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(54) Title: METHOD FOR BIOLOGICAL IDENTIFICATION USING HIGH TEMPERATURE SUPERCONDUCTOR ENHANCED NUCLEAR QUADRUPOLE RESONANCE

(57) Abstract: This invention relates to a method for identifying biological agents using high temperature superconductor enhanced nuclear quadrupole resonance. The targeted biological agents are attached to functionalized nanoparticles and the quadrupole nuclei in these nanoparticles are detected by the nuclear quadrupole resonance detection system.

WO 2005/081002 A2

TITLE

METHOD FOR BIOLOGICAL IDENTIFICATION USING HIGH
TEMPERATURE SUPERCONDUCTOR ENHANCED NUCLEAR QUADRUPOLE
RESONANCE

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Field of the Invention

This invention relates to the use of high
temperature superconductor enhanced nuclear quadrupole
resonance to detect biological agents.

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Background of the Invention

With the increased concern regarding bioterrorism
and the need to promote homeland security, it is
critical to have a method for the rapid detection and
identification of biological agents that could be used
for terrorism.

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The use of nuclear quadrupole resonance (NQR) as a
means of detecting explosives and other contraband has
been recognized for some time, see e.g. T. Hirshfield
et al, *J. Molec. Struct.* 58, 63 (1980), A.N. Garroway
et al, *Proc. SPIE* 2092, 318 (1993), and A.N. Garroway
et al, *IEEE Trans. on Geoscience and Remote Sensing* 39,
1108 (2001). NQR provides some distinct advantages
over other detection methods. NQR spectroscopy can
detect and discriminate specific solid state materials
containing quadrupole nuclei, *i.e.* nuclei with a
quadrupole moment. As with nuclear magnetic resonance
(NMR), a radio frequency coil produces an oscillating
magnetic field at a frequency identified with a
specific compound containing one or more quadrupole
nuclei. If the specific compound is present a return
NQR signal is detected. Unlike NMR, NQR requires no
static magnetic field. NQR spectroscopy is extremely
cost effective since it is a radio frequency (RF)
technique in a frequency region where silicon based

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electronics operate. NQR detection systems use non-ionizing magnetic fields near 5 MHz, and therefore present no health hazards to nearby workers and will not damage materials sensitive to ionizing radiation.

5 The average power of the applied oscillating magnetic field in a NQR detection system is about 100 Watts, and it can thus operate from standard alternating current (AC) electrical outlets (either 110V or 240V).

10 A number of fundamental problems exist for the conventional approach to NQR spectroscopy. These problems result in low throughput and long measurement times. The use of high temperature superconductor (HTS) self-resonant structures, particularly HTS self-
15 resonant receive coils, *i.e.* sensors, dramatically improves the sensitivity of the NQR spectrometer. For example, the high quality factor Q of an HTS sensor results in a 5-20 dB improvement in the signal-to-noise ratio (S/N) as compared to a conventional sensor. This
20 is important in view of the low intensity NQR signal. HTS enhanced NQR systems have been scientifically demonstrated for the detection of macroscopic samples of contraband such as explosives and drugs.

25 The object of this invention is to use HTS enhanced NQR systems to provide a method for detecting biological agents, particularly those that could be used for bioterrorism.

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Summary of the Invention

In one embodiment, this invention provides a method for detecting one or more targeted biological agents in air by:

35 (a) collecting a biological agent from the air and concentrating the biological agent in a liquid to form a sample thereof;

- 5 (b) placing functionalized nanoparticles in the liquid with the biological agent, wherein the functionalized nanoparticles contain nuclei with a quadrupole moment and wherein the functionalized nanoparticles attach to the one or more targeted biological agents to produce assembled nanoparticle-biological agent composites;
- 10 (c) filtering and drying the assembled nanoparticle-biological agent composites to form a nanoparticle-biological agent sample;
- 15 (d) placing the nanoparticle-biological agent sample in a NQR spectrometer, the NQR spectrometer comprising one or more high temperature superconductor coils that serve both as excitation coils to provide a radio frequency magnetic field to excite the quadrupole nuclei in the nanoparticles of the nanoparticle-biological agent sample and receive coils to detect the nuclear quadrupole resonance signal from the quadrupole nuclei; and
- 20 (e) using the NQR spectrometer to excite the quadrupole nuclei and detect the quadrupole NQR signal and thereby confirm the presence of the one or more targeted biological agents.

30 In another embodiment, this invention provides a method for detecting one or more targeted biological agents in air by:

- (a) collecting a biological agent from the air and concentrating the biological agent in a liquid to form a sample thereof;
- 35 (b) placing functionalized nanoparticles in the liquid with the biological sample, wherein the functionalized nanoparticles contain nuclei with a quadrupole moment and wherein

the functionalized nanoparticles attach to the one or more targeted biological agents to produce assembled nanoparticle-biological agent composites;

- 5 (c) filtering and drying the assembled nanoparticle-biological agent composites to form a nanoparticle-biological agent sample;
- (d) placing the nanoparticle-biological agent sample in a NQR spectrometer, the NQR spectrometer comprising:
- 10 (i) one or more coils used solely as excitation coils to provide a radio frequency magnetic field to excite the quadrupole nuclei in the nanoparticles of the nanoparticle-biological agent sample, and
- 15 (ii) one or more coils used solely as receive coils to detect the nuclear quadrupole resonance signal from the quadrupole nuclei; and
- 20 (e) using the NQR spectrometer to excite the quadrupole nuclei and detect the quadrupole NQR signal and thereby confirm the presence of the one or more targeted biological agents.

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In still another embodiment, this invention provides a method for detecting one or more targeted biological agents in air by:

- (a) collecting a biological agent to form a sample thereof;
- 30 (b) forming assembled nanoparticle-biological agent composites using functionalized nanoparticles and said biological agent contained in the sample, wherein the nanoparticles contain quadrupole nuclei;
- 35 (c) placing the nanoparticle-biological agent composites in a NQR spectrometer; and

- 5 (d) using the NQR spectrometer to excite the quadrupole nuclei and detect the quadrupole NQR signal and thereby confirm the presence of the one or more targeted biological agents.

In yet another embodiment, this invention involves a method for detecting one or more targeted biological agents using a NQR spectrometer by:

- 10 (a) preparing nanoparticle-biological agent composites, wherein the nanoparticles contain quadrupole nuclei;
- (b) placing the nanoparticle-biological agent composites in the NQR spectrometer; and
- 15 (c) using the NQR spectrometer to excite the quadrupole nuclei and detect the quadrupole NQR signal and thereby confirm the presence of the one or more targeted biological agents.
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Description of the Preferred Embodiments

The method of this invention addresses the biggest challenge for a biological agent detection system, the ability to pick out a specific signal from the targeted biological agent while minimizing any signals originating from nonpathogenic biological background. The technology that makes this possible is high temperature superconductivity enhanced nuclear quadrupole resonance. This technology has not previously been utilized for detecting biological agents.

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A critical key to the performance of a system based upon HTS enhanced NQR is the ability to miniaturize various critical RF components, such as the HTS self-resonant receive coils, sufficiently to detect small amounts of a biological agent collected during a

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short collection and analysis time such as a 2 minute
collection and analysis time. The biological agents of
interest are typically microorganisms that can cause
physical harm to or disease among personnel, animals or
5 plants. They can also cause the deterioration of
material. These agents generally fall into two broad
categories - pathogens (usually called germs) and
toxins. Pathogens are living microorganisms that cause
lethal or incapacitating diseases. Bacteria,
10 rickettsiae, fungi and viruses are included in the
pathogens. Toxins are poisons that plants, animals or
microorganisms produce naturally. Possible biological
war-fare toxins include a variety of neurotoxic
(affecting the central nervous system) and cytotoxic
15 (causing cell death) compounds.

When the biological agent is airborne, a sample of
a biological agent can be obtained in a variety of ways
such as by using one of the existing commercial aerosol
20 collection and concentration technologies, e.g.
BioCaptive™, MesoSystems, Kennewick, WA 99336. These
systems typically pass large volumes of air through the
collection system and disperse the biological agent in
a small volume of liquid such as water to form the
25 sample. When a sample is prepared in a cyclone
collector the larger particles, i.e. the particles of a
biological agent, are collected on the outer wall as a
result of centrifugal force and then fall into a
container. The smaller particles remain in the air
30 stream leaving through the air outlet. These current
systems are approximately 50% efficient in capture and
concentration of most bioterrorism agents with airflow
rates up to 1000 liters per minute.

35 If the commercial equipment does not form a sample
by dispersing the biological agent in a liquid, this
step may be carried out by simply placing the
biological agent in a small amount of liquid such as
water or any liquid that does not destroy the

biological agent or interfere with the attachment of the biological agent to a functional nanoparticle. Typically, about 10 mL or less of liquid can be used.

5 Functionalized nanoparticles, which have at least one dimension on the order of nanometers, are then added to the liquid sample containing the biological agent. Functionalized nanoparticles are prepared so that they attach themselves to the targeted biological agent, e.g. a virus, toxin, or bacterial spore. This attachment is based, for example, on nucleic acid, antibody/antigen binding or ligand/receptor interactions, and provides assembled nanoparticle-biological agent composites. The nanoparticles are
10 "functionalized" by treating their surfaces with a biological or chemical entity known to bind to the targeted biological agent. Typically, gold nanoparticles are used to make functionalized nanoparticles. Nanoparticles can, however, be made
15 from materials containing other metals such as aluminum, cobalt, copper or antimony. Functionalized nanoparticles and the biological sample can also be mixed in the dry state or in a gel. Mixing in a liquid is preferred, however, to provide a more rapid and
20 complete attachment of the functionalized nanoparticles to the biological agent.

 The functionalized nanoparticles can be of only one type that attaches to only one targeted biological agent, or can be a variety of types that attach to a
30 variety of targeted biological agents. The use of functionalized nanoparticles is a critical key to reducing the effect of nonpathogenic biological background in the environment.

35 The assembled nanoparticle-biological agent composites are filtered and, if they were prepared in liquid, dried to form a nanoparticle-biological agent

sample. Any separation process can be used that separates the assembled nanoparticle-biological agent composites from the nanoparticles that do not form a composite with the biological agent. A separation
5 system based on size is suitable because the assembled nanoparticle-biological agent composites are typically larger than the nanoparticles that do not form a composite with the biological agent. The nanoparticles that do not form a composite with the biological agent
10 can be re-used or disposed of after they have been separated from the sample.

The sample of the nanoparticle-biological agent, containing the assembled nanoparticle-biological agent
15 composites, is then placed in a NQR spectrometer. In view of the small quantity of biological material collected, the presence of nanoparticle-biological agent composites in the nanoparticle-biological agent is not visibly discernable.

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The NQR spectrometer is comprised of at least one excitation coil and at least one high temperature superconductor receive coil. A NQR spectrometer can have one or more coils that serve as both excitation
25 and receive coils or it can have separate coils that only excite and only receive. An excitation coil, *i.e.* transmit coil, of an NQR detection system provides a radio frequency (RF) magnetic field that excites the quadrupole nuclei in a sample, and results in their
30 producing their characteristic resonance signals that the receive coil detects.

In this invention, the quadrupole nuclei are in the nanoparticles of the nanoparticle-biological agent
35 sample. The quadrupole nuclei can be chosen from any of the nuclei with spin greater than or equal to 1, *i.e.* from nuclei that have a quadrupole moment. It is

preferred to use an element for which the quadrupole nucleus is a predominant isotope of that element.

5 If only one targeted biological agent is to be detected, only one type of functionalized nanoparticle, *i.e.* a functionalized nanoparticle that attaches to that targeted biological agent, is needed. In this case, detection of the nuclear quadrupole resonance frequency of the quadrupole nuclei in the nanoparticles
10 of the nanoparticle-biological agent sample confirms the presence of the targeted biological agent. If more than one targeted biological agent are to be detected, a functionalized nanoparticle that attaches to each of the different targeted biological agents is needed. If
15 each functionalized nanoparticle that attaches to at least one of the different targeted biological agents contains the same quadrupole nuclei, detection of an NQR signal will indicate that one or more of the targeted biological agents is present. Preferably,
20 however, each functionalized nanoparticle attaches to a different targeted biological agent, and each nanoparticle contain a different quadrupole nuclei. By attaching a nanoparticle containing a specific type of quadrupole nuclei to each specific targeted biological
25 agent, the detection of an NQR signal from that particular quadrupole nuclei will indicate that the specific targeted biological agent attached to the nanoparticle containing that specific type of quadrupole nuclei is present.

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In any case, if no targeted biological agent is present, there will be no nanoparticle-biological agent composites present in the sample, *i.e.* no quadrupole nuclei to excite, and therefore no NQR signal will be
35 detected. If no targeted biological agent is present, the nanoparticles will be removed from the sample by the separation process just as will those nanoparticles that do not for some reason form a composite with the

biological agent when it is present in the sample.
The nanoparticles that do form a composite will remain
in the sample after the separation process, and it is
the detection the quadrupole nuclei in those
5 nanoparticles that will indicate the presence of the
biological agent.

When the biological agent is available in a more
concentrated form, e.g. on a surface or in an envelope,
10 a biological sample can be obtained by collecting some
of the agent with a small scoop. Again the
functionalized nanoparticles and the biological sample
can be mixed in the dry state, in a gel or in a liquid
so that the functionalized nanoparticles can attach to
15 the biological agent to form assembled nanoparticle-
biological agent composites. A liquid is preferred.
Once the nanoparticle-biological agent composites are
formed, they are placed in a NQR spectrometer to detect
the one or more biological agents as described
20 previously.

It is especially advantageous to use a receive
coil, i.e. a sensor, made of a high temperature
superconductor (HTS) rather than copper since the HTS
25 self-resonant coil has a quality factor Q of the order
of 10^3 - 10^6 . The NQR signals have low intensity and
short duration. In view of the low intensity NQR
signal, it is important to have a signal-to-noise ratio
(S/N) as large as possible. The signal-to-noise ratio
30 is proportional to the square root of Q so that the use
of a HTS self-resonant coil as a receive coil results
in an increase in S/N by a factor of 10-100 over that
of a copper coil. Therefore, the use of a high
temperature superconductor receive coil with a large Q
35 provides a distinct advantage over the use of an
ordinary conductor coil. The measurements of the
method of this invention are enabled by the high Q and
extremely low losses of the HTS receive coils.

When separate coils are used for the excitation and receive coils in the method of this invention, the excitation coils can be made of copper, silver, aluminum or a high temperature superconductor. A copper, silver or aluminum coil is preferably in the form of a shielded-loop resonator (SLR) coil. SLR's have been developed to eliminate the detuning effect of the electrical interaction between the coil and the surrounding material.

When separate coils are used for the excitation and receive coils in the method of this invention, the receive coils are high temperature superconductor coils. When a single coil is used as both an excitation and a receive coil in the method of this invention, the coil is a high temperature superconductor coil. A high temperature superconductor coil is preferably in the form of a self-resonant planar coil, *i.e.* a surface coil, with a coil configuration of HTS on one or both sides of a substrate. High temperature superconductors are those that superconduct above 77K. The high temperature superconductors used to form the HTS self-resonant coil are preferably selected from the group consisting of $\text{YBa}_2\text{Cu}_3\text{O}_7$, $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$, $\text{TlBa}_2\text{Ca}_2\text{Cu}_3\text{O}_9$, $(\text{TlPb})\text{Sr}_2\text{CaCu}_2\text{O}_7$ and $(\text{TlPb})\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_9$. Most preferably, the high temperature superconductor is $\text{YBa}_2\text{Cu}_3\text{O}_7$ or $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$.

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CLAIMS

5 What is claimed is:

1. A method for detecting one or more targeted biological agents in air, comprising:
 - 10 (a) collecting a biological agent from the air and concentrating the biological agent in a liquid to form a sample thereof;
 - (b) placing functionalized nanoparticles in the liquid with the biological agent, wherein the functionalized nanoparticles contain nuclei
15 with a quadrupole moment and wherein the functionalized nanoparticles attach to the one or more targeted biological agents to produce assembled nanoparticle-biological agent composites;
 - 20 (c) filtering and drying the assembled nanoparticle-biological agent composites to form a nanoparticle-biological agent sample;
 - (d) placing the nanoparticle-biological agent sample in a NQR spectrometer, the NQR
25 spectrometer comprising one or more high temperature superconductor coils that serve both as excitation coils to provide a radio frequency magnetic field to excite the quadrupole nuclei in the nanoparticles of the
30 nanoparticle-biological agent sample and receive coils to detect the nuclear quadrupole resonance signal from the quadrupole nuclei; and
 - 35 (e) using the NQR spectrometer to excite the quadrupole nuclei and detect the quadrupole NQR signal and thereby confirm the presence

of the one or more targeted biological agents.

2. The method of claim 1, wherein two or more
5 targeted biological agents are to be detected, and the
functionalized nanoparticles are selected so that the
functionalized nanoparticles that attach to each
different targeted biological agent contain different
10 quadrupole nuclei, thereby insuring that there is a
specific type of quadrupole nuclei attached to each
different targeted biological agent.

3. The method of claim 1 or 2, wherein the one or
15 more high temperature superconductor coils are high
temperature superconductor self-resonant planar coils.

4. The method of claim 3, wherein the NQR
20 spectrometer further comprises one or more high
temperature superconductor self-resonant planar coils
used solely as receive coils.

5. A method for detecting one or more targeted
biological agents in air, comprising:

- 25 (a) collecting a biological agent from the air
and concentrating the biological agent in a
liquid to form a sample thereof;
- (b) placing functionalized nanoparticles in the
liquid with the biological agent, wherein the
30 functionalized nanoparticles contain nuclei
with a quadrupole moment and wherein the
functionalized nanoparticles attach to the
one or more targeted biological agents to
produce assembled nanoparticle-biological
agent composites;
- 35 (c) filtering and drying the assembled
nanoparticle-biological agent composites to
form a nanoparticle-biological agent sample;

- (d) placing the nanoparticle-biological agent sample in a NQR spectrometer, the NQR spectrometer comprising:
- (i) one or more coils used solely as excitation coils to provide a radio frequency magnetic field to excite the quadrupole nuclei in the nanoparticles of the nanoparticle-biological agent sample, and
 - (ii) one or more high temperature superconductor coils used solely as receive coils to detect the nuclear quadrupole resonance signal from the quadrupole nuclei; and
- (e) using the NQR spectrometer to excite the quadrupole nuclei and detect the quadrupole NQR signal and thereby confirm the presence of the one or more targeted biological agents.

6. The method of claim 5, wherein the one or more coils used solely as excitation coils are shielded-loop resonator coils.

7. The method of claim 5, wherein the one or more coils used solely as excitation coils are high temperature superconductor coils.

8. The method of claim 5, wherein two or more targeted biological agents are to be detected, and the functionalized nanoparticles are selected so that the functionalized nanoparticles that attach to each different targeted biological agent contain different quadrupole nuclei, thereby insuring that there is a specific type of quadrupole nuclei attached to each different targeted biological agent.

9. The method of any of claims 5-7, wherein the high temperature superconductor coils are high temperature superconductor self-resonant planar coils.

5 10. The method of claim 9, wherein two or more targeted biological agents are to be detected, and the functionalized nanoparticles are selected so that the functionalized nanoparticles that attach to each
10 different targeted biological agent contain different quadrupole nuclei, thereby insuring that there is a specific type of quadrupole nuclei attached to each different targeted biological agent.

15 11. A method for detecting one or more targeted biological agents using a NQR spectrometer, comprising:
 (a) preparing nanoparticle-biological agent composites, wherein the nanoparticles contain quadrupole nuclei;
 (b) placing the nanoparticle-biological agent
20 composites in the NQR spectrometer; and
 (c) using the NQR spectrometer to excite the quadrupole nuclei and detect the quadrupole NQR signal and thereby confirm the presence of the one or more targeted biological
25 agents.

 12. A method for detecting one or more targeted biological agents, comprising:
 (a) collecting a biological agent to form a
30 sample thereof;
 (b) forming assembled nanoparticle-biological agent composites using functionalized nanoparticles and the biological agent contained in the sample, wherein the
35 nanoparticles contain quadrupole nuclei;
 (c) placing the nanoparticle-biological agent composites in a NQR spectrometer; and

5 (d) using the NQR spectrometer to excite the quadrupole nuclei and detect the quadrupole NQR signal and thereby confirm the presence of the one or more targeted biological agents.

10 13. The method of claim 12, wherein two or more targeted biological agents are to be detected, and the functionalized nanoparticles used to form the assembled nanoparticle-biological agent composites are selected so that functionalized nanoparticles that attach to each different biological agent contain different quadrupole nuclei, thereby insuring that there is a specific type of quadrupole nuclei attached to each
15 different targeted biological agent.

20 14. The method of claim 12, wherein the NQR spectrometer is comprised of one or more high temperature superconductor coils that serve both as excitation coils to provide a radio frequency magnetic field to excite the quadrupole nuclei in the nanoparticles of the nanoparticle-biological agent composites and receive coils to detect the nuclear quadrupole resonance signal from the quadrupole nuclei.

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15. The method of claim 12, wherein the NQR spectrometer is comprised of:

30 (i) one or more coils used solely as excitation coils to provide a radio frequency magnetic field to excite the quadrupole nuclei in the nanoparticles of the nanoparticle-biological agent composites, and

35 (ii) one or more high temperature superconductor coils used solely as receive coils to detect the nuclear quadrupole resonance signal from the quadrupole nuclei.

16. The method of Claim 12 wherein the nanoparticle comprises gold.