LOCATION OF HEAVY ELEMENTS BY MONOCHROMATIC X-RAY BEAM

A.V. Shchagin, V.M. Sanin, V.V. Sotnikov, V.A. Voronko, A.M. Yegorov
National Science Center "Kharkov Institute of Physics and Technology",
61108, Kharkov, Ukraine;
E-mail: shchagin@kipt.kharkov.ua

The remote nondestructive detection of materials with heavy elements is an important task in number of applications, including needs for control of terrorist's activity. In the report, we discuss a possibility to use monochromatic X-ray beam in the X-ray locator. The locator should operate with a monochromatic polarized X-ray beam in the energy range up to about 130 keV to cover all atomic energies of heavy elements. The effect of Parametric X-ray Radiation (PXR) from relativistic electrons moving through a crystal is used in the X-ray generator of a monochromatic, polarized, tunable X-ray beam. Therefore, the locator is based on a linear electron accelerator with energy of about several tens of MeV. The locator is intended for remote sensing of heavy elements for several minutes at a tentative distance up to about ten(s) meters.

PACS: 95.55.Ka; 41.50+h; 41.60-m

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, ^{235}U, ^{233}U. 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 paper deals with the method of locating heavy elements through the use of the spectrometry of characteristic radiation excited by an external quasi-monochromatic 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 quasi-monochromatic) 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

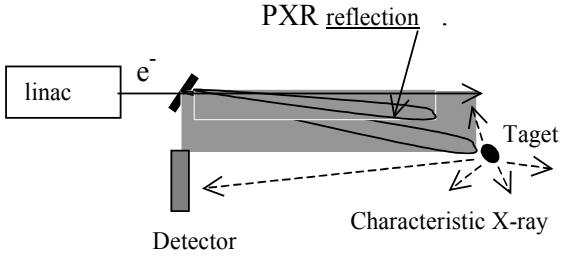

Fig 1. General scheme of the monochromatic X-ray locator using the PXR effect. The electron beam from a linac excites PXR in a crystal. Quasi-monochromatic X-ray beam of PXR excites characteristic X-ray radiation in the target (object under inspection). The characteristic X-ray radiation of the target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

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. 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 quasi-monochromatic 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

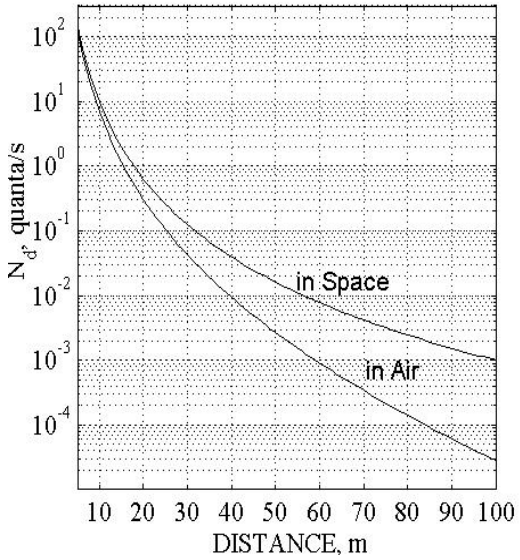

Fig.2. The number of characteristic radiation quanta (the sum of secondary radiations from all K-series spectral lines) arriving in 1 sec at the 100 cm^2 detector versus the distance of the locator to the object under inspection. The U target irradiated area is 1 cm^2

different spectral line energies of the characteristic radiation. Therefore, figures for these elements are similar to one shown in Fig.2.

PROBLEMS OF ATOMIC SIENCE AND TECHNOLOGY. 2004. № 1.
Series: Nuclear Physics Investigations (42), p.194-196.

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.

This paper became possible partially due to Grant 1030 from Science and Technology Center in Ukraine.

REFERENCES

1. Safeguards and security progress report. January-December 1989, 1990. Report N LA-11914-PR. Los Alamos National Laboratory, Los Alamos, NM (U.S.A.).
2. *Nuclear Safety*. 1974, v. 15, N 5.
3. A.V. Shchagin, V.I. Pristupa, N.A. Khizhnyak. Parametric X-ray radiation from relativistic electrons in a crystal in the vicinity and at angular distance from a Bragg direction //*Nucl. Instr. and Meth*. 1995, v. B99, p. 277-280.
4. A.V. Shchagin, N.A. Khizhnyak. Differential properties of parametric X-ray radiation from a thin crystal // *Nucl. Instr. and Meth*. 1996, v. B119, p. 115-122.
5. M. Bertschy, M. Crittin, J. Jolie, W Mondelaers, N. Warr. A tunable monochromatic gamma-ray source. Part 3. Feasibility study of heavy element tomography // *Nucl. Instr. and Meth*. 1995, v. B103, p. 330-338.
6. A.V. Shchagin. Investigations and Properties of PXR//*Electron-Photon Interaction in Dense Media*/ ed. by H. Wiedemann, NATO Science Series, II. *Mathematics, Physics and Chemistry*. 2002, v. 49, p.133-151.
7. *Monochromatic X-ray locator for control of nuclear materials nonproliferation*: Proceedings of the STCU Project 1030, v. 1/ ed. by A.V. Shchagin, Kharkov: KIPT, 2003.
8. A.V. Shchagin, N.A. Khizhnyak, R.B. Fiorito, D.W. Rule, X. Artru // *Nucl. Instr. and Meth*. 2001, v. B 173, p. 154-159.

ЛОКАЦИЯ ТЯЖЕЛЫХ ЭЛЕМЕНТОВ МОНОХРОМАТИЧНЫМ РЕНТГЕНОВСКИМ ПУЧКОМ

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

Удаленное неразрушающее обнаружение материалов с тяжелыми элементами - важная задача в ряде применений, включая необходимость контроля за действиями террористов. В статье мы обсуждаем возможность использовать монохроматический рентгеновский пучок в рентгеновском локаторе. Локатор должен работать с монохроматическим поляризованным рентгеновским пучком в энергетическом диапазоне до 130 кэВ, чтобы охватить все уровни энергий атомных электронов тяжелых элементов. Эффект параметрического рентгеновского излучения (ПРИ) от релятивистских электронов, движущихся через кристалл, используется в рентгеновском генераторе монохроматического, поляризованного, перестраиваемого, рентгеновского пучка. Поэтому локатор основывается на линейном электронном ускорителе с энергией приблизительно несколько десятков МэВ. Локатор предназначен для дистанционного зондирования тяжелых элементов на расстояниях порядка десяти метров со временем зондирования несколько минут.

ЛОКАЦІЯ ВАЖКИХ ЕЛЕМЕНТІВ МОНОХРОМАТИЧНИМ РЕНТГЕНІВСЬКИМ ПУЧКОМ

А.В. Щагін, В.М. Санін, В.В. Сотніков, В.А. Воронко, О.М. Єгоров

Вилучене виявлення матеріалів, що не руйнує з важкими елементами - важлива задача в ряді застосувань, включаючи необхідність контролю за діями терористів. У статті ми обговорюємо можливість використовувати монохроматичний рентгенівський пучок у рентгенівському локаторі. Локатор повинний працювати з монохроматичним поляризованим рентгенівським пучком в енергетичному діапазоні до 130 кеВ, щоб охопити всі

рівні енергій атомних електронів важких елементів. Ефект параметричного рентгенівського випромінювання (ПРВ) від релятивістських електронів, що рухаються через кристал, використовується в рентгенівському генераторі монохроматичного, поляризованого, що перебудовується, рентгенівського пучка. Тому локатор ґрунтується на лінійному електронному прискорювачі з енергією приблизно кілька десятків МеВ. Локатор призначений для дистанційного зондування важких елементів на відстанях порядку десяти метрів з терміном зондування кілька хвилин.

PROBLEMS OF ATOMIC SIENCE AND TECHNOLOGY. 2004. № 1.
Series: Nuclear Physics Investigations (42), p.194-196.