Birth Of 'Atometry' – Particle Physics Applied To Saving Human Lives

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"In the 20th century, citizens have considered security the norm and occasional insecurity an aberration. From now on, it will be the reverse. Insecurity will be the enduring reality and quest for national security a continuing preoccupation."

- Zbigniew Brzezinski ("The Choice", 2004)

REVISED January 2007

Abstract. Atometry, first non-intrusive explosive and bioagents diagnostic system, provides *stoichiometry of unknown substances by means of elementary particles*. The technique (1) *deciphers* empirical chemical formulas of unknown objects through steel and other barriers and displays, in real time, $C_aN_bO_c$, where a, b, and c are the atomic proportions of carbon, nitrogen, and oxygen, with a 97.5% (3σ) statistical probability; (2) retrieves their 2D or 3D images. This is achieved by a combined action of fast neutrons, γ rays and α particles (API) or only fast neutrons and γ rays (Non-API). Only *non*-pulsed (DC) neutrons are used. Operational experience with API Atometry, Non-API Straight Atometry and Non-API Mini Atometry are described. Atometry compares with the currently used explosive detection systems (EDS) like color with B & W photography. It has many potential, hitherto unexplored, medical and industrial applications.

Keywords: atometer, explosive detection system
PACS: 29.90,+r

MOTIVATION

Unlike most or all the papers presented at this conference, the work I will present here was motivated *not* by the pursuit of knowledge of fundamental processes but by the *conscience* of a physicist as an ordinary human being. In former Yugoslavia, my birthplace, landmines and unexploded munitions continue to kill or maim one human being every day, mostly children. Worldwide, landmines kill or maim one person every 20 minutes. It is even less known that scientific or technical methods and means to stop the massacre in the minefields do not exist. To this date, none of the Explosive Detection Systems (EDS) currently manufactured and used is chemically specific. They cannot discriminate explosive from non-explosive in the luggage without manual inspection.

YOU CANNOT SOLVE 21ST CENTURY PROBLEMS WITH 19TH CENTURY PHYSICS

Most EDS's are based on Electro-Magnetism (EM). Metal detectors and X-rays are 19th Century physics. Other EM based devices such as GPR, UV, IR and microwaves are chemically blind. They can detect the locations, shapes and density of hidden objects but have no ability to deduce their chemical composition. The only EM detector being used in practice that can tell more - whether the object contains low Z or high Z elements - is the back-scattered X rays. It reduces the false alarm rate but it still requires the invasive opening, that is, a human intervention, in each low Z case. There are 2 other EM methods, Quantum Magnetic Resonance and X-Ray diffraction, that can chemically identify certain explosives under certain conditions. We will not discuss them due to the limited space and the fact that they are currently of limited usefulness.
Detecting an explosive is a 2 step process: (1) primary *anomaly* detector, i.e. the alarmer of "possible" explosives and (2) secondary *confirmation* sensor, which conclusively determines by a close examination (until now always manual) whether the suspicious object contains explosive or is it a "false alarm."

False alarm rates in minefields are 99.75% to 99.87%. To find one landmine, de-miners have to unearth 400 to 800 objects that had been previously earmarked as 'anomalies' by the EM detectors. In airport luggage inspections, false alarm rates are 100%: no explosive has ever been found in the 10,000's X-ray monitors at 800-odd world airports.

ONLY ELEMENTARY PARTICLES CAN NON-INVASIVELY CHEMICALLY IDENTIFY EXPLOSIVES

Military explosives consist of 4 elements: H, C, N and O. E.g. stoichiometry of TNT is $C_7N_3O_6H_5$. For RDX, used in plastic bombs, it is $C_6N_6O_6H_6$. Non-military explosives, e.g. homemade terrorist bombs, are also detectable by atometry although they contain other elements. They are beyond the scope of this talk.
Fermi argued that the presence of nitrogen is the 'explosive signature' and should be detected *via* 10.8 MeV γ's emitted by thermal n capture in N^{14}. Westinghouse researchers followed his idea by a development program which was abandoned 10 years and $100 million later with the admission: "We developed a nitrogen detector, not an explosive detector." 1 m3 of air contains nearly a kilogram of N_2. Qualitatively detecting the mere presence of one or more elements of the explosive does not make an explosive detector.
Since there are no excited states of H, the task of atometry is to obtain, in a shortest time possible, *quantitative atomic ratio* of the 3 elements i.e. the subscripts a,b,c in $C_aN_bO_c$, to an accuracy sufficient to discriminate explosives from 1,000-odd innocuous substances also containing C, N and O.
Atometry is defined as *stoichiometry by means of elementary particles*. Atometry is achieved by quantitative high-resolution analysis of γ spectra from the inelastic scattering of fast neutrons. Neutrons of E>5 MeV, colliding with C, N and O produce characteristic γ's from each of the 3 elements, γ energies being 4.4, 5.1 and 6.1 MeV, respectively.
Neutrons are produced by a DC (non-pulsed) beam of deuterons in the reaction: $d+t \rightarrow \alpha + n + 17.8$ MeV (1). Next, they interact with nuclei of elements X: $n+X \rightarrow X^* \rightarrow X + \gamma + n'$ (2), where γ's are emitted by the transition between energy levels of X, the energy spectra of which are element-specific (See Fig. 1).

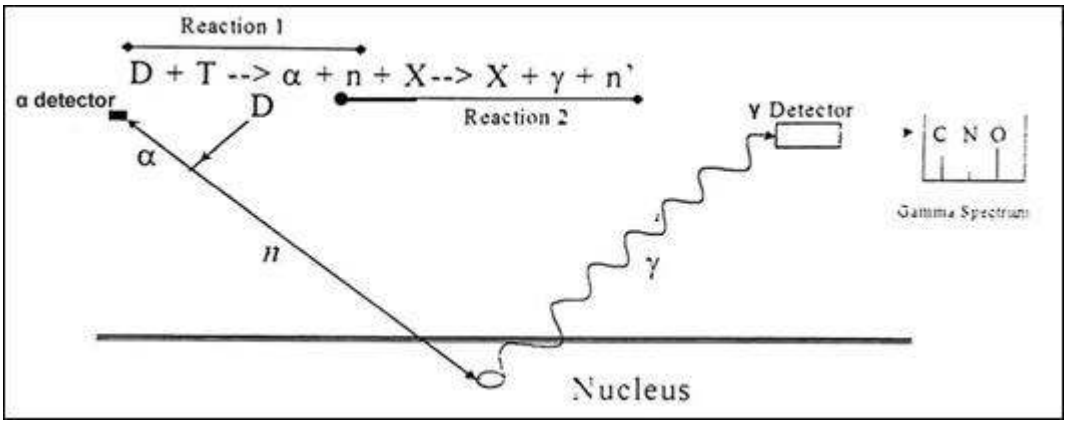

FIGURE 1. Associated Particle Imaging. Reaction 1: D beam of 100 KeV is incident upon T target (not shown); n and α are emitted at 180 deg to one another; α is detected in a position sensitive detector. Reaction 2: neutron hits a nucleus in a landmine and produces γ the energy of which is characteristic of the element. Coincidence is required between γ and α.

Associated Particle Imaging

In all previous work, the gamma detectors used were NaI and BGO, the resolutions of which are 5% and 7%, respectively. Uncollimated n's produce large γ background from the surrounding materials, which results in a low signal:noise (peak:background) ratio, 0.1, which prevents even a qualitative elemental analysis, let alone atometry.

In the early 1980s, the technique of suppressing the background noise without shielding, by an electronic quasi-collimation of n's, was invented. At the Naval Research Lab, γ signals from Reaction (2) detected in NaI, were put in *coincidence* with the α counts from Reaction (1). Since α is always emitted 180º to the neutron, measurement of the α direction gives the n direction. This is so called Associated Particle Imaging (API), which increases peak: background to about 1 with NaI detectors. API was able to get a *qualitative* picture of what elements were present ("chemical characterization of materials"). But because of the poor resolution of NaI, 6%, it was unable to separate N from O peaks. Generally, it failed to produce quantitative data. It was concluded that, in order to achieve stoichiometry, at least 10 times better γ resolution was needed. Solid state detectors, like germanium, with a resolution 30 times better than NaI were available. They were excluded, however, as an "impossibility" for the 6 reasons listed in the next section; each of which, by itself, was sufficient to render germanium useless at the time. The paradigm of the time was that it must be a scintillation detector, as solid state ones are not possible.
Proposals were made to compensate for the low energy resolution of NaI by high statistical accuracy by having 100 NaI detectors! In December 1989, a review committee of DOE declared the API method abandoned. Funding for all neutron based systems was terminated.

Solid state gamma detector is *sine qua non*

Seven years later (1996), our California team of Particle Physicists (Irvine, Berkeley, Santa Barbara) in collaboration with Lawrence Lidsky of MIT Nuclear Engineering Dept., re-examined

the failed attempts to achieve stoichiometric detection by API. Our unanimous conclusion was that scintillation detectors were the menace. All effort was made to resolve all the 6 problems that presumably rendered the germanium detectors "impossible;" and make the germanium feasible. See Table 1 below.

Problems	**our solution**
A. Poor time resolution 10 ns vs. <1 ns (NaI), believed to be needed for a tight coincidence circuit.	Time resolution of 3 ns has been achieved by electronics, unconventional.
B. Long recovery time, 300 ns determined by the charge collection time, required for the high resolution, which would limit the thruput rates to 10 Kcps vs. Mcps for NaI, needed for high statistics.	Artificially terminating charge collection time at 30 ns by allowing a 50% loss of the resolution (from 0.1 to 0.2 %), which was sufficient for stoichiometric analysis, thruput was increased by an order of magnitude, to over 100 Kcps.
D. Heavy weight of the device and irreproducible operation by tumbling of LN2	Elimination of LN2 and replacing it with Stirling Cryo cooler
E. High cost of germanium detector of efficiency comparable to that of NaI: $150,000 at the time ($80,000 now).	Replacing large germanium crystal with several inexpensive 20% efficient germanium detectors, with respect to NaI, by taking advantage of certain properties of the escape peaks.
F. Large computer processor required for fast analysis.	Elimination of computer processor altogether. Replaced by reprogrammable firmware, Field Programmed Gate Array Boards (FPGA), a C-based synthetic tool that accelerated chemical formula analysis-algorithms by a factor of 10. Also, eliminating laptop and replacing it with palm computer.

"Firmware:" turning software into silicon

These radical improvements, albeit radical, would alone not make a practical atometer. The successful operation was accomplished by the imaginative *dev elopment of the software* throug h an elaborate trial-and-error effort amounting to over 10,000 physicist hours. To achieve the speed required for online in-filed operation, the entire code has been turned into *one programmable chip*, FGPA board ("firmware"). If the chip is penetrated (by a terrorist?), it erases itself. Hence, computer is no longer needed, other than for the display screen.

Detection Time not fixed

The irradiation time is decided upon by the algorithm in each case until the statistical error on the atomic proportions (a, b, c) reaches 3σ, which corresponds to 97.5% confidence level. Depending on target mass, this takes anywhere from 5 sec. to 5 min. If 97.5% confidence is not reached in 5 minutes, atometry has failed and new conditions (distance, intensity, etc.) are attempted by the operator.

API Trials

First official trials were: (1) a stoichiometric detection of 4 Kg of cocaine hidden in bags of sugar (1998, Ref. 1 attached here as "white house paper"), conducted for US Customs, with a remarkable accuracy. We were able not only to decipher the complete empirical formula of cocaine, but also to conclude that the sample provided to us was not the real cocaine , but a cocaine simulant, whose formula differed from the real stuff by 1 atom. and (2) stoichiometric discrimination of 1 Kg of anthrax stimulant (dead spores) from yeast (2001)., conducted for DARPA/CIA (unpublished). Both were conducted at Special Technologies Laboratory, US DOE. Both reports were placed under US Army Secrecy Order soon after 9/11. The Order has been lifted from (1). We never applied for permission to publish (2).

Non-API 'Mini Atometer'

The high stoichiometric accuracy of our API system was offset by the long measurement time required to collect high statistics with one 50% efficient gamma detector: 10 hours. Even with 10 gamma detectors of 100% efficiency (a practical maximum), the collection time could not be reduced below 30 minutes. On the other hand, our customers (US Army's Night Vision and Electronic Sensors Directorate; AENA, Spanish Airport Security Police, Madrid; US Navy Surface Warfare Command, and numerous Police Bomb Squads) were interested only in a 1-3 minute portable, battery powered device. Moreover, US Atmy SOCOM (Special Operations Command, Atlanta, for 'low intensity conflicts' (mini wars)) gave us a contract to build an explosive detector whose weight must not exceed 20 lb.

We eliminated API and replaced electric neutron generator with 3 Curie radioactive Americium Beryllium radioactive neutron source (2 lb). The so made 'Mini Atometer' was able to distinguish TNT from RDX in 20 minutes. We indicated how the time can be reduced to 3 minutes, but SOCOM lost interest for the pursuit of this approach. Our report has never been published.

Non-API Non-Pulsed "Straight" Atometer

Naval Surface Warfare Center did not want a radioactive source. We replaced the AmBe neutron source with a commercial miniature neutron generator used in oil prospecting, which is sold as a pulsed system. Since the pileup renders pulsed particle measurements unworkable, we abandoned the pulse electronics and ran neutron generators in DC mode.

First live-ammunition open-air blind trials with such a Non-API Non-Pulsed portable system were conducted on January 9, 2003, by Naval Surface Warfare Center, at Indian Head, Md. Each of the 16 various artillery shells or metallic containers, irradiated from 30 cm distance, were correctly identified as "explosive" or "not a known explosive"; the exact explosive composition was correctly identified in 12 cases; in 6 cases the type explosive was incirrect5ly identified. In the period 2003 to date, over 20 successful blind tests of atometers were conducted by a dozen of organizations: Night Vision and Electronic Sensors Directorate (US Army's

landmine detection), AENA (Spanish aviation security administration), NATO (in Europe), Bomb Squads of Istanbul, Turkey; Army and Police, Riyadh, S.Arabia; FBI and a number of American Police Bomb Squads. In April of 2005, after 9 years of R&D&T, o first commercial fast neutron atometer, SIEGMA 3E3, was marketed and sold as a product. It can identify all military explosives, Cloratita, HMTD, as well as the acetone based ones.
Figure 2 and 3 show the gamma ray spectra of explosive systems PELAN and ANCORE, respectively, in comparison with that measured with our API and straight atometer, respectively

FIGURE 2. Gamma Spectra of Explosive System PELAN: pulsed neutrons, non-API; BGO detector (smooth line). System ATOMETER: DC neutrons, API, germanium (histogram with γ lines).

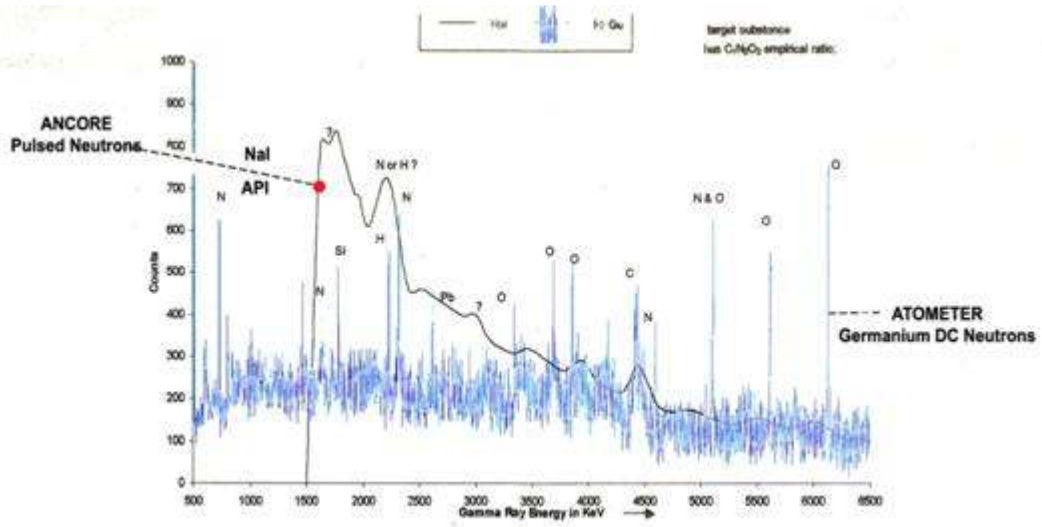

FIGURE 3. Gamma Spectra of Explosive System ANCORE: pulsed neutrons, quasi-API, NaI detector (smoth line). **STRAIGHT ATOMETER**: DC neutrons, germanium detector (histogram with γ lines).

Figure 4 shows a robot operating atometer inspecting a briefcase and in figure 5 the components of the atometer, accelerator (neutron source), germanium detector, and electronics, are shown. A picture of the atometer system display for the operator is given in figure 6.

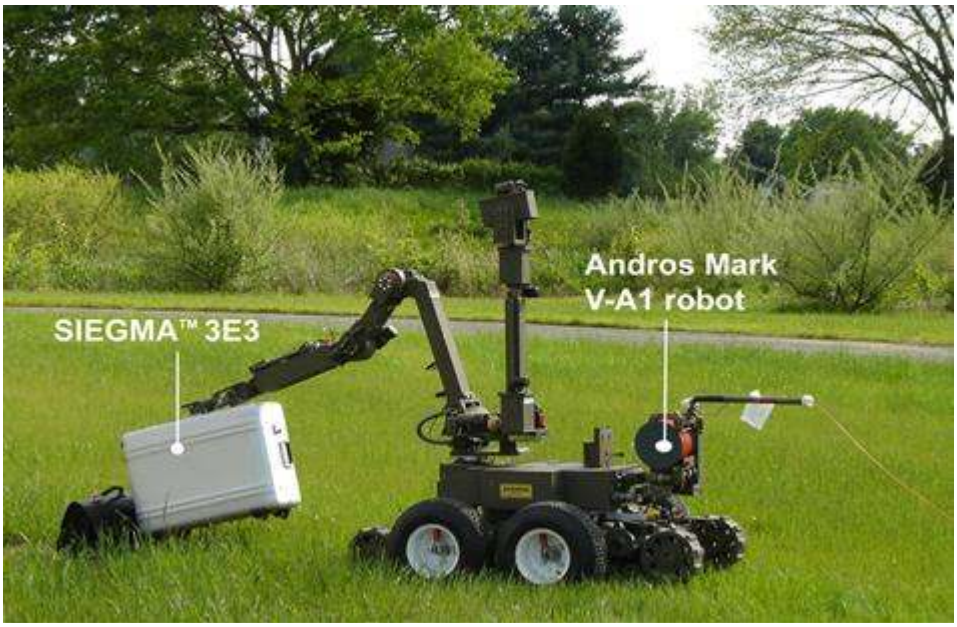

FIGURE 4. Robot-borne atometer "suitcase" model SIEGMA™ 3E3 inspects a briefcase, at Counter Terrorism in the Balkans Symposium, Belgrade, (2005). See open suitcase below.

HiEnergy Technologies, Inc. Detector for Improvised Explosive Devices (IED): **SIEGMA™**. (Open view of an earlier model).

FIGURE 5. The atometer system including a particle accelerator for the neutron production, the Germanium detector for the γ detection and the required electronics.

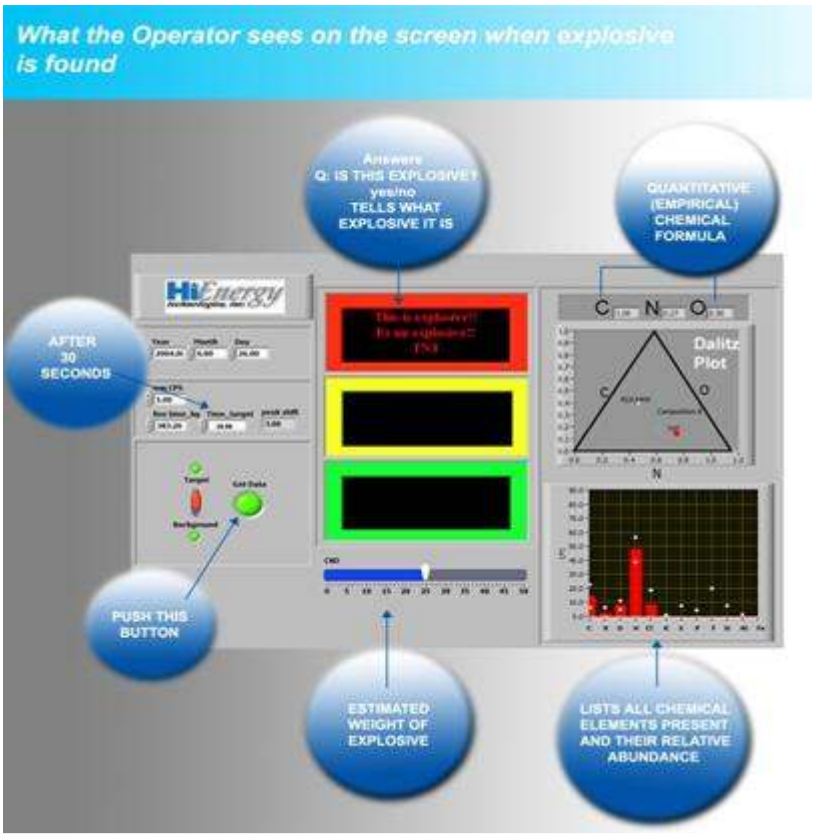

FIGURE 6. Display for the operator of the atometer system.

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Proceedings

1999 ONDCP International Technology Symposium

March 8-10, 1999
Washington, DC

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