

# Nuclear Forensics: History, Selected Cases, Curriculum, Internship and Training Opportunities and Expert Witness Testimony

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**Abstract:** Nuclear forensics is the investigation and analysis of the source of nuclear materials for nuclear attribution including trafficking and illegal possession and enrichment of natural materials. Nuclear forensics cases include radionuclide theft, illegal trafficking and possession, loss of nuclear weapons, and poisonings. To prepare forensic chemists to handle materials in these cases and law enforcement to thwart these threats, nuclear forensics courses are offered at United States colleges and universities. This paper reports upon the field of nuclear forensics including history and cases, ongoing threats that underscore the need for education, courses offered and topics covered, internship and training opportunities, and expert witness testimony in nuclear forensics. A robust reference list of peer-reviewed papers, websites, books and book chapters that can be used in such a course is included.

**Keywords:** Forensic science, nuclear forensics, case studies, curriculum, expert witness testimony

## Introduction

The goals of this paper are to introduce the reader to the history of nuclear forensics and selected cases as well as disseminate course options, curriculum content, textbooks and peer-reviewed journal article sources, internship and training opportunities, and expert witness testimony in nuclear forensics. The information has been collected and organized from various sources including peer-reviewed journal articles, government publications, internet searches, books and book chapters. Herein, existing courses and curriculum content is discussed along with a broad reference list that educators can use in implementing or designing nuclear forensics courses at their universities.

## A Brief History of Nuclear Chemistry

With the discovery of x-rays in 1895 by Wilhelm Conrad Roentgen and Henri Becquerel's discovery of radioactive properties in uranium in 1896, the field of nuclear chemistry was born. Beginning in 1898, Maria (Marie) Skłodowska-Curie and Pierre Curie discovered that pitchblende and chalcocite contained radioactive polonium, radium thorium among other elements (1). The early years of nuclear chemistry extend to World War II. Manmade elements were prepared by bombarding naturally-occurring elements with alpha particles, neutrons, and deuterons starting in 1919 when Ernest Rutherford reported upon his synthesis of oxygen-17 from nitrogen-14 using alpha particles. In 1934, Irène Joliot-

Curie (daughter of Marie and Pierre Curie) and her husband Frédéric Joliot-Curie bombarded aluminum-27 with alpha particles to yield phosphorus-30, the first demonstration of artificial radioactivity. In 1937, Ernest Lawrence bombarded molybdenum-42 with deuterons to form technetium-43. In 1938, Otto Hahn, Lise Meitner and Fritz Strassmann bombarded uranium with neutrons which led to their discovery of nuclear fission. From the 1930s, Glenn Seaborg and his colleagues at the University of California, Berkeley synthesized over 100 new elements and isotopes including cobalt-60, plutonium-239, neptunium and all transuranium elements through 102; some of the findings were delayed for publication until the post-war years (2-8).

## Nuclear Forensics: A Definition

While nuclear chemistry focuses on the study of the reactions that result in changes in the composition of atomic nuclei, nuclear forensics is the investigation and analysis of the source of nuclear materials for nuclear attribution including trafficking and illegal possession and enrichment of natural materials (6-8).

## Nuclear Forensics Cases

Nuclear forensics cases include radionuclide theft, illegal trafficking and possession, loss of nuclear weapons, and assassination poisonings (9-13). Although the International Atomic Energy Agency (IAEA) has policies and safeguards to prevent smuggling, radioactive material,

radioactive dispersal devices and nuclear bombs have all been lost and stolen. Table 1 lists selected nuclear forensics cases and the year of occurrence (9-15). While not comprehensive - dozens of such cases have been reported annually in recent years - it demonstrates the breadth of nuclear forensics cases encountered by law enforcement. The first seizure of radioactive material was in Switzerland in 1991 (11,12). Thousands of trafficking events have been reported since then (15). Reports involving the seizure of nuclear material have originated in Germany, Czech Republic, Hungary, Poland, Belarus, among other European countries, as well as Russia, the Middle East, Pakistan, and African countries (14).

Although most of the seized material is not nuclear weapons-grade, it is toxic and emits radioactivity and poses health risks upon exposure. Threats that the material could be used to create “dirty bombs”, explosive devices containing radioactive material, or be released in ventilation systems or subways incite fear in civilian populations. Radionuclides including cesium-137, iodine- 131, strontium-90, cobalt-60, iridium-192, americium-241, uranium-235, uranium-238 and plutonium-239 may be used in a dirty bomb. As noted by Sam Kean (16) in his book, *The Disappearing Spoon*, “...sprinkling a tenth of an ounce of cobalt-60 on every square mile of earth would pollute it with enough gamma rays to wipe out the human race.” (p.113)

In addition to illegally trafficked radionuclide material, “Broken Arrows” are nuclear weapons that were lost, stolen, accidentally launched or detonated (17). These incidents have been reported to occur at least 32 times since the 1950s with six weapons yet unrecovered (17). For example, the United States (U.S.) has lost at least seven nuclear weapons (18). A hydrogen bomb that was lost was found in 1989 (19). The James Martin Center for Nonproliferation Studies reported 155 incidents in 2013 and 170 incidents in 2014 where nuclear or radiological material was lost, stolen or outside regulatory control (20). U.S. nuclear materials including plutonium and cesium were reported missing by U.S. Department of Energy officials in 2017 and still not yet recovered over a year later (21). In August 2018, the Malaysian police reported that they cannot account for two radioactive dispersal devices (22) with one missing more than a year.

**Ongoing Threats and Need for Education**

Radionuclides are widely available due to their commercial use. Radionuclides are unstable atoms that readily decompose emitting particles and energy. Uses include research, medical equipment, smoke detectors, nuclear power plant fuel, specialized materials, and nuclear bombs for military use (10). Examples of applications include: phosphorus-32 use in leukemia therapy, cobalt-60 use in radiotherapy machines for cancer therapy and in food sterilization, technetium-99 use in imaging bones and the circulatory system, iodine-131 use in treating thyroid

diseases, cesium-131 use in treating prostate cancer, and iridium-192 use in treating coronary disease (10). As demonstrated in Table 1, household and commercial products can be the source of radionuclides for malicious use. An on-going potential threat recognized by the U.S. Nuclear Regulatory Commission is the use of radionuclides to produce a radiological dispersal device (RDD) or “dirty bomb” (24). Forensic chemists and crime scene investigators need to be trained to approach and analyze nuclear forensic evidence just as they would body fluids sampled to determine a DNA profile or chemical weapons samples to determine their identities and sources (21). First, the seized material must be analyzed to determine if it is indeed radioactive (21). Then age dating, isotope composition, presence of trace elements, isotope ratios, grain size, and shape can be determined and used in source attribution (25-29).

**TABLE 1** Selected nuclear forensics cases and year of occurrence (9-15,20-23)

Case	Year
Radioactive material seized in Switzerland in first reported case	1991
Boy Scout David Hahn dismantled household products to construct a nuclear reactor in a United States backyard shed	1991
Smugglers transported 56 kg of plutonium hidden in scrap metal from Russia to North Korea by train	1992
Russian naval officer stole 4 kg of 20% enriched uranium-235 nuclear fuel rods from Severomorsk, Russian	1993
363 g of plutonium-239 was seized at a Munich airport	1994
Turkish authorities arrest seven Turks in seizure of weapons grade uranium	1994
Russian authorities recovered four 90-kg containers of cesium-137 and arrested the thieves	1995
Polish guards at the Polish-Czech border discovered eleven strontium-90 filled cigarette pack-size containers	1995
Chechen separatist leader Shamil Basayev and associated militants buried a dirty bomb in a Moscow park	1995
German authorities detected cesium-137 smuggled from Zaire to Germany on a commercial flight	1996
Cobalt-60 containing radiotherapy machines sold as scrap metal cause eight people to be ill with radiation syndrome	1998
Highly enriched uranium intercepted at the Turkish-Bulgaria border	1999
Cobalt-60 containing radiotherapy machines sold as scrap metal resulted in radiation syndrome illness in ten people and three deaths	2000
Russian defector Litvinenko assassinated using polonium-210	2006
Cobalt-60 stolen by Mexican thieves	2013
Plutonium and cesium nuclear materials stolen from vehicle of U.S. Department of Energy officials	2017
Malaysian industrial radiography unit containing iridium-192 reported lost	2018

**Nuclear Forensics Courses Offered by U.S. College and Universities**

Although not as common as forensic science, forensic biology or forensic chemistry courses, several United States colleges and universities including Syracuse University, University of Utah and University of

Tennessee, Knoxville offer graduate courses in nuclear forensics as shown in Table 2. University of California - Berkeley offers an undergraduate course in Radiochemical Methods in Nuclear Technology and Forensics. In addition, Towson University offers a module in nuclear weapons and forensics in its Advanced Lecture Topics: Weapons of Mass Destruction undergraduate course. Other nuclear topics courses are offered by engineering departments at Clemson University, University of Texas – Austin, and Penn State University including Technical Nuclear Forensics, Nuclear Safety and Security, and Nuclear Security System Design, respectively.

**TABLE 2** Courses in nuclear forensics offered by U.S. colleges and universities

COURSE NO.	TITLE	INSITUATION
CHEM 146	Radiochemical Methods in Nuclear Technology and Forensics	University of California, Berkeley
NUC 520	Radiochemistry, Nuclear Fuel Reprocessing and Nonproliferation	Syracuse University
NE 635	Nuclear Forensics	University of Tennessee, Knoxville
FSC 654	Nuclear Forensics	Syracuse University
FSC 669	Science of Countering Weapons of Mass Destruction	Syracuse University
NUC 7220	Analytical Nuclear Forensics	University of Utah

### Course Topics

Nuclear forensics courses are focused on educating students about nuclear weapons of mass destruction (30) and how to perform source attribution (31) of nuclear samples (32). Topics covered by the courses include the history of nuclear chemistry (2,3,8,16), ethics of dual use research (33-36), defining radionuclides, sources of radiological materials (10), nuclear compounds and reactions, nuclear decay, aging samples (27,28), fission, safety, sample collection (37), sampling and handling, methods of detection, environmental nuclear forensics (37,38), and reporting of results (30). Additional topics include swipe and single particle samples, gas phase counting and separations, isotopic signatures, method of production, sample origin, nonproliferation, intended use, pre- and post-detonation analysis, nuclear fuel reprocessing, and spent fuel transport and storage (39-43). Key “fingerprinting” analysis in nuclear forensic cases for determining provenance includes determining isotopic and phase composition, morphology, microstructure, elemental composition, isotopic composition, isotope ratios, and rare earth element pattern. (26,29,42,44). For comparisons, the Japanese government has developed a prototype type

nuclear forensics library (NFL) (45), the European Commission has validated reference materials for dating nuclear materials (46), and the U.S. National Institute of Standards and Technology (NIST) has a Nuclear Materials Characterization group and produces standards. Cation exchange chromatography is used to separate rare earth elements (47). Instruments including Geiger-Mueller counters (1), liquid scintillation counters (1), alpha spectrometry (1), gamma spectrometry (1,48,49), X-ray fluorescence (XRF) (49) energy dispersive spectroscopy (EDS) (43,50), electron probe microanalysis (50), scanning electron microscopy (42,51,52), transmission electron microscopy (42), micro-Raman spectroscopy (42), inductively coupled plasma-mass spectrometry (ICP-MS) (29,31,49), secondary ion mass spectrometry (SIMS) (51), autoradiography (51) laser ablation (LA)-ICP-MS (47,53), and laser induced breakdown spectroscopy (LIBS) (54) are used in the experimental analysis of nuclear materials. Courses include theoretical and hands-on experience with these instruments. UV-Vis spectrophotometry, differential scanning calorimetry (DSC), powder X-ray diffraction (p-XRD), thermogravimetric analysis (TGA), TGA-mass spectrometry (TGA-MS) are used for morphological analysis (43,52). Case studies may focus on dismantling of household materials to recover and enrich radionuclides (6, 55), improper disposal of medical devices (10), illegal trafficking of radionuclides and nuclear weapons (56), poisonings attributed to radionuclides, detecting accidental release of radionuclides (10) and nuclear power plant accidents (57-60), and post-detonation analysis of environmental samples.

### Textbooks and Books

In addition to the peer-reviewed literature, textbooks are an excellent source of nuclear forensics content. Textbooks that offer chapters on nuclear chemistry, weapons of mass destruction, and chemical biological, radiological, nuclear and explosives (CBRNE) include Adventures in Chemistry by Julie Millard (6), Criminalistics: Forensic Science, Crime, and Terrorism by James Girard (7), and Introduction to Forensic Chemistry by Kelly Elkins (8). Choppin, Liljenzin and Rydberg’s book Radiochemistry and Nuclear Chemistry (1) includes a chapter on Detection and Measurement Techniques. Other general interest books with interesting information about the history of the elements, uses of radionuclides and case studies are The Disappearing Spoon by Sam Kean (16) and The Poisoner’s Handbook: Murder and the Birth of Forensic Medicine in Jazz Age New York by Deborah Blum (61).

### Internship and Training Opportunities

Several agencies worldwide offer internship programs in nuclear forensics and materials analysis and related

policy. The U.S. Department of Homeland Security offers a six-week Nuclear Forensics Summer School program taught on a rotating basis with selected colleges and universities. The U.S. Central Intelligence Agency (CIA) also recruits undergraduate and graduate students to internship positions as intelligence analysts; one track is the “Science, Technology & Weapons Analyst” position that is focused on the identification and analysis of weapons proliferation and proliferators including chemical, biological, and nuclear weapons. The U.S. Federal Bureau of Investigation (FBI) also offers undergraduate and graduate internships that focus on a broad range of issues. Training programs for U.S. undergraduate and graduate students and postdoctoral scholars are available through Oak Ridge Institute for Science and Education (ORISE) at national labs including Los Alamos, Pacific Northwest, and Oak Ridge. Internationally, internships are offered by the International Nuclear Safeguards, the Organisation for the Prohibition of Chemical Weapons (OPCW), the Nuclear Threat Initiative (NTI), the Nuclear Nonproliferation Education and Research Center (NEREC), the United Nations Regional Centre for Peace and Disarmament in Asia and the Pacific (UNRCPD), the Center for Arms Control and Non-Proliferation, the Arms Control Association (ACA), the Ploughshares Fund, and the Stockholm International Peace Research Institute (SIPRI), to name a few. Additional local opportunities may also be available to students and researchers worldwide through law enforcement and military agencies and their colleges and universities.

### Expert Witness Testimony

Students in forensics degree programs take courses in criminal justice, chemistry, biology, physics, geology, anthropology, computer science, statistics, and the law. In many courses, students are assigned groups with which to evaluate a case and take on different roles for presentation to the class. Students may be assigned the roles of defense attorney, prosecuting attorney, and expert witness. The questions asked of a witness in a nuclear forensics case may be unique to that type of case. Sample questions for an expert witness in a nuclear forensics case may include:

- Describe your education, experience, and specialized training in nuclear forensics.
- On how many cases have you served as an expert witness in nuclear forensics?
- Define radioactive material.
- Explain nuclear fission.
- How can radioactive material be detected?
- What is the detection limit of this method?
- What is the error rate of this method?
- Where was the nuclear material seized or obtained?
- How can you determine the source of the radionuclide?
- What is the source of the radionuclide in question?
- Is possession or movement of the material regulated?

- Does the country of origin have regulations that cover the radionuclide?
- How can this material be disposed of legally?
- Was the possession or movement of the material an accident or intentional?

### The Future of Nuclear Forensics Education

Radionuclides continue to be used in a variety of household and medical devices; improper use of these materials is always a possibility and trafficking continues. Chemists must be aware of radionuclides used in materials and the threats that each pose. They must also be prepared to determine the sources of the radionuclides. Due to the negative effects on human health caused by exposure, proper safety precaution and rapid detection of released radionuclides and materials is essential. It is imperative that the next generation of chemists and forensic scientists be equipped with knowledge of these materials and how to solve problems and cases that may be encountered. Forensic programs should consider offering electives in nuclear forensics to address these needs, if they are not doing so already.

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