(19)

LE GOUVERNEMENT
DU GRAND-DUCHÉ DE LUXEMBOURG
Ministère de l'Économie

(11) N° de publication : **LU102817**

(12) **BREVET D'INVENTION** **B1**

(21) N° de dépôt: LU102817

(51) Int. Cl.:
G21G 1/06, G21G 1/10, H05H 6/00

(22) Date de dépôt: 04/06/2021

(30) Priorité:
16/04/2021 CZ 2021-189

(43) Date de mise à disposition du public: 17/10/2022

(47) Date de délivrance: 17/10/2022

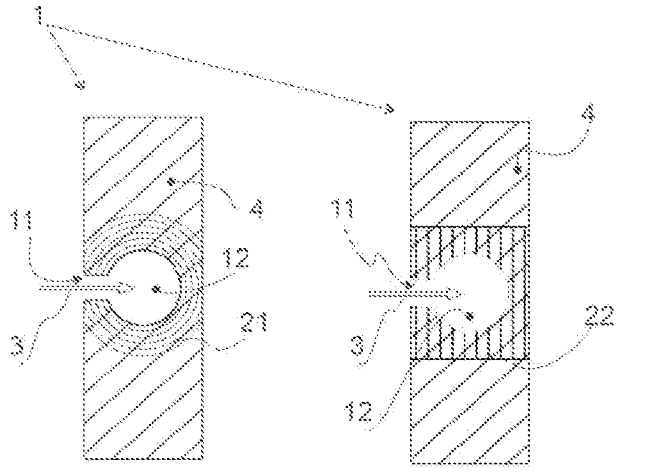
(73) Titulaire(s):
FYZIKALNI USTAV AV CR, V.V.I. – 182 21 PRAHA 8 (République tchèque)

(72) Inventeur(s):
KORN Georg – République tchèque, RIDKY Jan – République tchèque

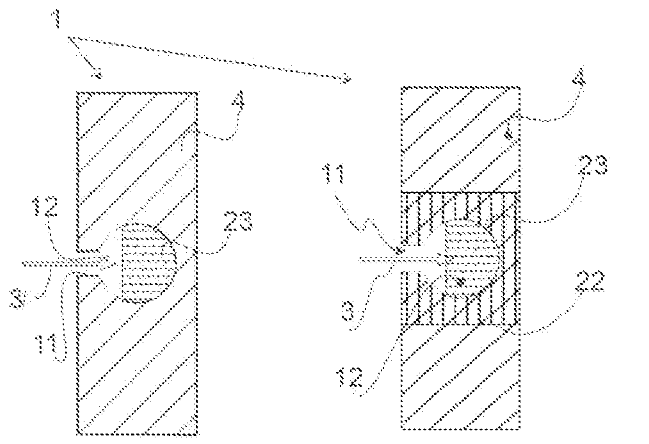
(74) Mandataire(s):
ELI Beamlines/CITT - Karel BAUER – 252 41 Dolni Brezany (République tchèque)

(54) **A nuclear target, method for inducing a nuclear reaction and a device suitable for carrying out the method.**

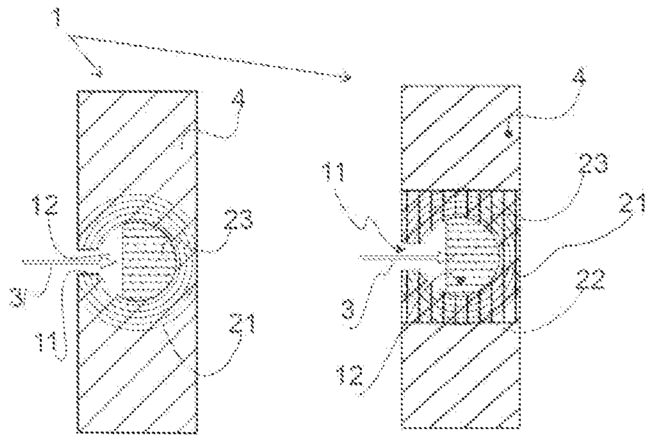
(57) Nuclear target, method for producing isotopes and device suitable for carrying out the same The present invention relates to a nuclear target (1), a method for inducing a nuclear reaction and a device capable of inducing nuclear reactions. According to the present invention, the nuclear target (1) is equipped with a hollow (12) into which projectile particles (3) are deposited. In the hollow (12), the projectile particles (3) interact with precursors (21 and/or 22 and/or 23), or projectile particles (3) are elastically scattered on isotopes (4). The nuclear target (1), method, or the device thus provides a more efficient induction of nuclear reactions and provides a higher yield of radioisotope production. In another embodiment, the nuclear target (1) can be used as a means used to nuclear waste transmutation, or as a means of sustainable exothermic nuclear reactions.



Obr. 1a Obr. 1b



Obr. 1c Obr. 1d



Obr. 1e Obr. 1f

CITT ref.: E18003

A nuclear target, method for inducing a nuclear reaction and a device suitable for carrying out the method

LU102817

Technical field

[001] The present invention relates to a nuclear target, a method for inducing a nuclear reaction by means of the nuclear target and controlled nuclear reactions. In a preferred embodiment, the method for creating isotopes is performed using a laser-driven accelerator.

[002] In another embodiments, the present invention relates to exothermic nuclear reactions and a method for converting nuclear energy into heat, a method for creating radioisotopes, in particular radiopharmaceuticals, and a method for treating burnt nuclear fuel, more specifically, a method for transmutation of nuclear fission products.

[003] In another embodiment, the present invention relates to a device capable of carrying out the methods disclosed herein.

Background of the Art

[004] There are plurality of radioisotopes that are currently being utilized in medicine, energy or diagnostic methods using ionizing radiation. Some radioisotopes, in particular those used in medicine, often have a relatively short half-life. Therefore, there is a general need for a method for producing radioisotopes either at the particular place, where they are intended to be utilized, or at a place in relatively close distance. On the other hand, the products of fission reactions of ^{235}U have a half-life of several decades. Therefore, there is a need for a method for transmuting radioactive material (waste) that is the final product of a fission nuclear reaction, preferably treating the waste at the place where they are going to be utilized, or at a place relatively close thereto.

[005] There is also a continuing need to provide a clean energy source. One way to achieve such a clean energy source is to use exothermic nuclear reactions. According to the state of the art, there are two technical directions how to achieve energy production therefrom. One is nuclear fission, the other is nuclear fusion.

[006] Laser is commonly used in industrial, scientific, and engineering applications. However, it is still new to controlled nuclear reactions, as there is still a number of technical gaps that need to be addressed.

[007] US 2016/0172065 discloses a nuclear target, system and method for creating isotopes thereof. The target contains a hollow, wherein a laser beam is focused into the hollow, creating plasma on the surface of the nuclear target. The target is then, but still during the plasma state, irradiated with a beam of projectile particles, such as protons. The target material and the type of particles are chosen according to the need of the nuclear reaction. Disclosed examples are, for example, $^{14}N(p,\alpha)^{11}C$; $^{11}B(p,n)^{11}C$; $^{18}O(p,n)^{18}F$; $^{20}Ne(d,n)^{18}F$ – as disclosed by the patent application; $^{16}O(p,\alpha)^{13}N$; $^{13}C(p,n)^{13}N$; $^{14}N(d,n)^{15}O$; $^{15}N(p,n)^{15}O$.

[008] According to US 2016/0172065, the system comprises:

1) means configured to convert the target to a plasma state; e.g. laser or z-pinch;
2) a particle source set to irradiate the target into the plasma state by particles which induce the above-mentioned nuclear reactions; and
3) isotope recovery means configured to recover isotopes generated by nuclear reactions.

[009] The use of the system according to US 2016/0172065 is exclusively disclosed for the creation of radioisotopes. The present solution is also very energy-demanding and lossless energy generation is impossible in the context of the present state of the art.

[010] Another disclosed solution for generating high-energy particles for controlled nuclear reactions using a high-intensity laser is US 2002/0172317. The apparatus contains two planar targets. The primary target, containing a thin Mylar film, is irradiated with a laser beam. Upon laser bombardment, the first target emits energetic particles, such as protons or deuterons, emitted towards the secondary target. The secondary target contains ^{10}B, thereby inducing nuclear reactions due to proton or deuteron radiation emitted from the primary target.

[011] An example of a disclosed nuclear target, apparatus and method for controlling fusion nuclear reactions is EP2833365. The target is planar and comprises two layers. The first layer comprises hydrogen-enriched silicon so that protons are emitted into the second layer upon the laser pulse irradiation. The second layer comprises boron, which in certain embodiments induces an exothermic nuclear reaction.

[012] There are also capsule-shaped targets, as disclosed, for example, in US20120114088, wherein a compression of the envelope of the nuclear target occurs as a result of the mechanism of the laser radiation. Once atomic nuclei reach a certain distance, they fuse within a given target.

[013] However, the above mentioned solutions provide low efficiency in the manufacturing of radioisotopes, since the target must always be supplied with a substantial part of energy, e.g. by means of laser radiation and/or external heating. In the case, in which the device is to lead to the fusion of nuclei, it is technically difficult to achieve the desired density of the generated plasma. Due to the growing application of radioisotopes in various fields of technology, there is a growing need for their generation using controlled nuclear reactions. The technical problem, which the present invention solves to a certain extent, lies in the method of more efficient generation of radioisotopes, or a more effective method for inducing a nuclear reaction.

Description of the Invention

[014] The first embodiment of the present invention relates to a nuclear target suitable for increasing the efficiency to induce nuclear reactions, and thus also for the production of radioisotopes, in particular radiopharmaceuticals, or transmutation of burnt nuclear fuel and/or as means able to effectively induce exothermic nuclear reactions with significant thermal energy production.

[015] The nuclear target according to the present invention, and as defined by claim 1, has the character of a bulk of material, comprising a hollow, wherein the shape of the hollow is preferably optimized with respect to the intention of the secondary nuclear reactions. The nuclear target is made of material comprising precursors. In a certain embodiment, the precursor may be implanted in the solid material of the target, while in another embodiment, the precursor may be placed in the hollow of the target in solid (e.g. powder), liquid, or gaseous form. In another embodiment, at least part of the nuclear target consists of the precursor. In another preferred embodiments, it is possible to combine the localization of the precursors as mentioned above, i.e. to provide powder precursor into the hollow of the nuclear target, while at least part of the nuclear target surrounding the hollow consists of the same or further precursor. The precursor is formed by a specific predetermined isotope which, upon collision with a projectile particle, forms the desired product of a nuclear reaction, such as a radioisotope. The material of the nuclear target, more specifically the precursor, or a plurality of precursors, is selected for the nuclear reaction of the precursor(s) and the projectile particle(s) to achieve the final product(s), most often radioisotopes. The nuclear target further comprising at least one opening for the passage of a beam of projectile particles. The nuclear target is further equipped with a hollow in the bulk of the material located behind the opening, used for the incidence of projectile particles.

Projectile particles passing through the opening and incident on the hollow of the bulk of the material are either elastically scattered on at least one nucleus/nuclei of the isotope in the hollow, or the desired nuclear reaction with the isotope occurs depending on the energy of the projectile particle. Some projectile particles may be reflected back – out of the hollow, wherein the reflected particles generate losses. Losses can be minimized by the shape of the hollow, in particular, the geometry – by the position of the opening and the hollow. The elastic scattering of projectile particles on isotopes/nuclei in the hollow provides at least two technical effects. The first technical effect leads to the dissipation of energy inside the hollow, and thereby to the heating of the nuclear target material. The second technical effect relates to the transfer of kinetic energy to the target/isotope nuclei, which can thus exceed the threshold energy of the desired reactions. LU102817

[016] The above-mentioned technical effects then provide a synergistic technical effect relating to the increased efficiency of radioisotope production or the yield of another desired nuclear reaction, for example the frequency of exothermic reactions or transmuted nuclei.

[017] As mentioned above, the nuclear target is formed by a bulk of material, wherein the shape of the hollow is optimized with respect to the course of the desired nuclear reactions. In a certain embodiment, the bulk of the material can be a single bulk. In another embodiment, the single bulk can be divided into a plurality of segments. In another embodiment, the opening of the target facing the hollow may be slightly curved and/or contain a texture, in particular on the inner side of the hollow. However, the nuclear target must always contain at least one opening, preferably only one opening, for having projectile particles enter into the hollow of the nuclear target. Thus, the hollow of the nuclear target is never completely surrounded by the material containing the precursor(s) and isotopes on which the projectile particle is elastically scattered. The above preferred embodiment of only one opening provides the advantage of effectively trapping the scattered projectile particles, secondary particles and precursor particles accelerated by them. The probability of projectile particles escaping from the hollow, due to backscattering, can be minimized by a suitable geometry of the shape of the hollow.

[018] The hollow can be of any shape. In a certain embodiment, the shape of the hollow may be part of an ellipsoid or a sphere. The optimized shape of the hollow, preferably of a more complex shape, can be generated by means of segments which form a single bulk upon their connection. In a preferred embodiment, the hollow comprises

at least two parts. The first part consists of a narrower passage, while the second part consists of a wider and larger space. The first part can be in the shape of a cylinder, block or polyhedron, while the second part then follows seamlessly in the shape of a part of an ellipsoid, sphere or, for example, polyhedron. The geometry of the hollow, which is divided into at least two parts, offers the technical advantage of effectively trapping the projectile particles in the hollow, while considerably limiting the backscattering of the same. In a more preferred embodiment, the cross-sectional size of the first part of the hollow corresponds to the transverse size of the beam of projectile particles.

[019] In the context of the present invention, a precursor refers to an atomic nucleus that interacts with a projectile particle, in particular there is a collision of a projectile particle with the atomic nucleus, with the interaction resulting in an induced nuclear reaction. The end or intermediate product may be a radioisotope that further decay, for example, by an alpha, beta, and/or gamma decay, wherein the decay is further utilized in a particular industrial application. Intermediates may also be neutrons necessary for achieving the desired nuclear reactions. In a certain embodiment, the precursor may be implemented in the material, for example, by ion-atom implementation, or CVD, or PVD by atomic deposition onto a substrate. In another embodiment, the nuclear target can consist of precursor material surrounding the hollow, wherein at least one isotope, on which a projection particle is scattered, is presented in the material of the nuclear target. In another embodiment, the precursor may form part of the hollow so as to fill the precursor to a certain volume. In another embodiment, the precursor may be included in both the material and the cavity filling. In this case, the precursor need not necessarily be one particular, but the first precursor may be implemented in the wall of the hollow or can form the hollow, while the second precursor may be part of the filling. The precursor may be, for example, ^{10}B; ^{11}B; natural mixture of boron; ^{13}C; ^{14}N; ^{15}N; ^{16}O; ^{18}O; ^{20}Ne; radiopharmaceuticals of ^{99}Mo,^{186}W, fission reaction products, ^{233}U,^{235}U,^{239}Pu. In a certain embodiment, the bulk of the material of the nuclear target can be manufactured from the respective precursor material.

[020] Projectile particles are particles that bombard the nuclear target. Projectile particles can be, for example, protons, neutrons, deuterons, α-particles, light ions – for example ^{14}C, ^{16}O, medium-heavy ions (e.g. ^{27}Al) or even heavy nuclei such as ^{197}Au in case of use and depending on the material of the laser target. Projectile particles can be

produced by state-of-the art accelerators or can be emitted by radioisotopes, e.g. AmBe or PuBe or can be produced by laser driven accelerator. LU102817

[021] The isotopes, on which elastic scattering with the projectile particles occur, may be the nuclei of the nuclear target, nuclei of the precursor and nuclei of the secondary products of the reactions already occurred if the energy of the projectile particles does not correspond to the resonant width of the allowed channels. If the precursor is not implemented in the material of the nuclear target, it is desirable that the possible reaction of the projectile and secondary particles with the nuclear target nuclei is the elastic scattering. These particles are thus partially reflected back and can interact with the nuclei of the precursor. For example, a tungsten nuclear target contains ^{180}W, ^{182}W, ^{183}W, ^{184}W and ^{186}W isotopes, wherein, in the case of protons as projectile particles with a proton energy of up to 6 MeV, practically only elastic scattering occurs. The energy of the protons can dissipate through a multiple elastic scattering until it reaches resonant energy of some possible reaction with the precursor.

[022] The induced nuclear reaction in the context of the present invention may be a nuclear transmutation, a spallation or fission nuclear reaction, a fusion reaction, or a compound nucleus reaction. Examples of suitable induced nuclear reactions are given below.

[023] In a preferred embodiment, the nuclear target is further equipped with a laser target emitting projectile particles upon laser irradiation. The laser target can preferably be placed on the nuclear target opening. In another embodiment, the laser target may be positioned in front of the opening of the nuclear target to create space between the laser target emitting the projectile particles and the nuclear target opening. The space can be preferably used to filter out other particles formed by the laser irradiation of the laser target. In another embodiment, the opening between the laser target and the nuclear target may be closed and filled with a fluid, such as a fluid containing precursor nuclei. The embodiment disclosed above with the laser target further provides an advantage in the case of a nuclear target material comprising an electrically conductive material. A laser pulse emitted by, for example, a high-power pulsed laser may cause the generation of an electric current inside an electrically conductive nuclear target. In this case, the inset of the laser target is preferably in terms of a certain isolation of electromagnetic radiation affecting the electrically conductive nuclear target. In one embodiment, the parameters of the laser pulse can be taken from EP2833365.

[024] In a certain embodiment, the material of the nuclear target may be suitably selected to consist only of a material containing exactly two isotopes. The first isotope is a precursor, and the second isotope is an isotope on which projectile particles are elastically scattered. The technical advantage of this embodiment is that only two interactions occur in the hollow of the nuclear target immediately after irradiation. The first interaction induces a nuclear reaction of the precursor with the projectile particle. The second interaction represents elastic scattering of the projectile on the isotope. Thus, the efficiency of induction of the nuclear reaction or production of radioisotopes is enhanced. After some time, however, due to the nuclear interaction with the precursor, the products hereof appear, also entering into the ongoing interactions. LU102817

[025] In another embodiment, the laser target material can be preferably selected to comprise multiple isotopes. If a laser target consists of multiple isotopes, their emitted ions forming projectile particles will interact with the nuclear target in a certain sequence. This can be used to influence the kinetics of the ongoing reactions. The above sequence of incident projectile particles providing a sequence of induced nuclear reactions in the hollow of the nuclear target can be ensured by making a nuclear target provided with an inset laser target. The size of the inset can be advantageously selected according to reaction kinetics.

[026] In accordance with the IAEA convention, hereinafter, we will use the so-called abbreviated notation of nuclear reactions, i.e. the reaction projectile *P* + target *T* → emitted particle *X* + residual nucleus *R* as T (P, X) R. The isotopes ^{1}H, ^{2}H, ^{3}H and ^{4}He are accordingly labelled, when they act in the reaction as a target, i.e. a precursor, or a residual nucleus. ^{2}H and ^{3}H are sometimes labelled in accordance with the convention as *D* and *T*, respectively. If the isotopes ^{1}H, ^{2}H, ^{3}H and ^{4}He appear as projectile or emitted particles, we will denote them in accordance with the convention of *p*, *d*, *t* and *α*, respectively. Other isotopes are labelled by default in all roles in the reaction.

[027] In another preferred embodiment, the inner wall of the hollow is provided with a layer comprising material emitting secondary projectile particles, which are emitted from this layer upon the interaction of the primary projectile particle or another particle with sufficient momentum. In another embodiment, the hollow can be provided, in its volume, with a material capable of emitting secondary projectile particles upon an interaction of the projectile and/or another particle. The above approaches may also be combined. Examples of such materials are: ^{1}H, ^{2}H which, for practical reasons, may be present in the form of compounds, e.g. polyethylene or HDPE (high density

polythylene). The inner wall of the hollow does not have to be entirely covered with this layer; only a covered part is sufficient. The advantage of this embodiment is the chain growth of the projectile particles in the hollow. The primary projectile particles and the secondary projectile particles need not be the same. For example, the primary projectile particle may be a proton and the secondary projectile particle may be, for instance, an alpha particle or a neutron.

[028] In another preferred embodiment, the nuclear target can be provided with a plurality of openings following on the corresponding plurality of hollows. This preferred embodiment represents an advantage in the continuous operation of induced exothermic nuclear reactions and/or the production of radioisotopes. The nuclear target can be placed on a motorized holder which moves with the nuclear target in any direction and/or rotates it. As soon as a sufficient amount of radioisotopes is produced according to the corresponding induced nuclear reaction, or the entire precursor in the hollow of the nuclear target is consumed, the nuclear target is moved so that the incident projectile particles fall into the next hollow or hollows containing still unconsumed precursor.

[029] In another preferred embodiment, the material of the nuclear target or the precursors may be selected according to the respective industrial application. In a certain embodiment being advantageous for radioisotope production, the following precursors ^{11}B, ^{98}Mo, ^{186}W, or a mixture of precursors ^{98}Mo and ^{2}H, may be selected. In another embodiment being advantageous for the production of isotopes suitable for diagnostic methods using ionizing radiation, precursors may be selected from the following group of ^{185}Re, ^{187}Re or a natural mixture of ^{Nat}Re. In another embodiment being advantageous for industrial applications of spent nuclear waste transmutation, a nuclear target precursor is selected, or the material of the nuclear target is made up of isotopes with a longer half-life. Such isotopes include the fission products of ^{233}U, ^{235}U, ^{239}Pu. In this case, it is also suitable to use as an additional precursor a material also providing neutrons after being irradiated with projectile particles, e.g. ^{2}H upon irradiation with protons or ^{3}H upon irradiation with deuterons. In another embodiment, preferred for the conversion of nuclear energy into heat, ^{2}H, ^{6}Li, ^{7}Li, ^{10}B, ^{11}B, ^{15}N or a mixture thereof is selected as the precursor.

[030] In another preferred embodiment, a luminophore or scintillator can be applied to the opening and/or into a part of the hollow. The luminophore, or scintillator, brings a dual technical function. The first function consists in controlling the emission of radioactive particles from the hollow of the nuclear target. Emissions of radioactive particles need

not necessarily be subatomic or atomic particles but may also form a macroscopic part of the hollow which, due to the reaction mechanism, has ejected part of the material out of the hollow. The second technical function consists in controlling the focusing of the beam of projectile particles and the deposition thereof into the hollow of the nuclear target, or in controlling the optimal shape of the same.

[031] A second embodiment of the present invention relates to a method for inducing a nuclear reaction as defined by claim 12. The method according to the present invention is fully universal and can be applied to a number of industrial issues, which are mentioned above.

[032] The method includes a step of providing a beam of projectile particles incident on a nuclear target from a precursor-containing material bulk. The nature of the invention for carrying out this method is characterized in that the beam of projectile particles is focused into the hollow of the nuclear target, with the projectile particles being elastically scattered on the nuclei of at least one isotope inside the hollow; the elastic scattering preferably occurs on the isotopes contained in the hollow fill and/or on the isotopes of the wall of the nuclear target. The projectile particles are elastically scattered until they induce a nuclear reaction on the precursor, or until the occurrence of an interaction between the projectile particle and the precursor.

[033] In a preferred embodiment, the projectile particles are generated in a laser-controlled accelerator. A laser-controlled accelerator is generally considered to be a more compact and cheaper option compared to commonly used accelerators.

[034] In another preferred embodiment, radiopharmaceuticals can be produced by the method of the invention, wherein the projectile particles and precursors are selected according to the following nuclear reactions $^{11}B(p,n)^{11}C$, $^{98}Mo(p,n)^{99m}Tc$, $^{186}W(p,n)^{186}Re$ or a mixture of precursors ^{98}Mo and ^{2}H to induce simultaneous reactions of $^{2}H(d,n+p)^{2}H$ and/or $^{2}H(d,n)^{3}He$ with a subsequent reaction of $^{98}Mo(p,n)^{99m}Tc$ and $^{98}Mo(n,\gamma)^{99m}Tc$, when using projectiles *d*. Reactions of $^{185}Re(n,\gamma)^{186}Re$, $^{187}Re(n,\gamma)^{188}Re$ are also possible, again in a preferred embodiment using deuterium as a projectile particle, more preferably deuterium generated from a laser target and/or deuterium present in the hollow of the nuclear target and activated by an elastic collision with any projectile particle.

[035] In another preferred embodiment, the nuclei of the spent nuclear waste can be transmuted by the method, wherein the projectile particles and precursors are selected according to the following nuclear reactions $^{233}U(p,fission)$, $^{235}U(p,fission)$,

^{239}Pu(p,fission), and, in particular, ^{233}U(n,fission), ^{235}U(n,fission), ^{239}Pu(n,fission), or ^{60}Co(n,γ)^{61}Co. During fission induced by neutrons, neutrons must be produced by the interaction of neutrons as projectile particles with the precursor. In a certain embodiment, neutron production can be achieved, for example, by an additional projectile particle and a precursor containing deuterons. In the interaction of the particles of this embodiment, reactions of ^{2}H(d,n)^{3}He and/or ^{2}H(d,n+p)^{2}H, or ^{2}H(d,p)^{3}H and subsequently of ^{2}H(t,n)^{4}He occur, or the precursor will contain tritium ^{3}H, wherein a reaction of ^{3}H(d,n)^{4}He occurs.

[036] In another preferred embodiment, nuclear energy can be converted into heat by the method, wherein the projectile particles and precursors are selected according to the following nuclear reactions ^{3}He(d,p)^{4}He, ^{6}Li(d,α)^{4}He, ^{7}Li(p,α)^{4}He, ^{10}B(p,α)^{7}Be, ^{11}B(p,2α)^{4}He, ^{15}N(p,α)^{12}C or ^{6}Li(p,^{3}He)^{4}He followed by secondary reactions ^{6}Li(^{3}He,2α)^{1}H a ^{3}He(^{3}He,2p)^{4}He. Other possible reactions include ^{3}H(d,n)^{4}He, ^{2}H(t,n)^{4}He, ^{2}H(n,γ)^{3}H, ^{6}Li(n,^{3}He)^{4}He, ^{10}B(n,α)^{7}Li, ^{7}Be(n,p)^{7}Li, ^{13}C(n,γ)^{14}C, ^{14}N(n,p)^{14}C, ^{17}O(n,α)^{14}C, ^{21}Ne(n,α)^{18}O, ^{22}Na(n,p)^{22}Ne or ^{37}Ar(n,α)^{34}S. In a more preferred embodiment, heat is conducted from the nuclear target using a heat exchanger.

[037] A third embodiment of the present invention relates to a device suitable, i.e. not exclusively used, for carrying out the method according to the second embodiment of the present invention, or preferred embodiments. The device is defined in claim 19.

[038] The device comprises a projectile particle source and a nuclear target according to the present invention, wherein the projectile particle source is configured to deposit projectile particles into the hollow of the nuclear target according to the present invention.

[039] In a preferred embodiment, the device comprises a nuclear and a laser target, wherein the nuclear target is a nuclear target according to the present invention and the laser target is capable of emitting projectile particles upon laser pulse strike. The laser target can be solid-state, such as the laser target disclosed in EP2833365, or a gas jet target can also be used, using the laser-wakefield acceleration phenomenon.

[040] In other preferred embodiments, the device is configured to carry out the methods according to the present invention.

Description of the Drawings

[041] FIGs. 1a – 1f are schematic illustrations of the first embodiment of a nuclear target according to the present invention in various alternatives of precursor placement in the target.

[042] FIGs. 2a and 2b are schematic illustrations of the second preferred embodiment of a nuclear target according to the present invention with the first and second part of the hollow.

[043] FIGs. 3a, 3b and 3c are schematic illustrations of another preferred embodiment of a nuclear target according to the present invention comprising a laser target capable of generating projectile particles, wherein Fig. 3b illustrates a more preferred embodiment with an inset laser target, Fig. 3c illustrates a preferred embodiment comprising a precursor in a liquid or gaseous form, where the precursor is contained in the hollow of the nuclear target.

[044] FIG. 4 is a schematic illustration of an embodiment of a nuclear target hollow according to the invention, wherein the hollow is equipped with a layer emitting secondary projectile particles upon interaction with the primary projectile particle.

[045] FIG. 5 is a schematic illustration of an embodiment of a continuous band provided with nuclear targets according to the present invention.

[046] FIGs. 6a and 6b are schematic illustrations of an embodiment of a nuclear target provided with a luminophore.

[047] FIG. 7 is a schematic illustration of an embodiment of a nuclear target in combination with a heat exchanger.

[048] FIGs. 8a – 8e illustrate different embodiments of a nuclear target hollow geometry according to the invention.

[049] FIGs. 9a and 9b are schematic illustrations of a device comprising a laser-controlled accelerator generating projectile particles comprising a nuclear target according to the invention.

Detailed description of the embodiments

[050] Radioisotopes are produced by bombarding or irradiating a nuclear target **1** comprising precursor(s) **21** or **22** and/or **23**. Precursor **21** and/or **22** and/or **23** refers

to, and is generally known in the art, an atomic nucleus that interacts with a projectile particle **3** to achieve the final product. The final product is often an unstable radioisotope that further decays by alpha, beta and/or gamma decay. The generation of products by induced nuclear reactions according to the present invention takes place substantially inside the hollow **12** of the nuclear target **1**, wherein at least a portion of the precursors **21** and/or **22** and/or **23** present/comprised in the hollow **12** interact with projectile particles **3** and form the final product by nuclear reactions. In most cases, the product formed, most often a radioisotope, is consequently mixed with another material forming the nuclear target **1**, wherein the untransformed precursor **21** and/or **22** and/or **23** remains randomly distributed in said nuclear target **1**. Certain portion of the converted precursors **21** and/or **22** and/or **23** to the final product(s) can be separated using chemical methods. An example of a chemical method for separating converted radioisotopes consists in dissolving the nuclear target **1**, or the content of the hollow **12** of the target **1**, in a strong acid, followed by filtration of radioisotopes and precipitation thereof.

[051] The nuclear target **1** according to the present invention comprises at least one nucleus of the precursor **21** or **22** in the envelope of the nuclear target **1** and/or the precursor **23** inside the hollow **12**, which is transformed into the product nucleus by the nuclear reaction; and an isotope **4** on which the projectile particle **3** is elastically scattered until the interaction with the nucleus of the precursor **21** and/or **22** and/or **23**. In the case of the example according to FIG. 1a - f, the precursor **21** and/or **22** or the precursor **23** itself can be the isotope **4** until the kinetic energy of the projectile particle **3** equals the energy of a reaction channel. Examples of such materials may include, for example, ^{10}B as the nucleus of the precursor **21** and/or **22** and/or **23**, p as the projectile particle **3**, wherein the isotope **4** on which the projectile particle **3** is elastically scattered is one of the stable isotopes **4** W (^{180}W,^{182}W,^{183}W,^{184}W,^{186}W; or a natural mixture thereof, in accordance with FIG. 1a), and wherein the resulting nuclear reaction is $^{10}B(p,\alpha)^{7}Be$. In another example, $^{11}B(p,\alpha)^{8}Be$ can be selected, wherein ^{8}Be further decays according to $^{8}Be \rightarrow 2\alpha$, with the W isotopes **4** being used as nuclei on which the projectile particles **3** are elastically scattered. Another example may include a nuclear reaction of $^{98}Mo(p,n)^{99m}Tc$, wherein the isotopes **4** on which the projectile particles **3** are elastically scattered are W isotopes **4** forming the envelope of the nuclear target **1**. In another embodiment, it is possible to place the precursor **21** or **22** into the body of the nuclear target **1**, for examples, as part of the envelope of the hollow **12** (Figs. 1a, 1b, 1d, 1e and 1f), and/or place it in the hollow **12** of the nuclear

target **1** (Figs. 1c, 1d, 1e and 1f). It is also possible to combine the above placements of the precursors **21** and/or **22** and/or **23b** as schematically illustrated in Fig. 1d – 1f.

[052] According to another example of an embodiment, the nuclear target **1** may contain a natural mixture of boron, i.e. 20% of ^{10}B and 80% of ^{11}B, as the nuclei of the precursor **21** and/or **22** and/or **23**. Figure 1a schematically illustrates the ordered distribution of the precursors **21** corresponding in cross-section to the circles. In this embodiment, the respective precursors **21** can be implanted into the body of the nuclear target **1** using various chemical-physical processes such as chemical or physical vapour deposition (CVD or PVD, respectively). Figure 1b schematically illustrates a situation where the precursor **22** is deposited in a defined area and forms a bulk of a material with a hollow **12**. Figure 1c illustrates an embodiment where the precursor **23** is placed directly into the hollow **12** of the nuclear target **1**, i.e. the precursor **23** is not implanted in the material of the nuclear target **1**, but is placed in a part of the hollow **12** of the nuclear target **1** and is used as a fill in the hollow **12**. The precursor **22** can also be placed directly into the hollow **12** of the nuclear target **1** using known methods of PVD, CVD or ion implantation or as a bulk of the material. Figure 1d schematically illustrates a possible combination of the placement of the two precursors **22** and **23**. Similarly, it is possible to provide an embodiment according to Fig. 1e, where precursors **21** and **23** are present, wherein the first precursor **21** forms part of the material bulk. The second precursor **23** is placed in the hollow **12**. The first and second precursors **21** and/or **22** and **23** according to Fig. 1f can be the same isotope. In another embodiment, the isotopic composition of the first and second precursors **21** and/or **22** or **23**, respectively, differs according to Fig. 1f. The preferred embodiment according to Fig. 1d – 1f can be used in particular in the field of heat production by means of a fission nuclear reaction. In this preferred embodiment, the nuclear target **1** may comprise in the envelope precursors **21** and/or **22** containing, for example, the isotopes ^{233}U, ^{235}U and ^{239}Pu. At the same time, the nuclear target **1** comprises a hollow **12**, which is filled with the precursor **23**, serving at least partially as a fill. The second precursor **23** may be ^{3}H or LiD to emit neutrons capable of initiating a fission nuclear reaction onto the precursor **21** and/or **22** when interacting with the projectile particle **3**. Finally, exothermic nuclear reactions occur as a result of interactions of the above-selected precursors **21** and/or **22** and **23** with the projectile particles **3**.

[053] In another embodiment, the nuclear target **1** can be enriched, for example a target having ^{10}B with up to 90% in concentration, thereby inducing an appropriate reaction scheme according to the nuclear reaction mentioned above. It is also possible to

select the distribution of precursors **21** and/or **22** and/or **23**, e.g. a higher concentration of precursors **21** and/or **22** and/or **23** at the edges of the nuclear target **1** in accordance with its intended use. It is also possible to use two types of precursors **21** and/or **22** and/or **23**, or a simultaneous placement, for example, the arrangement according to Fig. 1d – 1f.

[054] The nuclear target **1** may be substantially of a planar shape, being provided with an opening **11** and a hollow **12** in a bulk of material located behind the opening **11**. The hollow **12** can take any shape. Figures 1a – 1d illustrate schematic cross-sections of the nuclear target **1**, where a part of the cross-section of the hollow **12** corresponds substantially to the shape of a circle. In another embodiment, e.g. according to Figures 8, the cross-sectional shape of the hollow **12** may correspond to a section of an ellipse, rectangle, mushroom or polygon with a tapered opening **11**. However, the nuclear targets **1** always comprise openings **11** for projectile particles **3** to pass into the hollow **12** of the nuclear target **1**.

[055] In the preferred embodiment schematically illustrated in Fig. 2a, the hollow **12** can be formed of two parts. The first part **121** represents a narrower part of the hollow **12** through which the projectile particle **3** passes. In the second part **122** of the hollow **12**, which is more voluminous than the first part **121**, the projectile particle **3** is deposited and elastically scatters on the nuclei of isotopes **4** or induces a nuclear reaction on a particular precursor **21** and/or **22** and/or **23**. The advantage of the narrower part **121** of the hollow **12** of the nuclear target **1** is to minimize backscattered particles **31** emanating from the nuclear target **1** outside the area of the hollow **12**. Another advantage of the hollow **12** having parts **121** and **122** is characterized in that it is not necessary for the beam **3** of projectile particles **3** to be focused perpendicularly to the nuclear target **1**. The beam of projectile particles **3** can be deposited into the hollow **12**, e.g. according to Fig. 2b under particular angle. The elastic scattering of the projectile particles **3** in the hollow **12** ensures a sufficient amount of trapped projectile particles **3** to induce a sufficient number of nuclear reactions on the precursors **21** and/or **22** and/or **23**.

[056] The opening **11** of the nuclear target **1** serves for the entry of projectile particles **3**, such as protons, deuterons, light nuclei, which can be accelerated in commonly used particle accelerators. In another embodiment, laser-controlled accelerators may be used. In another embodiment, a collimated beam of projectile particles **3** from static emitters, such as AmBe, RaBe or PuBe, can also be used. In the case of neutrons used as projectile particles **3**, it is also possible to use spallation sources or a

collimated beam of neutron coming from a fission reactor. The projectile particles **3** pass through the opening **11** of the nuclear target **1** and are deposited in the cavity **12** thereof. Ideally, there are exactly two possible interactions occurring in the hollow **12**. The first interaction consists of the induced nuclear reaction of the projectile particle **3** with the precursor **21** and/or **22** and/or **23**, wherein the projectile particle **3** and the precursor **21** and/or **22** and/or **23** are suitably selected according to the industrial application. In the latter case of the desired interaction, the projectile particles **3** are elastically scattered on the isotopes **4**, wherein the kinetic energy of the projectile particles **3** is dissipated until the projectile particle **3** interacts with the desired nuclear reaction selected from possible interaction channels and a nuclear reaction occurs on the precursor **21** and/or **22** and/or **23**.

[057] The volume of the nuclear target **1**, the thicknesses of the walls of the nuclear target **1**, the size and shape of the hollow **12**, the distribution of the precursors **21** and/or **22** and/or **23**, and other commonly needed parameters of the nuclear target **1** are appropriately selected according to the desired nuclear reaction and relevant industrial application. Commonly used computer programs can be used to determine the above parameters.

[058] The final product of the reaction of the projectile particles **3** with the nuclei of the precursor **21** and/or **22** and/or **23** may be, for example, radioisotopes used in radiation therapy, radioisotopes used for imaging in medical applications and/or diagnostics of materials. In another embodiment, the final product may be a stable isotope **4** having a short and/or medium half-life. In another embodiment, the final product may be a stable isotope **4** made in exothermic nuclear reaction, which can then be converted to heat **9** in a heat convertor **91**.

[059] In the embodiments according to Figures 3a and 3b, the nuclear target **1** may be further equipped with a laser target **5** comprising a layer **50** emitting projectile particles **3**, if the reare side **51** of the layer **50** is exposed to laser beams. Thus, a beam of accelerated projectile particles **3** is emitted from the layer **50**, which can be used to induce nuclear reactions in the hollow **12** of the nuclear target **1** according to the present invention. In the embodiment shown in Fig. 3a, a laser target **5** provided with a layer **50** is tightly placed in front of the opening **11** of the nuclear target **1**. After being struck by the laser pulse **52**, projectile particles **3** are emitted directly into the hollow **12** of the nuclear target **1**, where they induce a nuclear reaction or are elastically scattered. Emission of projectile particles **3** can be provided using the TNSA mechanism (M. Roth, M. Schollmeier. Ion Acceleration—Target Normal Sheath

Acceleration. Vol. 1 (2016): Proceedings of the 2014 CAS-CERN Accelerator School: Plasma Wake Acceleration, DOI: https://doi.org/10.5170/CERN-2016-001.231). In another embodiment, shown in Fig. 3b, the laser target **5** can be placed to the hollow **12** of the nuclear target **1** inset in front of the opening **11** to accelerate the projectile particles **3** into the hollow **12** of the nuclear target **1**. The advantage of the inset between the laser target **5** and the opening **11** of the nuclear target **1** provides the possibility of placing a vacuum pump **6**, which sucks out the impurities emitted from the laser target **5**, under the influence of the laser pulse **52** and the use of the laser wake field acceleration. A preferred embodiment also presents an offset of the laser target **5** with the layer **50**, providing shielding between the electromagnetic pulse of the laser radiation and the nuclear target **1**, in case, in which the material of the nuclear target **1** is electrically conductive. In case the projectile particles **3** represent a mixture of isotopes **4**, the inset makes it possible to configure the time sequence in which the projectile particles **3** will hit the precursor **21** and/or **22** and/or **23** and interact with it, or with the products of the interactions of the previous wave of projectile particles **3** with the precursor **21** and/or **22** and/or **23**. Such an exemplary embodiment with a time sequence of the incidence of projectile particles **3** into the hollow **12** can be taken from Torrisi, Lorenzo & Cavallaro, Stefano & Cutroneo, M. & Krasa, Josef & Klir , Daniel. (2014). D – D nuclear fusion induced by laser-generated plasma at 10^{16} W cm^{-2} intensity. Physica Scripta. 2014. 014026. 10.1088/0031-8949/2014/T161/014026. The sequence of the incident projectile particles **3** and the interaction with the precursors **21** and/or **22** and/or **23** is provided by more complex laser target **5** configurations, such as the "catcher – pitcher" reported in D. Margarone, et. al. (2020). Generation of α-Particle Beams With a Multi-kJ, Peta-Watt Class Laser System. Frontiers in Physics, September 2020, Vol B, Article 343.

[060] Preferred embodiments provided with a laser target **5** are capable of providing a high-energy beam of hadron particles, such as protons, light nuclei, heavy nuclei (e.g. Au) or neutrons, but also an electron beam without the need for complex beam-transport. The preferred embodiment illustrated in Figs. 3b, inter alia, enables the use of laser-controlled accelerators, which are generally considered as a more compact and cheaper option to conventional accelerators.

[061] Figure 3c further schematically illustrates another embodiment which comprises a nuclear target **1** and a laser target **5**. The area between the laser target **5** and the nuclear target **1** is closed to prevent the exchange of fluids with the surrounding

environment. The closed area can then be filled with a liquid or gas containing precursors **23**. LU102817

[062] In another preferred embodiment, the material of the laser target **5**, structure and thickness thereof can be selected so that a suitably selected focus of the laser pulse (pulse cross-section) using the TNSA mechanism leads to the production of optimal spectrum of projectile particles, both in intensity and the energy spectrum of the particles. In a certain example of the embodiment, the isotopic composition of the nuclear target **1** is selected to consist of exactly two isotopes. The first isotope is a precursor **21** and/or **22** and/or **23**, which is localized in the envelope and/or hollow **12** of the nuclear target **1**. The second isotope is a nucleus on which the projectile particles **3** are elastically scattered. This embodiment provides an advantage in that immediately after the bombardment of the projectile particles **3**, only the interaction with precursor **21** and/or **22** and/or **23** is allowed, or the projectile particles **3** are elastically scattered on the isotopes **4** until they interact with the nucleus of the precursor **21** and/or **22** and/or **23**. In the next phase, products of ongoing nuclear reactions with projectile particles **3** may also enter the process. These may by, for instance, ions with a smaller mass-to-charge ratio, which reach the hollow **12** with a certain delay, as reported by Torrisi, Lorenzo & Cavallaro, Stefano & Cutroneo, M. & Krasa, Josef & Klir, Daniel. (2014). D – D nuclear fusion induced by laser-generated plasma at 10^{16} W cm^{-2} intensity. Physica Scripta. 2014. 014026. 10.1088/0031-8949/2014/T161/014026. Ultimately, the yield of the nuclear reaction increases.

[063] In the example illustrated in Fig. 4, the inner side **123** of the hollow **12** of the nuclear target **1** is provided with a layer **32**. The layer **32** comprises atomic nuclei that are capable of emitting secondary projectile particles **320** after interacting with the projectile particle **3**. Figure 4 represents a specific embodiment provided with a laser target **5**. However, it is clear to the person skilled in the art that the technical function of the layer **32** is completely separable from the technical function of the laser target **5** and can thus be implemented, without any further technical difficulties, in any embodiment, for example according to the figures 1a - 1f and/or 2a, 2b, or advantageous technical effects can be combined with any of the above examples. More specifically, for example, the technical function of the layer **32** according to the embodiment illustrated on Fig. 4 can be used and implemented in the embodiment according to Fig. 2a or 3b, i.e. it is possible to construct the hollow **12** of the nuclear target **1** of the first part **121** and the second part **122** so that the backscattered particles **31** hit the layer 32, or to provide the nuclear target **1** with the layer **32** with a

laser target **5**. The technical functions remain completely separable, including the advantages provided. The layer **32** is then capable of emitting additional, secondary projectile particles **320** as a result of the interaction with the primary projectile particle **3**. This preferred embodiment provides a possibility of chain reaction, i.e. releasing more projectile particles **3** into the hollow **12** than originally deposited by the beam of primary projectile particles **3**. Similarly, this advantage can be achieved by a suitable combination of precursors **23** in the hollow **12**. For example, if the laser target **5** is made of high-density polyethylene (HDPE), there will be protons and carbon ions ^{12}C among the projectile particles **3**. If hydrogen is also contained in the precursor **21** and/or **22** and/or **23** together with, for instance,^{11}B, nuclei - protons thereof will be gradually accelerated to an energy of 150 keV and higher by secondary reactions with the projectile, thereby allowing further reactions, e.g. $^{11}B(p,2\alpha)^{4}He$. The hydrogen nuclei in the precursor **23** will also be accelerated by α-particles formed in previous $p^{11}B$ reactions.

[064] Figure 5 illustrates a band with a plurality of nuclear targets **1** according to the present invention comprising a plurality of openings **11** and hollows **12**. This embodiment represents an advantage in moving the nuclear target **1** in direction **7**. If a certain number of nuclei of precursors **21** and/or **22** and/or **23** are consumed in the volume of the first hollow **12**, the nuclear target **1** is moved in such a direction **7** that the beam of projectile particles **3** falls into the next hollow **12** with the unconsumed precursor **21** and/or **22** and/or **23**, thereby allowing continuity of induction of the nuclear reaction. This example can be used, for example, in the case of exothermic nuclear reactions with a heat exchanger **91** located around the nuclear target **1**. Another advantage of this embodiment is characterized in that the nuclear target **1** can form an endless band which is irradiated by one source of projectile particles **3**, wherein the nuclear target **1** moves in the direction **7** as necessary.

[065] Figures 6a and 6b illustrate an embodiment of a nuclear target **1** which is provided with a luminophore **8** applied on the opening **11**. More specifically, the outer side **110** of the opening **11** is provided with a luminophore **8**. Commonly used luminophores **8**, such as $Gd_3Ga_3Al_2O_{12}$:CeMg, can be used. Figure 6 illustrates a situation, in which projectile particles **3** are generated from a laser target **5** by means of a laser-controlled accelerator, with the laser pulse **52** being focused on the laser target **5**. The projectile particles **3** are emitted into the hollow **12** of the nuclear target **1**, while interacting with the nuclei of the precursor **21** and/or **22** and/or **23**. In one embodiment, the interaction between the projectile particles **3** and the nuclei of the precursors **21** and/or **22** and/or

23 can be an exothermic nuclear reaction. A circumstance, in which too much gas **9** is released in the hollow **12** of the nuclear target **1** as a secondary product of interactions, may also arise, or due to the not entirely optimal shape of the hollow **12**, such circumstance causes a large backflow of particles against the direction of the pulse **52**. As a result, parts of the inside of the hollow **12** may be torn off and emitted outwards in the direction **81**. The emissions in the direction **81** do not necessarily represent atomic and/or subatomic particles, or backscattered projectile particles **31**, but it may also be small particles visible to the naked eye. Luminophore **8**, in the case of the above scenario, offers a safety function that is able to detect whether a part of the nuclear target **1** has torn off and fell outside the area of the hollow **12**. It is also possible to use this advantageous embodiment when handling dangerous isotopes **4** such as nuclear fission products. The embodiment on Fig. 6a illustrates a luminophore **8**, which may also be mixed with the precursor **23** in the hollow **12**. Similarly, Fig. 6b illustrates the application of a luminophore **8**, which may help optimize the intensity and energy spectrum of projectile particles **3**. This puts the laser beam intentionally out of focus. If the laser is misaligned, the pulse track **52** may not optimally overlap with the opening **11**. The subsequent distribution of the luminophore **8** after irradiation can be used to optimize the internal shape of the hollow **12** according to the purpose of use, e.g. optimizing the shape of the hollow **12** according to Fig. 8. Figure 8e illustrates a preferred embodiment of a shape of a hollow **12** of a nuclear target **1**, wherein the shape of the hollow **12** is optimized so that the back-scattered particles were further reflected into the hollow **12**. The nuclear target **1** according to Fig. 8e is composed of several segments **13** which provide an advantage in manufacturing essentially any shape of a hollow **12** of a nuclear target **1**. The individual segments **13** of the nuclear target **1** are assembled to effectively prevent the scattering of projectile particles **3** outside the area of the hollow **12**. The shape of the hollow is thus optimized against possible nuclear reaction yield losses.

[066] The above-mentioned embodiments can be combined with the preferred nuclear reactions selected in accordance with the use of the present invention. In one embodiment, a nuclear target **1** further provided with a laser target **5** can be used, for example consisting of a layer **50** of polymer $(CD_2)_n$ –polyethylene, where hydrogen nuclei are replaced by deuterium nuclei, e.g. according to Torris, L. and Cutroneo, M., “Triple nuclear reactions (d, n) in laser-generated plasma from deuterated targets”, Physics of Plasmas, vol. 24, no. 6. 2017. doi: 10.1063/1.4984997. The nuclear target **1** can be made of tungsten and is filled with precursors **21** or **22** and **23** of ^{6}LiD and/or ^{7}LiD or ^{Nat}LiD. A beam of accelerated deuterons, carbon nuclei and proton admixture,

which forms a beam of projectile particles **3** that is emitted from the laser target **5** towards the hollow **12** of the nuclear target **1**. The projectile particles **3** collide with the nuclei of the precursor **21** and/or **22** and/or **23** contained in the hollow **12** of the nuclear target **1**. This induces the respective nuclear reactions inside the hollow **12** of the nuclear target **1**, which in the case of the D-D and Li-D ($^{7}Li(d,n)^{8}Be$) reactions produce neutrons. The projectile particles **3**, which do not collide with the nuclei of the precursor **21** and/or **22** and/or **23**, are elastically scattered on the isotopes **4**, or on the nuclei of the products of the occurred reactions of the projectile particles **3** with the precursor **21** and/or **22** and/or **23** until the respective nuclear reaction occurs on precursor **21** and/or **22** and/or **23**.

[067] In another example, the laser target **5** may consist of a layer **50** of HDPE. According to this example, accelerated projectile particles **3**, protons, are generated from the laser target **5**, leading to an induced nuclear reaction with the precursor **21** and/or **22** and/or **23** in the form of, for instance, powdered amorphous ^{10}B and/or ^{11}B or ^{Nat}B. In this example, the following reactions are possible: $^{11}B(p,n)^{11}C$ with the ongoing parallel reactions of $^{11}B(p,\alpha)^{8}Be$ and $^{10}B(p,\alpha)^{7}Be$. The resulting radioisotopes can then be chemically separated, with one of the resulting products, namely ^{11}C, being a pure positron emitter with a half-life of 20 minutes and can be used for medical diagnostics or diagnostics of defects in materials. In another embodiment, the laser target **5** can be a layer **50** of a polymer film $(CD_2)_n$ capable of emitting deuterons, wherein ^{185}Re, ^{187}Re, or a natural mixture of ^{Nat}Re may be used as the precursor **21** and/or **22** and/or **23** in the nuclear target **1**. Natural rhenium consists of two isotopes, ^{185}Re and ^{187}Re in a ratio of 37.4 : 62.6. According to this example, projectile particles **3**, deuterons, are generated from the laser target **5**, and if deuterons are contained in the precursor **21** and/or **22** and/or **23** in the hollow **12** of the nuclear target **1**, the nuclear reactions of $^{2}H(d,n)^{3}He$ or $^{2}H(d,n+p)^{2}H$ lead to the production of neutrons and, subsequently, the reactions of $^{185}Re(n,\gamma)^{186}Re$, $^{187}Re(n,\gamma)^{188}Re$ lead to the production of ^{186}Re and ^{188}Re radionuclides with half-lives of 90 and 17 hours, used in medicine like ^{99m}Tc.

[068] In another example, it is possible to use the reactions $^{3}He(d,p)^{4}He$, $^{6}Li(d,\alpha)^{4}He$, $^{7}Li(p,\alpha)^{4}He$, $^{10}B(p,\alpha)^{7}Be$, $^{11}B(p,2\alpha)^{4}He$, $^{15}N(p,\alpha)^{12}C$ or $^{6}Li(p,^{3}He)^{4}He$ followed by secondary reactions $^{3}He(^{6}Li,2\alpha)^{1}H$ and $^{3}He(^{3}He,2p)^{4}He$ for the purpose of inducing an exothermic nuclear reaction. Other possible exothermic nuclear reactions include $^{3}H(d,n)^{4}He$, $^{2}H(n,\gamma)^{3}H$, $^{6}Li(n,^{3}He)^{4}He$, $^{10}B(n,\alpha)^{7}Li$, $^{7}Be(n,p)^{7}Li$, $^{13}C(n,\gamma)^{14}C$, $^{14}N(n,p)^{14}C$, $^{17}O(n,\alpha)^{14}C$, $^{21}Ne(n,\alpha)^{18}O$, $^{22}Na(n,p)^{22}Ne$ or $^{37}Ar(n,\alpha)^{34}S$. The released energy can be converted into heat **9**. Figures 6 and 7 schematically illustrate examples in which heat

9 is generated in a nuclear target **1**. Figure 7 schematically illustrates projectile particles **3** generated from synchrotron **301**. In view of the above preferred embodiments, commonly used projectile particle accelerators **3** can be used as the generator of projectile particles **3**. The projectile particle **3** induces an exothermic nuclear reaction in the nuclear target **1** upon collision with the nucleus of the precursor **21** and/or **22** and/or **23**, in which heat **9** is generated in the hollow **12** of the nuclear target **1**. The heat **9** is then conducted by means of a heat exchanger **91** outside the nuclear target **1**. The heat exchanger **91** can subsequently be connected to a steam generator for generating electrical energy. The nuclear target **1** can be placed together with the exchanger **91** in the containment **92** according to the respective nuclear safety regulations. LU102817

[069] In the following examples of the embodiments, the invention discloses methods for inducing nuclear reactions. In a first step, a beam of projectile particles **3** is provided. The projectile particles **3**, in a preferred embodiment, have a spectrum and intensity optimized with respect to the desired reactions. These projectile particles **3** are deposited in the hollow **12** of the nuclear target **1** containing the nuclei of the precursors **21** and/or **22** and/or **23**. The projectile particles **3** either induce a nuclear reaction or are elastically scattered on the isotope **4** of the material from which the nuclear target **1** is made. In a certain step of the method of the invention, after the induced reaction is burned up, the radioisotope production method ends or may be repeated; the repetition may occur in the same hollow **12** of the nuclear target **1**, or the nuclear target **1** may be further moved and the projectile particles **3** are focused into a new hollow **12** containing previously unconsumed precursors **21** and/or **22** and/or **23**.

[070] One way to detect the number of nuclear reactions that have occurred on the precursor **21** and/or **22** and/or **23** is to measure the ionizing radiation emanating from the nuclear target **1**. In one embodiment, nuclear reactions $^{10}B(p,\alpha)^{7}Be$ can be used, thereby detecting gamma radiation from de-excitation of ^{7}Be. Monitoring of gamma radiation can then serve as an indicator of the number of induced nuclear reactions.

[071] The accelerated projectile particles **3** can also be positive ions that can induce nuclear fusion or nuclear fission with other materials inside the hollow **12** of the nuclear target **1**.

[072] In a certain example, by combining the materials of the irradiated nuclear target **1**, preferably by generating accelerated projectile particles **3** by means of the laser target **5**, it is possible to induce many reactions other than those mentioned above.

[073] Another combinations include collisions of protons, as high energy projectile particles **3** with high energy, with the nuclei of ^{16}O of the precursor **21** and/or **22** and/or **23**. The collision may induce a nuclear reaction of $^{16}O(p,\alpha)^{13}N$, wherein ^{13}N is a short half-life radioisotope that may further decay by alpha decay.

[074] In another embodiment, protons, as accelerated projectile particles **3**, collide with a nuclear target **1** containing nuclei ^{18}O of the precursor **21** and/or **22** and/or **23**, thereby inducing a nuclear fusion $^{18}O(p, n)^{18}F$, wherein ^{18}F is a radioisotope with a half-life of 109 minutes.

[075] In another example, protons, as accelerated projectile particles **3**, collide with a nuclear target **1** containing ^{10}B, which induces a nuclear reaction of $^{10}B(p,\alpha)^{7}Be$, wherein ^{7}Be is a radioisotope with a half-life of 53 days.

[076] In another example, protons, as accelerated projectile particles **3**, collide with a nuclear target **1** containing ^{15}N, which induces a nuclear reaction of $^{15}N(p,n)^{15}O$, wherein ^{15}O is a radioisotope with a short half-life.

[077] By using other projectile particles **3**, or using another laser target **5**, it is possible to generate positive ion projectile particles **3**. In a certain embodiment, it may be a high-energy deuteron falling into the hollow **12** of the nuclear target **1** containing the nuclei of ^{12}C of the precursor **21** and/or **22** and/or **23** which may induce a nuclear reaction of $^{12}C(d,n)^{13}N$, wherein ^{13}N is a radioisotope with a short half-life.

[078] In another example, the collision of deuterons, as accelerated projectile particles **3**, with the nucleus of ^{14}N of the precursor **21** and/or **22** and/or **23** may induce a nuclear reaction of $^{14}N(d,n)^{15}O$, wherein ^{15}O is a radioisotope with a short half-life.

[079] In another example, the collision of deuterons, as accelerated projectile particles **3**, with the nucleus of ^{20}Ne of the precursor **21** and/or **22** and/or **23** may induce a nuclear reaction of $^{20}Ne(d,\alpha)^{18}F$, wherein ^{18}F is a radioisotope with a short half-life.

[080] In other examples, a neutron can be used as the projectile particle **3**, wherein it can either be accelerated by a two-stage laser target **5**, where protons generated in the first laser target fall on the second laser target made of, for instance, LiF. Further, as part of the deuteron, stripping reactions are used in the reactions with the precursor

21 and/or **22** and/or **23,** neutrons can be produced directly in the hollow **12**, for example by means of $^{2}H(d,n)^{3}He$, $^{2}H(d,n+p)^{2}H$ reactions and, in particular, $^{3}H(d,n)^{4}He$. LU102817

[081] In another embodiment, neutrons can also be used as projectile particles **3** for nuclear fission according to the scheme by means of the $^{2}H(d,n)^{3}He$, $^{2}H(d,n+p)^{2}H$ reactions and, in particular, $^{3}H(d,n)^{4}He$.

[082] In another example, the nuclear target **1** can be enriched with nuclei of burnt nuclear fuel or made from the material of burnt nuclear fuel, wherein a tritium precursor **23** bombarded with projectile particles **3** – deuterons – is placed in the hollow **12**, forming a neutron pulse that fissions nuclei of heavy nuclei in ^{233}U(n,fission), ^{235}U(n,fission), ^{239}Pu(n,fission) reactions.

[083] Figure 9a schematically illustrates a laser-controlled laser beam emitting accelerator which irradiates the laser target **5** with laser pulses **52**. The laser target **5** consists of a reversed layer **51** which is exposed to the laser pulse **52**, with the laser target **5** being provided with a layer **50** generating accelerated projectile particles **3** towards the hollow **12** of the nuclear target **1** by the TNSA mechanism. The accelerated projectile particles **3** pass into the hollow **12** through the opening **11**, through the narrower part **121** of the hollow **12** into the wider part **122** of the hollow **12**. In the hollow **12**, the projectile particles **3** either collide with the nuclei of the precursor **23** or elastically scatter on isotopes **4**. The narrower part **121** of the hollow **12** prevents the backscattered projectile particles **31** from leaving the hollow **12**. In the example according to Figure 9a, the nuclear target **1** is separated from the laser target **5**, which is part of the laser accelerator.

[084] In another example of the embodiment – schematically illustrated according to Fig. 9b, it is possible to pre-equip the nuclear target **1** with a laser target **5**, i.e. fix strongly to the nuclear target **1** so that projectile particles **3** are emitted from the laser target **5** after the laser pulse **52** strikes into the hollow **12** of the nuclear target **1**. In the example according to Fig. 9b, the device is further equipped with a nuclear target **1** comprising a luminophore **8** which is deposited on the outer side **110** of the opening **11**. Hence, the layer **50** emitting the projectile particles does not have to be part of the accelerator and can be supplied together with the nuclear target **1** as one product. The pre-configured laser target **5** provides the advantage of at least partially shielding the electromagnetic pulse caused by the high-power pulsed laser. This arrangement also allows the use of liquid precursors **23**.

Industrial Applicability

[085] The present invention finds application in several industries, as, to some extent, it represents a universal method for inducing nuclear reactions. In a certain industrial application, the present invention can be used for producing radioisotopes, particularly radiopharmaceuticals. In another industrial application, the present invention can be used for transmutation of burnt nuclear fuel so that hazardous nuclear waste is converted to stable isotopes, or at least isotopes with a short half-life. In a third, but not last, industrial application, the present invention can be used to produce heat from a controlled nuclear reaction.

Reference Signs List

1	Nuclear target
11	Opening
110	Outer side of the opening
12	Hollow
121	First part of the hollow having a narrower cross-section
122	Second part of the hollow having an enlarged cross-section
123	Inner side of the hollow
13	Nuclear target segment
21	Precursor implanted in the material of the nuclear target around the hollow
22	Precursor forming the hollow
23	Precursor in the hollow
3	Projectile particle
31	Backscattered particles
32	Layer providing secondary projectile particles
320	Secondary projectile particles
301	Synchrotron
4	Isotope
5	Laser target
50	Layer emitting projectile particles
51	Reverse side of the layer 5 exposed to laser beam
52	Laser pulse
6	Vacuum pump
7	Shift in direction
8	Luminophore

81	Emission (macroscopic) particles direction
9	Heat
91	Heat exchanger
92	Containment

CLAIMS

1. A nuclear target (1) forming a bulk, wherein the nuclear target (1) comprises at least one precursor (21 and/or 22 and/or 23) capable of inducing a nuclear reaction upon interaction with a projectile particle (3), **characterized in that** the nuclear target (1) comprises:

   – at least one opening (11) for the passage of a beam of projectile particles (3); and
   – a hollow (12) in the bulk of the nuclear target (1) located behind the opening (11), wherein
     – the hollow (12) comprises and/or is formed and/or is surrounded by the precursor (21 and/or 22 and/or 23); and wherein
   – the nuclear target (1) comprises at least one isotope (4) on which the projectile particle (3) is elastically scattered.

2. The nuclear target according to claim 1, **characterized in that**, the isotope (4) on which the projectile particle (3) is elastically scattered is:

   – isotope (4) being different nuclei from the nuclei of the precursor (21 and/or 22 and/or 23); or

   – isotope (4) being the same nuclei as the nuclei of the precursor (21 and/or 22 and/or 23), wherein the impinging projectile particle (3) has kinetic energy, which differs over the threshold energy for induction of the nuclear reaction.

3. The nuclear target (1) according to anyone of the preceding claims, **characterized in that**, at least part of the nuclear target (1) is formed by the precursor (22) surrounding the hollow (12) and/or comprises the precursor (23) in the hollow (12).

4. The nuclear target (1) according to anyone of the preceding claims, **characterized in that**, the nuclear target (1) comprises at least two same precursors (21 and/or 22 and/or 23) or different precursors (21 and/or 22 and/or 23) differently located therein.

5. The nuclear target (1) according to anyone of the claims 1 – 3, **characterized in that**, the nuclear target (1) consists of two isotopes, wherein the first isotope is the precursor (21 and/or 22 and/or 23) and the second isotope is the isotope (4) on which the projectile particle (3) is elastically scattered.

6. The nuclear target (1) according to anyone of the preceding claims, **characterized in that**, the nuclear target (1) is further equipped with a laser target (5) capable of emitting projectile particles (3) after interaction with laser radiation.

7. The nuclear target (1) according to any one of the preceding claims, **characterized in that**, the inner side (123) of the hollow (12) is provided with a layer (32) of the material and/or the hollow (12) comprises the material emitting secondary projectile particles (320) in the case of interaction of a projectile particle (3) or another particle produced by the interaction in the hollow (12).

8. The nuclear target (1) according to any one of the preceding claims, **characterized in that,** the nuclear target (1) is provided with a plurality of openings (11) and a corresponding number of hollows (12).

9. The nuclear target (1) according to any one of the preceding claims, **characterized in that**, the nuclear target (1) contains isotopes (4) selected from nuclei having threshold of inelastic scattering with the nuclei of projectile particles (3) or precursor (21 and/or 22), or the nuclei of the products of the reactions of projectiles with precursors (21 and/or 22 and/or 23) is higher than the energy of the interacting nuclei.

10. The nuclear target (1) according to any one of the preceding claims, **characterized in that**, the opening (11) and/or a part of the hollow (12) is provided with luminophore (8) and/or scintillator.

11. The nuclear target (1) according to any one of the preceding claims, **characterized in that**, the nuclear target (1) consists of plurality of segments (13) configured so that, the segments form a single bloc of material, wherein the shape of the hollow (12) is configured for suppression of scattering of the projectile particles (3) outside an area of the hollow (12).

12. A method for inducing a nuclear reaction comprising the steps of:

   – providing a beam of projectile particles (3) impinging on the nuclear target (1) according to any one of the preceding claims;

   characterized in that

   – the beam of projectile particles (3) is focused into the hollow (12) of said nuclear target (1); wherein

– the projectile particles (3) are elastically scattered on the nuclei of at least one isotope (4) inside the hollow (12) of the nuclear target (1) until the projectile particles (3) interact with the precursor (21 and/or 22 and/or 23).

13. The method for inducing a nuclear reaction according to claim 12, **characterized in that**, the projectile particles (3) are generated by a laser-driven accelerator.

14. A method for producing radioisotopes, **characterized in that,** the method comprises the method for inducing a nuclear reaction according to claim 12 or 13, wherein the projectile particle (3) is selected from the group *p, d, n* and the precursor (21 and/or 22 and/or 23) is selected from the group ^{2}H, ^{3}H, ^{10}B and/or ^{11}B or ^{Nat}B, ^{99}Mo, ^{186}W, ^{185}Re, ^{187}Re or a natural mixture of ^{Nat}Re, wherein the combination of projectile particles (3) and precursors (21 and/or 22 and/or 23) is preferably selected to induce nuclear reactions of $^{11}B(p,n)^{11}C$, $^{98}Mo(p,n)^{99m}Tc$, $^{186}W(p,n)^{186}Re$, or $^{2}H(d,n)^{3}He$ a $^{2}H(d,n+p)^{2}H$ for neutron production followed by $^{98}Mo(n,\gamma)^{99m}Tc$, $^{185}Re(n,\gamma)^{186}Re$, $^{187}Re(n,\gamma)^{188}Re$ reactions.

15. A method for nuclear waste transmutation, **characterized in that**, the method comprises the method for producing radioisotopes according to claim 12 or 13, wherein the projectile particle (3) is selected from the group consisting of p, d, n and the precursor (21 and/or 22 and/or 23) is selected from nuclear waste products, wherein the combination of projectile particles (3) and precursors (21 and/or 22 and/or 23) is preferably selected so that the following nuclear ^{233}U(p,fission), ^{235}U(p,fission), ^{239}Pu(p,fission) and particularly ^{233}U(n,fission), ^{235}U(n,fission), ^{239}Pu(n,fission), or $^{60}Co(n,\gamma)^{61}Co$, and wherein during neutron fission their production also occurs upon interaction with the precursor (21 and/or 22 and/or 23), particularly $^{2}H(d,n)^{3}He$ and/or $^{2}H(d,n+p)^{2}H$, or $^{2}H(d,p)^{3}H$ reactions and subsequently $^{2}H(t,n)^{4}He$ reaction, or directly in reaction $^{3}H(d,n)^{4}He$ when ^{3}H is used as a precursor (21 and/or 22 and/or 23).

16. A method for inducing an exothermic nuclear reaction, **characterized in that**, the method comprises the method for inducing a nuclear reaction according to claim 12 or 13 wherein the nuclear reactions are selected from the group: $^{3}He(d,p)^{4}He$, $^{6}Li(d,\alpha)^{4}He$, $^{7}Li(p,\alpha)^{4}He$, $^{10}B(p,\alpha)^{7}Be$, $^{11}B(p,2\alpha)^{4}He$, $^{15}N(p,\alpha)^{12}C$, $^{6}Li(p,^{3}He)^{4}He$ followed by secondary reactions $^{6}Li(^{3}He,2\alpha)^{1}H$ and $^{3}He(^{3}He,2p)^{4}He$, $^{3}H(d,n)^{4}He$, $^{2}H(t,n)^{4}He$, $^{2}H(n,\gamma)^{3}H$, $^{6}Li(n,^{3}He)^{4}He$, $^{10}B(n,\alpha)^{7}Li$, $^{7}Be(n,p)^{7}Li$, $^{13}C(n,\gamma)^{14}C$, $^{14}N(n,p)^{14}C$, $^{17}O(n,\alpha)^{14}C$, $^{21}Ne(n,\alpha)^{18}O$, $^{22}Na(n,p)^{22}Ne$ or $^{37}Ar(n,\alpha)^{34}S$.

17. A method for recovering heat from an exothermic nuclear reaction, **characterized in that**, the method comprises the method of claim 15 or 16, wherein the heat (9) is conducted to a heat exchanger (91).

18. The method according to any one of claims 12 – 17, **characterized in that,** the projectile particles (3) emitted from the laser target (5) are sequentially impinging into the hollow (12) of the nuclear target (1) by weight and/or mass-to-charge ratio of the projectile particle (3).

19. A device suitable for the production of radioisotopes, wherein the device comprises a source of projectile particles (3) adjustable so that the projectile particles (3) fall on the hollow (12) of a nuclear target (1), **characterized in that**, the nuclear target (1) is the nuclear target (1) according to any one of claims 1-11.

20. The device suitable for the production of radioisotopes according to claim 14, **characterized in that,** the device comprises a laser target (5) capable of emitting projectile particles (3) after being struck by a laser pulse (52), wherein the laser target (5) is placed in front of the opening (11) of the nuclear target (1) so that the emitted projectile particles (3) fall into the hollow (12) of the nuclear target (1).

ANSPRÜCHE

1. Kerntarget (1), das eine Masse bildet, wobei das Kerntarget (1) mindestens einen Vorläufer (21 und/oder 22 und/oder 23) umfasst, der in der Lage ist, bei Wechselwirkung mit einem Projektilteilchen (3) eine Kernreaktion zu induzieren, dadurch gekennzeichnet, dass das Kerntarget (1) umfasst:

mindestens eine Öffnung (11) für den Durchgang eines Strahls von Projektilteilchen (3); und

einen Hohlraum (12) in der Masse des Kerntargets (1), der sich hinter der Öffnung (11) befindet, wobei

der Hohlraum (12) den Vorläufer (21 und/oder 22 und/oder 23) umfasst und/oder von diesem gebildet und/oder umgeben ist; und wobei

das Nukleartarget (1) mindestens ein Isotop (4) umfasst, an dem das Projektilteilchen (3) elastisch gestreut wird.

2. Nukleartarget nach Anspruch 1, dadurch gekennzeichnet, dass das Isotop (4), an dem das Projektilteilchen (3) elastisch gestreut wird, ist:

Isotop (4), das andere Kerne als die Kerne des Vorläufers (21 und/oder 22 und/oder 23) sind; oder

Isotop (4), das die gleichen Kerne wie die Kerne des Vorläufers (21 und/oder 22 und/oder 23) sind, wobei das auftreffende Projektilteilchen (3) eine kinetische Energie hat, die über der Schwellenenergie für die Induktion der Kernreaktion liegt.

3. Kerntarget (1) nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass zumindest ein Teil des Kerntargets (1) durch den den Hohlraum (12) umgebenden Vorläufer (22) gebildet ist und/oder den Vorläufer (23) im Hohlraum (12) umfasst.

4. Nukleartarget (1) nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass das Nukleartarget (1) mindestens zwei gleiche Vorläufer (21 und/oder 22 und/oder 23) oder verschiedene Vorläufer (21 und/oder 22 und/oder 23) umfasst, die unterschiedlich darin angeordnet sind.

5. Nukleartarget (1) nach einem der Ansprüche 1 bis 3, dadurch gekennzeichnet, dass das Nukleartarget (1) aus zwei Isotopen besteht, wobei das erste Isotop der Vorläufer (21 und/oder 22 und/oder 23) ist und das zweite Isotop das Isotop (4) ist, an dem das Projektilteilchen (3) elastisch gestreut wird.

6. Nukleartarget (1) nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass das Nukleartarget (1) ferner mit einem Lasertarget (5) ausgestattet ist, das in der Lage ist, Projektilteilchen (3) nach Wechselwirkung mit Laserstrahlung zu emittieren.

7. Nukleartarget (1) nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass die Innenseite (123) des Hohlraums (12) mit einer Schicht (32) des Materials versehen ist und/oder der Hohlraum (12) das Material umfasst, das im Falle der Wechselwirkung eines Projektilteilchens (3) oder eines anderen Teilchens, das durch die Wechselwirkung im Hohlraum (12) erzeugt wird, sekundäre Projektilteilchen (320) emittiert.

8. Kerntarget (1) nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass das Kerntarget (1) mit einer Vielzahl von Öffnungen (11) und einer entsprechenden Anzahl von Hohlräumen (12) versehen ist.

9. Nukleartarget (1) nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass das Nukleartarget (1) Isotope (4) enthält, die aus Kernen ausgewählt sind, deren Schwellenwert für inelastische Streuung mit den Kernen von Projektilteilchen (3) oder Vorläufern (21 und/oder 22) oder den Kernen der Produkte der Reaktionen von Projektilen mit Vorläufern (21 und/oder 22 und/oder 23) höher ist als die Energie der interagierenden Kerne.

10. Kerntarget (1) nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass die Öffnung (11) und/oder ein Teil des Hohlraums (12) mit Luminophor (8) und/oder Szintillator versehen ist.

11. Nukleartarget (1) nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass das Nukleartarget (1) aus einer Vielzahl von Segmenten (13) besteht, die so konfiguriert sind, dass die Segmente einen einzigen Materialblock bilden, wobei die Form des Hohlraums (12) zur Unterdrückung der Streuung der Projektilteilchen (3) außerhalb eines Bereichs des Hohlraums (12) konfiguriert ist.

12. Verfahren zum Induzieren einer Kernreaktion, das die folgenden Schritte umfasst:

Bereitstellen eines Strahls von Projektilteilchen (3), der auf das Kerntarget (1) nach einem der vorhergehenden Ansprüche auftrifft;

dadurch gekennzeichnet, dass

der Strahl von Projektilteilchen (3) in den Hohlraum (12) des Kerntargets (1) fokussiert wird; wobei

die Projektilteilchen (3) elastisch an den Kernen mindestens eines Isotops (4) innerhalb des Hohlraums (12) des Kerntargets (1) gestreut werden, bis die Projektilteilchen (3) mit dem Vorläufer (21 und/oder 22 und/oder 23) wechselwirken.

13. Verfahren zur Induktion einer Kernreaktion nach Anspruch 12, dadurch gekennzeichnet, dass die Projektilteilchen (3) durch einen lasergetriebenen Beschleuniger erzeugt werden.

14. Verfahren zur Herstellung von Radioisotopen, dadurch gekennzeichnet, dass das Verfahren das Verfahren zum Induzieren einer Kernreaktion nach Anspruch 12 oder 13 umfasst, wobei das Projektilteilchen (3) aus der Gruppe p, d, n ausgewählt ist und der Vorläufer (21 und/oder 22 und/oder 23) aus der Gruppe 2H, 3H, 10B und/oder 11B oder NatB, 99Mo, 186W, 185Re, 187Re oder einer natürlichen Mischung von NatRe ausgewählt ist, wobei die Kombination von Projektilteilchen (3) und Vorläufern (21 und/oder 22 und/oder 23) vorzugsweise so ausgewählt ist, daß sie Kernreaktionen von 11B(p, n)11C, 98Mo(p,n)99mTc, 186W(p,n)186Re, oder 2H(d,n)3He a 2H(d,n+p)2H zur Neutronenproduktion, gefolgt von 98Mo(n,γ)99mTc, 185Re(n, γ)186Re , 187Re(n, γ)188Re Reaktionen.

15. Verfahren zur Nuklearabfalltransmutation, dadurch gekennzeichnet, dass das Verfahren das Verfahren zur Herstellung von Radioisotopen nach Anspruch 12 oder 13 umfasst, wobei das Projektilteilchen (3) aus der Gruppe ausgewählt ist, die aus p, d, n besteht, und der Vorläufer (21 und/oder 22 und/oder 23) aus nuklearen Abfallprodukten ausgewählt ist, wobei die Kombination von

Projektilteilchen (3) und Vorläufern (21 und/oder 22 und/oder 23) vorzugsweise so ausgewählt ist, dass die folgenden nuklearen 233U(p, Spaltung), 235U(p,Spaltung), 239Pu(p,Spaltung) und insbesondere 233U(n,Spaltung), 235U(n,Spaltung), 239Pu(n,Spaltung), oder 60Co(n,γ)61Co, und wobei bei der Neutronenspaltung bei Wechselwirkung mit der Vorstufe (21 und/oder 22 und/oder 23) auch deren Erzeugung erfolgt, insbesondere in 2H(d,n)3He und/oder 2H(d,n+p)2H, oder in 2H(d,p)3H-Reaktionen und anschließender 2H(t,n)4He-Reaktion, oder direkt in der Reaktion 3H(d,n)4He, wenn 3H als Vorläufer (21 und/oder 22 und/oder 23) verwendet wird.

16. Verfahren zum Induzieren einer exothermen Kernreaktion, dadurch gekennzeichnet, dass das Verfahren das Verfahren zum Induzieren einer Kernreaktion nach Anspruch 12 oder 13 umfasst, wobei die Kernreaktionen ausgewählt sind aus der Gruppe: 3He(d,p)4He, 6Li(d,α)4He, 7Li(p,α)4He, 10B(p,α)7Be, 11B(p,2α)4He, 15N(p,α)12C, 6Li(p,3He)4He gefolgt von den Nebenreaktionen 6Li(3He,2α)1H und 3He(3He,2p)4He, 3H(d,n)4He, 2H(t,n)4He, 2H(n,γ)3H, 6Li(n,3He)4He, 10B(n,α)7Li, 7Be(n,p)7Li, 13C(n,γ)14C, 14N(n,p)14C, 17O(n,α)14C, 21Ne(n,α)18O, 22Na(n,p)22Ne oder 37Ar(n,α)34S.

17. Verfahren zur Rückgewinnung von Wärme aus einer exothermen Kernreaktion, dadurch gekennzeichnet, dass das Verfahren das Verfahren nach Anspruch 15 oder 16 umfasst, wobei die Wärme (9) zu einem Wärmetauscher (91) geleitet wird.

18. Verfahren nach einem der Ansprüche 12 bis 17, dadurch gekennzeichnet, dass die vom Lasertarget (5) emittierten Projektilteilchen (3) nacheinander in den Hohlraum (12) des Kerntargets (1) einfallen, und zwar nach Gewicht und/oder Masse-Ladungs-Verhältnis der Projektilteilchen (3).

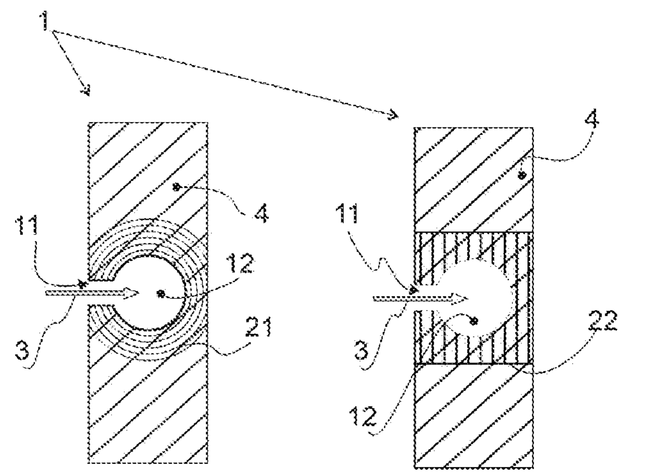
19. Vorrichtung, die zur Herstellung von Radioisotopen geeignet ist, wobei die Vorrichtung eine Quelle von Projektilteilchen (3) umfasst, die so einstellbar ist, dass die Projektilteilchen (3) auf den Hohlraum (12) eines Kerntargets (1) fallen, dadurch gekennzeichnet, dass das Kerntarget (1) das Kerntarget (1) nach einem der Ansprüche 1-11 ist.

20. Vorrichtung zur Herstellung von Radioisotopen nach Anspruch 14, dadurch gekennzeichnet, dass die Vorrichtung ein Lasertarget (5) umfasst, das in der Lage ist, Projektilteilchen (3) zu emittieren, nachdem es von einem Laserpuls (52) getroffen wurde, wobei das Lasertarget (5) vor der Öffnung (11) des Kerntargets (1) angeordnet ist, so dass die emittierten Projektilteilchen (3) in den Hohlraum (12) des Kerntargets (1) fallen.

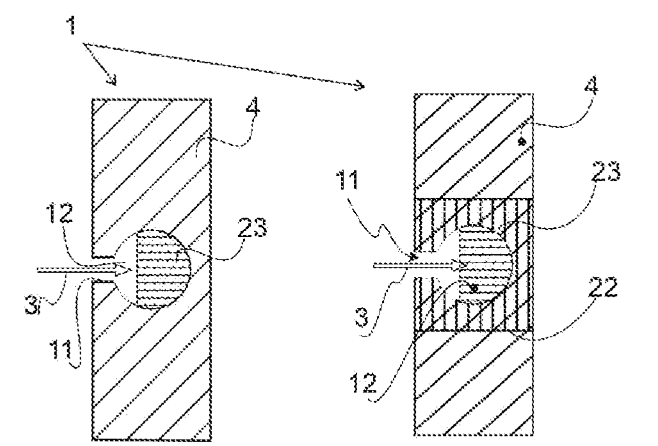
CITT ref.: E18003

Drawings

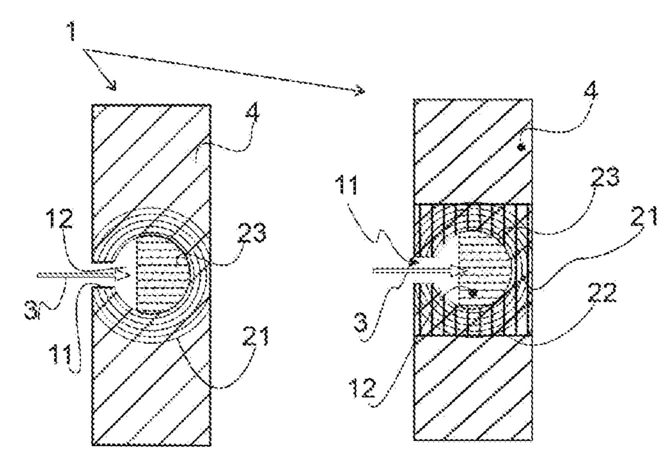
LU102817



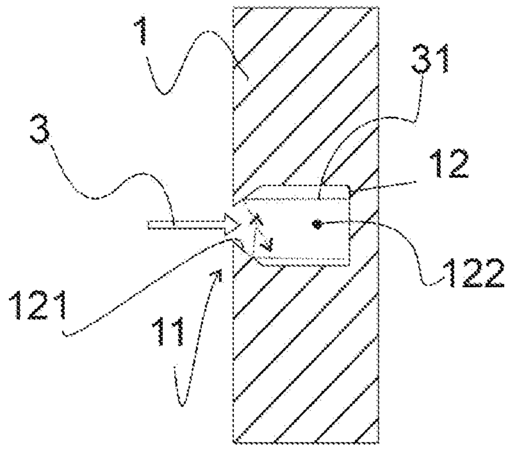
Obr. 1a   Obr. 1b



Obr. 1c   Obr. 1d

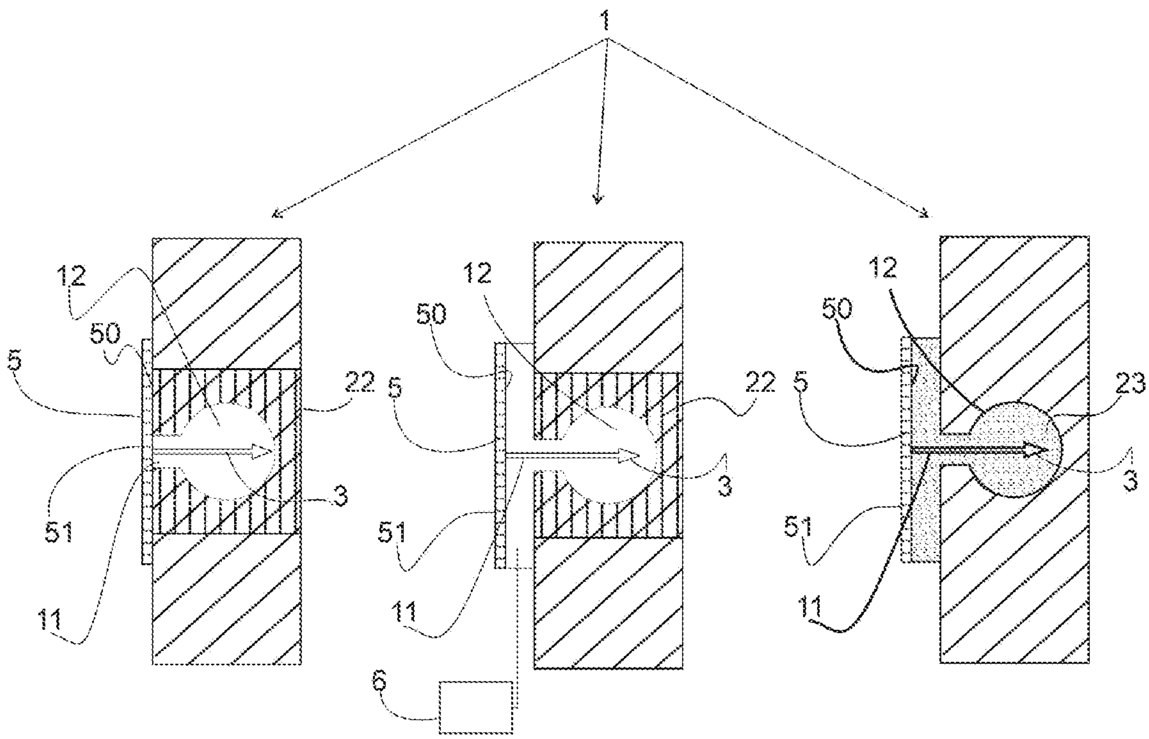


Obr. 1e   Obr. 1f



Obr. 2a

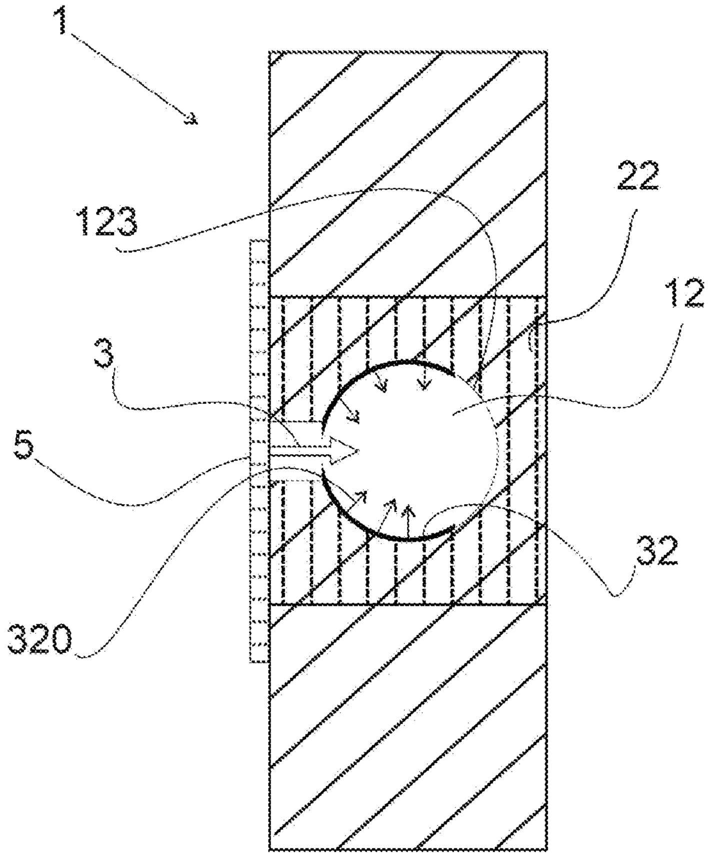
Obr. 2b



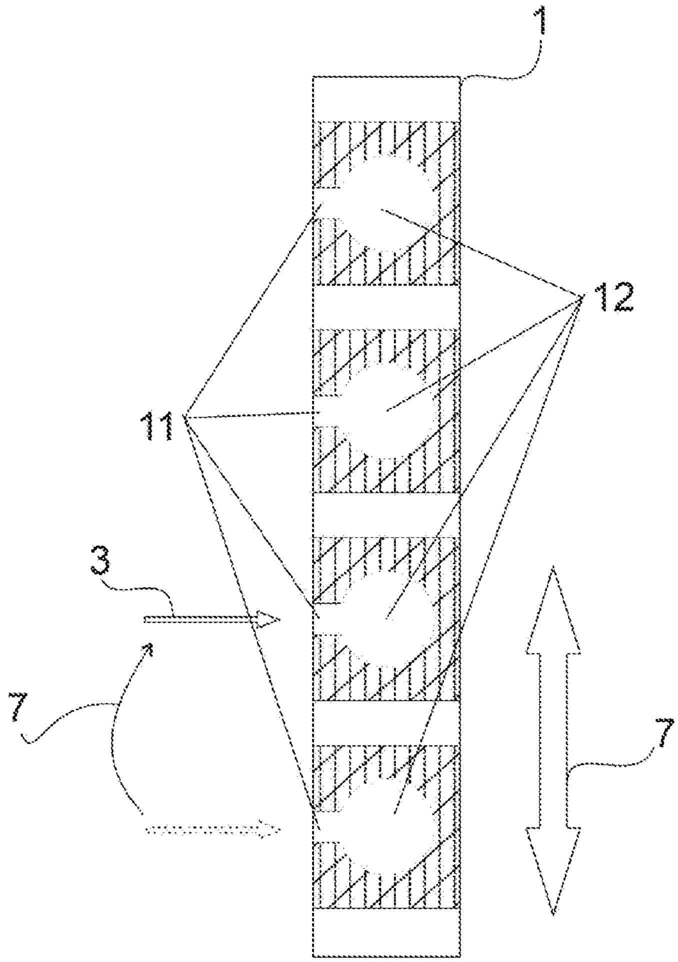
Obr. 3a

Obr. 3b

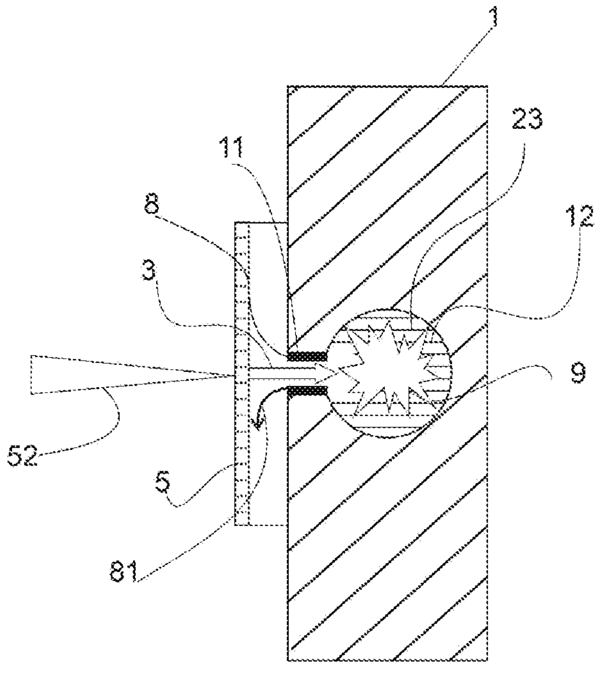
Obr. 3c



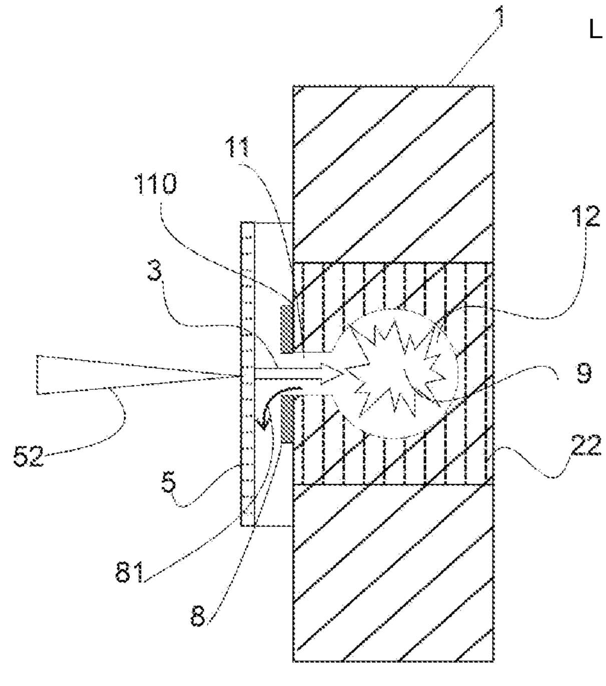
Obr. 4



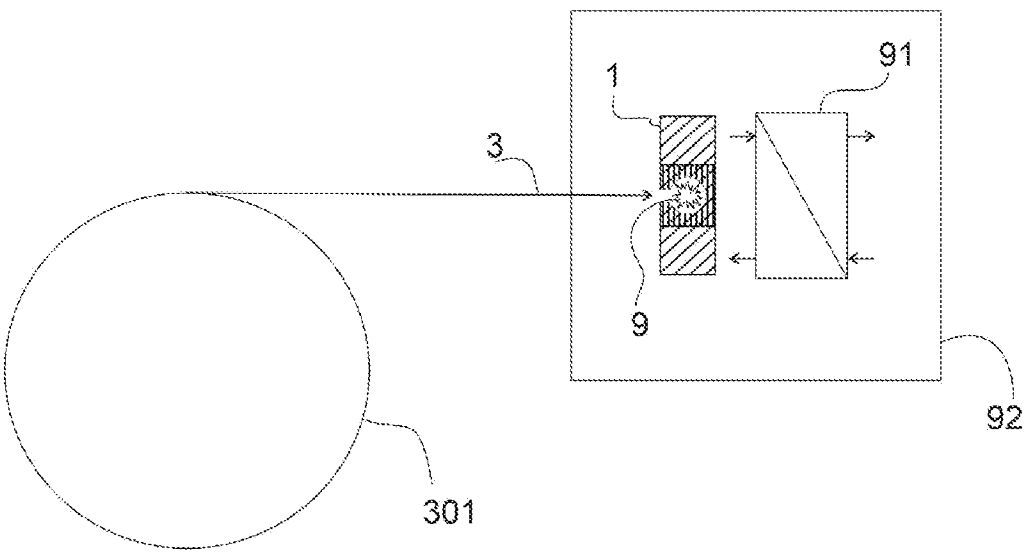
Obr. 5



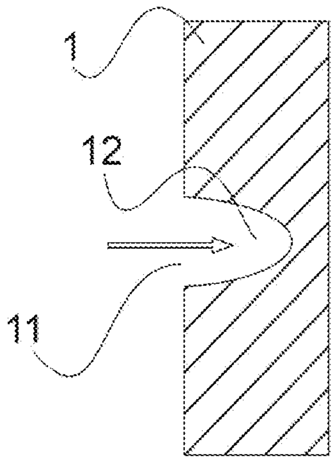
Obr. 6a



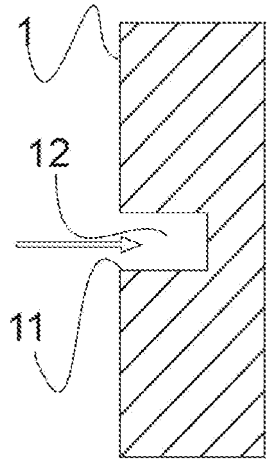
Obr. 6b



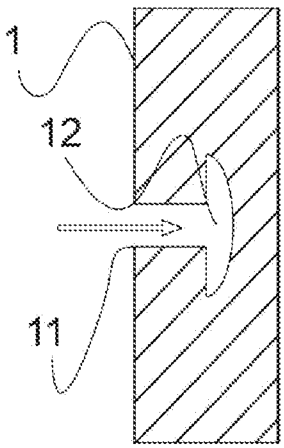
Obr. 7



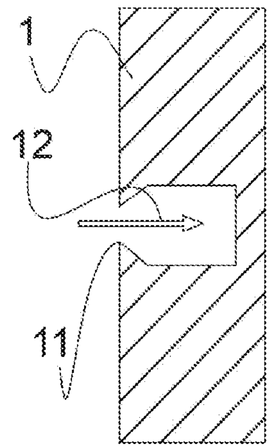
Obr. 8a



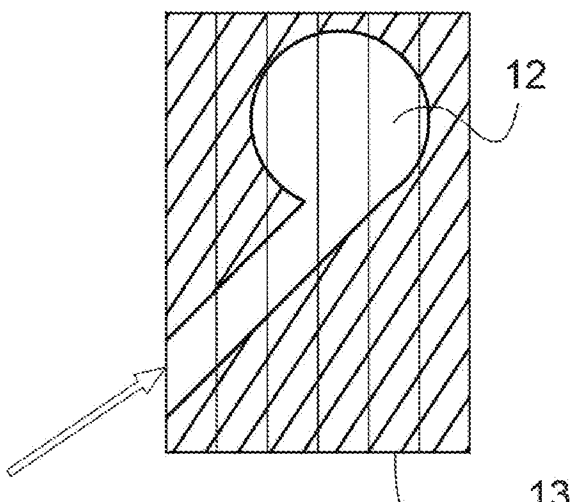
Obr. 8b



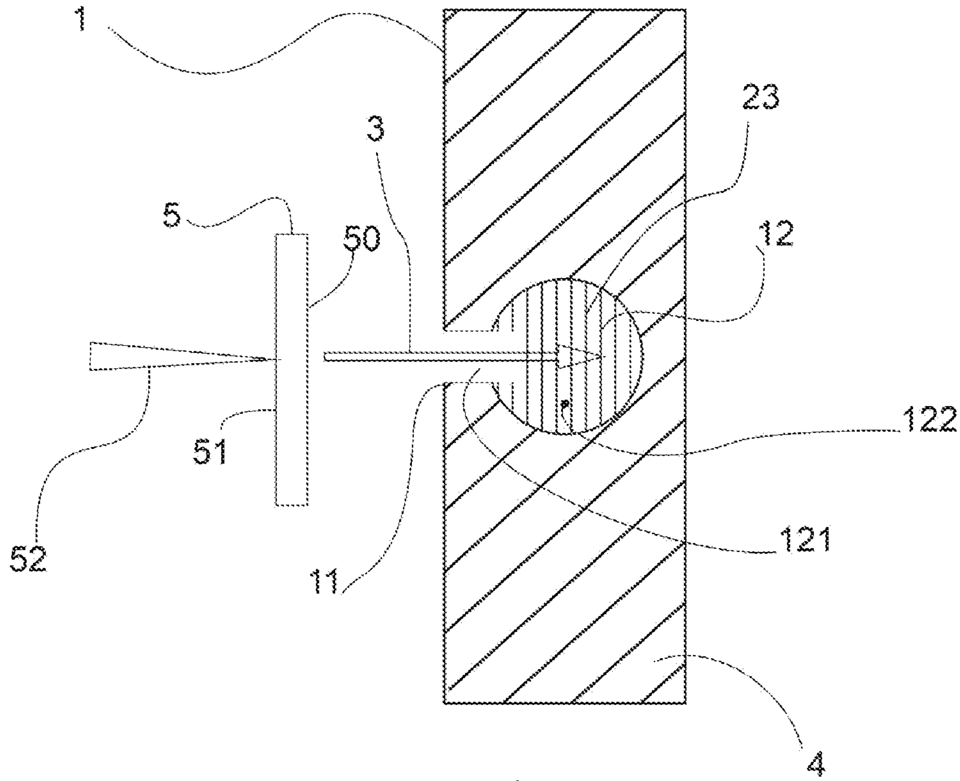
Obr. 8c



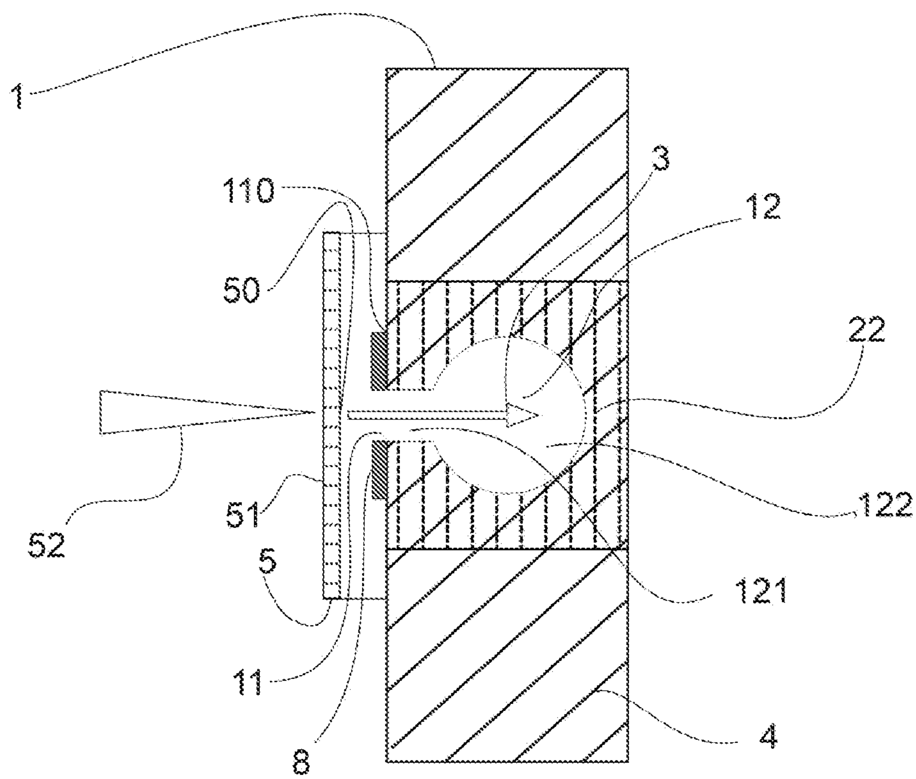
Obr. 8d



Obr. 8e



Obr. 9a



Obr. 9b