A neutron source comprising an electrostatic particle accelerator (10; 30) and a neutron-emitting target material (14; 40) arranged such that charged particles (22; 36) may be accelerated by the electrostatic particle accelerator to hit the neutron-emitting target material, releasing neutrons (16; 42). The electrostatic particle accelerator comprises concentric shells (102) each divided into two parts at an equatorial plane (103), and further comprises diodes connected to shell parts across the equatorial plane.
A COMPACT, LOW ENERGY NEUTRON SOURCE

The present invention relates to neutron sources, and in particular provides a compact, low energy neutron source which can be used in a number of applications.

Neutron sources are known and find use in diverse applications, such as fault detection in turbine blades, cancer treatment, production of Molybdenum-99 (Mo-99) isotope for use in nuclear medicine, and for security inspection.

Certain types of neutron sources are known for use in such applications, but each have their drawbacks.

Isotope sources rely on radioactive decay of a selected isotope to generate free neutrons directly. Typically, Californium-252 (Cf-252) is employed. The safe use of a Cf-252 source requires a large amount of shielding, making its use and transport very difficult. An example is described in US2009/0225922.

Neutron tubes are known. These have a limited lifetime unless they are continually refilled. They contain tritium \(^{(3}H\) which restricts general application. Such sources have been used for down-hole well logging (e.g. US7139349, US6922455).

Nuclear reactors can generate large numbers of free neutrons with a wide range of energies. For applications requiring low-energy neutrons, the neutrons from the reactor would need to be moderated. Such facilities are large. They are not portable and their range of applications is restricted by the size of the necessary installation. Only a small number of suitable reactors are available in the world, and have
lengthy maintenance schedules. Safety concerns limit their wider application.

Neutron sources based on particle accelerators have conventionally been least favoured, for example because of their cost and complexity, for example their requirement for long radio frequency quadrupoles (e.g. US2006/0140326). The present invention provides a small and compact, energy efficient neutron source providing neutrons of relatively low energy in an energy efficient manner.

Accordingly, the present invention provides apparatus and methods as defined in the appended claims.

The above, and further, objects, advantages and characteristics of the present invention will become more apparent from the following description of certain embodiments thereof, in conjunction with the appended drawings, wherein:

Fig. 1 schematically illustrates a DC accelerator useful in a method according to a first embodiment of the invention;

Fig. 2 schematically illustrates apparatus for producing a neutron flux according to the first embodiment of the present invention;

Fig. 3 schematically illustrates a tandem DC accelerator useful in a method according to a second embodiment of the invention;

Fig. 4 schematically illustrates apparatus for producing a neutron flux according to the second embodiment of the present invention; and
Fig. 5 schematically illustrates the known interaction between boron atoms and thermal neutrons in BNCT.

The present invention provides methods and apparatus for producing a neutron flux using an electrostatic accelerator.

In order to enable neutron based techniques to be utilised in non-specialist environments, that is, other than in direct association with the conventional reactors or large accelerators, a much smaller compact energy efficient system is provided. This can be achieved according to the present invention by using a compact electrostatic accelerator having a footprint of less than 2m².

The present invention provides a neutron source comprising a compact electrostatic particle accelerator with one or more suitable targets. Charged particles are accelerated towards a target by the particle accelerator. Once a charged particle hits a target, a different type of particle is released. In some embodiments, a single target is provided. Charged particles hit the single target and release neutrons. In other embodiments, more than one target is provided, in "tandem". Accelerated charged particles hit a first target, and release a different type of charged particle. An example of such action is the stripping of electrons from H⁻ ions:

$$H^- \rightarrow 2e^- + H^+$$

Those released charged particles hit a second target, and release neutrons.

A type of electrostatic particle accelerator was described by the inventors in the proceedings of the 1st International
As disclosed in the above-mentioned proceedings, the electrostatic accelerator comprises concentric shells each divided into two parts at an "equatorial" plane. Such parts may be halves, but need not be exactly equal. However, they will be referred to within the present description as "halves" for ease of reading. By appropriately connecting diodes between shell halves, across the equatorial plane, a self-contained high voltage source is generated. The concentric shells perform as capacitors in a Cockcroft-Walton (or Greinacher) cascade. By applying an alternating voltage to the two outer shell halves of the capacitor-diode chain so formed, a very large voltage can be generated at the innermost shell. The potential difference between neighbouring shells will be double the peak applied voltage. By controlling that voltage, and knowing the separation distance between neighbouring shells, very large potential gradients can be generated as required.

The electrostatic accelerator is preferably operated in a high vacuum, enabling higher electric fields to be generated than would be the case with pressurised gas insulation between the shells, for example in excess of 10MV/m. 

A series of aligned holes through the shell halves (capacitor electrodes) serves as a beam tube.
An example of such an electrostatic accelerator is illustrated in Fig. 1, where concentric shells 102 are divided 103 at an equatorial plane, while a series of aligned holes 104 allows an incoming particle beam 105 to reach a target 100 within a central region 101, within an innermost shell.

Each shell is charged to a high voltage as compared to its outwardly neighbouring shell. For example, thirty concentric shells may used, charged up by a 100kV eff, 100 kHz AC inverter. This provides a voltage of 5MV at the centre, and a voltage gradient of 5MV/ (30x15mm) = 11.11kV/mm. In another example, twenty five concentric shells are used, charged up by a 100kV eff, 100 kHz AC inverter. This provides a voltage of 2.45MV at the centre, and a voltage gradient of 2.45MV/ (25x11.3mm) = 8.8kV/mm. By charging the shells with a voltage of polarity opposite to that of the charged particles, the beam 105 of charged particles is accelerated towards the centre of the accelerator. The beam 105 of particles hits target 100 within an innermost region 101 and undergoes the required reaction.

Fig. 2 shows a further development of this idea, in a so-called tandem electrostatic accelerator. In such an accelerator, an electric field is generated which attracts first particles 105 of a first polarity, as described with reference to Fig. 1. Such first particles are accelerated through the concentric shell structure until they reach the central region 101 within the innermost shell. There, they hit a particle converter target 200 and release a beam 205 of second charged particles of a second polarity, opposite to the first polarity. Such second charged particles are repelled out of the accelerator through a second series of aligned holes 204 in the concentric shells by a voltage
gradient of opposite polarity to that which accelerated the first particles into the accelerator. The second particles reach a second target 210.

Each shell is charged to a high voltage as compared to its outwardly neighbouring shell. In an example, thirty concentric shells may be used, charged up by a 100kVeff, 100 kHz AC inverter. This provides a voltage of 5MV at the centre, and a voltage gradient of 5MV/ (30x15mm) = 11.11kV/mm. In another example, thirteen concentric shells are used, charged up by a 100kVeff, 100 kHz AC inverter. This provides a voltage of 1.29MV at the centre, and a voltage gradient of 1.29MV/ (13x10.8mm) = 9.2kV/mm. By charging the shells with a voltage of polarity opposite to that of the charged particles, the beam 105 of charged particles is accelerated towards the centre of the accelerator.

According to the present invention, such concentric-shell electrostatic accelerators form a component of compact, low-energy neutron sources.

Fig. 3 shows a neutron source according to a first embodiment of the invention. Protons ($^1$H$^+$ ions) 22 may be accelerated from a source 12 to the centre of the accelerator 10 where they hit a neutron generator target 14, such as a proton spallation target, for example, lithium, beryllium or carbon. A lithium Li-7 target produces neutrons 16 from the ($p$,n) reaction Li-7 ($p$,n)Be-8.

The resultant neutron flux 16 is unaffected by the electrostatic field, and exits the accelerator for use as required.
Such a system is compact enough to allow mobile deployment or relatively easy incorporation into existing sites.

Fig. 4 schematically illustrates a second embodiment of the present invention, in which a tandem accelerator 30, such as shown in Fig. 2, is employed. Rather than placing a neutron-source target 14 in the centre of the accelerator, as in the example of Fig. 3, a particle converter target 34 is placed in that position. First charged particles 36 are provided by a source 32 and are directed towards the particle converter 34.

The first charged particles 36 interact with the particle converter 34, and produce second charged particles 38, of polarity opposite to that of the first charged particles 36 and travelling in the same trajectory as the first charged particles. As the second charged particles have the opposite charge as compared to the first charged particles, they will be accelerated out of the accelerator 30, while the original particles are accelerated into the accelerator along path 204 (Fig. 2).

For example, $\text{H}^-\text{ions}$ 36 may hit a particle converter 34, being an ion stripper arrangement and conventional in itself, and be converted to $\text{H}^+\text{ions}$, protons 38. The accelerator 30 would need to be charged to a positive voltage to ensure that $\text{H}^-\text{ions}$ 36 are accelerated towards the particle converter 34, and $\text{H}^+\text{ions}$, protons 38, are accelerated away from it.

A target 40 is positioned outside of the accelerator. The second charged particles 38 leave the accelerator and hit target 40. The beam of second charged particles 38 hits target 40 and causes emission of other particles 42. In embodiments of the present invention, the other particles 42
are neutrons.

With a tandem accelerator 30, particles are accelerated both into the accelerator and back out again. The potential difference (voltage) between the outermost shell and the innermost shell need therefore only be half of the required acceleration voltage of the second charged particles, while in the case of a linear accelerator 10 of Figs. 1, 3, the potential difference (voltage) between the outermost shell and the innermost shell should equal the required acceleration voltage.

The present invention may accordingly be applied both to linear accelerators and tandem accelerators. Various different targets may be used, as will be described in more detail in the following examples.

According to a first example, a neutron flux may be produced using a compact linear neutron generator.

As schematically represented in Fig. 3, a conventional linear DC electrostatic accelerator 10, similar to that described with reference to Fig. 1, is provided with a beam 22 of protons (H\(^+\) ions) from a proton source 12. In the centre of the DC electrostatic accelerator is a target of neutron source material 14, such as a thin Lithium Li-7 target, which produces neutrons 16 from the \((p,n)\) reaction Li-7 (p, n)Be-8 or similar.

The Li-7 reaction is particularly advantageous because it is a transition reaction which, at around 1.885 MeV, produces a collimated neutron beam 16. Depending on their required energy the collimated neutron beam 16 can be directed at a moderator 18 to produce an epithermal neutron spectrum. An
epithermal neutron is a neutron that has energy greater than that of a thermal neutron, but not as large as for fast neutrons, so having a modest requirement for shielding. Alternatively, by controlling the voltage applied to the accelerator 10, epithermal neutrons of about 2.3MeV may be generated directly.

The epithermal neutrons, generated directly or emerging from moderator 18 may then be employed as required.

In an example DC electrostatic accelerator, the protons (H\(^+\) ions) are accelerated to the centre of the accelerator 10, at which point they cross the centre into the shell structure of the accelerator on the opposite side, which has a decelerating field.

Some of the incident proton beam 22 loses a portion of its energy as it passes through neutron-source material 14. This resulting proton beam 24 exits the target, and is gradually slowed as it passes through the accelerator 10 and is collected in the structure of the DC electrostatic accelerator, acting as a collector assembly. In this way, the energy of the beam is recovered, as may be understood from conservation of energy. The incident proton beam accelerates as it gains energy from the electrostatic field. Energy is continually supplied from a power supply unit to maintain the accelerating electric field. As the same charged particle beam exits the accelerator, the beam sees a decelerating field and the protons slow down giving energy back to the accelerator.

In a second example of the first embodiment of the invention, similar to the first example, the proton source 12 is replaced with a source of deuterium ions \(2\text{H}^+\) (D\(^+\)). The
neutrons are generated as a result of accelerated particles of deuterium $^2\text{H}^+$ ($\text{D}^+$) hitting a target of beryllium Be-10 in a Be-10 ($d, n$)C-11 reaction to produce carbon-11 and a free neutron. Alternatively, neutrons may be generated as a result of accelerated particles of deuterium $^2\text{H}^+$ ($\text{D}^+$) hitting a target of beryllium Be-9 in a Be-9 ($d, n$)C-10 reaction to produce carbon-10 and a free neutron. The free neutron may then be employed as required.

According to a second embodiment of the invention, alternative apparatus and methods are provided for producing a neutron flux using a tandem compact neutron generator, such as illustrated in Fig. 4.

According to a first example of this second embodiment of the invention, a tandem DC electrostatic compact accelerator 30, similar to that described with reference to Fig. 2, is provided with a source 32 of $\text{H}^-$ ions, and produces a beam 36 of $\text{H}^-$ ions directed towards the centre of the accelerator 30. In the centre of the tandem electrostatic accelerator 30 is an ion stripper arrangement 34 (such as a carbon stripper foil which is conventional in itself), which converts $\text{H}^-$ ions to $\text{H}^+$ ions (protons) by removal of two electrons from each ion. The resulting $\text{H}^+$ beam 38 is incident upon a target material 40 which produces a neutron flux 42 in reaction to the incident protons. For example, the material 40 may be a proton spallation target such as Li, Be, C.

Conventional ion stripper arrangements are described, for example, in Proceedings of EPAC08, Genoa, Italy pp3620-3622 04 T12 A.Takagi et al. "Temperature Measurement of Carbon Stripper Foil by Pulsed 650keV H- ion beam"; and the 2002 publication by T. Spickermann et al. "Comparison of Carbon
Stripper Foils Under Operational Conditions at the Los Alamos Proton Storage Ring. Copies of these papers are filed with copending UK patent application number GB1100442.1.

The Li-7 \((p,n)\)Be-7 reaction which takes place if a lithium target is used is particularly advantageous because it is a transition reaction which, at around 1.885\(\text{MeV}\), produces a collimated neutron beam 42. Other materials may produce similar results. The collimated neutron beam 42 may be directed at an optional moderator 44, which could be a simple water vessel or wax block, to produce a neutron spectrum of appropriate energy profile. The resultant neutron flux may be employed as required.

The neutron sources of the present invention, as described above and defined in the appended claims, have the advantages of being compact with a small footprint and requiring modest amount of power, mainly for the ion source and vacuum pumps. The apparatus would also have a very simple user friendly interface for non-expert operation. Furthermore, the system could be made portable using a simple electrical generator.

The compact low-energy neutron source of the present invention may find many applications, and the following description will give some examples of practical uses for the neutron sources of the present invention.

SECURITY APPLICATIONS

The neutron sources of the present invention may be employed in various processes and applications for scanning materials for explosives and nuclear materials as described for example in patent publications US2009/0225922A1, US2009/0114834A1,
The present invention provides a compact particle accelerator for use in the generation of neutrons, suitable for use in security inspection. Examples of security inspection which may benefit from the present invention include: for luggage, cargo containers, vehicles, mine detection. A security inspection system with a small footprint would enable the detection of explosive and fissile materials. In general, for such applications, low-energy neutrons with energy ranging from Thermal-8MeV are required. Such neutron beams may be generated by the neutron source of the present invention, for example by a 10MeV ~mA proton or deuterium beam accelerated into a neutron generator material such as Li, Be, C etc. Here the proton spallation generates a high flux of neutrons in this energy spectrum.

Such a system would have the benefit of possible mobile deployment, or relatively easy incorporation into existing sites. The additional features of being compact with a small footprint and requiring modest amount of power, mainly for the ion source and vacuum pumps, having a very simple user friendly interface for non-expert operation, would enable easy siting and running in the vicinity of regular inspection areas such as airports or ports.

BORON NEUTRON CAPTURE THERAPY

In the medical sector, there is significant interest in using neutrons to treat certain types of cancer via Boron Neutron Capture Therapy (BNCT). The technique is well known and described in patents US4516535, US6228362, US6695619 and US7138103 detailing radiobiology in the body. Here a tumour is seeded with a compound carrying Boron-10 which is
preferentially absorbed by the cancer. Boron interacts with thermal neutrons to produce an alpha particle and a Lithium nucleus which destroys the local cells. The cross-section for this reaction is orders of magnitude larger than that of the neutron absorption for other elements found in the body, with the result that a much greater fraction of the neutron dose is deposited in the tumour. This enables the treatment of tumours which spread into surrounding healthy tissue.

Such interaction is schematically represented in Fig. 5. A cancerous cell 50 is seeded with a compound containing boron-10 52. An incident neutron 54 interacts with a boron-10 nucleus to form an unstable boron-11 nucleus 56. This breaks down into a lithium-7 nucleus 57 having an energy of 0.84 MeV and an alpha-particle 58 having an energy of 1.47 MeV, with the emission of a 0.478 MeV photon 59. The combined range of the lithium-7 nucleus 57 and the alpha particle 58 is understood to be in the range of 8-9 microns, while the typical cell diameter is about 10 microns. This means that radiation damage is confined mostly within the target cell.

However, this requires a large neutron flux to keep a typical cancer treatment to around 30 minutes. Currently, nuclear reactors and large particle accelerators are used for this form of therapy. Such devices mean that the technique can only be performed at specialized facilities and not suitable for sitting in or near a hospital.


The methods and apparatus of present invention allow production of a neutron flux for use in BNCT, without the
need for a large facility or use of a nuclear reactor.

For BNCT a neutron flux of about $10^9$ epithermal neutrons/cm$^2$/s is required in order to keep the treatment time to 30 minutes, which is regarded as a maximum acceptable treatment time due to considerations of patient comfort and patient throughput. The latest theory suggests that epithermal energies are best suited for this treatment as these then thermalise in tissue. If thermal neutrons are used, the tumour has to be exposed as thermal neutrons do not penetrate far enough into the body but get stopped. Epithermal neutrons enter the body and are slowed down after a few centimetres, allowing them to reach a patient's tumour without having to surgically expose the tumour. The element most often studied to produce these epithermal neutrons is lithium, which has a resonance for neutron production between 2.3 - 2.5 MeV, just above 1.88 MeV, the threshold proton energy at which neutrons begin to be produced from this target. Preferably, epithermal neutrons are generated directly before being used to treat the patient.

According to the present invention, a compact DC electrostatic accelerator is configured with an voltage just above the threshold for boron neutron capture with an H$^+$ ion source. H$^+$ ions are accelerated to ~2.3 MeV to the centre of the accelerator where they hit a lithium neutron generator target. The subsequent collimated epithermal neutrons, unaffected by the electrostatic field exit the accelerator and enter a patient undergoing BNCT.

Such a system would have the benefit of possible siting in a modified oncology suite at a hospital or such facility, enabling the on-site production of a neutron flux from readily generated H$^+$ or H$^-$ ion beams without the use of large
specialist installations. This avoids the conventional requirement for a neutron source, which is usually a large piece of equipment, or a reactor.

PRODUCTION OF RADIOISOTOPES e.g. Mo-99

As is well known, Nuclear Medicine is currently used in the diagnosis of tumours, and investigations into other medical conditions.

Technetium Tc-99m is an important radioisotope used in Nuclear Medicine. Currently, it is produced in a two-part process. The first part of the process involves the production of Molybdenum Mo-99. The Mo-99 produced then decays to Tc-99m with a half life of 66 hours.

Typically, the Mo-99 is produced in a high flux nuclear reactor using HEU (highly enriched Uranium).

This is currently the most popular but in the future there may be others both for SPECT and/or PET systems. The latter currently focus on proton reactions from cyclotrons because compact neutron sources are less common.

Conventionally, a Tc-99m generator is a device used to extract the metastable isotope Tc-99m of technetium from a source of decaying molybdenum Mo-99 at the point of use. Mo-99 has a half-life of 66 hours and can be easily transported over long distances to hospitals, whereas its decay product technetium Tc-99m is extracted and used for a variety of nuclear medicine diagnostic procedures. Technetium Tc-99m has a half-life of only 6 hours, which is inconvenient for transport, but is useful in medical diagnostic procedures.
Conventional Mo-99 / Tc-99m generators use column chromatography, in which Mo-99 in the form of molybdate, MoO₄²⁻ is adsorbed onto acid alumina (Al₂O₃). When the Mo-99 decays, it forms pertechnetate TcO₄⁻, which because of its single charge is less tightly bound to the alumina. Pulling normal saline solution through the column of immobilized Mo-99 elutes the soluble Tc-99m, resulting in a saline solution containing the Tc-99m as the pertechnetate, with sodium as the counterbalancing cation.

The solution of sodium pertechnetate may then be added in an appropriate concentration to a pharmaceutical to be used, or sodium pertechnetate can be used directly without pharmaceutical tagging for specific procedures requiring only the Tc-99m₀₄⁻ as the primary radiopharmaceutical.

A large percentage of the Tc-99m generated by a Mo-99/Tc-99ₗ generator is produced in the first 3 parent half lives, or approximately one week. Hence, clinical nuclear medicine units purchase at least one such generator per week, or order several in a staggered fashion.

There has been considerable disruption to the Mo-99 supply chain due to the small number of reactors in the world: recently estimated at five, and their lengthy maintenance schedules due to their age and safety concerns of operating a nuclear reactor.

Mo-99 is currently the most commonly used radioisotope in nuclear medicine, but in the future there may be other radioisotopes which may be prepared using the neutron source of the present invention, and may be found useful for SPECT (single-photon emission computed tomography) and/or PET.
(positron emission tomography) systems. The latter currently focus on proton reactions from cyclotrons because compact neutron sources are less common.

As will be described below, the neutron generation sources and methods of the present invention enable alternative methods and apparatus for producing radioisotopes such as Mo-99. Mo-99 finds utility both as a product in itself, and as an intermediate product in a method of producing Tc-99m, which methods and apparatus do not require the use of a high flux nuclear reactor and HEU.

In a first example, Mo-99 may be produced using a compact neutron generator through a Mo-98 \((n, \gamma)\)Mo-99 route. Using a linear electrostatic accelerator in a neutron source, as illustrated in Fig. 3, a neutron beam may be produced and directed towards moderator 18. After the moderator 18, the neutrons hit a target 20 including Mo-98. This interaction results in the production of Mo-99 through an Mo-98 \((n, \gamma)\)Mo-99 reaction.

The neutron beam may be produced as described above, either by a proton beam acting upon a lithium target, or deuterium ions \(^2\text{H}^+\text{ (d)}^+\) hitting a target 14 of beryllium Be-10 in a Be-10(d,n)C-11 reaction to produce carbon-11 and a free neutron.

The free neutron may then be directed towards the Mo-98 target 20 to produce Mo-99 in an Mo-98 \((n, \gamma)\)Mo-99 reaction.

Alternatively, Mo-99 may be produced through a U-235 fission route with an energy recycling proton beam. As above, at the centre of the electrostatic accelerator 10 is a material 14 which produces neutron beams 16 in response to an incident proton or deuterium ion beam 22.
The resultant collimated neutron beam 16 is directed at a moderator 18, which produces an epithermal neutron spectrum.

After the moderator 18, the neutrons hit a subcritical Uranium U-235 target to produce U-236 through the U-235 (n,γ)U-236 reaction. The U-236 fissions to become Mo-99 plus other fission products and neutrons. Mo-99 may then be separated from other fission products in a hot cell.

The resulting Mo-99 is removed from the U-235 target by a chemical process which is conventional in itself.

In another alternative, Mo-99 using a tandem compact neutron generator, such as illustrated in Fig. 4, through a Mo-98 (n,γ)Mo-99 reaction route. A generated neutron beam is directed towards a Mo-98 target, which transitions to become Mo-99, with the emission of a gamma photon.

Fig. 4 schematically represents an example of apparatus according to second embodiment of the present invention, using a tandem DC electrostatic accelerator.

Collimated neutron beam 42 is directed at a moderator (not shown in the drawing, but could be a simple water vessel or wax block) to produce an epithermal neutron spectrum. After the moderator, the neutrons hit a Mo-98 target 44, producing Mo-99 through the Mo-98 (n,γ)Mo-99 reaction.

In a second example of generating Mo-99 using a tandem compact neutron generator as shown in Fig. 4, Mo-99 is produced through the U-235 fission route. Again, at the centre of the electrostatic accelerator 10 is an ion stripper arrangement 34 which produces a proton beam 38 in response to
the incident H− ions 36. The proton beam is directed to
target 40, which produces neutron beams 42 in reaction to the
incident protons. The target 40 may be of Li-7 as described
above. In this example, after a moderator (not shown), the
neutrons hit a subcritical Uranium U-235 target 44 to produce
U-236 through the U-235 (n, γ)U-236 reaction. The U-236
fissions to become Mo-99 plus other fission products and
neutrons. Mo-99 may then be separated from other fission
products in a hot cell. The resulting Mo-99 is removed from
the U-235 by a chemical process which is conventional in
itself.

Accordingly, the neutron beam generating apparatus and
methods of the present invention allow simplified on-site
production of Molybdenum Mo-99 without the use of large and
unwieldy, or hazardous, apparatus. Mo-99 is of use, for
example, in the preparation of Technetium Tc-99m for use in
Nuclear Medicine.

According to the present invention, neutron beams are
produced in-situ from readily generated H+, H+ or H− ion
beams. This avoids the conventional requirement for a
neutron source, which is usually a large piece of equipment,
a particle accelerator or a reactor.

Fig. 6 shows an electrical schematic diagram of a Cockcroft-
Walton (or Greinacher) cascade. In the electrostatic
particle accelerator employed in the present invention, the
capacitors 61 are formed by the concentric shells, and diodes
62 are used to join the shells together in an appropriate
manner to form a Cockcroft-Walton (or Greinacher) cascade.
CLAIMS:

1. A neutron source comprising an electrostatic particle accelerator (10; 30) and a neutron-emitting target material (14; 40) arranged such that charged particles (22; 36) may be accelerated by the electrostatic particle accelerator to hit the neutron-emitting target material, releasing neutrons (16; 42), characterised in that

5 the electrostatic particle accelerator comprises concentric shells (102) each divided into two parts at an equatorial plane (103), and further comprising diodes connected to shell parts across the equatorial plane.

10 2. A neutron source according to claim 1 wherein a series of aligned holes (104; 204) is provided through the shell parts as a beam tube.

15 3. A neutron source according to claim 1 or claim 2, wherein the neutron-emitting target material (14) is positioned within an innermost shell of the concentric shells.

20 4. A neutron source according to claim 1 or claim 2, wherein a particle-converting target material (34) is positioned within an innermost shell of the concentric shells, and the neutron-emitting target material (40) is positioned outside of an outermost shell of the concentric shells.

25 5. A neutron source according to claim 4, wherein a first series of aligned holes (104) is provided through the shell parts as a beam tube for introducing a first particle beam (105; 22), comprising particles of a first charge polarity, into the electrostatic particle accelerator towards the particle-converting target material, and a second series of
aligned holes (204) is provided through the shell parts as a
beam tube for carrying a second particle beam (205; 38),
comprising second particles of a second charge polarity
opposite to the first charge polarity, from the particle-
converting target material to the neutron-emitting target
material (40).

6. A neutron source according to claim 5, in conjunction with
a source (32) of H⁻ ions, wherein the particle-converting
target material is an ion stripper arrangement (34), arranged
such that H⁻ ions from the H⁻ ion source accelerate into the
electrostatic particle accelerator (30) as first particles of
a first charge polarity, and impact upon the ion stripper
arrangement (34), which emits protons (38) as the second
particles of a second charge polarity.

7. A neutron source according to any preceding claim wherein
space between the concentric shells is evacuated.

8. A neutron source according to any preceding claim wherein
the neutron-emitting target material comprises lithium Li-7.

9. A neutron source according to any of claims 1-7 wherein
the neutron-emitting target material comprises beryllium Be-
10.

10. A neutron source according to any preceding claim, further
comprising a collector assembly in the electrostatic
accelerator (10), arranged to catch and recycle energy from
accelerated charged particles.

11. A neutron source according to any preceding claim, further
comprising a moderator to reduce the energy of
neutrons in the neutron beam.
12. Apparatus for producing Mo-99 comprising:
- a neutron source according to any preceding claim; and
- a target (18; 44), arranged to be hit by the neutron beam (16; 42) and contains a species which becomes Mo-99 in response to the incident neutron beam.

13. Apparatus according to claim 12 wherein the target contains Mo-98.

14. Apparatus according to claim 12 wherein the target contains U-235.

15. Apparatus according to claim 12 wherein the target contains Mo-100.

16. Apparatus for performing security inspections comprising a neutron source according to any of claims 1-11.

17. Apparatus for performing boron neutron capture therapy, comprising a neutron source according to any of claims 1-11.

18. Use of a neutron source according to any of claims 1-11 in a method for producing Mo-99, wherein neutrons released by the neutron source are directed to a target (20; 44), which contains a species which becomes Mo-99 in response to the incident neutrons.

19. Use according to claim 18 wherein the target contains Mo-98.

20. Use according to claim 18 wherein the target contains U-235.
21. Use according to claim 18 wherein the method further comprises the step of reducing the energy of released neutrons before they hit the target by passing the neutrons through a moderator (18).

22. Use of a neutron source according to any of claims 1-11 in a method for performing security inspections.

23. Use of a neutron source according to any of claims 1-11 in a method for performing boron neutron capture therapy.
### INTERNATIONAL SEARCH REPORT

**International application No**
PCT/GB2012/05Q008

**A. CLASSIFICATION OF SUBJECT MATTER**

INV. H05H3/06  H05H5/04  H05H5/06  G21G1/06

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

H05H  G21G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
</table>

Further special categories of cited documents:

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier document published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

**Date of the actual completion of the international search**
11 April 2012

**Date of mailing of the international search report**
17/04/2012

**Name and mailing address of the ISA**
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Crescenti, Massimo
# INTERNATIONAL SEARCH REPORT

## DOCUMENTS CONSIDERED TO BE RELEVANT

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**Information on patent family members**

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