



(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
27.12.2023 Bulletin 2023/52

(51) International Patent Classification (IPC):
G21K 1/02 (2006.01)

(21) Application number: **23177560.2**

(52) Cooperative Patent Classification (CPC):
G21K 1/02

(22) Date of filing: **06.06.2023**

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA
Designated Validation States:
KH MA MD TN

(72) Inventors:
• **NAKAYAMA, Kohichi**
Kawasaki-shi, Kanagawa (JP)
• **NITTOH, Koichi**
Minato-ku, Tokyo, 105-0023 (JP)
• **UEMATSU, Mikio**
Minato-ku, Tokyo, 105-0023 (JP)
• **SONODA, Yukio**
Minato-ku, Tokyo, 105-0023 (JP)

(30) Priority: **21.06.2022 JP 2022099731**

(71) Applicants:
• **Kabushiki Kaisha Toshiba**
Minato-ku
Tokyo 105-0023 (JP)
• **Toshiba Energy Systems & Solutions Corporation**
Saiwai-ku
Kawasaki-shi
Kanagawa (JP)

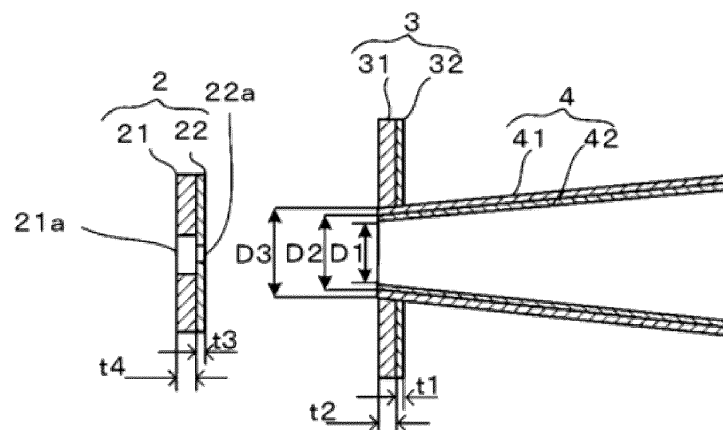
(74) Representative: **Hoffmann Eitle**
Patent- und Rechtsanwälte PartmbB
Arabellastraße 30
81925 München (DE)

(54) **NEUTRON AND GAMMA-RAY COLLIMATOR AND RADIOGRAPHY DEVICE**

(57) A neutron and gamma-ray collimator (2) comprises: a neutron diaphragm (21); a gamma-ray diaphragm (22); a diaphragm fixing plate (3) that fixes the neutron diaphragm (21) and the gamma-ray diaphragm (22); and a flight tube (4) integrated with the diaphragm fixing plate (3) and having a neutron shield (41) and a

gamma-ray shield (42) lining an inner side of the neutron shield (41). The gadolinium compound is used as the neutron diaphragm (21) and the neutron shield (41) of the flight tube (4), and the bismuth compound is used as the gamma-ray shield (42) of the flight tube (4).

FIG. 3



Description

FIELD

[0001] Embodiments of the present invention relate to a neutron and gamma-ray collimator and a radiography device.

BACKGROUND

[0002] There has conventionally been used a collimator that collimates a flux of radiations, in particular, neutrons, γ -rays, and X-rays that are generated from a nuclear reactor, an accelerator, or a radioisotope source, while blocking secondary radiations that are generated when those radiations react with a substance to reflect or scatter.

[0003] Radiations such as X-rays, γ -rays, and neutron beams extracted in a beam form are used in the industrial fields and the medical fields. Radiation sources that naturally produce these radiations, as well as nuclear reactors that produce them through nuclear reactions, emit neutrons, γ -rays, and X-rays (hereinafter referred to as γ -rays as a representative name for both X-rays and γ -rays, since they have different generation mechanisms but share similar properties) as spheres in all directions.

[0004] To use them as the beam form on a place to be irradiated, it is necessary to extract the generated radiations and lead them through a moderator, a reflector, a diaphragm, a conduit (flight tube), or the like. In a radiation source having a particularly large volume, such as an RI (radioisotope) source and a nuclear reactor, a diaphragm is used as a stop for extracting the radiations in a restricting manner as is done by a stop of a camera for light.

[0005] To prevent scattered beams from turning around from the periphery of a radiation source to reach the place to be irradiated and prevent the radiations extracted by the diaphragm from reflecting to reach the place to be irradiated, a flight tube (this mainly aims at shielding the place to be irradiated, from radioactive components that have been emitted from the radiation source and have scattered or reflected) is sometimes installed. Radiation shielding ability is important for the basic materials of both the diaphragm and the flight tube. These diaphragm and flight tube will be collectively called a collimator.

[0006] An LID value is used as a performance index of a radiation flux collimator, wherein the LID value is the relationship between the opening diameter: D of the diaphragm and the distance: L of the flight tube from the diaphragm up to the place to be irradiated with beams. The larger the LID value, the higher the performance of the collimator, and in the use for radiography imaging, this value has a great influence on the resolution of image quality. As the LID value is larger, the resolution is higher, but with the distance L not varied, the value of D becomes smaller (narrower), resulting in a smaller amount of the

radiations passing through the diaphragm and thus a longer irradiation time or photographing time in an imaging system if the sensitivity is not varied.

[0007] The materials of the diaphragm and the flight tube must have capability of radiation-shielding, and their materials and shapes need to be optimized according to the type and energy of the radiation. For example, in a visible light camera, a stop corresponding to the diaphragm is made of a thin light-shielding material. Naturally, a transparent material does not function as the stop. Similarly, a material that is translucent or transmits even a slight amount of light does not satisfy the function as the stop. Further, in the case where the stop part is thick even if light shielding is achieved, light reflects/scatters on the inner wall part of the stop, resulting in poor stop performance. Therefore, as the stop, a material that is thin and has high light shielding ability is suitable. This also applies to the diaphragm. The generation of beams for neutron imaging is well known in detail.

[0008] In the case of γ -rays, which exhibit similar nature as that of light, their amount transmitted by a material of a stop varies in proportion to its atomic number Z to the fourth power, and a material having a low density easily transmits them. Therefore, a material whose atomic number Z is large and whose density (specific gravity) is high such as lead (Pb, Z = 82, density = 11.34 g/cm³) or tungsten (W, Z = 74, density = 19.25 g/cm³) is suitable. However, against neutrons, these lead and tungsten do not work as shielding materials and thus works in the same manner as a transparent material does against light.

[0009] Against neutrons, gadolinium (Gd, Z = 64, density = 7.90 g/cm³) has the highest shielding effect (the largest reaction cross section) among natural elements when the neutron energy is 0.025 eV in a thermal neutron region, though the shielding effect depends on their energy. Gd has a smaller atomic number Z than that of lead, but has a larger atomic number Z and a higher density than those of boron (B, Z = 5, density = 2.08 g/cm³) and lithium (Li, Z = 3, density = 0.534 g/cm³) which are other elements having a high shielding effect against neutrons, and thus has a higher γ -ray shielding effect than boron and lithium. Therefore, as a material that has a shielding capability against both thermal neutrons and γ -rays at the same time, gadolinium is superior to boron, lithium, lead, and tungsten.

[0010] Natural isotopes of gadolinium are Gd-152, 154, 155, 156, 157, 158, and 160, among which Gd-158 with a natural abundance of 24.84% causes an (n, γ) reaction where it reacts with thermal neutrons to emit γ -rays. As a result of this reaction, internal conversion electrons and β -rays (mainly 970.6 keV: emission rate 62%, 912.6 keV: 26%, 607.09 keV: 12%, 622.42 keV: 0.31%) and γ -rays (mainly 363.55 keV: 11.4%, 58 keV: 2.15%, 348.16 keV: 0.234%, 226.01 keV: 0.215%) from generated Gd-159 (half-life 18.479 hours) are emitted.

[0011] In the case where gadolinium is used for an imaging system in neutron radiography, gadolinium is set

as a converter in close contact with a film or the like, and the internal conversion electrons generated during neutron irradiation are used for imaging. In photographing whose imaging time is real-time or is short, a generation amount of the β -rays and γ -rays from Gd-159 whose half-time is longer than the imaging time is small and they have only a small influence. However, in the case where it is used as a diaphragm or a collimator of a flight tube, the generated nuclide Gd-159 has an influence in long irradiation.

[0012] The application of a neutron and gamma-ray collimator includes the medical field, where BNCT (Boron Neutron Capture Therapy) is used. In recent years, a method using an accelerator instead of a nuclear reactor as a neutron source of BNCT has been developed, and generated fast neutrons are decelerated to an epithermal region to be used.

[0013] BNCT is a method to dose a patient with a boron compound, irradiate a place where it accumulates on cancer cells with neutrons, and kill the cancer cells by α -rays generated in an (n, α) reaction where the isotope B-10 of boron reacts with the neutrons to emit the α -rays. Neutron beams used for the treatment, which need to have an energy high enough to reach a deep part of the tissue, are required to have a high energy intensity in an epithermal neutron region and have a low energy intensity in a fast neutron region and a thermal neutron region. From the viewpoint of achieving efficient and effective radiation treatment in a short time, from the viewpoint of avoiding damage to normal cells, and from the viewpoint of reducing exposure, a shielding material and a collimator are devised so that an affected part of a patient can be appropriately irradiated.

[0014] The feature of this collimator differs from the idea of a collimator for radiography. They are the same in that a through hole is provided in a radiation-shielding partition wall, which is the basis of the collimator, but this collimator is structured to focus neutrons passing through the through hole to shape a radiation field of view. This is different from the structure of the collimator for radiography that eliminates as many scattered beams as possible. In particular, this collimator is intended to extract as many epithermal neutrons as possible to radiate them. Therefore, the collimator design needs to be optimized according to the neutron energy that is to be used.

[0015] As for the materials of a neutron moderating and radiating device and an extension collimator for BNCT, magnesium fluoride is used as a moderator, lead, graphite, iron, beryllium, bismuth, nickel, or the like is used as a reflector, boron-polyethylene, lithium fluoride-polyethylene, boron carbide, or the like is used as an absorber, and the same material as that of the reflector is used as a collimator. Note that this collimator is also designed to extract the energy of epithermal neutrons as much as possible, but is required to block the energy in a thermal neutron region and γ -rays as much as possible.

[0016] The basis of a neutron and gamma-ray collimator is that it is structured to shield a place other than a

field of view to be irradiated, from radiations and that it is capable of shielding such that energy components other than neutrons and gamma rays that are to be radiated are reduced, as much as possible according to the energies of the neutrons and the γ -rays.

[0017] The structure of a collimator greatly differs depending on its intended use. Similarly to a camera, a collimator for imaging such as radiography has a structure having a stop and a hood or a cylinder preventing the entrance of scattered beams, and a collimator for BNCT is structured to focus neutrons including scattered beams in the same manner that a lens condenses light.

[0018] These collimators are both structured to block energy other than neutron energy and γ -ray energy that are to be used in a radiation field of view (for BNCT, γ -rays are also blocked as much as possible in the radiation field of view). Further, it is required that they have a thin or small and compact shielding structure in which a complicated combination of materials is avoided as much as possible.

[0019] However, in the case where a neutron source is handled, depending on the energy of neutrons, radiations with various energies such as γ -rays and β -rays are generated in their reaction with a collimator material. In particular, gadolinium (Gd), which is a natural element having the largest reaction rate (reaction cross section) with thermal neutrons, undergoes an (n, γ) reaction where it reacts with the neutrons to emit γ -rays, so that the γ -rays and internal conversion electrons are emitted. In the case where a device that is affected by these γ -rays, electron beams, and β -rays is used in the radiation field of view, a problem to be solved is that these have to be eliminated.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020]

FIG. 1 includes a side view FIG. 1A, a rear view FIG. 1B, and a front view FIG. 1C schematically illustrating the configuration of a neutron and gamma-ray collimator according to an embodiment.

FIG. 2 includes a view schematically illustrating the configuration of a neutron diaphragm FIG. 2A and a view schematically illustrating a gamma-ray diaphragm FIG. 2B that are enlarged views of the configuration of an essential part of the neutron and gamma-ray collimator in FIG. 1.

FIG. 3 is an enlarged view illustrating the sectional configuration of the essential part of the neutron and gamma-ray collimator of the embodiment in FIG. 1. FIG. 4 is a view schematically illustrating the arrangement of the neutron and gamma-ray collimator in FIG. 1 with respect to a neutron source.

FIG. 5 illustrates graphs of the calculation results of γ -ray transmittance of shielding materials with a 1 cm thickness.

FIG. 6 illustrates graphs of the calculation results of

transmittance for γ -rays with an effective energy of 100 keV, with respect to the thicknesses of the shielding bodies.

FIG. 7 illustrates graphs of the test results of thermal neutron transmittance with respect to the thicknesses of step wedges.

DETAILED DESCRIPTION

[0021] It is an object of the present invention to provide a neutron and gamma-ray collimator that is capable of leading thermal neutrons and γ -rays for radiography simultaneously or either of these selectively to a radiation field of view and to provide a radiography device.

[0022] As an embodiment, a neutron and gamma-ray collimator comprises: a neutron diaphragm; a gamma-ray diaphragm; a diaphragm fixing plate that fixes the neutron diaphragm and the gamma-ray diaphragm; and a flight tube integrated with the diaphragm fixing plate and having a neutron shield and a gamma-ray shield lining an inner side of the neutron shield, wherein a gadolinium compound is used as the neutron diaphragm and the neutron shield of the flight tube, and wherein a bismuth compound is used as the gamma-ray shield of the flight tube.

[0023] Hereinafter, a neutron and gamma-ray collimator and a radiography device according to an embodiment will be described with reference to the drawings.

[0024] This embodiment relates to a neutron and gamma-ray collimator and radiography device utilizing the same. The neutron and gamma-ray collimator extracts radiations, in particular, neutrons, γ -rays, and x-rays generated from a nuclear reactor, an accelerator, or a radioisotope source and collimates a flux of the radiations, while blocking secondary radiations generated when those radiations (neutrons, γ -rays, and x-rays) react with a substance to reflect or scatter.

[0025] Examples of facilities where the neutron and gamma-ray collimator of this embodiment is applied include a nuclear reactor, accelerator facilities, and RI neutron source facilities as facilities where neutrons are generated, and also BNCT (Neutron Capture Therapy) facilities in the medical field. In these facilities, radiations are extracted to be used for non-destructive inspection and treatment by medical radiation. What is particularly necessary is that the surrounding areas other than a place (field of view) that is to be irradiated with the extracted beams be fully shielded.

[0026] A neutron and gamma-ray collimator is used to lead and extract the radiations that are to be used to the place to be irradiated. The design of the collimator differs according to its intended use. In the case where neutrons are focused and radiated to an affected part of a patient as in medical radiation, the neutrons of a generating source are gathered as much as possible while reflected, to be gathered to an opening of a collimator outlet.

[0027] On the other hand, a collimator for imaging in non-destructive inspection is devised as in a camera of

light such that a diaphragm and a flight tube corresponding to a stop and a shielding cylinder (shielding box) selectively focus the radiations and block radiations from the outside, and the focused radiations do not scatter on the inner surface of the flight tube. In this embodiment, the latter neutron and gamma-ray collimator for imaging in non-destructive inspection will be particularly described.

[0028] It is basically important both for the diaphragm and the flight tube of the collimator that they are made of materials capable of radiation shielding according to the type of the radiations to be collimated (in the case of light, this corresponds to light shielding ability) and their inner surfaces do not cause the reflection or scattering of the radiations.

[0029] The X-ray and γ -ray transmittance characteristics of a substance to be irradiated depend on its atomic number Z , and a substance with a larger atomic number Z and with a higher density is more difficult to transmit X-rays and γ -rays. Elements having close atomic numbers Z to each other have substantially the same transmittance for (shielding effect against) X-rays and γ -rays if their densities are substantially equal. Further, the transmission amount of X-rays differs depending on absorption edge energy which differs according to orbits of electron shells such as K shells and L shells of atoms, but the transmission amount does not differ depending on the kind of isotopes. Further, as the energies of X-rays and γ -rays are higher, the transmittance is higher (the shielding efficiency is lower).

[0030] On the other hand, typically, though the state of the interaction between neutrons and a substance does not depend directly on the atomic number, it varies according to atomic isotopes. Therefore, different isotopes, even if they are of the same element, have different rates of reaction and absorption with respect to the energy of the neutrons and have different rates of transmittance for (shielding effects against) neutron beams. This reaction rate is represented by a neutron cross section (unit barn (b): $1b = 10^{-24} \text{ cm}^2$), and this neutron cross section is used as an index indicating the interaction between neutrons and a substance. A product of a neutron cross section by atomic number density ρ is called macroscopic cross section $\Sigma \text{ (cm}^{-1}\text{)}$, which corresponds to a linear attenuation coefficient of X-rays.

[0031] Neutron scattering has roughly two characteristics of coherent scattering and incoherent scattering. It is said that the coherent scattering is dominant in many elements. The scattering by an element having a large coherent cross section is mainly diffraction scattering, and a Bragg edge appears due to a difference in neutron energy. The incoherent scattering is scattering with atomic motion, and the cross section increases in inverse proportion to neutron velocity V equivalent to neutron energy. This is called "1/V law", and for example, elements such as the isotope B-10 of boron and the isotope Li-6 of lithium follow the 1/V law, and as the energy is higher (the velocity V is higher), a reaction is more difficult to

occur, so that shielding efficiency worsens. In addition to these scattering cross sections, there is an absorption cross section due to resonance capture that appears in different neutron energy regions depending on an element isotope.

[0032] Neutron beams output from a neutron source usually contain neutrons with various energies. If the energy is lower than 1 MeV, a reaction following the $1/V$ law or a reaction in a resonance region such as resonance absorption (a reaction in which due to a reaction mainly with neutrons, γ -rays are emitted, which will be hereinafter referred as an (n, γ) reaction)) occurs. On the other hand, if the energy is 1 MeV or more, reactions different from the above reactions, threshold reactions occur. The threshold reactions include an $(n, 2n)$ reaction of emitting two neutrons by a reaction with one neutron, an (n, p) reaction of emitting a proton by a reaction with neutrons, an (n, α) reaction of emitting α -rays by a reaction with neutrons, and so on. In particular, unlike a reaction with γ -rays, in the reaction with the neutrons, an element change may occur, for example, boron turns into lithium, and sulfur turns into phosphorus, or an element that is not originally a radioactive substance turns into a radioactive substance. An index of the time from an instant when the substance turns into the radioactive substance up to an instant when its radiation emission rate becomes half in accordance with disintegration is represented by half-life. If the half-life is on the order of milliseconds or nanoseconds, there occurs no problem because it becomes a nonradioactive substance almost instantaneously, but if a substance is exposed to high dose radiation to have a long half-life, the shield itself works as a radiation emitting source over a long period and does not satisfy the role as the shield.

[0033] A neutron reactant in boric acid (B_2O_3) or boron carbide (B_4C) used as a neutron shielding material is boron. Isotopes of natural boron are B-10 (natural abundance 19.9%: also represented by ^{10}B) and B-11 (natural abundance 80.1%: also represented by ^{11}B). Nuclear data JENDL-4 showing the reaction rate with neutron energy (Cross Section, measured in the unit of barn) can be confirmed from data research groups of Japan Atomic Energy Agency (https://www-wndc.jaea.go.jp/jendl/j40/J40_J.html#Reports). [Cited document: K. Shibata, O. Iwamoto, T. Nakagawa, N. Iwamoto, A. Ichihara, S. Kunieda, S. Chiba, K. Furutaka, N. Otuka, T. Ohsawa, T. Murata, H. Matsunobu, A. Zukeran, S. Kamada, and J. Katakura: "JENDL-4.0: A New Library for Nuclear Science and Engineering" J. Nucl. Sci. Technol. 48(1), 1-30 (2011)]

[0034] Out of B-10 and B-11, B-10 has a larger cross section for a thermal neutron region by about six digits. However, for a region with a high energy exceeding 1 MeV, B-10 and B-11 have a substantially equal reaction cross section to each other. In the reaction of B-10, it reacts with neutrons to emit α -rays to become Li-7. More accurately, this reaction is described as a $^{10}B(n, \alpha)^7Li$ reaction. 7Li is given an initial recoil energy of 840 keV

by the (n, α) reaction, and then emits 478 keV prompt γ -rays while moving in a short life of 0.105 ps, to be ground-state Li-7. Therefore, in the case where a natural mineral or the like is used from the viewpoint of radiation shielding, the radiation shielding performance is determined by the product of the atomic number of boron present therein, a proportion of a B-10 isotope, in B, whose reaction rate with neutrons is high, and a cross section of B-10, which depends on neutron energy. Further, if the energy of neutrons is high, the cross section is small, and therefore, it is important to decrease the energy of high-energy neutrons by their collision with a moderator such as hydrogen or carbon, thereby achieving an efficient reaction. Further, since the 478 keV prompt γ rays are emitted, shielding against these γ -rays also has to be considered. The density of a compound containing boron is about 2.5 g/cm³, which is about 1/3 of that of iron, and boron also has a small atomic number Z of $Z=5$. A mass attenuation coefficient μ/ρ (μ : linear absorption coefficient, ρ : density of a substance) which is important in the interaction with X-rays or γ -rays is generally said as being proportional to Z to the third to fourth power. Therefore, a compound containing boron has a low shielding effect against γ -rays.

[0035] In this embodiment, we pay attention to gadolinium which, among elements, has the largest reaction cross section for thermal neutrons, and pay attention to the fact that it also has a high shielding effect against γ -rays because its atomic number is $Z=64$. Gadolinium belongs to the rare earth elements and is a rare metal. Six kinds of its isotopes Gd-154 (2.18%), Gd-155 (14.80%), Gd-156 (20.47%), Gd-157 (15.65%), Gd-158 (24.84%), and Gd-160 (21.86%) exist in nature (% in the parentheses is a natural abundance). In particular, Gd-157 and Gd-155 have larger cross sections for a thermal neutron region of a 0.0253 eV neutron energy than that of B-10. Gd-157 has a 66 times as large cross section and Gd-155 has a 15.8 times as large cross section as that of B-10. For an energy of 100 eV to around 1 keV, the isotopes of Gd including the other isotopes have a plurality of resonance absorption peaks and have a larger cross section than B-10.

[0036] The main reaction of gadolinium with neutrons, which is different from the reaction of boron, is an (n, γ) reaction of emitting γ -rays. In the case of boron, 7Li is generated by the (n, α) reaction, and it emits the 478 keV prompt γ -rays in the process of turning into Li-7. In the case of Gd, Gd-155, Gd-156, Gd-157, and Gd-158 generated respectively by $^{154}Gd(n, \gamma)^{155}Gd$, $^{155}Gd(n, \gamma)^{156}Gd$, $^{156}Gd(n, \gamma)^{157}Gd$, and $^{157}Gd(n, \gamma)^{158}Gd$ become stable isotopes, and there is no emission of β -rays and γ -rays accompanying disintegration. Gd-159 generated by a $^{158}Gd(n, \gamma)^{159}Gd$ undergoes β disintegration to become a stable isotope Tb-159. This disintegration is accompanied by the emission of β -rays with the energies 970.6 keV (62%), 912.6 keV (26%), 607.09 keV (12%), and 622.42 keV (0.31%) and the emission of γ -rays with the energies 363.55 keV (11.4%), 58 keV (2.15%),

348.16 keV (0.234%), and 226.01 keV (0.215%). In particular, Gd-157 and Gd-155 having large reaction cross sections for the thermal neutron region emit 8 MeV neutron capture γ -rays in the (n, γ) reaction.

[0037] The above γ -ray emission modes are roughly classified into two: (1) continuous spectrum (93.8%) and (2) discrete spectrum (6.2%). Most of the modes are classified into (1) continuous spectrum. This spectrum (1) from an unstable compound nucleus up to a stable ground level has not a single peak at energy of 8 MeV but has peaks in wide range from a high energy to a low energy. Discrete spectrum (2) has peaks at 5.62 MeV + 2.25 MeV (1.3%), 5.88 MeV + 1.99 MeV (1.6%), 6.74 MeV + 1.11 MeV (3.2%), and 7.87 MeV (0.02%). The energy of the discrete spectrum is high but the proportion of the discrete spectrum is small.

[0038] Here, what is important for the radiation shielding technique in a collimator is that collimation ability differs depending on the kind of radiation. Also what is important is the radiation sensitivity of a utilized detector. High-energy γ -rays that can pass through a substance having a large atomic number Z pass through a detector element that is a thin film formed of a light element as it passes through a shielding material. That is, if LET (Linear Energy Transfer: representing how much energy the radiation gives to a substance while passing through the substance) by the radiation to a substance to be protected is small, the energy given to substance through which the radiation passes is small, leading to no detection. On the contrary, as LET is larger, the energy given to the substance is higher, leading to a high detection effect.

[0039] Considering the object attained by the shielding by the collimator material, it is possible to achieve the object of the shielding even if a γ -ray shielding material transmits high-energy γ -rays, though this depends on the degree of their energy. For example, even if having a monochromatic energy (strictly speaking, having an energy width) at the generation instant, γ -rays with 1 MeV and 50 keV attenuate in energy because of a photoelectric effect, Compton scattering, or the like caused by the interaction between the γ -rays and the substance makes their energies reach a low energy region. In particular, for the low-energy region, the γ -ray shielding material reacts more with the 50 keV γ -rays than with the 1 MeV γ -rays, so that the 50 keV γ -rays attenuate. Then, LET by γ -rays with several ten keV or less to a device such as a sensor is larger as their energy is lower, resulting in fogging of imaging to cause poor image sharpness.

[0040] The γ -ray transmittances of shielding materials with a 1 cm thickness of a collimator were calculated. In particular, lithium fluoride (LiF) and boron carbide (B_4C) which are used as thermal neutron shielding materials, lead (Pb) and iron (Fe) which have high γ -ray absorption, and a gadolinium oxysulfide (Gd_2O_2S) (hereinafter, referred to as GOS) used in this embodiment were compared. The graphs in FIG. 5 show the results. As shown by the graphs in FIG. 5, it is seen that at 0.5 MeV (500 keV) or lower, GOS has a shielding effect about twice or

more as high as those of lithium fluoride and boron carbide which are neutron shielding bodies, and the shielding effect of GOS is also higher than that of iron though not reaching that of lead.

[0041] Considering the sensitivity characteristics of a film and an imaging plate that are actually used in imaging, transmittances for γ -rays having an effective energy of 100 keV with respect to the thicknesses of the shielding bodies were compared. FIG. 6 shows the results. As shown by the graphs in FIG. 6, it is seen that GOS is also higher in shielding effect than iron.

[0042] In order to examine concretely thermal neutron transmittances, step wedges different in thickness were fabricated which were a GOS resin sample and a GOS concrete sample, and a comparison test was conducted. Step wedges for comparison have the same shape as the GOS resin sample and the GOS concrete sample, one of which was formed of lead (Pb) and the other of which was formed of heavy concrete whose aggregate was iron. In the test, a thermal neutron irradiation port of an accelerator-driven pulsed neutron source "HUNS" of Hokkaido University was used. Dysprosium foils were used as converters and were radioactivated at the transmittances of the step wedges, and the radioactivated dysprosium foils were transferred to an imaging plate (IP), and from brightness data (PSL value) of images obtained as a result of the transfer, the transmittances were digitally found. Being not influenced by γ -rays, this transfer method is capable of purely finding the state of the transmission of thermal neutrons.

[0043] The graphs in FIG. 7 show the results of the studies on the thermal neutron relative transmittances with respect to the thicknesses of the step wedges as in the case of the studies on the gamma-ray transmission. The transmittance with respect to the thickness should linearly decrease as an exponential function, similarly to those of Pb and the heavy concrete whose aggregate is iron in FIG. 7. However, GOS has a tendency, regardless of whether it is in the resin or in the concrete, that its transmittance abruptly decreases to 2/100 to 3/100 at a thickness of 5 mm and thereafter saturates in measurements. According to the calculation, its transmittance linearly decreases as an exponential function similarly to those of the lead and the heavy concrete, but it is inferred that because of a large thermal neutron absorption cross section of gadolinium, the influence of base brightness appears also in IP in the measurement. The results show that at a thickness of 1/50 or less, GOS has the same shielding ability as that of the heavy concrete. Its shielding ability is about thirty times as high as that of lead having large γ absorption. The above results show that the use of GOS as the shielding material of the collimator in which thermal neutrons are involved is effective for composite shielding against thermal neutrons and γ -rays.

[0044] However, there are concerns about gadolinium and thermal neutrons. Gd-159 generated by the ^{158}Gd (n, γ) ^{159}Gd reaction undergoes the β disintegration to be a stable isotope Tb-159. In this disintegration, the en-

ergies 970.6 keV (62%), 912.6 keV (26%), 607.09 keV (12%), and 622.42 keV (0.31%) of β -rays are emitted, and the energies 363.55 keV (11.4%), 58 keV (2.15%), 348.16 keV (0.234%), and 226.01 keV (0.215%) of γ -rays are emitted. Regarding the transmission of the thermal neutrons, sufficient shielding is achieved even if the thickness is 5 mm, but considering the reflection in the collimator, it is necessary to block the β -rays and the low-energy γ -rays for which a detector has a high efficiency.

[0045] Here, we have paid attention to bismuth which does not emit, in particular, γ -rays in its reaction with neutrons, and the inner side of the GOS shielding material (the GOS concrete or the GOS resin) (the inner side of a later-described flight tube 4) is lined with a bismuth compound [for example, bismuth oxide (Bi_2O_3), bismuth subgallate ($\text{C}_7\text{H}_5\text{BiO}_6$), bismuth oxychloride (BiOCl), and bismuth subnitrate $\text{Bi}_5\text{O}(\text{OH})_9(\text{NO}_3)_4$] with a thickness of several mm to several cm. As for bismuth (Bi), its Bi-209 isotope whose natural abundance is 100% undergoes mainly the (n, γ) reaction with neutrons, so that Bi-210 is generated. Bi-210 has a half-life of 5.013 days and emits β -rays with 1.162 MeV without emitting γ -rays. Bismuth has a relatively small thermal neutron cross section, so that thermal neutrons from the inner side pass through the bismuth inner liner to react with a surface layer of the GOS shielding material. The β -rays and the low-energy γ -rays which are emitted as a result of the reaction are absorbed by the bismuth material and thus scarcely reach the collimator inner surface, which makes it possible to provide a detector with an image having a small influence of fogging or noise and having high sharpness.

[0046] The gadolinium compound is preferably a ceramic or a sintered body having a density of 6.5 g/cm³ or more and insoluble in water. Examples of such a gadolinium compound include gadolinium oxide (Gd_2O_3) with a 7.4 g/cm³ density, gadolinium gallium garnet ($\text{Gd}_3\text{Ga}_5\text{O}_{12}$) with a 7.09 g/cm³ density, gadolinium oxysulfide ($\text{Gd}_2\text{O}_2\text{S}$) with a 7.3 g/cm³ density, and gadolinium silicate (Gd_2SiO_5) with a 6.7 g/cm³ density. Also usable is a phosphor material in which any of these is a base metal and praseodymium (Pr), terbium (Tb), europium (Eu), cerium (Ce), or the like is mixed as an activator. Any of those gadolinium compounds is used as an aggregate and cement is mixed to form a concrete shielding material, or one that is formed using a resin in place of cement forms a shielding wall.

[0047] As previously described, the internal conversion electrons generated by the (n, γ) reaction of gadolinium with neutrons are emitted and the β -rays and the γ -rays from generated Gd-159 are emitted. However, gadolinium having a thickness of several mm attenuates the thermal neutrons by about two digits or more to achieve thermal neutron shielding, and the internal conversion electrons and the β -rays generated within this several mm are also blocked if the thickness is several mm. Further, if the gadolinium compound has several cm, the γ -rays are also self-shielded by the gadolinium itself. It is applicable particularly to the formation of a

component of a diaphragm of a collimator.

[0048] As for the diaphragm of the collimator, GOS is usable as a shielding material against thermal neutrons, and is usable as a shielding material against γ -rays, tungsten, a tungsten compound, a heavy alloy which is a tungsten compound, a bismuth compound, or the like is usable, for instance, and a combination of any of these is usable. In particular, against the γ -rays, the thickness of the diaphragm is preferably thinner similarly to that of a stop for light. As the thickness is larger, the γ -rays more reflect on the inner surface of the hole, resulting in more scattered beams. Therefore, its material preferably has a large atomic number Z and a high density (specific gravity). Further, to achieve the shielding also against the γ -rays generated by the reaction with the neutrons, it is preferable to install the diaphragm made of the GOS shielding material on the radiation source side and install the diaphragm made of the tungsten compound or the like on the outlet side.

[0049] As described hitherto, the neutron and gamma-ray collimator of this embodiment is structured such that the shielding material made of a gadolinium compound, for example, GOS is used as the neutron diaphragm, a shielding material made of tungsten, a tungsten compound, a bismuth compound, or the like is used as the gamma-ray diaphragm, and the inner surface of the GOS shielding material of the flight tube is lined with a bismuth compound. This structure shields the β -rays and the low-energy γ -rays from Gd-159 generated in the reaction of the thermal neutrons with gadolinium, making it possible to provide thermal neutron and γ -ray imaging images with a high S/N.

[0050] Hereinafter, the configurations of the neutron and gamma-ray collimator and the radiography device according to the embodiment will be described with reference to FIGs. 1 to 4. The configurations described below are only examples and do not limit the scope of the present invention at all. Further, in the description of the drawings, the same elements are denoted by the same reference signs and a redundant description thereof will be omitted when appropriate. Further, in the drawings referred to in the following description, the size and thickness of each constituent member are only for convenience's sake and do not necessarily indicate the actual size or ratio.

[0051] FIG. 1 includes a side view FIG. 1A, a rear view FIG. 1B (a view seen from the left side of the side view in FIG. 1A), and a front view FIG. 1C (a view seen from the right side of the side view in FIG. 1A) schematically illustrating the configuration of a neutron and gamma-ray collimator 1 according to an embodiment. The neutron and gamma-ray collimator 1 includes a diaphragm 2, a diaphragm fixing plate 3 for fixing the diaphragm 2, and a flight tube 4 integrated with the diaphragm fixing plate 3.

[0052] FIG. 2 includes FIG. 2A of a view schematically illustrating the configuration of a neutron diaphragm 21 and FIG. 2B of a view schematically illustrating a gamma-ray diaphragm 22 that are enlarged views of the config-

uration of an essential part of the neutron and gamma-ray collimator in FIG. 1. As illustrated in FIG. 2, the diaphragm 2 includes a neutron diaphragm 21 serving as an aperture for neutrons and a gamma-ray diaphragm 22 serving as an aperture for γ -rays. A through hole 21a is provided at the center portion of the neutron diaphragm 21, and a through hole 22a is provided at the center portion of the gamma-ray diaphragm 22. The diameter D4 of the through hole 22a is smaller than the diameter D5 of the through hole 21a. As illustrated in FIG. 3, the neutron diaphragm 21 and the gamma-ray diaphragm 22 are attached to the diaphragm fixing plate 3 with the gamma-ray diaphragm 22 located on the diaphragm fixing plate 3 side.

[0053] Assuming that the sizes of the neutron diaphragm 21 and the gamma-ray diaphragm 22 are, for example, the same, their length is represented by A1 and their width by A2. A1 and A2 may be equal. The dimension of the neutron and gamma-ray collimator 1 differs depending on a neutron source for which it is installed. Therefore, in the drawings, specific dimensions are not given but the dimensions are indicated by signs in consideration of scale.

[0054] The neutron diaphragm 21 and the gamma-ray diaphragm 22 are stacked on the diaphragm fixing plate 3 to be fixed, for example, at four corners by screwing or the like. As the material of the gamma-ray diaphragm 22, a material having a high γ -ray shielding ability, having a large atomic number Z, and having a high density (for example, tungsten, a tungsten compound, a heavy alloy which is a tungsten compound, or the like, or the afore-said bismuth compound) is selected. These high-Z and high-density materials are capable of shielding against up to a relatively high energy region and thus increase the performance of the diaphragm for γ -rays, though this depends on the energy of the γ -rays. Further, the use of any of these materials also allows the thickness t3 to be thin. As the opening diameter D4 which is the diameter of its aperture is smaller, the resolution becomes higher as in the case of light, but at the same time, the γ dose also reduces, necessitating increasing the intensity of the radiation source or elongating the photographing time.

[0055] In this embodiment, as the material of the neutron diaphragm 21, a GOS shielding material (a GOS plate, a GOS resin, or GOS concrete) is used. Gadolinium of GOS has a high shielding effect against thermal neutrons even if its thickness is small. Note that t4 indicated in FIG. 3 is the thickness of the neutron diaphragm 21. An index indicating the resolution of thermal neutron beams is represented by $L/D = L1/D5$, where D is the opening diameter of the diaphragm (the diameter of the through hole 21a) (D5 indicated in FIG. 2A) and L is the length of the collimator (L1 indicated in FIG. 1A), and the larger this value, the higher the resolution.

[0056] As described above, the opening diameter D5 (FIG. 2A) of the neutron diaphragm 21 is set larger than the opening diameter D4 (FIG. 2B) of the gamma-ray

diaphragm 22. Setting the opening diameter D4 and the opening diameter D5 in this manner makes it possible for the gamma-ray diaphragm 22 to block γ -rays generated in the reaction of the gadolinium of the neutron diaphragm 21 with neutrons, and in particular, makes it possible to reduce the influence of low-energy γ -rays to which a detector or an imaging element is highly sensitive, to obtain a γ -ray imaging image with a high S/N. On the other hand, for the neutrons, the gamma-ray diaphragm 22 has a small cross section because it is thin, and thus the neutrons are not influenced by the aperture in the gamma-ray diaphragm 22.

[0057] As illustrated in FIG. 3, the diaphragm fixing plate 3 is an integrated structure of a neutron shielding plate 31 and a gamma-ray shielding plate 32. The diaphragm fixing plate 3 fixes the neutron diaphragm 21 and the gamma-ray diaphragm 22, and in addition, its neutron shielding plate (in this embodiment, made of a GOS shield) 31 (illustrated in FIG. 3 and having a thickness t2) blocks thermal neutrons that are generated when neutrons emitted from a neutron source 51 illustrated in FIG. 4 are decelerated by a moderator 52 and a moderator and shield 53 around and behind the neutron source, and its gamma-ray shielding plate 32 (illustrated in FIG. 3 and having a thickness t1) blocks the γ -rays emitted in the reaction of GOS of the neutron shielding plate 31 with the neutrons.

[0058] As the γ -ray shield forming the gamma-ray shielding plate 32, a bismuth compound that does not easily react with neutrons and does not emit γ -rays is suitably used, but besides, tungsten, a tungsten compound, a heavy alloy which is a tungsten compound (a sintered body mainly composed of tungsten and containing nickel and copper), or the like is also usable. Further, the diaphragm fixing plate 3 is integrated also with the flight tube 4 and is structured to support the collimator. Therefore, as for the dimensions of the diaphragm fixing plate 3, its height A3 and width A4 indicated in FIG. 1B are set in consideration of the size of the neutron source for which the collimator is installed. Further, depending on the shape of an installation place, it may have a circular outer shape or the like. Note that in FIG. 1B, W1 indicates the height of the flight tube 4 and W2 indicates the width of the flight tube 4.

[0059] The flight tube 4 illustrated in FIGs. 1 has a quadrangular pyramid shape but the flight tube 4 may have a circular conical shape. This flight tube 4 is intended to block neutrons and γ -rays from the moderator and shield 53 illustrated in FIG. 4, and as illustrated in FIG. 3, has, on its outer side, a neutron shield (in this embodiment, a GOS shield) 41 with a thickness of $((D3 - D2)/2)$ and has, on its inner side, a gamma-ray shield (in this embodiment, a bismuth compound) 42 with a thickness of $((D2 - D1)/2)$, and they are integrated. The inner gamma-ray shield (bismuth compound) 42 is provided to prevent γ -rays which are emitted in a reaction of the outer neutron shield (GOS shield) 41 with the neutrons from being emitted into the collimator.

[0060] FIG. 4 is a view illustrating a schematic configuration of the radiography device 100 in which the neutron and gamma-ray collimator 1 is installed for the neutron source and is a simplified and simulated view assuming that the neutron source is that of accelerator neutrons. In a pneumatic tube 54, electron beams or proton beams pass, which react with a target of the neutron source 51 to emit neutrons, γ -rays, or bremsstrahlung X-rays. In the case where the neutron source is a nuclear reactor, there is no pneumatic tube 54, and the neutron source is a fuel rod. Further, in the case of an RI neutron source, there is no pneumatic tube 54 as in the case of the nuclear reactor, and the neutron source is an RI neutron source. On the right end of the neutron and gamma-ray collimator 1 in FIG. 4, an object 200 to be imaged is placed.

[0061] The neutron and gamma-ray collimator 1 in FIG. 4 is installed such that the extension of the collimator center line reaches the neutron source 51. That is, when the tip of the collimator is seen from a collimator outlet, the neutron source 51 is on the extension. In this case, high-energy neutrons and high-energy γ -rays from the neutron source 51 are emitted from the neutron and gamma-ray collimator 1. To prevent this and extract only low-energy neutrons, the whole neutron and gamma-ray collimator 1 can be installed so as to deviate upward or downward from the center line in FIG. 4 or incline slantingly or vertically so that the neutron source 51 is not seen from the collimator outlet. That is, when used, the installation manner of the neutron and gamma-ray collimator 1 can be changed according to the energies of neutrons and γ -rays that are to be extracted therefrom.

[0062] As described hitherto, according to the neutron and gamma-ray collimator of this embodiment, it is possible to radiate neutron beams and γ -rays (including bremsstrahlung X-rays) emitted from the neutron source while collimating their flux and reducing their scattered beams. In particular, it achieves γ -ray imaging with little noise and with the minimized influence of γ -rays that are emitted in a reaction with thermal neutrons because thermal neutron components are involved in imaging, which problem does not arise in a collimator only for γ -rays. At the same time, in the thermal neutron imaging, it is also possible to obtain a clear image with only a small number of noise components ascribable to scattered beams and with little fogging ascribable to the scattered beams. This enables simultaneous neutron radiography and γ -ray radiography in non-destructive inspection. The neutron and gamma-ray collimator can be also selectively used as a collimator only for thermal neutrons or a collimator only for γ -rays.

[0063] While the embodiments of the present invention have been described above, the embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions. Further, the embodiments can be embodied in a variety of other forms, and various omissions, substitutions and changes may be made without departing from the spirit of the in-

ventions. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the inventions.

5 REFERENCE SIGNS LIST

[0064] 1.....neutron and gamma-ray collimator, 2..... diaphragm, 3.....diaphragm fixing plate, 4.....flight tube, 21.....neutron diaphragm, 21a.....through hole, 22.....gamma-ray diaphragm, 22a.....through hole, 31.....neutron shielding plate, 32.....gamma-ray shielding plate, 41.....neutron shield, 42.....gamma-ray shield, 51 neutron source, 52.....moderator, 53.....moderator and shield, 54.....pneumatic tube, 100..... radiography device, 200.....object

Claims

20 1. A neutron and gamma-ray collimator (1) comprising:

a neutron diaphragm (21);
a gamma-ray diaphragm (22);
a diaphragm fixing plate (3) that fixes the neutron diaphragm (21) and the gamma-ray diaphragm (22); and
a flight tube (4) integrated with the diaphragm fixing plate (3) and having a neutron shield (41) and a gamma-ray shield (42) lining an inner side of the neutron shield (41),
wherein a gadolinium compound is used as the neutron diaphragm (21) and the neutron shield (41) of the flight tube (4), and
wherein a bismuth compound is used as the gamma-ray shield (42) of the flight tube (4).

2. The neutron and gamma-ray collimator (1) according to claim 1,
wherein tungsten, a tungsten compound, or a bismuth compound is used as the gamma-ray diaphragm (22).

3. The neutron and gamma-ray collimator (1) according to claim 1 or 2,

wherein the gadolinium compound is a ceramic or a sintered body having a density of 6.5 g/cm³ or more and insoluble in water, and
wherein the gadolinium compound is a phosphor material includes a base metal and an activator mixed in the base metal, the base metal being any one of gadolinium oxide (Gd₂O₃) with a density of 7.4 g/cm³, gadolinium gallium garnet (Gd₃Ga₅O₁₂) with a density of 7.09 g/cm³, gadolinium oxysulfide (Gd₂O₂S) with a density of 7.3 g/cm³, and gadolinium silicate (Gd₂SiO₅) with a density of 6.7 g/cm³, the activator being at least one of praseodymium (Pr), terbium (Tr), euro-

pium (Eu), and cerium (Ce).

4. The neutron and gamma-ray collimator (1) according to claim 1 or 2,
wherein the bismuth compound is any one of bismuth oxide (Bi_2O_3), bismuth subgallate ($\text{C}_7\text{H}_5\text{BiO}_6$), bismuth oxychloride (BiOCl), and bismuth subnitrate ($\text{Bi}_5\text{O}(\text{OH})_9(\text{NO}_3)_4$). 5
5. The neutron and gamma-ray collimator (1) according to claim 1 or 2,
wherein the diaphragm fixing plate (3) includes a neutron shielding plate (31) and a gamma-ray shielding plate (32). 10
15
6. The neutron and gamma-ray collimator (1) according to claim 5,
wherein a gadolinium compound is used as the neutron shielding plate (31). 20
25
7. A radiography device (100) that irradiates an object to be imaged with a neutron and a gamma-ray emitted from a radiation source to obtain an image,
wherein the neutron and gamma-ray collimator (1) according to claim 1 or 2 collimates the neutron and the gamma-ray emitted from the radiation source. 25
30
35
40
45
50
55

FIG. 1C

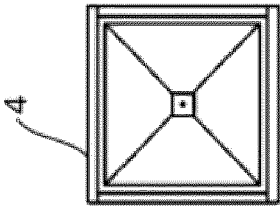


FIG. 1B

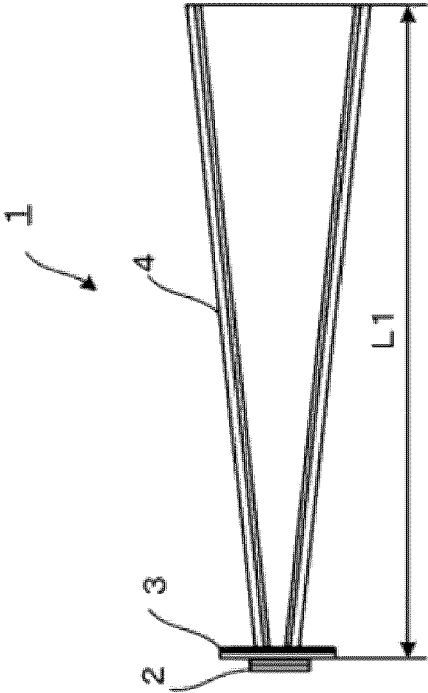


FIG. 1A

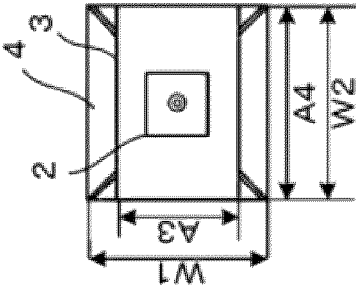


FIG. 2B

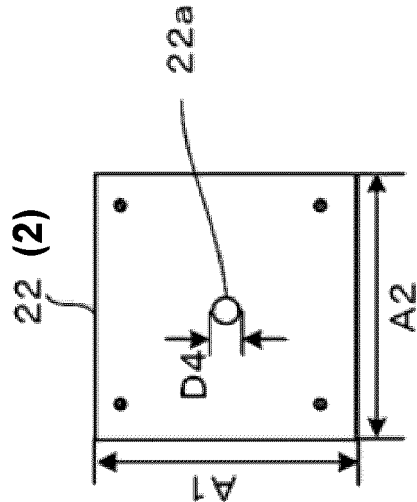


FIG. 2A

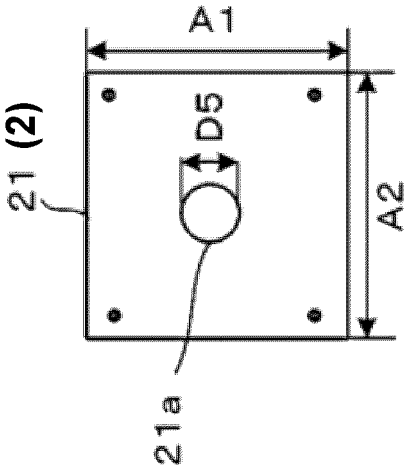


FIG. 3

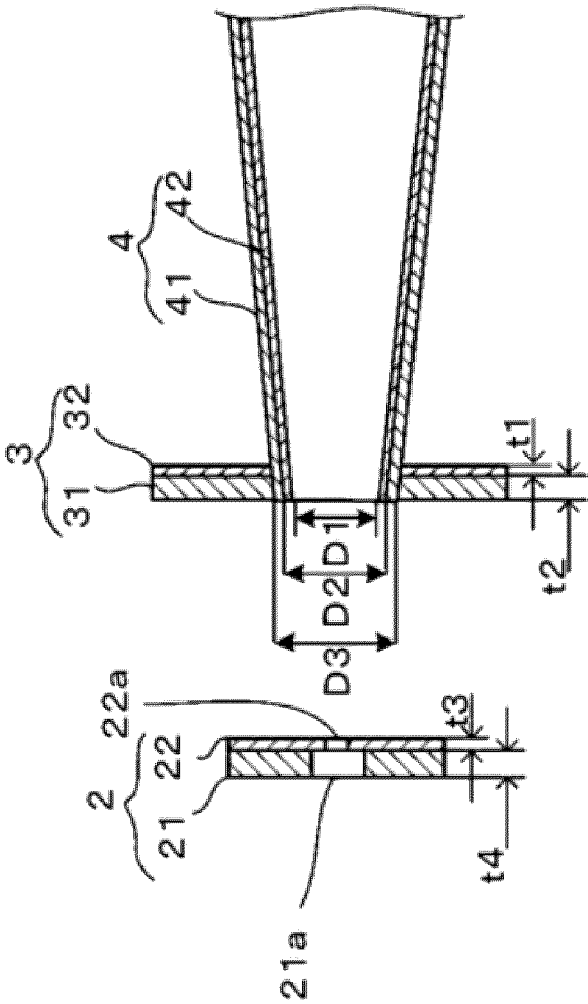


FIG. 4

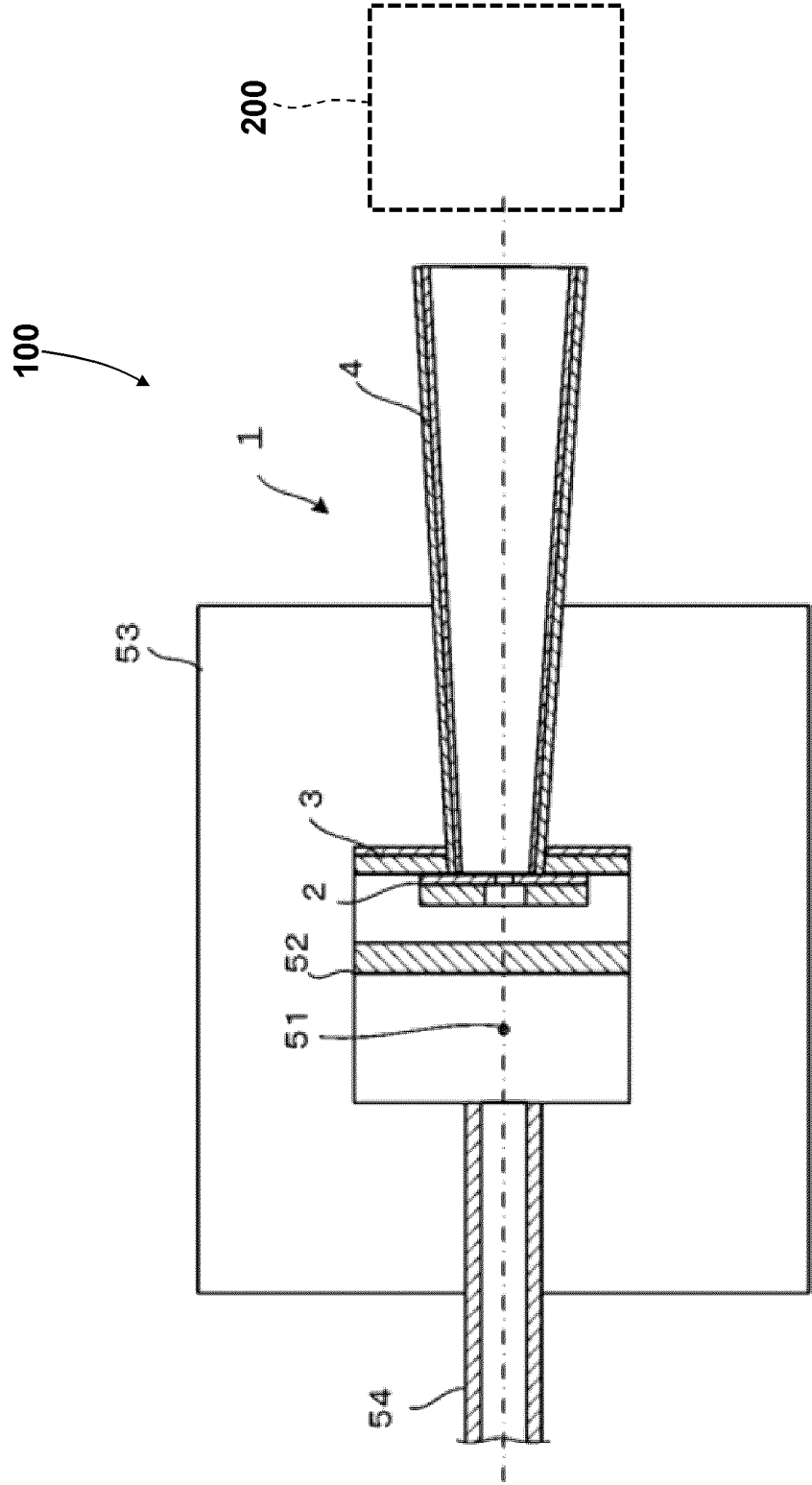


FIG. 5

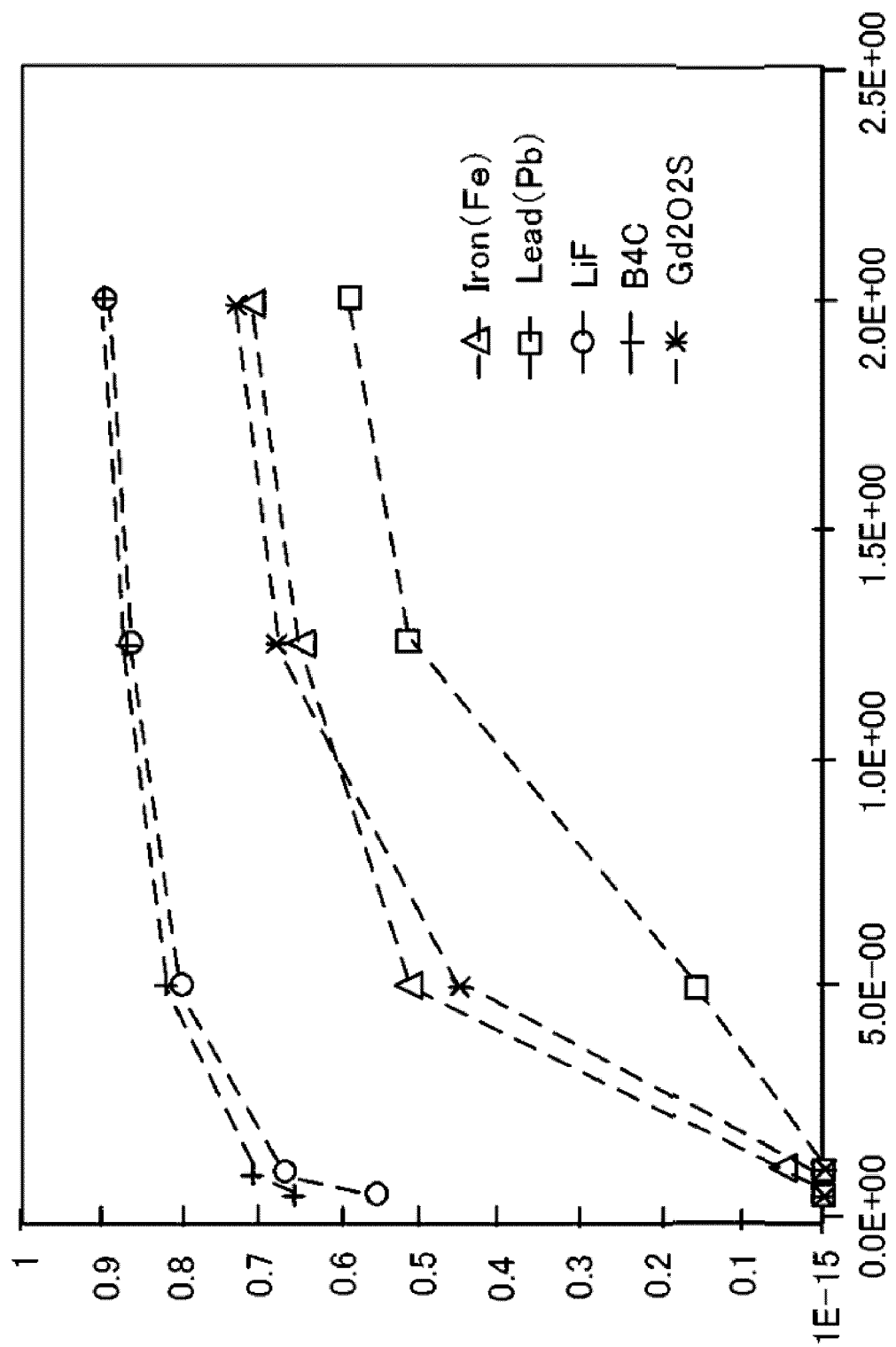


FIG. 6

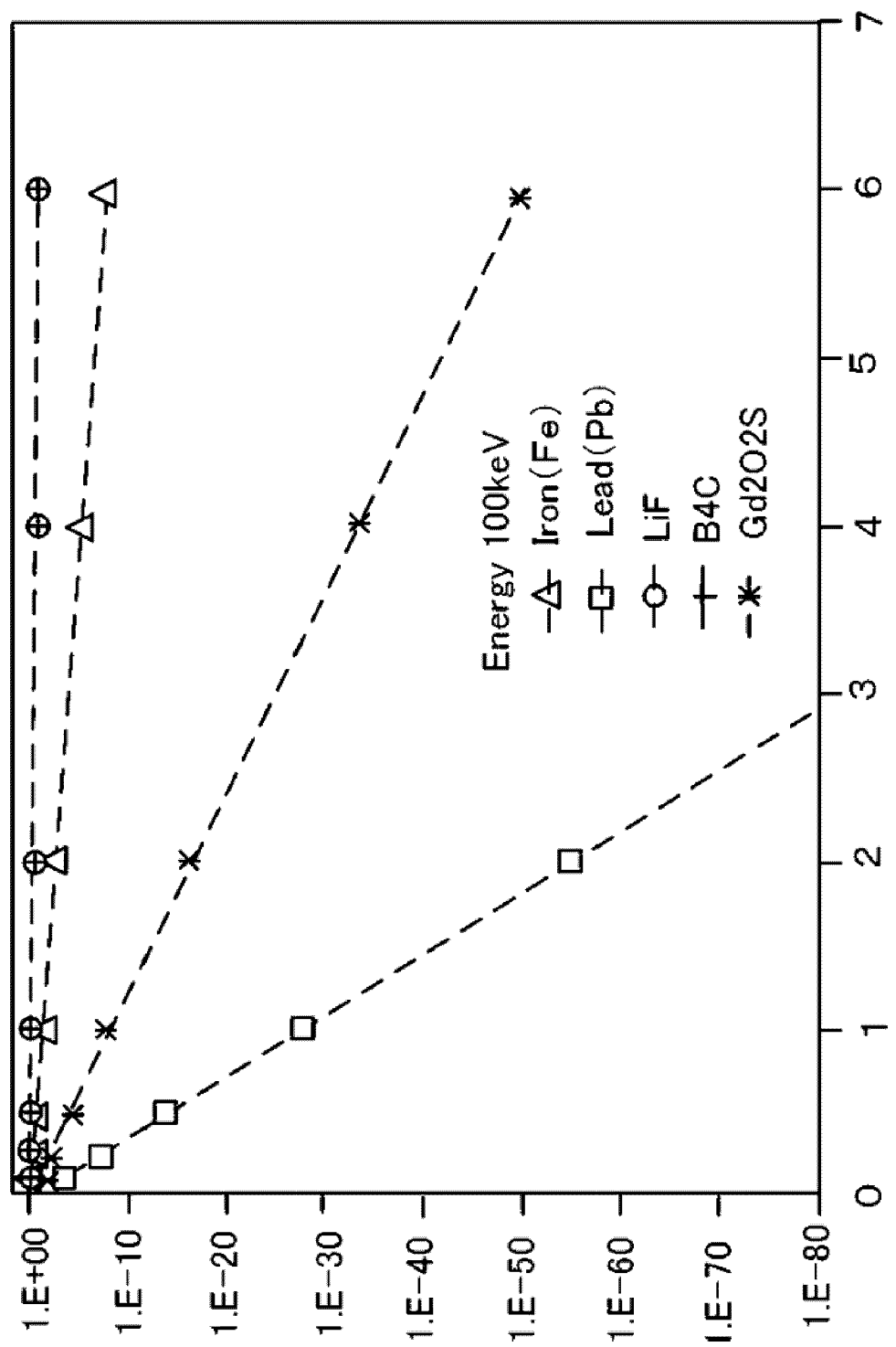
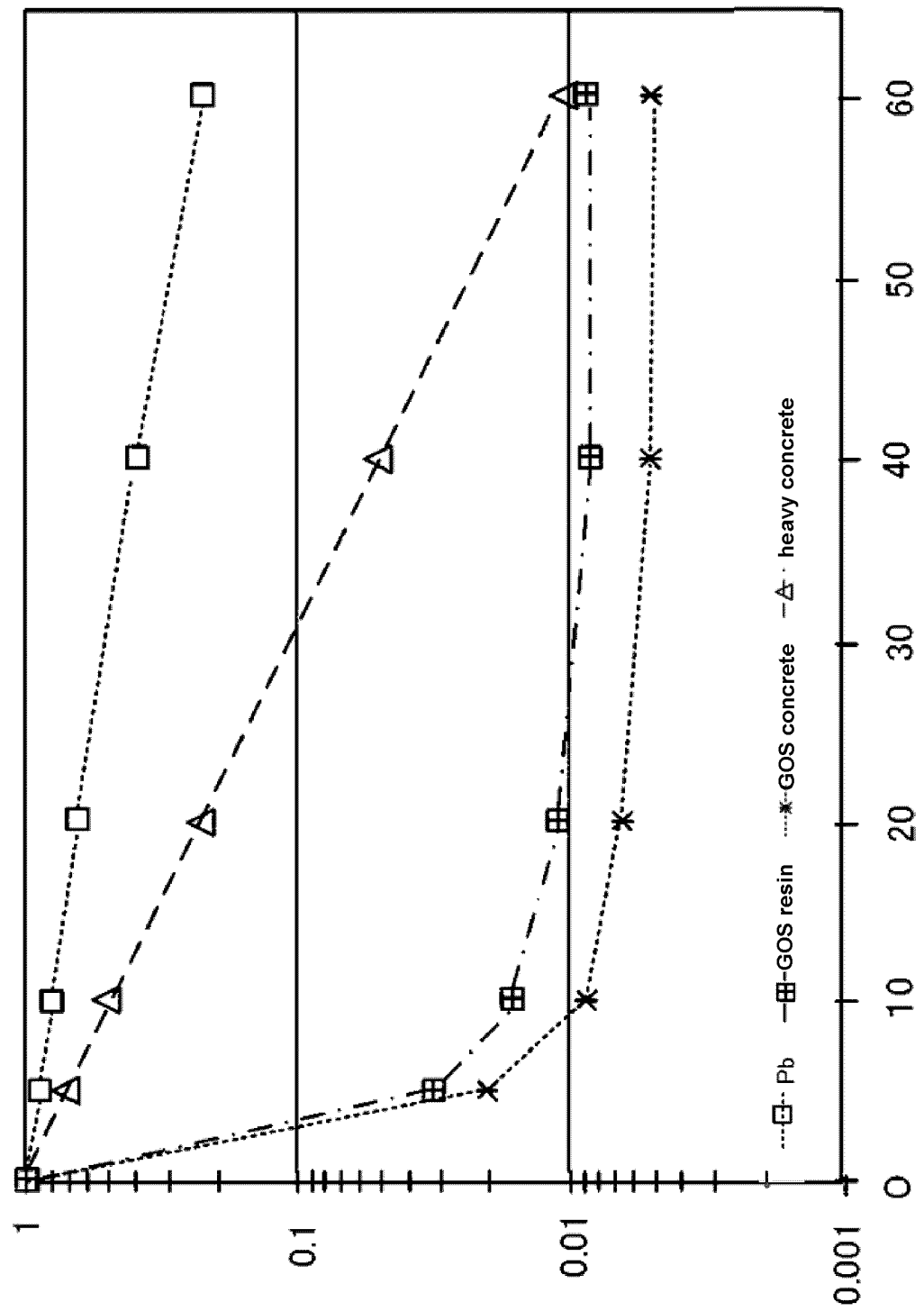


FIG. 7





EUROPEAN SEARCH REPORT

Application Number

EP 23 17 7560

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	US 4 582 999 A (DANCE WILLIAM E [US] ET AL) 15 April 1986 (1986-04-15) -----	1-7	INV. G21K1/02
A	JP 2018 161449 A (YAGAMI CO LTD; UNIV NAGOYA) 18 October 2018 (2018-10-18) -----	1-7	
T	Anonymous: "Neutron Capture Cross-Section - an overview ScienceDirect Topics", / 27 October 2023 (2023-10-27), XP093095727, Retrieved from the Internet: URL:https://www.sciencedirect.com/topics/chemistry/neutron-capture-cross-section [retrieved on 2023-10-27] * page 1 - page 2 * -----		
			TECHNICAL FIELDS SEARCHED (IPC)
			G21K H01J

The present search report has been drawn up for all claims

2

Place of search	Date of completion of the search	Examiner
Munich	27 October 2023	Krauss, Jan
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document		

EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.

EP 23 17 7560

5 This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

27-10-2023

10	Patent document cited in search report	Publication date	Patent family member(s)	Publication date
	US 4582999 A	15-04-1986	NONE	

15	JP 2018161449 A	18-10-2018	JP 6935878 B2	15-09-2021
			JP 2018161449 A	18-10-2018

20				
25				
30				
35				
40				
45				
50				
55				

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Non-patent literature cited in the description

- **K. SHIBATA ; O. IWAMOTO ; T. NAKAGAWA ; N. IWAMOTO ; A. ICHIHARA ; S. KUNIEDA ; S. CHIBA ; K. FURUTAKA ; N. OTUKA ; T. OHSAWA.**
JENDL-4.0: A New Library for Nuclear Science and Engineering. *J. Nucl. Sci. Technol.*, 2011, vol. 48 (1), 1-30 **[0033]**