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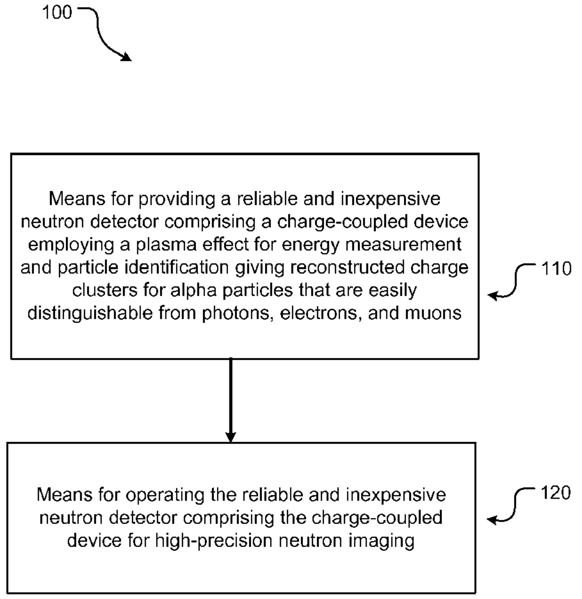

FIGURE 1

(57) Abstract: In a particular embodiment, a device is disclosed that includes means for providing a reliable and inexpensive neutron detector comprising a charge-coupled device employing a plasma effect for energy measurement and particle identification giving reconstructed charge clusters for alpha particles that are easily distinguishable from photons, electrons, and muons. The device also includes means for operating the reliable and inexpensive neutron detector comprising the charge-coupled device for high- precision neutron imaging. In another particular embodiment, a method is disclosed that includes steps for providing a reliable and inexpensive neutron detector comprising a charge-coupled device employing a plasma effect for energy measurement and particle identification giving reconstructed charge clusters for alpha particles that are easily distinguishable from photons, electrons, and muons. The method also includes steps for operating the reliable and inexpensive neutron detector comprising the charge-coupled device for high-precision neutron imaging.

WO 2013/116792 A1

METHOD AND APPARATUS FOR ADAPTATION OF CHARGE-COUPLED DEVICES (CCDS) FOR NEUTRON DETECTION AND IMAGING

INVENTOR:

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Juan Estrada, Ph.D.

I. Cross-Reference to Related Application

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 61/593,854, filed February 1, 2012, which is hereby incorporated by reference in its entirety, as if set out below.

II. Field of the Disclosure

[0002] The present disclosure is generally related to reliable and inexpensive neutron detection and, in particular, to a high resistivity charge-coupled device (CCD) employing a plasma effect for energy measurement and particle identification for high-precision neutron imaging.

III. Summary

[0003] In a particular embodiment, a device is disclosed that includes means for providing a reliable and inexpensive neutron detector comprising a charge-coupled device employing a plasma effect for energy measurement and particle identification giving reconstructed charge clusters for alpha particles that are easily distinguishable from photons, electrons, and muons. The device also includes means for operating the reliable and inexpensive neutron detector comprising the charge-coupled device for high-precision neutron imaging.

[0004] In another particular embodiment, a method is disclosed that includes steps for providing a reliable and inexpensive neutron detector comprising a charge-coupled device employing a plasma effect for energy measurement and particle identification giving reconstructed charge clusters for alpha particles that are easily distinguishable from photons, electrons, and muons. The method also includes steps for operating the reliable and inexpensive neutron detector comprising the charge-coupled device for high-precision neutron imaging.

IV. Brief Description of the Drawings

[0005] The following figures form part of the present specification and are included to further demonstrate certain aspects of the present invention. The present invention may be better understood by reference to one or more of these drawings in combination with the description of embodiments presented herein.

[0006] Consequently, a more complete understanding of the present disclosure and advantages thereof may be acquired by referring to the following description taken in conjunction with the accompanying drawings, in which the leftmost significant digit(s) in the reference numerals denote(s) the first figure in which the respective reference numerals appear, wherein:

[0007] Figure 1 is a diagram illustrating an embodiment of an apparatus including means for providing a reliable and inexpensive neutron detector comprising a charge-coupled device employing a plasma effect for energy measurement and particle identification giving reconstructed charge clusters for alpha particles that are easily distinguishable from photons, electrons, and muons and means for operating the reliable and inexpensive neutron detector comprising the charge-coupled device for high-precision neutron imaging; and

[0008] Figure 2 is a flow diagram of an illustrative embodiment of a method including steps for providing a reliable and inexpensive neutron detector comprising a charge-coupled device employing a plasma effect for energy measurement and particle identification giving reconstructed charge clusters for alpha particles that are easily distinguishable from photons, electrons, and muons and steps for operating the reliable and inexpensive neutron detector comprising the charge-coupled device for high-precision neutron imaging.

V. Detailed Description

[0009] Illustrative embodiments of the present invention are described in detail below. In the interest of clarity, not all features of an actual implementation are described in this specification. It will of course be appreciated that in the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of the present disclosure.

[0010] Particular embodiments of the present disclosure are described with reference to the drawings. In the description, common features are designated by common reference numbers.

[0011] Referring to Figure 1, a diagram illustrating an embodiment of an apparatus is depicted and indicated generally, for example, at 100. The apparatus 100 includes means for providing a reliable and inexpensive neutron detector comprising a charge-coupled device employing a plasma effect for energy measurement and particle identification giving reconstructed charge clusters for alpha particles that are easily distinguishable from photons, electrons, and muons 110 and means for operating the reliable and inexpensive neutron detector comprising the charge-coupled device for high-precision neutron imaging 120.

[0012] Referring to Figure 2, a flow diagram of an illustrative embodiment of a method is depicted and indicated generally, for example, at 200. The method 200 includes steps for providing a reliable and inexpensive neutron detector comprising a charge-coupled device employing a plasma effect for energy measurement and particle identification giving reconstructed charge clusters for alpha particles that are easily distinguishable from photons, electrons, and muons 210 and steps for operating the reliable and inexpensive neutron detector comprising the charge-coupled device for high-precision neutron imaging 220.

[0013] Attached herewith as an Appendix to this specification is a document describing more details about various illustrative embodiments, which Appendix to this specification is incorporated by reference as if set forth below. More details about various illustrative embodiments may be found by referring to the Appendix.

[0014] The present invention is well adapted to carry out the objects and attain the ends and advantages mentioned, as well as those that are inherent therein. While the present invention has been depicted, described and is defined by reference to exemplary embodiments of the present invention, such a reference does not imply a limitation of the present invention, and no such limitation is to be inferred. The present invention is capable of considerable modification, alteration, and equivalency in form and function as will occur to those of ordinary skill in the pertinent arts having the benefit of this disclosure. The depicted and described embodiments of the present invention are exemplary only and are not exhaustive of the scope of the present invention. Consequently, the present invention is intended to be limited only by the spirit and scope of the appended claims, giving full cognizance to equivalents in all respects.

[0015] The particular embodiments disclosed above are illustrative only, as the present invention may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Furthermore, no limitations are intended to the details of composition or design herein shown, other than as described in the claims below. It is therefore evident that the particular embodiments disclosed above may be altered or modified and all such variations are considered within the scope and intent of the present invention. In particular, every range of values (of the form, “from about a to about b,” or, equivalently, “from approximately a to b,” or, equivalently, “from approximately a-b”) disclosed herein is to be understood as referring to the power set (the set of all subsets) of the respective range of values, in the sense of Georg Cantor. Accordingly, the protection sought herein is as set forth in the claims below.

[0016] The particular embodiments of the present invention described herein are merely exemplary and are not intended to limit the scope of this present invention. Many variations and modifications may be made without departing from the intent and scope of the present invention. Applicants intend that all such modifications and variations are to be included within the scope of the present invention as defined in the appended claims and their equivalents.

[0017] While the present invention has been illustrated by a description of various embodiments and while these embodiments have been described in considerable detail, it is not the intention of the Applicants to restrict, or any way limit the scope of the appended claims to such detail. The present invention in its broader aspects is therefore not limited to the specific details, representative apparatus, methods, and illustrative examples shown and described. Accordingly, departures may be made from such details without departing from the scope of Applicants' general inventive concept.

APPENDIX

Phase I-SBIR/STTR Fiscal Year 2012 (Release 1)

(All information provided on this page is subject to release to the public.)

FIRM NAME: **MuPlus Inc.**	RESEARCH INSTITUTION: **Fermi National Accelerator Laboratory** **Dr. Juan Estrada, subgrant PI**
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PROJECT TITLE: **Adaptation of CCDs for Neutron Detection and Imaging**

PRINCIPAL INVESTIGATOR: **Dr. Mary Anne Cummings**

TOPIC: 21 SUBTOPIC: c

STATEMENT OF THE PROBLEM OR SITUATION THAT IS BEING ADDRESSED

The need for reliable, inexpensive neutron detection is growing with the increasing demand for safer, environmentally sound nuclear energy, control of nuclear fuel, proliferation issues and quality control on hydrogen fuel cell development. Neutron imaging can complement the array of active interrogation techniques, and for particular materials assessment, micron-level resolutions may be desirable.

STATEMENT OF HOW THIS PROBLEM OR SITUATION IS BEING ADDRESSED

The CCDs deployed for dark energy searches have been designed to measure a broad range of photon spectra. These high resistivity CCDs employ plasma effect for energy measurement and particle ID. In particular, the reconstructed charge clusters for alpha particles are easily distinguishable from photons, electrons and muons. It has been suggested that with proper conversion coatings and innovative reconfiguration, these CCDs, can be readily adapted to neutron detection, particularly for high-precision neutron imaging.

WHAT WILL BE DONE IN PHASE I

There are a variety of possible coatings for neutron to alpha particle conversion and detection, but their efficiency and consistency need to be systematically determined. Thin film coatings applied directly to the CCDs promise much higher neutron detection efficiency than current thin-film coated semiconductors, but a deposition method must be determined that will not compromise their sensitivity and high resolution read-out. A systematic approach to film coatings onto CCDs will be tested and evaulated, novel configurations of CCD and coating layers will be tested, and a test program in the FNAL neutron therapy area for CCD imager array for a Phase II will be proposed.

COMMERCIAL APPLICATIONS AND OTHER BENEFITS

Low cost, micron-level resolution neutron detectors would have a wide range of applications from material interrogation for nuclear materials to quality assessment on hydrogen cell production, superconducting RF facbrication and other industrial applications.

KEY WORDS: neutron detection, neutron imaging, materials control, fuel cycles.

SUMMARY FOR MEMBERS OF CONGRESS

Cutting edge technology from cosmology can be applied to materials testing and control for nuclear power and proliferation issues, and other industrial applications.

Adaptation of CCDs for Neutron Detection and Imaging

Table of Contents

b. Proprietary Data Legend – Not Applicable

Project Overview

Nuclear power provides over 20 percent of the U.S. electricity supply without harmful greenhouse gases or air pollutants, and demand is not likely to decrease anytime soon. On the contrary, many new technologies are being studied and prototyped that produce fission without achieving criticality that could encourage a renaissance of nuclear energy without its major safety hazard. For example, accelerator driven subcritical (ADS) reactors[1],[2] will allow for the use of alternatives to enriched uranium fuel such as thorium and depleted uranium. This also provides the solution for handling generations of nuclear waste. These involve accelerators as sources of neutrons for driving reactions.

This will only increase the need for new, robust methods and technologies to address key issues concerning nuclear fuel transport and storage, future deployment of nuclear energy, in order to preserve the U.S. leadership in nuclear technology and engineering, while reducing the risk of nuclear proliferation. Among other fronts, advanced technologies for the fabrication, characterization and non-destructive testing of high quality nuclear reactor fuel need to be explored.

Imaging materials radiography/tomography that could assist in new safeguards approaches for spent fuel storage and processing. We will investigate how to adapt CCDs as neutron detectors in neutron imaging systems that can scan for milliradian-level deflections for material assessments. The CCDs under consideration will exploit their low-noise resolution capablitlies of thi

c. Identification and Significance of the Problem or Opportunity, and Technical Approach

Identification and Significance of the Problem or Opportunity

Active interrogation, a measurement technique which uses a radiation source to probe materials and generate unique signatures useful for characterizing those materials, is a powerful tool for assaying special nuclear material. The most commonly used technique for performing active interrogation is to use an electronic neutron generator as the probe radiation source. Some examples include measuring the plutonium content of spent fuel, assaying plutonium residue in spent fuel hull claddings, assaying plutonium in aqueous fuel reprocessing process streams, and assaying nuclear fuel reprocessing facility waste streams to detect and quantify fissile material. Advanced fuels to be used in these initiatives will be hybridized mixtures of not only uranium and plutonium but also other transuranic elements including americium, neptunium, and curium. The presence of these extra materials adds complexity to the safeguards problem, which means more and advanced and complementary methods of interrogation need to be employed. In particular, neutron imaging has been identified as having an important role in materials assessment[3].

Neutron Imaging

Neutron imaging has wide industrial and scientific significance and can provide detailed information concerning the inner structure and composition of objects. The principle of neutron imaging is based on the attenuation, through both scattering and absorption, of a directional neutron beam by the matter through which it passes. Since different materials vary in their ability to attenuate neutrons, both composition and structure can be probed. The neutron imaging technique, rather than being in competition with X-ray imaging, is entirely and ideally complimentary to it. Whereas X-rays are scattered and absorbed by the electrons, and as such atoms with greater electron shells interact more strongly, neutrons on the other hand interact with the atomic nuclei. Furthermore there is no real periodic regularity dictating the degree of this interaction, and even isotopes of the same element may differ markedly in their attenuation ability. Of particular practical significance is the high contrast between hydrogen, which interacts very strongly with neutrons, and most metals, which offer effective transmission of neutrons, as illustrated in Figure 1. This is directly opposed to X-ray imaging, and offers the means to effectively visualize the dynamics of organic hydrogen-containing substances in metal containers, such as the ability to visualize fuel within engines. The degree of attenuation for some materials can sometimes depend on the neutron energy, fast or thermal neutrons, such is the case with iron.

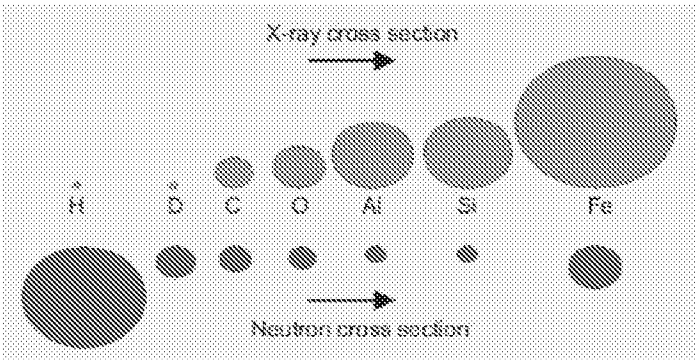

Figure 1. Neutron and x-ray scattering compared. Note the strong interaction with hydrogen while penetrating aluminum.

Strong neutron sources like research reactors and accelerator-based spallation neutron sources can provide intense neutron beams, required for efficient and practical neutron imaging. Such beams have been successfully used for neutron radiography during the last two decades and neutron radiography has found its greatest applications in the examination of nuclear fuels, explosives, electronic components and engine turbines blades. Another example of a beam of collimated low energy (thermal) neutrons is the NIST Center of Neutron Research (CNR) facility. Progress in furthering applications has led to the development of three-dimensional imaging methods (tomography), the exploitation of different neutron energies in the impinging beam to gain additional information and the real-time analysis of systems. The outcome from the application of the neutron imaging depends strongly on the neutron source properties and the detection system used. This has, in turn, generated much demand for research and development in these areas.

Digital Neutron Imaging Detectors

Detection systems have taken a big jump from conventional photographic film to digital real-time imaging. Thin-film-coated semiconductor devices have been investigated for thermal neutron detection, all of which have generally used ^{10}B, ^{6}Li, ^{6}LiF, and Gd coatings as the neutron reactive layer. Each has advantages and disadvantages regarding neutron detection efficiency and background gamma ray discrimination. Figure 2 illustrates the scheme: neutrons absorbed in the neutron-reactive film release charged particle reaction products in opposite directions. Only one reaction product may enter the semiconductor detector. Charged particles entering the detector lose their energy through Coulombic scattering, thereby creating a high-density plasma cloud of columnar ionization in the form of electron-hole pairs. The semiconductor diode detector is voltage biased to separate the electron-hole pairs and drift the charges to their respective contacts.

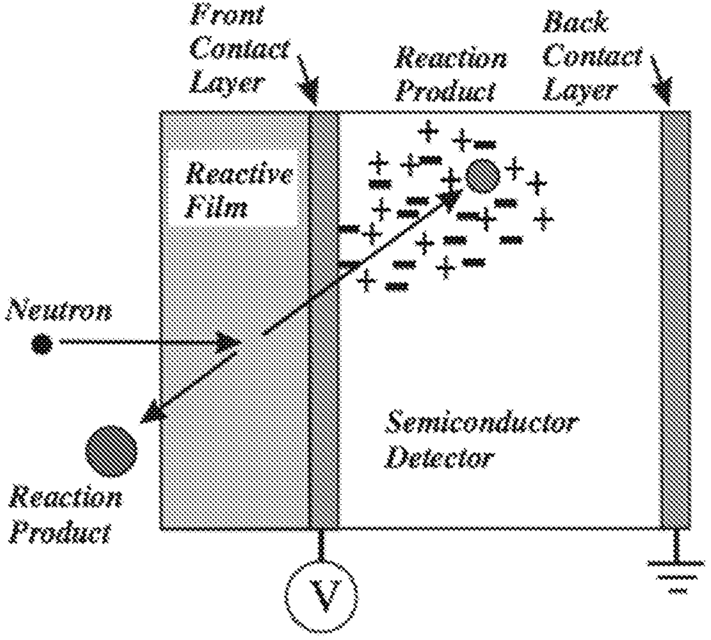

Figure 2. The fundamental approach to a thin-film-coated semiconductor neutron detector.

Unfortunately, with front-irradiated devices, the basic design limits the thermal neutron detection efficiency to only 3.95% for ^{10}B-coated devices and only 4.3% for ^{6}LiF-coated devices. Detection efficiency and particle ID is significantly improved two ways. The semiconductor detector we will consider was developed for the Dark Energy Camera (DECam) built for the Dark Energy Survey [4],[5]. These particular high-resistivity silicon charge coupled devices (CCDs) exploit the plasma effect for particle ID high resolution. Layering and deposition methods with micronized boron 10 (such as will be described below), that do not compromise the performance of these detectors will be the consideration of this Phase I.

CCD Detectors and High Resolution Neutron Detection.

The DECam CCDs are 250 mm thick, fully depleted, back-illuminated devices fabricated on high-resistivity silicon. The CCDs considered for this proposal have 8 million 15 µm X 15 µm pixels. Figure 3(a) shows the 3-phase, p-channel CCD design. The 10kΩ-cm resistivity corresponds to a dopant density of around 10^{11} cm^{-3}, allowing a fully depleted operation at bias voltages of ~ 20-25 V for 250 mm thick devices. The effect of the bias voltage is to remove free electrons from the extremely small number of phosphorous dopant atoms in the silicon, creating an electric field due to the dopant atoms that are now ionized and positively charged. The field extends essentially all the way to the backside contact, depleting the entire volume of the CCD substrate. Figure 3(b) shows the modeled, two-dimensional potential field distribution within the substrate.

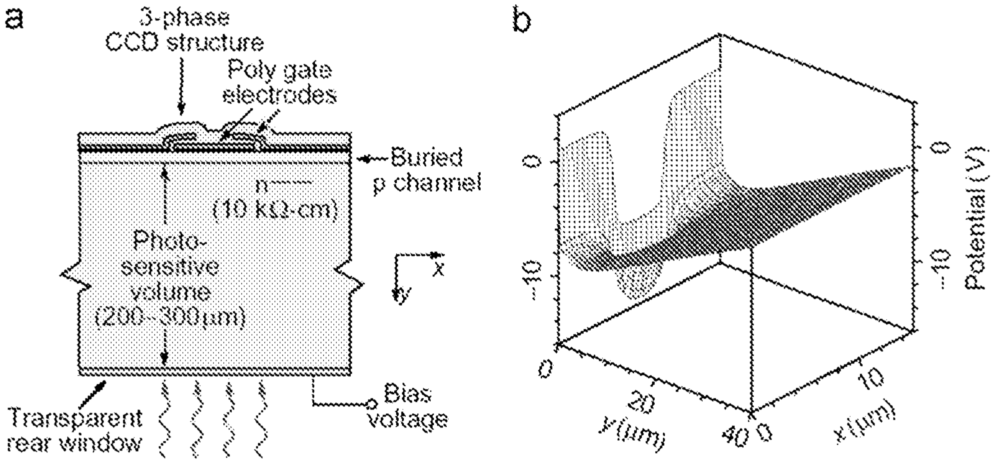

Figure 3. (a) Cross-section of the LBNL fully depleted CCD. A conventional buried channel CCD is fabricated on a high-resistivity silicon substrate. A bias voltage applied to the backside electrode results in full depletion. (b) A two-dimensional simulation showing the potential in a fully depleted CCD that directs the photo-generated carriers into the potential wells formed by voltages on the frontside CCD gate electrodes.

The DECam CCDs were tested for alpha particle detection in two energy regimes: a few MeV from an ^{241}Am source and a lower energy regime. For the latter, a 5 mm thick ^{10}B layer was placed 3mm away from the CCD, and irradiated with a ^{252}Cf neutron source. The nuclear reactions (with their respective probabilities) inside the borated layer are:

$n + {}^{10}B \rightarrow {}^{7}Li$ (1.015 MeV) + α(1.777 MeV) 6%

$n + {}^{10}B \rightarrow {}^{7}Li$ (840 keV) + α(1.470 MeV) 94%

Due to the plasma effect, the reconstructed charge clusters for α-particles are easily distinguishable from photons, β-particles and muons. The reconstructed tracks produce large circular hits, with a second order moment of _2 pixels for energies of 4 MeV. Given the small pixels of the CCDs (15 µm x 15 µm) the centroid of each of these α-particle tracks can be measured with a precision of a few micrometers.

Figure 4 shows the difference among the limited diffusion hits (point like events), tracks due to muons, and circles generated by α-particles. Photons with energies below ~100 keV interact with the silicon mostly through photo electric effect, producing a localized charge deposit. At energies ~1 MeV gammas will be clearly separated from alphas because they will not produce a large cloud of charge, just a small cluster of Compton electrons.

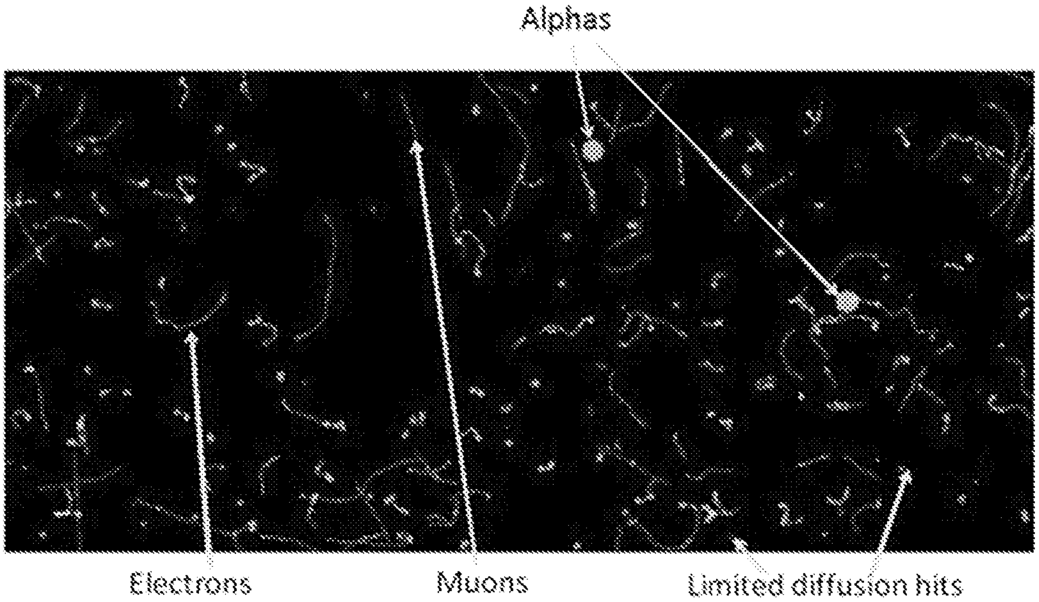

Figure 4. Picture of an exposure of the DECam CCD to cosmic rays. Muons, alphas, electrons and low energy photons can be distinguished by their signatures on the CCD [6].

Neutron imaging, the direct production of images by transmitting a beam of thermal neutrons through an object, could benefit from this high resolution tracking of α-particles. The resolution for neutron imaging application has typically two components: the beam collimation and the detector. Usually the detector corresponds to an active medium, such as a scintillator, that converts the thermal neutrons into photons or other charged particles of higher energy. These particles are projected into the detector that produces the image. By using a boron-coated CCD as a detector, α-particles would be produced by the thermal neutrons, achieving resolutions of only a few microns for the imaging, as illustrated in Figure 5.

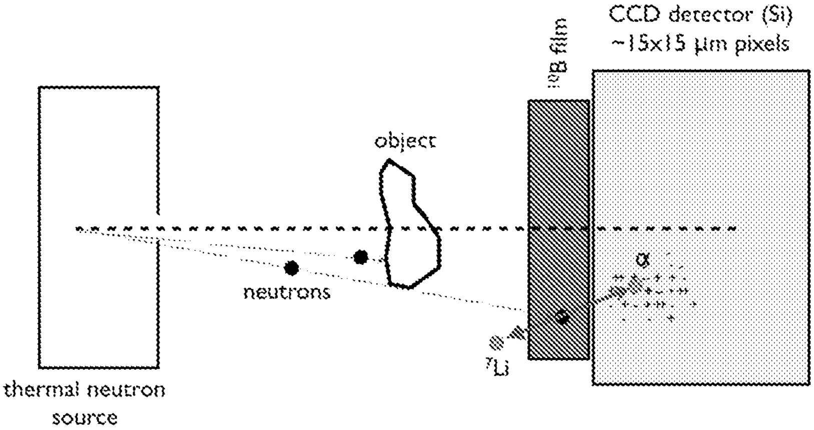

Figure 5. Neutron imaging is performed by transmitting a beam of thermal neutrons through an object onto a thin film of Boron-10 deposited on a CCD.

One novel configuration that we will be exploring is the “sandwiching” deposition layers between two layers of CCDs, back to back. This will increase information about the neutron interaction by the ability to read-out out the recoil nuclear fragment as well as the alpha particle. This is illustrated in Figure 6.

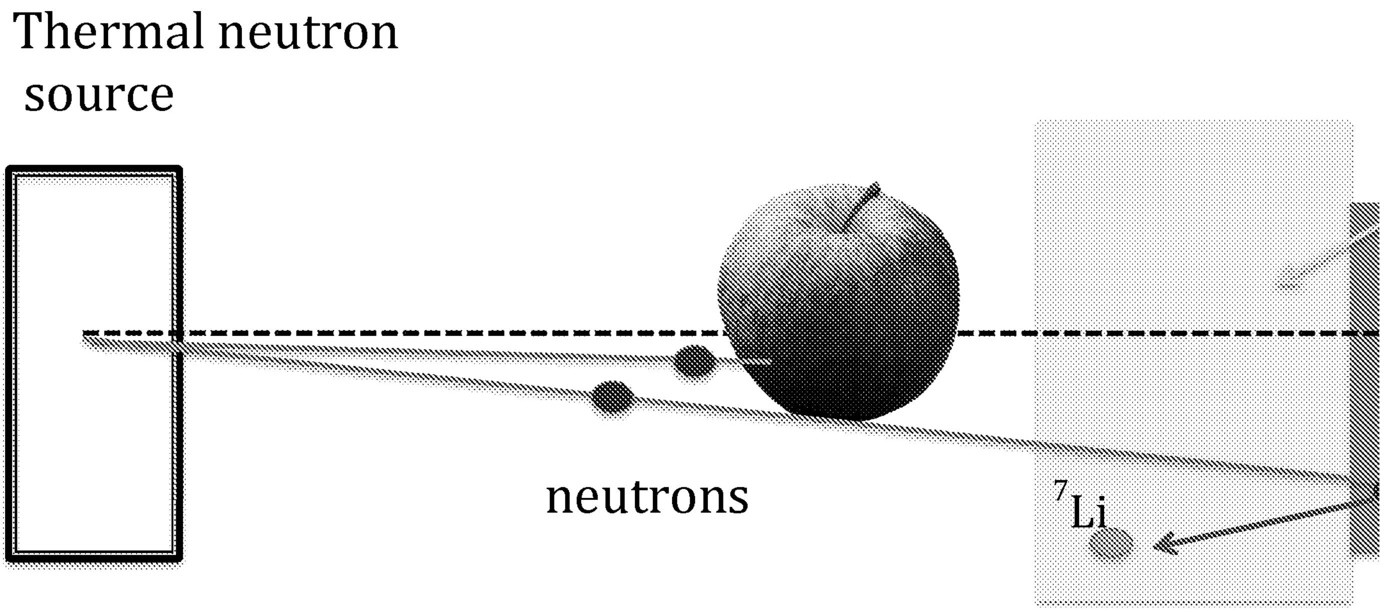

Figure 6. Neutron imaging from two sides of a boron layer.

In Phase I we will investigate adapting these CCDs with suitable boron coating for neutron detection. We anticipate that these CCDs will allow us to achieve micron level resolution and at the same time 1 frame per second. A comparison to other techniques is shown in Figure 7.

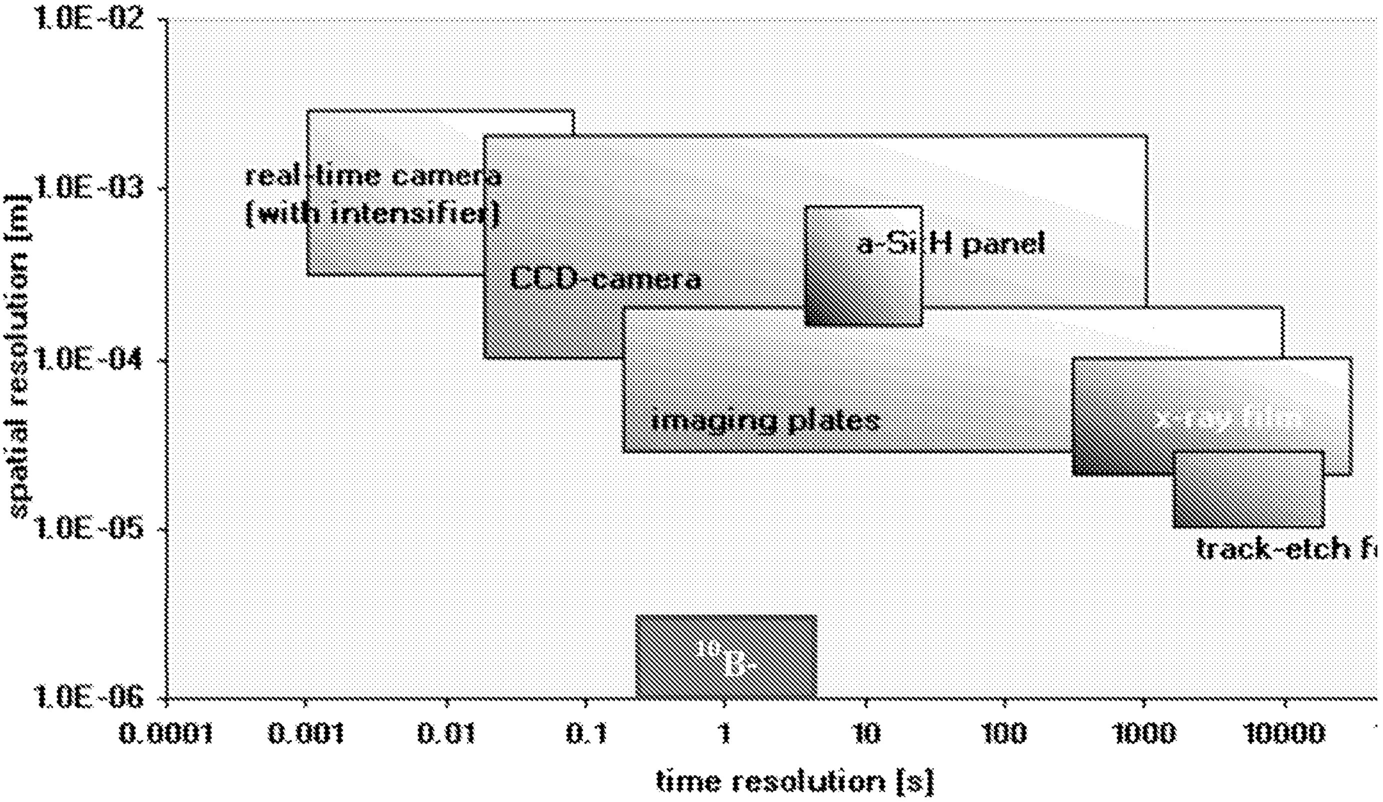

Figure 7. Comparison of neutron imaging detectors in terms of spatial resolution and read-out times.

Technical Approach

We would like to develop a method of directly coating the CCDs that does not compromise their low-noise performance, and can produce neutron detectors of high efficiency and uniform response. We will concentrate first on variations of a cold gas spraying technique that is illustrated in Figure 8.

Traditional thermal spray coating methods (plasma, electric arc, HVOF) require high temperature of material particles to adhere to a surface. Typically this temperature exceeds the material melting point thereby creating problems inherent in thermal spray. Traditional thermal methods by definition create undesirable chemistry changes and associated stresses along with defect causing oxidation.

The application of cold gas dynamic spray technology is straightforward: A powdered metal, metal/ceramic blend, or polymer is accelerated by compressed air through a supersonic nozzle and is sprayed on the surface to be coated. The hardness, porosity, and thickness of deposited coatings can be controlled by adjustments to the air pressure, pre-heater, and nozzle. Spraying at supersonic velocity forms a strong bond without the undesirable side effects inherent in conventional thermal methods. The cold gas dynamic spray method is that the application equipment and deposited coatings have no limitations inherent in other thermal coating methods and without the complexity of detonation or exotic gas inherent in other deposition methods.

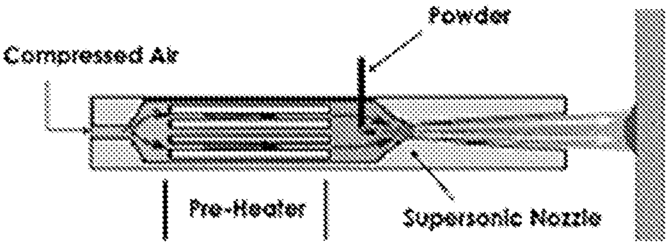

Figure 8. Schematic of the application of cold gas dynamic spray.

We intend to do a study of various coatings of micronized boron, varying thicknesses of deposition layers and purity of the boron. We want to develop a coating process onto the CCDs that will optimize the detection of neutrons and can be standardized for production of a complete neutron detector array for neutron beam tests.

d. Anticipated Public Benefits

Apart from materials interrogation, nuclear proliferation issues, there is a growing demand for imaging on a variety of scientific and industrial applications.

The NSF has appreciated the importance and potential of neutron imaging by devoting a center to it. High resolution imaging by neutrons can complement current photon and electron interrogation methods by providing resolution in areas where these technologies fall short as illustrated above.

In addition to national security, nuclear energy and hydrogen fuel cell development, the next generation of particle physics machines, including Neutrino Factories and Muon Colliders will be depend on superconducting RF for large accelerating gradients. Hydrides appear to be a big factor in performance limitation in SRF cavities. Neutron imaging may be a superior technology replacing the TEM schemes currently employed [7].

e. Technical Objectives

We have two objectives for the Phase I proposal:

1. Create durable boron high performance coatings for CCDs.
2. Design and build a CCD array to enhance neutron imaging over large areas.

f. Phase I Work Plan

1. Setup test stand for CCD neutron imager. This includes a vacuum vessel and vacuum system capable of attaining 5x 10^{-5} atm cc/sec. vacuum (remove water vapor), CCD

holder, data cables, a cold finger to cool CCDs to -100c using a cyro-cooler. Setup preamp/amplifier and data acquisition system along with associated power supplies.

2. Find and identify boron particle size and purity best suited for coating CCDs.

3. Create a mask and ground system to allow coating CCDs without temperature and electro static discharge (ESD) related problems.

4. Coat blank silicon wafers with high purity boron using cold dynamic spraying. This process would reduce the problem of high temperatures and esd which are two failure modes in handling and using CCDs.

5. Install CCD in test vessel connected to copper frame support for cyro-cooler connection, ground and signal conditioning as well as cable strain relief and stabilizing CCD alignment for accurate imaging.

Responsibilities

MuPlus, Inc.: The direction of the project is the responsibility of the company and the PI. The project activities include test development and plans for the CCD coatings and test set-up.

FNAL: Dr. Juan Estrada will be responsible for the FNAL subgrant.

g. Phase I Performance Schedule

3 months after start of funding:

1. Will have found vendors for high purity sub micron boron
2. Determined coating procedure for boron coating.
3. Will have created test stand for source testing CCD performance
4. Will have sample coated a silicon substrate with sub-micron boron using cold dynamic spraying

6 months after start of funding:

1. Will have tested several different particle sizes of boron to evaluate CCD performance.
2. Tested CCDs with CA 252 neutron source in test stand.

9 months after start of funding:
1. Completed feasibility evaluation of cold dynamic spray (or other) process.
2. Completed boron coating evaluation.
3. Completed neutron test stand data analysis.
4. Experiment with “sandwich” or multilayer configuration to increase efficiency.

5. Development of complete CCD array for beam test
6. Preparation of Phase II proposal

h. Related Research or R&D

The complete MuPlus, Inc. program is summarized in the Commercialization Plan document that is part of this proposal. Related projects that are associated with next generation particle detection and intense background studies for a muon collider are described there. Our parent company, Muons, Inc., is a member of the Large Area Fast Photo-Detectors (LAPD) Collaboration, and have been involved in pico-second fast time of flight counters in previous SBIR/STTR contracts. Our parent company is also involved in a variety of projects involving superconducting RF, for which neutron imaging may prove a valuable to in enhancing cavity performance.

i. Principal Investigator and other Key Personnel

MuPlus, Inc. Scientist and Principal Investigator: Dr. Mary Anne Cummings most recently worked at Northern Illinois University on neutrino factory and muon collider R&D, and remains on the graduate faculty there. Her previous experience at NIU has including work on high energy physics experiments (Minerva and the D0 experiment) and astrophysics experiments (for AUGER and RICE). She has been the spokesperson for a proposed Radio-coherence experiment at Fermilab in conjunction with the RICE collaboration (now part of ICECUBE). Her primary responsibilities on D0 included leading the muon detector calibration group and the “alljets” top quark analysis group. She is currently working with the scientists in the MAP group on background calculations for muon collider interaction regions, and designing elements for six-dimensional cooling channels for muon accelerators.

FNAL subgrant Principal Investigator: Juan Estrada is a Fermilab scientist at the Center for Particle Astrophysics. He is the principal scientist building and testing imaging sensors for the Dark Energy Camera. He has set himself apart by using the same technology in a side project to search for dark matter called DAMIC for Dark Matter in CCDs. He had worked on cosmology as an undergraduate in Argentina, and started at Fermilab as a student from the University of Rochester working on the DZero experiment. He eventually earned a Wilson Fellowship. He is a 2010 recipient of the Presidential Early Career Award for Scientists and Engineers for his innovation in CCDs that resulted in the best detector in the world for spotting low-mass dark matter particles. Estrada builds charge-coupled devices, the same type of imaging sensors found in digital cameras, for the 570-megapixel Dark Energy Camera. These CCDs are specifically designed to capture the light that reaches Earth from extremely distant galaxies and supernovae. The Dark Energy Survey will use data from the camera to search of signs of dark energy, which scientists theorize affects the evolving shape of the universe.

j. Facilities/Equipment

MuPlus Inc. currently shares facilities with Muons, Inc. This includes a building of approximately 4000 square feet of floor space in Batavia, Illinois, a short drive from Fermilab, which is used as office space, conference rooms, workshop area, and living quarters as needed. We also share office space with Muons, Inc. in Wilson Hall at Fermilab (Batavia, IL) and in the ARC building at Jefferson Lab (Newport News, VA). We have several high-performance personal computers and workstations with high-speed net access and sufficient computing power to perform simulations and CAD work.

Fermilab is located on a site of 6800 acres in Batavia, Illinois. It needs no introduction here. For this particular project, it has all the necessary facilities and equipment for testing CCDs in Phase I, and for a prototype CCD imaging array construction and tests for Phase II. In particular, hundreds of individual CCDs are available left over from the DECam project, some configured into instrumented arrays or engineering "packages" which will be good for deposition tests.

k. Consultants and Subcontractors

Our partner Research Institution is Fermi National Accelerator Laboratory. The certifying official is:

Dr. Bruce Chrisman
M.S. 200
Fermilab
P.O. Box 500
Batavia, IL 60510
Phone: (630) 840-6657
E-mail: chrisman@fnal.gov

We have no plans for another research partner or consultants during Phase I of this project.

References

[1] http://world-nuclear.org/info/inf35.html
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[3] D. L. Chichester and E. H. Seabury, *Active Interrogation Using Electronic Neutron Generators for Nuclear Safeguards Applications,* CAARI, Ft. Worth, TX, 2008.
[4] S.E. Holland, D.E. Groom, N.P. Palaio, R.J. Stover, M. Wei, IEEE Transactions on Electron Devices ED-50 (2003) 225.
[5] C. Abbott, et al., Ground-based and airborne instrumentation for astronomy, in: I.S. McLean, M. Iye (Eds.), Proceedings of the SPIE, vol. 6269, 2006.
[6] J. Estrada *et al.*, Nuclear Instruments and Methods in Physics Research A 665 (2011) 90–93.
[7] http://www.cryogenicsociety.org/7782/news/romanenko_improves_srf_cavities/

CLAIMS

1. A device comprising:

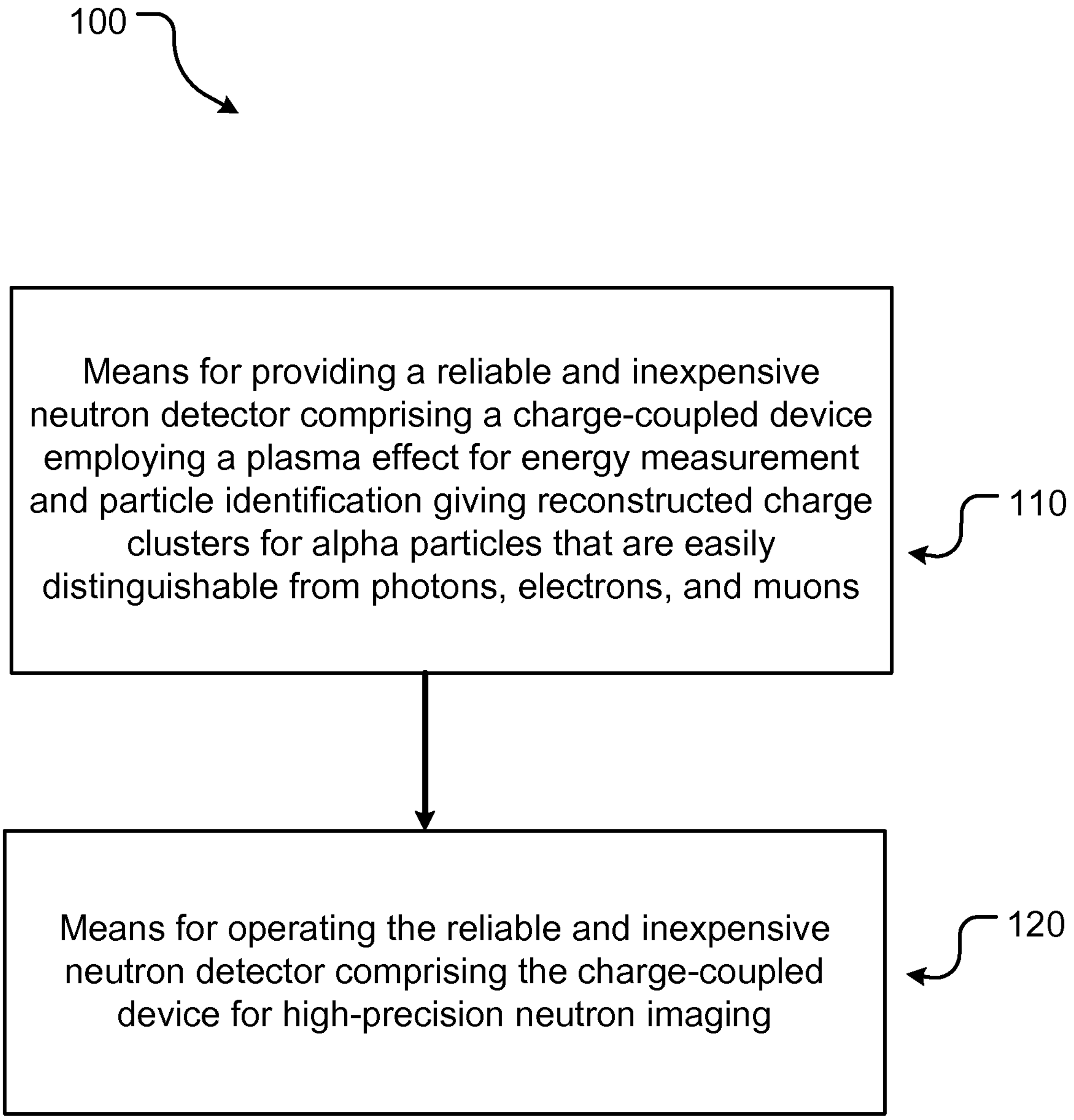
means for providing a reliable and inexpensive neutron detector comprising a charge-coupled device employing a plasma effect for energy measurement and particle identification giving reconstructed charge clusters for alpha particles that are easily distinguishable from photons, electrons, and muons; and

means for operating the reliable and inexpensive neutron detector comprising the charge-coupled device for high-precision neutron imaging.

2. A method comprising:

steps for providing a reliable and inexpensive neutron detector comprising a charge-coupled device employing a plasma effect for energy measurement and particle identification giving reconstructed charge clusters for alpha particles that are easily distinguishable from photons, electrons, and muons; and

steps for operating the reliable and inexpensive neutron detector comprising the charge-coupled device for high-precision neutron imaging.



Means for providing a reliable and inexpensive neutron detector comprising a charge-coupled device employing a plasma effect for energy measurement and particle identification giving reconstructed charge clusters for alpha particles that are easily distinguishable from photons, electrons, and muons

Means for operating the reliable and inexpensive neutron detector comprising the charge-coupled device for high-precision neutron imaging

FIGURE 1

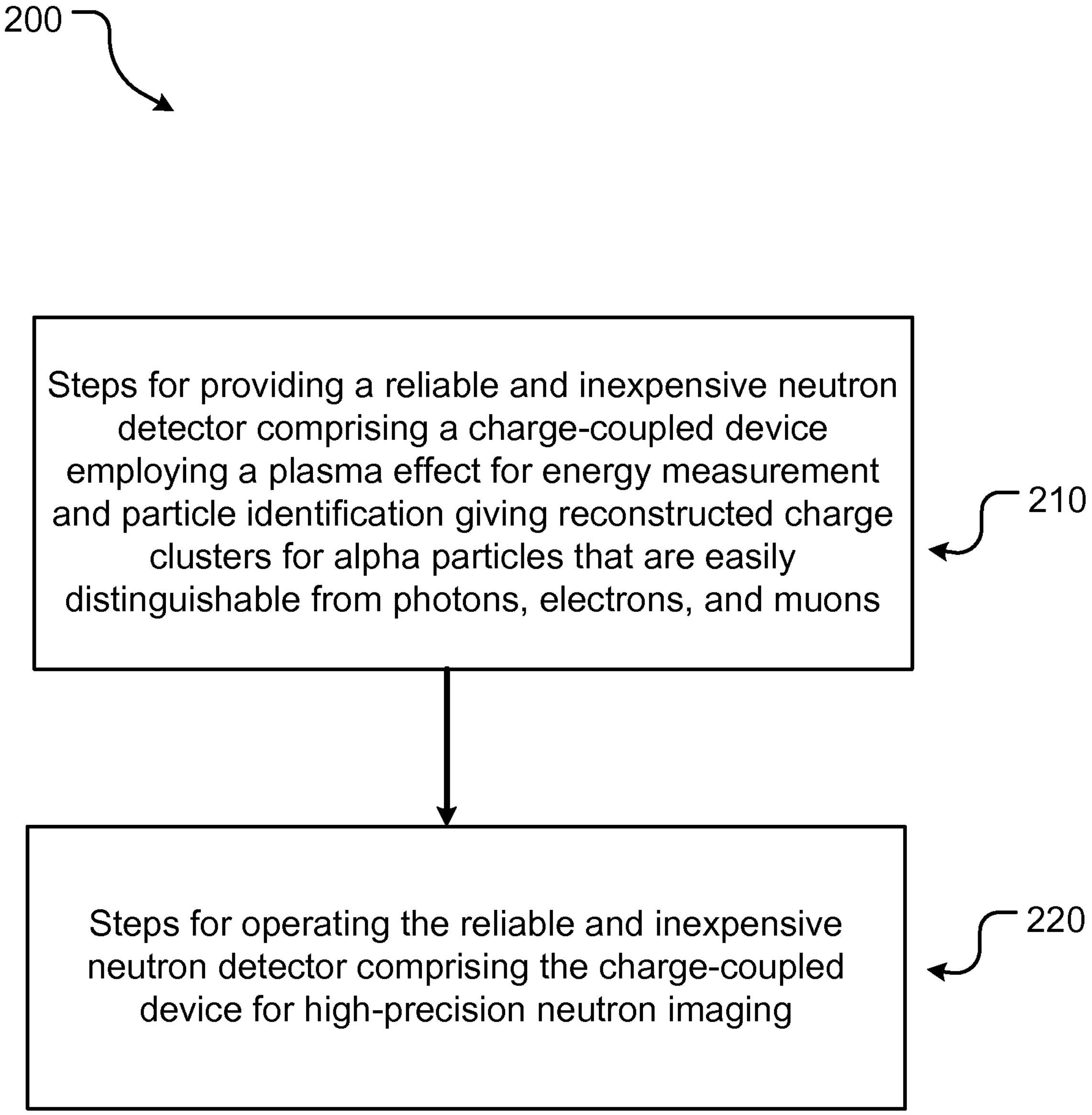

200
Steps for providing a reliable and inexpensive neutron detector comprising a charge-coupled device employing a plasma effect for energy measurement and particle identification giving reconstructed charge clusters for alpha particles that are easily distinguishable from photons, electrons, and muons
210
Steps for operating the reliable and inexpensive neutron detector comprising the charge-coupled device for high-precision neutron imaging
220

FIGURE 2

INTERNATIONAL SEARCH REPORT	International application No. PCT/US 2013/024521

A. CLASSIFICATION OF SUBJECT MATTER *H01L 31/115 (2006.01)* 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) G01N 23/00, 23/02, G01T 1/00, 1/185, 3/00, 3/08, H01L 39/00, 31/115
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 practicable, search terms used) PatSearch (RUPTO internal), Esp@cenet, PAJ, USPTO

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2008/0121809 A1 (INTEGRATED SENSOR, LLC) 29.05.2008, [0002], [0015], [0026]-[0123]	1-2
A	US 2009/0072141 A1 (JAPAN SCIENCE AND TECHNOLOGY AGENCY et al.) 19.03.2009	1-2
A	US 7902513 B2 (THE UNITED STATES OF AMERICA AS REPRESENTED BY THE SECRETARY OF THE NAVY) 08.03.2011	1-2
A	RU 2207550 C2 (VSEROSYSKY NAUCHNO-ISSLEDOVATELSKY INSTITUT AVTOMATIKI) 27.06.2003	1-2

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document but 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)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"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	"&"	document member of the same patent family

Date of the actual completion of the international search 18 March 2013 (18.03.2013)	Date of mailing of the international search report 25 April 2013 (25.04.2013)
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