtained relatively accurately by gamma-ray spectrometry [15–18]. The shape and size of uranium components are a sensitive determiner of the inner structure and design level of a nuclear warhead, but they are not allowed to be measured in many situations. In addition, the multiplication can be considered a secondary parameter of the attribute-estimation procedure, because it is related to enrichment, mass, and shape and can provide valuable information in analyzing an attribute of a uranium component.

This paper focuses on spherical or hemispherical shells of uranium with mass between 0 to 20 kg. Sixty-four selected uranium spherical shells with eight different radial thicknesses and eight different average radii are used as a test group for data fitting. Their coincidence-count spectra are simulated in a typical time-dependent coincidence-count measuring layout [11]. For components with a uranium enrichment factor of 90%, mass and multiplication of the fitted group are listed in Table 1.

The measuring layout of the numerical simulation is depicted in Fig. 1. The two semicircular detectors form a 1-cm-thick ring with a 29.5-cm inner radius, a 30.5-cm outer radius. The uranium component is located in the center of the ring. The distances from the object and the detectors are selected to balance the effects of the neutron transport time inside and outside the uranium object. The DT neutron tube is used as a neutron source, and is 30 cm away from the component center. Although the emitted neutron covers a solid angle of 4π, only neutrons directed toward the