QUASIMONOCHROMATIC BEAM OF PARAMETRIC X-RAY RADIATION FOR CONTROL OF HEAVY ELEMENTS

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Possibility to use quasimonochromatic X-ray beam of parametric X-ray radiation (PXR) in the X-ray locator for control and location of heavy elements is considered. The locator should operate with a tunable quasimonochromatic polarized X-ray beam in the energy range up to about 130 keV to cover all atomic energies of heavy elements. The effect of PXR from relativistic electrons moving through a crystal will be used in the X-ray generator of a quasimonochromatic, polarized, tunable X-ray beam. Therefore, the locator is based on a linear electron accelerator that provides the electron beam with energy of about several tens of MeV. The response signal of characteristic K-lines of X-ray radiation from the object under inspection is registered by spectrometric X-ray detector. The locator is able to detect of heavy elements at a tentative distance up to about several meters for several minutes.

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1. INTRODUCTION

There are three basic hazards from nuclear materials: 1) as weapons, 2) as biological poisoning matter and 3) as radiation source. Some of high-Z materials can be turned into weapon: plutonium, 235U, 233U. Such weapon even roughly manufactured and inefficiently detonating, can result in to powerful enough explosion (ton of an equivalent TNT), and in addition can diffuse many highly radioactive nuclear materials. The sprayed plutonium is highly radiotoxic matter with a half-life period of 24 thousand years resulting in illnesses or death of the people.

Thefts of nuclear materials are possible practically on the most of the nuclear cycle stages. The problem of strife with this phenomenon includes both organizational measures, and technical. The general problems of safety of a nuclear cycle surveyed in the reports [1,2].

The present report deals with the method of locating heavy elements through the use of the spectrometry of characteristic radiation excited by an external quasimonochromatic X-ray beam. The idea of an X-ray locator based on the parametric X-ray radiation (PXR) was first put forward in refs. [3, 4]. Experiments on detection of heavy elements with the use of a monochromatic X-ray beam have been described in ref. [5]. By this method, the object is irradiated with a photon flux of energy somewhat higher than the absorption K-edge in nuclear materials. The absorption K-edge for Pu is 121.8 keV. Therefore, the photon beam energy must exceed this value. The secondary fluorescent radiation spectrum will consist of characteristic lines of elements entering into the composition of the object under inspection. These spectra are well known and investigated. Applying the detecting apparatus with a sufficiently high energy resolution, one can determine the elemental composition of the object. The spectral K-lines from nuclear materials have the energies about 90 - 121 keV. Therefore, they will be better seen due to lower absorption in surrounding materials. In case of intentional protection, the spectra of secondary radiation will exhibit the characteristic lines of lead (or tungsten and other possible heavy elements), and this may be indirect evidence for the presence of nuclear materials and for the necessity of additional inspection.

2. THE GENERATOR OF PRIMARY X-RAY BEAM

The X-ray radiation source used in the proposed method of heavy element location must be monochromatic (or quasimonochromatic) and tunable in the quantum energy ranging from a few tens of keV to about 130 keV. For this purpose, a generator of X-ray radiation, based on the PXR effect [6], is proposed. The general scheme of heavy element location for the case under consideration is shown in Fig. 1. The relativistic electron beam from the linear accelerator, passing through the crystal-radiator (Si, Ge or diamond), generates the parametric X-ray radiation. The angular distribution of the PXR yield is characterized by a sharp directionality (PXR reflection) in the vicinity of the Bragg direction. The energy distribution and the average energy of X-ray quanta in the PXR reflection, generated from a certain set of parallel crystallographic planes of the crystal, are determined by the angle between the electron beam direction and the chosen crystallographic plane.

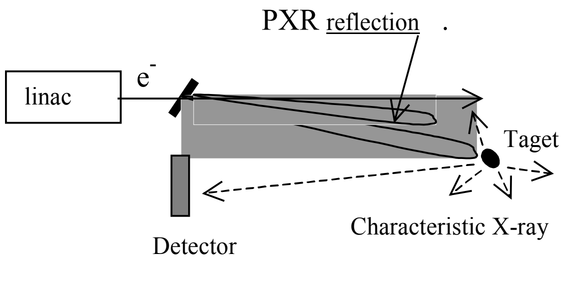

Fig. 1. General scheme of the monochromatic X-ray locator using the PXR effect. The electron beam from a linac excites PXR in a crystal. Quasi-monochromatic X-ray beam of PXR excites characteristic X-ray radiation in the target (object under inspection). The characteristic X-ray radiation of the target can be registered be a spectrometric detector

The primary X-ray beam (PXR reflection) is directed at the object to be inspected and excites there the secondary characteristic X-ray radiation, which is then registered by the detecting system.

We have performed detailed calculations of PXR-generator characteristics for different electron-beam energies, various types of crystals and crystallographic planes [7]. The optimum crystal-radiator thickness was chosen with due regard for the influence of multiple electron scattering. In particular, it has been shown that if the electron beam energy is 120 MeV, then the 90 µm thick germanium crystal with the working crystallographic plane (220) will be the optimum choice of the crystal-radiator. In this case, the maximum differential yield of X-ray radiation with a spectral line energy of 135 ± 13 keV will be 0.004 quanta/(e^-·sr); that will make $2.5 \cdot 10^{12}$ quanta/sr per second at an electron beam current of 100 µA.

Note that the generator based on the coherent bremsstrahlung (CB) effect may also be a promising source of quasimonochromatic and energy-tunable X-ray radiation. In this case, the general scheme of location is the same as in Fig. 1., except for a change in the X-ray beam direction along the electron beam. Our preliminary estimations show that the use of CR may permit an increase in the primary X-ray beam intensity at an electron beam energy of ~15 to 30 MeV. However, CR is not so monochromatic in comparison to the PXR.

3. THE RESPONSE SIGNAL FROM THE OBJECT UNDER INSPECTION

The general formula to calculate the intensity of a single detector-registered spectral line of a certain element inspected is written as

$$N_{ij} = C_i \rho \cdot \omega_{Ki} \cdot p_{ij} \cdot r_{Ki} \cdot \frac{\mu_{pEi}}{\mu_E + \mu_{ij}} \exp\left[-\left(\mu_E^a + \mu_{ij}^a\right)\rho^a L\right] \times$$

$$\left\{1 - \exp\left[-\left(\mu_E + \mu_{ij}\right)\rho d\right]\right\} \cdot Y_E \cdot \frac{S_d S_t \varepsilon_{ij}}{4\pi L^4}, \qquad (1)$$

where N_{ij} is the number of characteristic radiation quanta (for the *j*-th spectral line of the *i*-th element to be identified) registered by the detector in *1 s*, C_i is the concentration of the *i*-th element in the sample, *d* is the sample thickness, ρ is the density of the sample, ρ^a is the air density, ω_{Ki} is the fluorescence yield for the *K*-levels, p_{ij} is the statistical weight of the spectral line, r_{Ki} is the relative portion of photons absorbed by the *K*-shell, μ_{pEi} is the partial coefficient of absorption (relative to the photoeffect) of the primary radiation of energy *E*, μ_{ij} is the mass coefficient of characteristic radiation *absorption* in the sample, μ_{ij}^a is the mass coefficient of characteristic radiation *attenuation* in air, μ_E is the mass coefficient of primary radiation (energy *E*) *absorption* in the sample, μ_E^a is the mass coefficient of primary radiation *attenuation* in air, *L* is the distance from the sample inspected to the detector (and to the X-ray source), S_t is the scanned area of the sample inspected, S_d is the area of the detector, ε_{ij} is the efficiency of characteristic radiation registration by the detector, Y_E is the differential yield of primary photons having the energy *E*.

If the primary beam is not monochromatic, then expression (1) should be integrated over the photon energy. For thick specimens, the factor $\left\{1 - \exp\left[-\left(\mu_E + \mu_{ij}\right)\rho d\right]\right\}$ tends to 1, and the object thickness may be neglected in calculations. For heavy elements, this approximation holds if the sample thickness exceeds several millimeters, because in this case the e-fold absorption length of the X-rays with energy ~130 keV does not exceed 1 mm (e.g., 0.14 mm for *Pu*, 0.15 mm for *U*, 0.37 mm for *Bi,* for monoelement samples).

Fig. 2 shows the calculated response signal values versus the distance from the locator (radiation source and detector) to the object under inspection. In the calculations, the U target irradiated area was assumed 1 cm^2, and depth no less then 0.15 mm. Also, it is assumed that the object is irradiated with a primary beam of 135 ± 13 keV X-ray quanta with the differential yield $Y_E = 2.5 \cdot 10^{12}$ quanta/sr per second. The area of the detector is 100 cm^2. Note that approximately the same response signal values will be observed from other heavy elements, e.g., *Pu, Th, Ta, W, Pb, Bi*, but with different spectral line energies of the characteristic radiation. Therefore, figures for these elements are similar to one shown in Fig. 2.

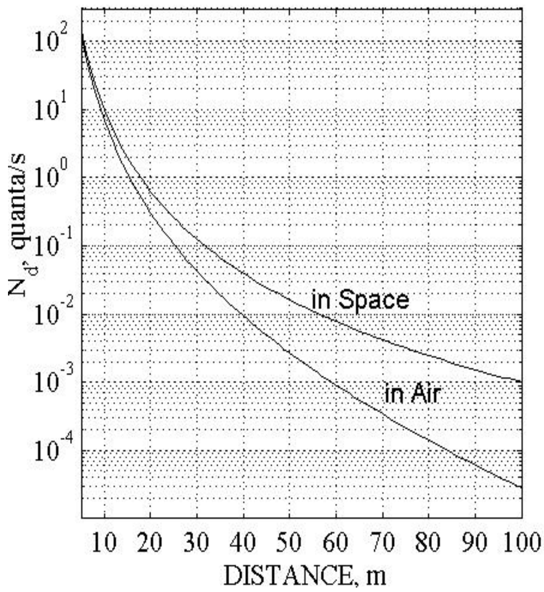

Fig. 2. The number of characteristic radiation quanta (the sum of secondary radiations from all K-series spectral lines) arriving in 1 sec at the 100 cm^2 detector versus the distance of the locator to the object under inspection. The target irradiated area is 1 cm^2

Assuming that for the reliable assessment of the presence of the element inspected in the sample it is sufficient to register ~50 counts in the detector, and the inspection time should not exceed, for example, 5 minutes, we obtain the detection range for unprotected uranium sample (with irradiated area 1 cm^2) to be about 23 m (or 30 m in outer space).

Registration of a response signal may be performed, for example, by assembly of CdTe semiconductor spectrometric detectors of thickness about 4 mm at one platform. To reduce the influence of background conditions on the measurement results, active + passive protection, as well as a collimator system must be used. Besides, a hard X-ray telescope similar to one used for research in outer space may be applied for registration of response signal. Calibration of such telescope may be performed by the PXR source [8].

4. CONCLUSION

The present estimates of the response signal from the object under inspection demonstrate that the locator, based on the PXR effect, permits the location of heavy elements, including nuclear materials at distances up to 23 m in air and up to 30 m in outer space (at a given inspection time of no more than 5 minutes and visible dimensions of the irradiated part of the sample surface ~1 cm^2). The detection range and the inspection time mainly depend on both the intensity of the primary X-ray source and the working area of the detecting system. The X-ray generator based on the coherent bremsstrahlung effect may also be a promising source of X-ray beam, but detail investigations are necessary to study this possibility. An increase up to 1 m^2 in the area of the detector that detects the secondary X-ray radiation will enable a 3-fold increase in the detection range (outer space) or a decrease in the location time.

The locator may be used at airports, railways, seaports, etc. for search of materials, that consists of heavy elements, to prevent terrorist's activities, and also, in science and technologies for remote nondestructive control of different objects. The PXR source may be beneficial for the development of heavy element tomography similar to the technique described in ref. [5]. Furthermore, the locator may be launched into space and used for search of heavy elements on asteroids and other bodies. In this case, a hard X-ray locator may be used as a detector.

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КВАЗИМОНОХРОМАТИЧНЫЙ ПУЧОК ПАРАМЕТРИЧЕСКОГО РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ ДЛЯ КОНТРОЛЯ ЗА ТЯЖЁЛЫМИ ЭЛЕМЕНТАМИ

А.В. Щагин, В.М. Санин, В.В. Сотников, В.А. Воронко, А.М. Егоров

Рассмотрена возможность использования квазимонохроматичного рентгеновского пучка ПРИ в рентгеновском локаторе для контроля и обнаружения тяжёлых элементов. Локатор основывается на линейном ускорителе электронов с энергией порядка нескольких десятков МэВ. Сигнал отклика характеристических К-линий рентгеновского излучения от объекта инспекции регистрируется с помощью спектрометрического детектора. Локатор способен обнаруживать тяжёлые элементы на расстоянии нескольких метров в течении нескольких минут.

КВАЗІМОНОХРОМАТИЧНИЙ ПУЧОК ПАРАМЕТРИЧНОГО РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ ДЛЯ КОНТРОЛЮ ЗА ВАЖКИМИ ЕЛЕМЕНТАМИ

А.В. Щагин, В.М. Санин, В.В. Сотников, В.О. Воронко, О.М. Єгоров

Розглянуто можливість використання квазімонохроматичного рентгенівського пучка ПРВ в рентгенівському локаторі для контролю і виявлення важких елементів. Локатор ґрунтується на лінійному прискорювачі електронів з енергією порядку декількох десятків МеВ. Сигнал відгуку характеристичних К-ліній

рентгенівського випромінювання від об'єкта інспекції реєструється за допомогою спектрометричного детектора. Локатор здатний виявляти важкі елементи на відстані декількох метрів протягом декількох хвилин.