γ- ray self-absorption of cylindrical fissile material

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Abstract The self-absorption of γ-ray emitted from cylindrical fissile materials, such as ^{235}U and ^{239}Pu, does not possess spherical symmetry. The analytical formulae of self-absorption for γ-ray throughout the cylinder have been obtained. The intensity of γ-ray is a function of γ-ray outgoing directions and cylindrical configurations, accordingly one can acquire the information about geometrical configuration of cylindrical fissile materials through multi-location measurements. Further more, the method is given in this article. The result can be applied to the fissile material safeguard, such as nuclear monitoring and verifying.

Keywords Fissile material, Isotopic composition, Multi-location measurement, γ-ray self-absorption

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1 Introduction

So far a great amount of nuclear fissile materials, uranium (^{235}U) and plutonium (^{239}Pu) have been produced and stockpiled in the world. The risk of proliferation of fissile materials has been increasing. Especially smuggling and stealthy carrying of these materials controlled by terrorists have been concerned by the international society.[1-5]

The International Atomic Energy Agency (IAEA) has appealed to strengthen and support the international supervisory system and the R & D of related supervising techniques.[6] The isotopic composition (uranium or plutonium) of fissile materials can be easily obtained from the spectra of γ-ray emitted from the materials. A typical γ spectrum of enriched uranium is shown in Fig.1.[7] It is still unknown whether the geometrical information on nuclear device including size, geometric configuration and the shield thickness of the outside packing can be obtained according to the intensity ratio caused by the variety of absorption coefficient of γ-ray with different energy in nuclear material along with the variety of emitting direction.

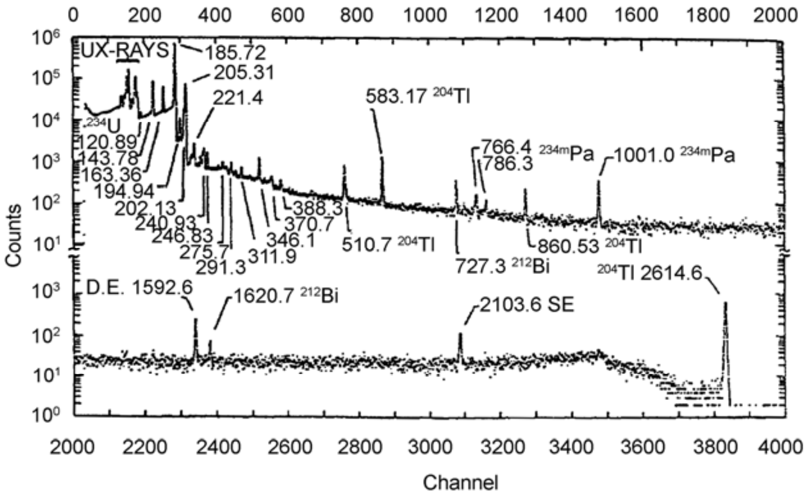

Fig.1 The γ-spectrum of highly enriched uranium.

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In 1989, teams of scientists from Natural Resource Defence Council of the United States and Academy of Science of the Soviet Union measured the nuclear warhead of an SS-N-12 cruise missile in the cruiser Slava of the Black Sea marine. The results of measurement and analysis were published in *Science*.[8] Their conclusion was whether the warhead consisted of uranium or plutonium was decided by its γ-ray spectrum. However, the measurements had not given the design information referred to geometrical configuration because of the restrictive location and time of measurements. As a matter of fact, the warhead was supposed to be spherical or with a spherical surface in the calculation of that article, in other words, the warhead was supposed to have spherical symmetry in geometry.

After 1997, Tian et al.[9] brought forward that the geometric information of nuclear material can be resolved according to self-absorption of nuclear material in different directions. Tian et al. calculated exactly the self-absorption coefficient of the spherical material in their article. As for cylindrical material, when γ-ray was detected along the axis direction, they made an approximate calculation.

In this article the research extent will be widened. The self-absorption correction will be obtained exactly when γ-ray was emitted throughout the cylinder. Further, we resolve the geometric configuration of the nuclear device through the detection of γ-ray in any direction.

2 Space partition outside the cylindrical nuclear material

The space outside the cylinder is divided into three parts: Part I the space in the cylindrical side face except the cylinder; Part II the space between the two basal faces of the cylinder except the cylinder; and Part III the space outside the cylinder except Part I and Part II. See Fig.2.

3 Expression of the self-absorption correction coefficient

Here expressions of self-absorption correction coefficient G will be given, what's more, the discussion in the interfaces will be done.

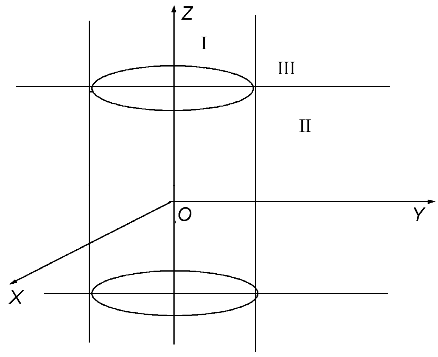

Fig.2 Cylindrical nuclear material's space partition.

3.1 Geometry of the γ-ray detection in Part I

We confine the γ-ray detection deviating from the cylindrical axis in the region where $r^2 \leqslant R^2$ and $z \geqslant H/2$ or $z \leqslant -H/2$ in the cylindrical coordinates. We take polar coordinates of D as (r_0, θ_0, z_0), polar coordinates of S as (r, θ, z) and the cylindrical radius as R, as shown in Fig.3.

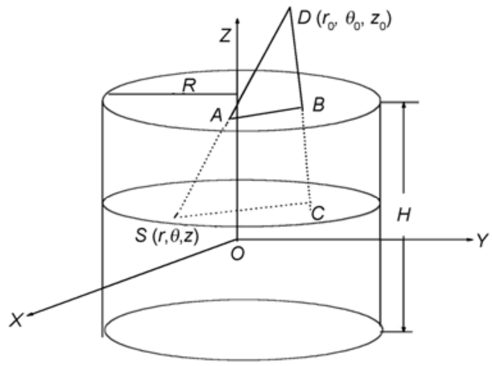

Fig.3 Detection of γ-ray in Part I of the cylinder.

The radial distance t in Part I is given by:

$$t(r,\theta,z) \equiv SA = \frac{CB}{CD} \times SD = \frac{H/2 - z}{z_0 - z} \times \sqrt{(r\cos\theta - r_0\cos\theta_0)^2 + (r\sin\theta - r_0\sin\theta_0)^2 + (z - z_0)^2} \tag{1}$$

Considering the symmetry, we take $\theta_0 = 0$, Eq.(1) will become:

$$t(r,\theta,z) = \frac{H/2 - z}{z_0 - z} \times \sqrt{r^2 + r_0^2 - 2rr_0\cos\theta + (z - z_0)^2} \tag{2}$$

The self-absorption coefficient G simply becomes:

$$G = \int_{-H/2}^{H/2} \mathrm{d}z \int_0^R r\mathrm{d}r \int_0^{2\pi} \exp[-\mu(E_\gamma)t(r,\theta,z)]\mathrm{d}\theta \quad (3)$$

Let r_0=0, Eq.(2) will become:

$$t(r,\theta,z) = \frac{H/2 - z}{z_0 - z} \times \sqrt{r^2 + (z - z_0)^2} \quad (2')$$

the self– absorption coefficient G is the same as Eq.(3). That is the case that the detector is placed in the axis of the cylinder as in Ref.[10].

3.2 Geometry of the γ-ray detection in Part II

In Fig.4, adopting the cylindrical coordinates, the detector is placed at the point D in Part II. Considering symmetry, polar coordinates of point D are (r_0, 0, z_0). S (r, θ, z) is a point in the bulk of the cylinder.

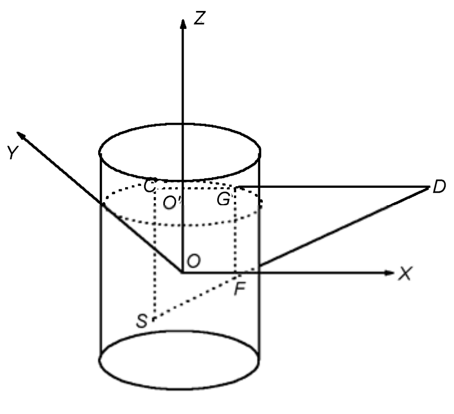

Fig.4 Detection of γ-ray in Part II of the cylinder.

From Fig.4 one can easily acquire the following relations:

$$SF = SD \times \frac{CG}{CD}, \text{ where}$$

$$CD = t_1 = \sqrt{r^2 + r_0^2 - 2rr_0 \cos\theta}$$

$$CG = \frac{1}{t_1}\left[r^2 - r_0 r\cos\theta + \sqrt{r_0^2 r^2 \cos^2\theta - 2R^2 r_0 r\cos\theta - (r_0^2 - R^2)r^2 + R^2 r_0^2} \right]$$

$$SD = \sqrt{r^2 + r_0^2 - 2rr_0 \cos\theta + (z - z_0)^2}$$

The absorption distance SF can be expressed by:

$$t(r,\theta,z) \equiv SF = \left[r^2 - r_0 r\cos\theta + \sqrt{r_0^2 r^2 \cos^2\theta - 2R^2 r_0 r\cos\theta - (r_0^2 - R^2)r^2 + R^2 r_0^2} \right] \times \frac{\sqrt{r^2 + r_0^2 - 2rr_0\cos\theta + (z - z_0)^2}}{r^2 - 2r_0 r\cos\theta + r_0^2} \quad (4)$$

$$G = \int_{-H/2}^{H/2} \mathrm{d}z \int_0^R r\mathrm{d}r \int_0^{2\pi} \exp[-\mu(E_\gamma)t(r,\theta,z)]\mathrm{d}\theta \quad (5)$$

Let z_0=0, Eq.(4) will become:

$$t(r,\theta,z) = \frac{1}{r^2 - 2Lr\cos\theta + L^2} \times \left[r^2 - Lr\cos\theta + \sqrt{L^2 r^2 \cos^2\theta - 2R^2 Lr\cos\theta - (L^2 - R^2)r^2 + R^2 L^2} \right] \times \sqrt{L^2 + z^2 + r^2 - 2Lr\cos\theta} \quad (4')$$

where L=r_0, the radius of the cylinder. The self-absorption coefficient G is the same as Eq.(5). That is the case that the detector is placed on the plane XOY of the cylinder as in Ref.[10].

3.3 Geometry of the γ-ray detection in space of Part III

3.3.1 Plane Equation

A plane that goes through the line DE and is parallel to the axis OY is named after plane β. Since point A's and point D's coordinates are respectively $A(R,0,H/2)$ and $D(r_0, \theta_0, z_0)$, the plane equation is immediately expressed as follows:

$$\begin{cases} z - z_0 = \dfrac{z_0 - H/2}{r_0 - R}(x - r_0) \\ y = y \end{cases} \quad (6)$$

Using the equation, the point E's coordinate is easily written as

$$E\left[-R, 0, z_0 - \frac{z_0 - H/2}{r_0 - R}(R + r_0) \right]$$

3.3.2 Calculation of self-absorption distance

When the point in the bulk of the cylinder is above the plane β, the calculation of self-absorption distance is analogous to the case of Part I, and their expressions are analogous too, seeing Fig.5.

$$t_u \equiv SF = \frac{KH}{DK} \times SD = \frac{H/2 - z}{z_0 - z} \times \sqrt{r^2 + r_0^2 - 2rr_0\cos\theta + (z - z_0)^2} \quad (7)$$

When the point in the bulk of the cylinder is under the plane β, the calculation of self-absorption distance is analogous to the case of Part II, and their expressions are analogous.

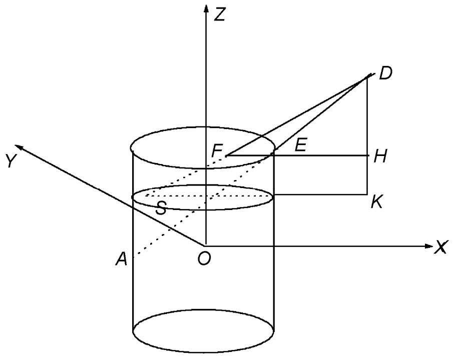

Fig.5 Calculation of the radiant distance in Part III (a).

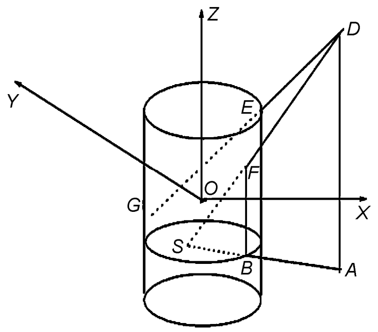

Fig.6 Calculation of the radiant distance in Part III (b).

From Fig.6 $SF = \dfrac{SB}{SA} \times SD$ are gained, where

$$SA = \sqrt{r^2 + r_0^2 - 2rr_0 \cos\theta}$$

$$SD = \sqrt{r^2 + r_0^2 - 2rr_0 \cos\theta + (z - z_0)^2}$$

$$SB = \frac{1}{\sqrt{r^2 + r_0^2 - 2rr_0 \cos\theta}} \times \Big[r^2 - r_0 r \cos\theta + \sqrt{r_0^2 r^2 \cos^2\theta - 2R^2 r_0 r \cos\theta - (r_0^2 - R^2) r^2 + R^2 r_0^2} \Big]$$

So we obtain

$$t_d \equiv SF = \Big[r^2 - r_0 r \cos\theta + \sqrt{r_0^2 r^2 \cos^2\theta - 2R^2 r_0 r \cos\theta - (r_0^2 - R^2) r^2 + R^2 r_0^2} \Big] \times \frac{\sqrt{r^2 + r_0^2 - 2rr_0 \cos\theta + (z - z_0)^2}}{r^2 - 2r_0 r \cos\theta + r_0^2} \tag{8}$$

3.3.3 Expressions of self-absorption coefficient G in Part III

In order to give the expressions of coefficient G in part III, two situations are considered. The first case is shown in Fig.7. The plane β is above the diagonal plane.

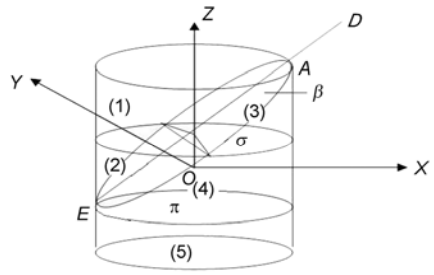

Fig.7 Expressions of coefficient G in Part III (a).

The whole cylinder is divided into five parts for the explicit expressions of coefficient G. The plane β and the side face intersect at point E through which a plane π goes. Under the plane π is part (5). The area above the part (5) is divided into two parts by the plane β. The plane β and the axis OZ intersect one point through which a plane σ goes vertical with the axis OZ. The plane σ splits the area above the part (5) into the parts (1), (2), (3) and (4).

Here we write coefficient G expressions of every part:

$$G_1 = \int_{z_0 - r_0 \frac{z_0 - H/2}{r_0 - R}}^{H/2} \mathrm{d}z \int_{-\arccos\frac{x}{R}}^{\arccos\frac{x}{R}} \mathrm{d}\theta \int_0^{\frac{x}{\cos\theta}} \exp(-\mu t_u) r \mathrm{d}r + \int_{z_0 - r_0 \frac{z_0 - H/2}{r_0 - R}}^{H/2} \mathrm{d}z \int_{\arccos\frac{x}{R}}^{2\arccos(-\frac{x}{R}) + \arccos\frac{x}{R}} \mathrm{d}\theta \int_0^R \exp(-\mu t_u) r \mathrm{d}r$$

$$G_2 = \int_{z_0 - \frac{z_0 - H/2}{r_0 - R}(R + r_0)}^{z_0 - r_0 \frac{z_0 - H/2}{r_0 - R}} \mathrm{d}z \int_{\arccos\frac{x}{R}}^{2\arccos(-\frac{x}{R}) + \arccos\frac{x}{R}} \mathrm{d}\theta \int_{\frac{x}{\cos\theta}}^{R} \exp(-\mu t_u) r \mathrm{d}r$$

$$G_3 = \int_{z_0 - \frac{z_0 - H/2}{r_0 - R} r_0}^{H/2} \mathrm{d}z \int_{-\arccos\frac{x}{R}}^{\arccos\frac{x}{R}} \mathrm{d}\theta \int_{\frac{x}{\cos\theta}}^{R} \exp(-\mu t_d) r \mathrm{d}r$$

$$G_4 = \int_{z_0 - \frac{z_0 - H/2}{r_0 - R}(r_0 + R)}^{z_0 - \frac{z_0 - H/2}{r_0 - R} r_0} \mathrm{d}z \int_{\arccos\frac{x}{R}}^{2\arccos(-\frac{x}{R}) + \arccos\frac{x}{R}} \mathrm{d}\theta \times \int_0^{\frac{x}{\cos\theta}} \exp(-\mu t_d) r \mathrm{d}r +$$

$$\int_{z_0-\frac{z_0-H/2}{r_0-R}(r_0+R)}^{z_0-\frac{z_0-H/2}{r_0-R}r_0} \mathrm{d}z \times$$

$$\int_{-\arccos\frac{x}{R}}^{\arccos\frac{x}{R}} \mathrm{d}\theta \int_0^R \exp(-\mu t_d) r\mathrm{d}r$$

$$G_5 = \int_{-H/2}^{z_0-\frac{z_0-H/2}{r_0-R}(R+r_0)} \mathrm{d}z \int_0^R r\mathrm{d}r \int_0^{2\pi} \exp[-\mu(E_\gamma)t_d]\mathrm{d}\theta$$

where $x \equiv r_0 + \dfrac{(z-z_0)(r_0-R)}{z_0-H/2}$, and t_{u} and t_{d} are given by (7) and (8) respectively.

The total coefficient G in Part III is the sum of the five parts:

$$G = \sum_{i=1}^{5} G_i \tag{9}$$

The other case's figure is shown below in Fig.8.

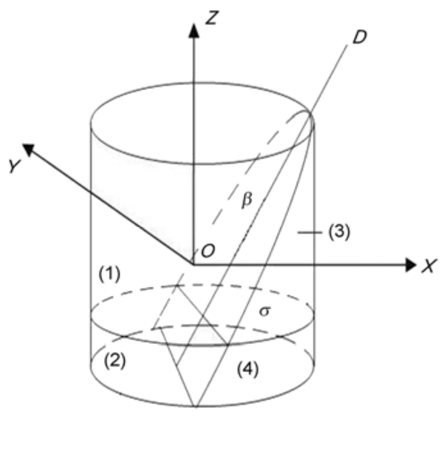

Fig.8 Expressions of coefficient G in Part III (b).

The whole cylinder is divided into four parts for the explicit expressions of coefficient G. This case is apparently easier than the first one. Their area partitions are analogical and so are the expressions. Here are the expressions below.

$$G_1 = \int_{z_0-r_0\frac{z_0-H/2}{r_0-R}}^{H/2} \mathrm{d}z \int_{-\arccos\frac{x}{R}}^{\arccos\frac{x}{R}} \mathrm{d}\theta \int_0^{\frac{x}{\cos\theta}} \exp(-\mu t_u) r\mathrm{d}r +$$

$$\int_{z_0-r_0\frac{z_0-H/2}{r_0-R}}^{H/2} \mathrm{d}z \int_{\arccos\frac{x}{R}}^{2\arccos(-\frac{x}{R})+\arccos\frac{x}{R}} \mathrm{d}\theta \int_0^R \exp(-\mu t_u) r\mathrm{d}r$$

$$G_2 = \int_{-H/2}^{z_0-r_0\frac{z_0-H/2}{r_0-R}} \mathrm{d}z \int_{\arccos\frac{x}{R}}^{2\arccos(-\frac{x}{R})+\arccos\frac{x}{R}} \mathrm{d}\theta \times$$

$$\int_{\frac{x}{\cos\theta}}^{R} \exp(-\mu t_u) r\mathrm{d}r$$

$$G_3 = \int_{z_0-\frac{z_0-H/2}{r_0-R}r_0}^{H/2} \mathrm{d}z \int_{-\arccos\frac{x}{R}}^{\arccos\frac{x}{R}} \mathrm{d}\theta \times$$

$$\int_{\frac{x}{\cos\theta}}^{R} \exp(-\mu t_d) r\mathrm{d}r$$

$$G_4 = \int_{-H/2}^{z_0-\frac{z_0-H/2}{r_0-R}r} \mathrm{d}z \int_{\arccos\frac{x}{R}}^{2\arccos(-\frac{x}{R})+\arccos\frac{x}{R}} \mathrm{d}\theta \int_0^{\frac{x}{\cos\theta}} \exp(-\mu t_d) r\mathrm{d}r +$$

$$\int_{-H/2}^{z_0-\frac{z_0-H/2}{r_0-R}r_0} \mathrm{d}z \int_{-\arccos\frac{x}{R}}^{\arccos\frac{x}{R}} \mathrm{d}\theta \int_0^R \exp(-\mu t_d) r\mathrm{d}r$$

In the above four formulae t_u, t_d and x are the same as the first case.The total coefficient G is the sum of the four parts:

$$G = \sum_{i=1}^{4} G_i \tag{10}$$

Besides the above two situations, the third case must be considered, seeing Fig.9. However, this situation is a special one of the second case. Actually as long as the second and the fourth terms are omitted from the formula (10), that is the coefficient G of this case.

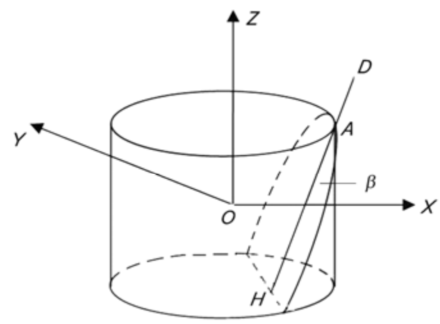

Fig.9 Expressions of coefficient G in Part III (c).

3.3.4 Boundary discussion

Here the boundary question is referred to two cases: (1) whether the two G expressions are consistent or not when the detector is placed on the diagonal plane of the cylinder; and (2) whether the G expressions between in Part III and in Part I and between in Part III and in Part II are consistent or not.

(1) Detector D is on the diagonal plane of the

cylinder.

In this case point *E*'s coordinate is (-*R*, 0, -*H*/2), that is to say, $z_0 - \frac{z_0 - H/2}{r_0 - R}(R + r_0) = -H/2$ * .

Then in the first above case $G = \sum_{i=1}^{5} G_i$ will become $G = \sum_{i=1}^{4} G_i$. Using the relationship * the first case and the second case will be found consistent.

(2) Boundary discussion between Part III and Part I, Part III and Part II

Part III and Part I

We must use the third case of part III, and compare it with Part I at the boundary. The result in the third case of Part III is $G=G_1+G_3$, the expressions of G_1 and G_3 are shown as follows:

$$G_1 = \int_{z_0 - r_0\frac{z_0 - H/2}{r_0 - R}}^{H/2} \mathrm{d}z \int_{-\arccos\frac{x}{R}}^{\arccos\frac{x}{R}} \mathrm{d}\theta \int_0^{\frac{x}{\cos\theta}} \exp(-\mu t_u) r \mathrm{d}r +$$

$$\int_{z_0 - r_0\frac{z_0 - H/2}{r_0 - R}}^{H/2} \mathrm{d}z \int_{\arccos\frac{x}{R}}^{2\arccos(-\frac{x}{R})+\arccos\frac{x}{R}} \mathrm{d}\theta \int_0^{R} \exp(-\mu t_u) r \mathrm{d}r$$

$$G_3 = \int_{z_0 - \frac{z_0 - H/2}{r_0 - R} r}^{H/2} \mathrm{d}z \int_{-\arccos\frac{x}{R}}^{\arccos\frac{x}{R}} \mathrm{d}\theta \int_{\frac{x}{\cos\theta}}^{R} \exp(-\mu t_d) r \mathrm{d}r$$

At the boundary $r_0=R$, so $x=R$ and $G_3=0$ and the first term of G_1, then G_1 becomes

$$G_1 = \int_{-\infty}^{H/2} \mathrm{d}z \int_0^{2\pi} \mathrm{d}\theta \int_0^{R} \exp(-\mu t_u) r \mathrm{d}r$$

$$= \int_{-H/2}^{H/2} \mathrm{d}z \int_0^{2\pi} \mathrm{d}\theta \int_0^{R} \exp(-\mu t_u) r \mathrm{d}r$$

This upper formula is the same as the result of Part I.

Part III and Part II

Here the first case in the part III is $G = \sum_{i=1}^{5} G_i$, at the boundary $z_0 = H/2$, $G_1=G_2=G_3=G_4=0$ because of the limits of integration, so $G=G_5$. Using the relationship $z_0 = H/2$ we can obtain $G = G_5 =$

$$\int_{-H/2}^{H/2} \mathrm{d}z \int_0^{R} r \mathrm{d}r \int_0^{2\pi} \exp[-\mu(E_\gamma) t_d] \mathrm{d}\theta$$

, which is just the result of Part II.

4 Methods of working out the cylindrical configuration by factor G

The two-location measurements are taken for convenient resolutions with higher precisions. The relative intensities can be obtained by the measurements of the characteristic γ-ray spectra of different locations. I_1 and I_2 are the intensities detected in the axis of the cylinder and on the *XOY* plane of the cylinder respectively. The distance *L* is considered much larger than the size of the cylinder. The relative intensity of different locations can be expressed by

$$\frac{I_2}{I_1} = \frac{G_2(R, H, L_2)/L_2^2}{G_1(R, H, L_1)/L_1^2} \quad (11)$$

If $L_1=L_2=L$, the above formula will become:

$$\frac{I_2}{I_1} = \frac{G_2(R, H, L)}{G_1(R, H, L)} \quad (12)$$

When the detective distance $L >> H$ and $L >> R$, the relative intensity I_2/I_1 is sensitive not to *R* and *H* of the cylindrical configuration but to the relative size *H*/*R*. Let *R* equal a special value, here we assume *R*=1.0 cm, then the relationship of *H*/*R*- I_2/I_1 will be worked out. That is to say, *H*/*R* depends on the relative intensity I_2/I_1. The real value of *R* is decided by characteristic γ-ray intensity *I* on the basis of the known *H*/*R*.

As a typical case, we assume *R*=1.0 cm and *L*=150 cm, the uranium's characteristic γ-ray energy *E*=185.72 keV, the attenuation coefficient[11] μ=31.60 g•cm^{-2}, the diagram of *H*/*R*-I_2/I_1 will be given numerically in Fig.10, where integral subroutine is programmed by Monte Carlo.

By data fitting, the relationship of *H*/*R* and I_2/I_1 is given by

$$H/R = -0.00916 + 1.58239\ I_2/I_1 \quad (13)$$

If *L*=150 cm, and *R*=1.0 cm, 1.5 cm, 2.0 cm, the diagram of *H*/*R*- I_2/I_1 will be given numerically in Fig.11, where integral subroutines are programmed by Monte Carlo too.

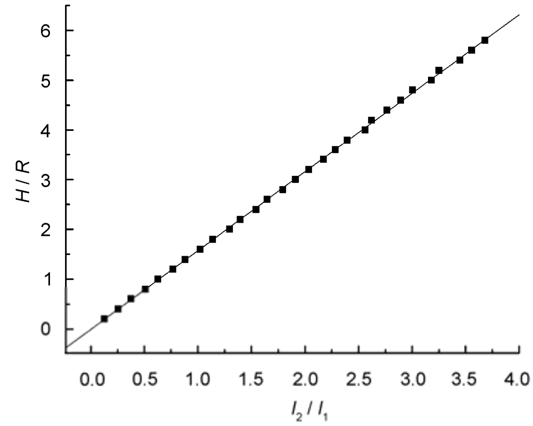

Fig.10 Relationship between H/R and I_2/I_1 (R=1.0).

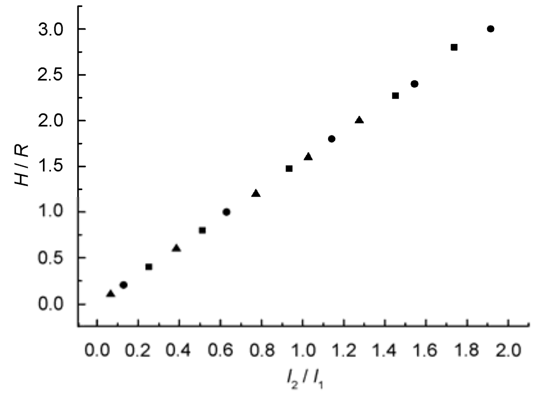

Fig.11 Relationship of H/R with I_2 / I_1.
● R=1.0 cm, ■ R=1.5 cm, ▲ R=2.0 cm.

When R=1.0 cm, 1.5 cm, 2.0 cm, the points in Fig. 11 are along a line, so all the points are linearly fitted together. By data fitting, the relationship of H/R and I_2/I_1 is given by

$$H/R = -0.00201 + 1.58179\ I/I_0 \tag{14}$$

Fortunately relationship of H/R and I_2/I_1 is linear and even considered direct proportional, where the region of H/R is about 0.1 to 6.0. Formulae (13) and (14) show that when $L >> H$ and $L >> R$, I_2/I_1 is sensitive not to R and H but to the relative size H/R. During actual calculation formula (14) is always used in order to get more accuracy.

The values of R and H can also be decided by either intensity. If the detection distance is long enough, that is to say, $L >> H$ and $L >> R$, then detected γ intensity $I = \frac{I_t}{4\pi} \times \frac{s}{L^2} \times G$, where I_t is nuclear material's total radiant intensity, s is the detected area of the detector, $I_t = kV\rho$ where k is γ radiant intensity of nuclear material per gram, V and ρ represent volume and density of the nuclear material respectively. So the formula will become

$$I = \frac{kV}{4\pi} \times \frac{s}{L^2} \times G\rho = (\frac{k\rho}{4\pi} \times \frac{s}{L^2}) \times GV \tag{15}$$

In the above formula GV is expressed in analytical form, $(\frac{k\rho}{4\pi} \times \frac{s}{L^2})$ is considered a constant. Because G is a dimensionless constant, the anterior discussion about G refers to the quantity of unit volume. GV is of course the former formulae. When H/R is worked out, the relationship of R and I will be given, from which R will be decided by the characteristic γ-ray intensity.

As a typical case, not losing generality, let H/R equal to 1.0, the relationship of cylindrical radius R and intensity I_1 detected in the axis is numerically given in Fig.12.

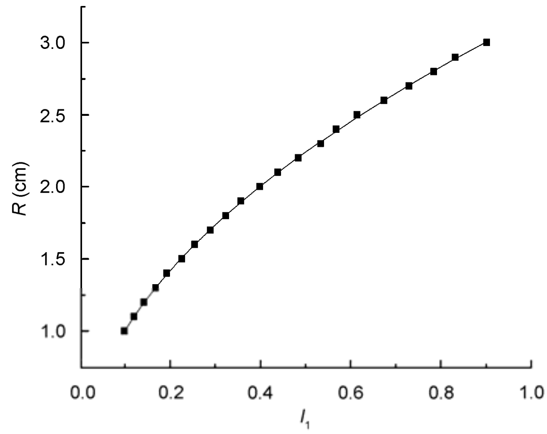

Fig.12 Relationship of R with I_1.

By data fitting, the relationship of R and I_1 will be given by

$$R = 3.16898\sqrt{(I_1 + 0.00081)} - 0.0024 \tag{16}$$

In the above formula we have taken $(\frac{k\rho}{4\pi} \times \frac{s}{L^2})$ as a unit of the γ-intensity, and centimeter as the unit of radius. When I_1 is known by measurement, R can be resolved by the above formula.

5 Summary

Fissile material can absorb γ- ray emitted from itself. The self-absorption correction coefficients throughout a cylinder are given. Multi-location measurements are able to solve the configuration of the cylinder. As a simplest case, two measurements are made in the axis and on the plane *XOY* of the cylinder. The γ intensity I_1 and I_2 is respectively given from the γ spectra of the twice measurements. The ratio of height to radius, *H/R*, can be decided by γ intensity radio I_2/I_1 through formula (14). When *H/R* is known, the absolute value of radius *R* can be derived from formula (16). In this paper we take γ intensity I_1 in the axis direction of the cylinder as *I* and obtain the numerical result about the relation between *R* and *I* as shown in formula (16). Accordingly *H* can be certainly decided by *H/R*.

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References

1 Albright D, Berkhouf F, Walker W. World inventory of plutonium and highly enriched uranium, 1992, SIPRI, Oxford University Press, 1993.

2 Whitney C. Smuggling of radioactive material said to double in a year, in the New York Times, 18 Feb. 1995:2.

3 Whitney C. Report tracks a big jump in East's nuclear smuggling international herald tribune, Feb.18, 1995.

4 Williams P, Woessner P N. Scientific American, 1996

5 Stern J. The Ultimate Terrorists. Harvard University Press, 1999.

6 Hibbs M. Nuclear Week, 1994:1 and also IAEA Safeguards, An Introduction, 1981; IAEA Safeguards Glossary, 1980.

7 Sampson T E. Plutonium isotopic composition by gamma-ray spectroscopy, Passive nondestructive assay of nuclear materials, LA-UR-90-732, March 1991.

8 Fetter S, Cochran T B, Grodzins L *et al*. Science, 1990, **248**: 824-834.

9 Tian Dongfeng, Xie Dong, Huo Yukun *et al*. Nucl Instr Meth A, 2000, **449**: 500-504.

10 Lu Fuquan, Tian Dongfeng, Wu Shimin *et al*. Journal of Fudan University (Natural science) (in Chinese), 2001, **40**: 245-248

11 http://physics.nist.gov/PhysRefData/XrayMassCoef/ElemTab/z92.html