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Active Interrogation in Nuclear Security

Science, Technology and Systems

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To our families

Preface

Nuclear security represents one of the most pressing global challenges. Our societies are threatened asymmetrically by terrorist groups, either operated independently or sponsored by rogue states. The prospect of nuclear terrorism, especially one that would involve a nuclear explosive constructed using special nuclear material (SNM), motivates a concerted effort spanning technical and policy means to control the production, possession, and movement of SNM. Formidable physics obstacles stand in the way of addressing this challenge. SNM spontaneously produces only a low level of unique detectable signature in the form of penetrating radiation. This signature is immersed in an abundant natural background radiation. In addition, the radiation signatures of SNM can be shielded with relative ease, effectively eliminating the possibility to detect even substantial quantities of SNM that could be used to construct a functioning nuclear explosive device.

These fundamental physics challenges have motivated the development of alternative methods to detect, locate, and identify SNM. It is becoming accepted today in the physics and security community that the only promising way to detect SNM in movement, especially associated with burgeoning international trade, is using an active method, frequently referred to as active interrogation (AI). The objective of this book is to address the multiple technical facets of AI in an integrated and coherent form that has not been available to date. The available literature in this area is mostly in the form of relatively disjointed project reports and technical journal articles. The existing books usually treat only a single aspect of AI, such as radiation sources, detectors, algorithms, electronics, and physics of the detection process. To the best of our knowledge there is no volume that presents this subject in integrated form. Aggregating the knowledge in disparate technical areas of AI and connecting it in a logical fashion therefore holds a great educational and more general scientific merit, which is why we decided to undertake the project of writing this book. This book has been prepared in the format of an edited volume, since we believe that the best way to convey the state of the art in AI is to engage some of the leading researchers and educators who perform research on this subject, or have made important technical contributions to it.

We believe this is the right time to publish a book with this type of content. The community is highly engaged, the research activity is consistently high, and many students and researchers are entering the field. Graduate students and masters- and doctoral-level professionals working in the area of nuclear security or security in general could profit from a volume that will provide them with a concise physical basis of AI, along with in-depth current status of key issues in AI, as the technical method of choice to counter the threat of nuclear terrorism.

The goal of the book is to achieve a high level of alignment with the material taught in courses associated with a major growing area of nuclear engineering while integrating the fundamental physics principles with the current and future technology trends. The book should be an appropriate reference for both senior undergraduate and graduate courses in the area of nuclear security, nonproliferation, safeguards, and detection. It could even be a principal text for a special topic course on AI, or a required/optional text in the broader areas listed above. Parts of the book would also find audience among a broader group of engineers (mechanical and electrical) and scientists (physicist, materials scientists, and chemists), as well as policy analysts. At the same time, the book does not purport to replace the well-known texts that specialize in any of the technical areas covered here.

A fraction of this book draws upon the material developed for special topics courses taught at Purdue University and Penn State University for a number of years, including the ones that resulted from the collaborative effort of Penn State University, Massachusetts Institute of Technology, and Texas A&M University to spearhead a formal Nuclear Security Education Program. We wish to thank our contributors, who invested their valuable time and effort into making this book possible. Simultaneously, we would like to acknowledge the support we have received over the years from our colleagues at universities, national laboratories, and federal agencies, which further motivated the writing of this book.

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November 2017

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Chapter 1
Introduction

Igor Jovanovic

Abstract The context for the emergence of nuclear security challenges is discussed, including some of the milestones in the development of nuclear weapons and the international efforts aimed to direct the use of nuclear technology to peaceful applications. The key terminology pertaining to nonproliferation is introduced, after which the focus of the chapter shifts to the problem of nuclear terrorism. The effects of a hypothetical terrorist attack using a relatively small, improvised, nuclear device are discussed. Next, the policy and the relevant treaties that have shaped the arms control regime over the past decades are introduced. The national and international efforts are subsequently discussed, which aim to provide a framework for prevention of nuclear terrorism. Finally, the general characteristics of the active interrogation technique are discussed, which will be expanded upon in the remainder of the book.

1.1 Historical Perspective on Nuclear Security

While the process of laying the foundations of the nuclear science can be traced to the early 1900s, in this context the discovery of the nuclear fission in 1938 by Meitner [1] can be singled out as a truly disruptive event. The potential for nuclear fission to lead to a new class of weapon that eclipses all the others in terms of its destructive power was quickly recognized (see, for example, the 1939 letter by Albert Einstein to US President Franklin Delano Roosevelt [2]). The discovery and exploration of the prospects for application of nuclear fission largely coincided with the Second World War, the most extensive and lethal conflict to date. In large part due to these circumstances, the effort to employ fission to develop a nuclear explosive device and to engineer its size and packaging such that is compatible with the state-of-the-art weapons delivery systems gained the highest priority in the U.S.

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war effort, and is known as the *Manhattan Project* [3]. This impressive scientific and technological development was fueled by an unprecedented combination of high concentration of scientific talent and essentially unlimited government support. At a final cost of approximately $27 billion (adjusted to 2016 dollars) [4], by 1945 a large team of scientists and engineers has developed two major embodiments of a nuclear bomb, based on highly enriched uranium and plutonium. The regrettable historical episode in which both of those designs were employed to accelerate the end of the war with Japan also led to an immediate and universal recognition of the urgent need to control the development and use of such weapons and limit the proliferation of nuclear weapons technology.

United States held the monopoly to nuclear weapons only for several years, until the demonstration of the Soviet plutonium implosion weapon in 1949. This quickly escalated into a nuclear weapons race, initially only between the United States and Soviet Union, but by 1960s the circle of nuclear weapons states has expanded to include the United Kingdom, France, and China. The nuclear weapons race came at a substantial cost, which required public support. In United States, the *Project Candor* was initiated in 1953 as a media campaign aimed to gather support for extensive nuclear armament expenditures by regularly informing the public about the perils of falling behind the Soviet nuclear weapons capabilities. As a part of this campaign, President D. Eisenhower delivered the famous *Atoms for Peace* speech to the United Nations General Assembly in December 1953, in which he urged the worldwide effort to employ nuclear energy for peaceful purposes. Within the Atoms for Peace program (Fig. 1.1), the United States government spearheaded an effort to pursue research into peaceful applications of nuclear science by providing training, equipment, and help to construct facilities such as research reactors in many countries that lacked nuclear capabilities at that time. Regrettably, the origin of the indigenous efforts to develop nuclear weapons programs in countries such as Israel, Iran, and Pakistan can be traced to the U.S. assistance provided under the Atoms for Peace program.

In the same address to the United Nations General Assembly in which he announced the establishment of the Atoms for Peace program, President Eisenhower also proposed that an international agency be established under the aegis of United Nations, with a dual mission: (1) to promote the peaceful uses of nuclear

Fig. 1.1 A 1955 U.S. stamp highlighting the Atoms for Peace program

energy, and (2) to inhibit its use for any military purpose, including nuclear weapons (https://www.iaea.org/about/mission). The agency was established in 1957 as the *International Atomic Energy Agency* (IAEA) and is headquartered in Vienna. It membership (as of 2017) includes 168 states.

With the formation of IAEA, the basis of the international framework was established such that the future use of nuclear science and engineering for weapons purposes can be curtailed. This philosophy has been implemented through the introduction and increased acceptance of various international treaties. This formal framework is described in more detail in Sect. 1.3.

It is in order here to introduce the key terminology relevant to the discussion of nuclear security in the remainder of this book.

- *Nuclear weapons states* are the five countries that have acquired nuclear weapons before January 1, 1967, and they include United States, Russia (as a successor to Soviet Union), United Kingdom, France, and China.
- *Nuclear proliferation* refers to the spread of nuclear weapons, fissile material, and the requisite technology and information that could be used to construct them, to the states that are not among the five nuclear weapons states. *Nonproliferation* then refers to efforts to curtail such proliferation activities through diplomatic, legal, and administrative methods.
- *Nuclear counterproliferation* is the effort to combat nuclear proliferation, but focusing on intelligence and military methods.
- *Nuclear safeguards* are measures that can be used to verify that countries comply with their international obligations not to use nuclear materials as nuclear explosives.
- *Nuclear treaty verification* refers to development and deployment of measures to ensure verifiable compliance with treaties and other international agreements, implementation of regimes to reduce nuclear weapons, and detection and dismantlement of undeclared nuclear programs.
- *Nuclear forensics* refers to the development of methods and practices that can be used to determine the provenance (origin) of the nuclear material, whether after its use (post-detonation) or in the cases when it is intercepted (pre-detonation).
- *Weapons of mass destruction* include weapons that operate on the basis of nuclear, radiological, chemical, biological, or other principles that can lead to large loss of life, damage to infrastructure, or biosphere.

The list of states that developed their own nuclear weapons has since expanded to India (1974), Pakistan (1998), and North Korea (2006); it is widely accepted that Israel has also acquired nuclear weapons capability as early as in 1960s. There are also several nuclear weapons sharing states (Belgium, Germany, Italy, the Netherlands, and Turkey), which host U.S. nuclear weapons under the NATO's nuclear sharing policy. While South Africa developed nuclear weapons, it has voluntarily given up this capability, along with the former Soviet states of Belarus, Ukraine, and Kazakhstan (Fig. 1.2).

The nuclear weapons states have found the cost of developing and maintaining a nuclear stockpile to be substantial, and therefore a large burden on their

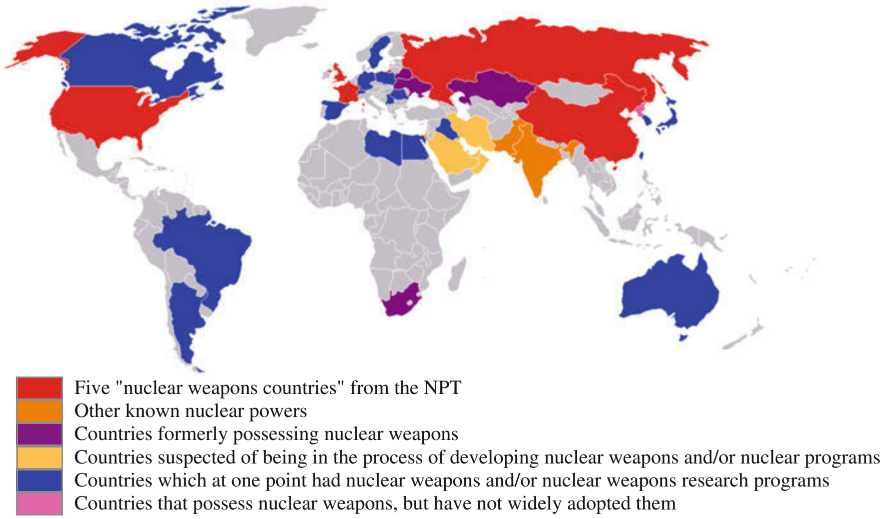


Fig. 1.2 Current status of nuclear weapons possession worldwide (2017)

economies. This extraordinary and recurring cost of maintaining a large nuclear weapons capability has contributed to the collapse of the Soviet economy and the subsequent dissolution of Soviet Union in 1991. The U.S. National Nuclear Security Administration has played an important role in ensuring the security of the former Soviet nuclear stockpile and the consolidation of Soviet nuclear material in Russia.

With the demise of the Soviet Union and the subsequent large (multifold) reductions of nuclear weapons stockpiles, the risk of nuclear conflict and the magnitude of its aftereffects was significantly reduced, despite the increasing threat of a nuclear conflict surrounding the recent development of nuclear capability and rapid advancement towards intercontinental delivery systems by North Korea. As a result, since the 1990s, the international community has shifted its focus from the threat of full-scale nuclear conflict to the threat of nuclear terrorism. The recognition of this important threat has gained momentum after the series of coordinated terrorist attacks on September 11, 2001 and the continued political instability, conflict, and nuclear ambitions in the Middle East and in North Korea.

1.2 The Problem of Nuclear Terrorism

Nuclear terrorism refers to an act of terrorism in which a person or people belonging to a terrorist organization detonates a nuclear or radiological device. In this context, a *radiological device* refers to an assembly containing a significant amount of radioactive material that could be used to inflict damage by delivering large radiation doses to humans or contaminating areas important to economic activities, such as city centers or transport hubs.

While the threat of nuclear terrorism has gathered more attention since the 1990s, it has been anticipated in the early days of development of nuclear weapons. In 1945, the Manhattan Project director J. Robert Oppenheimer attended a congressional hearing, in which Senator William Milliken famously asked:

> "We…have mine-detecting devices, which are rather effective…I was wondering if anything of that kind might be available to use as a defense against *that particular type* of use of atomic bombs."

Here, Senator Milliken was referring to the possibility for a nuclear bomb to be delivered not by a standard military vehicle (at that time, a heavy bomber), but rather as a clandestine shipment, owing to the weapon's relatively small size. The Oppenheimer's response was:

> "If you hired me to walk through the cellars of Washington to see whether there were atomic bombs, I think my most important tool would be a screwdriver to open the crates and look. I think that just walking by, swinging a little gadget would not give me the information."

As the lead developer of the atomic bomb, Oppenheimer had a deep understanding of the physical principles governing weapons design and the properties of fissile materials such as highly enriched uranium and plutonium, including the nature and strength of their characteristic signatures. This mastery of the physical problem, along with the knowledge of the state-of-the-art detection technology, led him to immediately conclude that the task of detecting clandestine nuclear device would be very difficult and beyond the reasonable practical reach of the then-available technology. Importantly, Oppenheimer recognized that there was no obvious path to the development of advanced technological means to detect special nuclear material, especially in shielded configurations.

The possibility of nuclear terrorism has been identified as one of the important threats of our time by many leaders. For example, in the inaugural Nuclear Security Summit in 2010 President Obama remarked [5]:

> "The single biggest threat to U.S. security, both short-term, medium-term and long-term, would be the possibility of a terrorist organization obtaining a nuclear weapon."

He further summarized the potential impact of a nuclear terrorist attack at the Nuclear Security Summit held 6 years later [6]:

> "At hundreds of military and civilian facilities around the world, there's still roughly 2000 tons of nuclear material, and not all of this is properly secured. And just the smallest amount of plutonium – about the size of an apple – could kill and injure hundreds of thousands of innocent people. It would be a humanitarian, political, economic, and environmental catastrophe with global ramifications for decades. It would change our world."

It has been long recognized that the single greatest obstacle to developing a nuclear weapon is obtaining the necessary special nuclear material (highly enriched uranium or plutonium), since the production of a suitable quantity and quality of material is beyond the capability of any non-state actor. With highly enriched material in possession, even a moderately technically advanced group would likely construct an operational weapon relatively quickly. In the case of plutonium, the construction of a nuclear weapon would prove more challenging, but the required

Fig. 1.3 A model of special atomic demolition ammunition exhibited in the National Museum of Nuclear Science and History, Albuquerque, New Mexico

quantity of material is significantly smaller. The possible pathways for a terrorist group to obtain special nuclear material include theft and smuggling, unauthorized receipt of any unaccounted material from major weapons programs (such as the former Soviet Union's nuclear weapons enterprise), or a voluntary supply by a rogue state that has the capability and resources to enrich uranium or nuclear reactors to produce plutonium.

There are many possible methods of delivery that are available to a terrorist group, but it is important to recognize that the accuracy of delivery is not as important as in the case of conventional explosives to achieve the desired effect. To illustrate the ease of delivery, one can consider the case of *special atomic demolition ammunition*, a class of man-portable nuclear devices that have been developed for the purpose of destruction of infrastructure or port facilities. For example, the device shown in Fig. 1.3 has been designed to be delivered as a "backpack" by two members of Special Forces. It is therefore conceivable that a nuclear device could be readily delivered in a personal vehicle, truck, boat, or even a small private aircraft.

By far the most studied mode of delivery has been the cargo traffic. There are millions of cargo containers that cross borders worldwide every year, and they are exceptionally well suited for transporting clandestine nuclear materials due to the relative ease with which they can be shielded and the absence of an effective inspection method that is compatible with the large flow of container traffic. Research on how to detect special nuclear material in cargo containers has therefore been the centerpiece of the research portfolio by agencies such as the U.S. Department of Homeland Security. There has been also been a significant interest in *standoff* detection, which could help address scenarios such as small boats approaching ports from international waters. The problem of true standoff detection is daunting and in its most literal interpretation, where no detector or probe can be located near the object, no technological solutions have been demonstrated even at a rudimentary level.

The effects of nuclear explosions are relatively well understood and can be used to predict the consequences of a nuclear detonation carried out by terrorists in a major population center. Besides blast damage and thermal radiation, the population and structures would be exposed to powerful ionizing radiation and an electromagnetic pulse. Since one major effect of a nuclear explosion (especially when conducted at higher altitudes) is the occurrence of a powerful electromagnetic pulse capable of destroying critical electrical infrastructure with severe long-term consequences, the possibility of such terrorist attack must be carefully considered as well. Models of impact of a nuclear terrorist attack have been developed, and here we first provide an example of study conducted by the RAND Corporation for Department of Homeland Security [7], where a relatively modest 10-kt bomb delivered in a shipping container is detonated in a major port (Long Beach, California). The RAND model predicts 60,000 short-term fatalities, 150,000 people requiring emergency medical treatment, and an economic impact on the order of $1 trillion. In another study led by Lawrence Livermore National Laboratory [8], extensive modeling has been done to predict a devastating aftermath of a hypothetical nuclear terrorist attack carried out in downtown Washington, DC (Fig. 1.4). One may further speculate about the wide-ranging effects that such an event would have on the society, including the possible global retreat to more authoritarian forms of government.

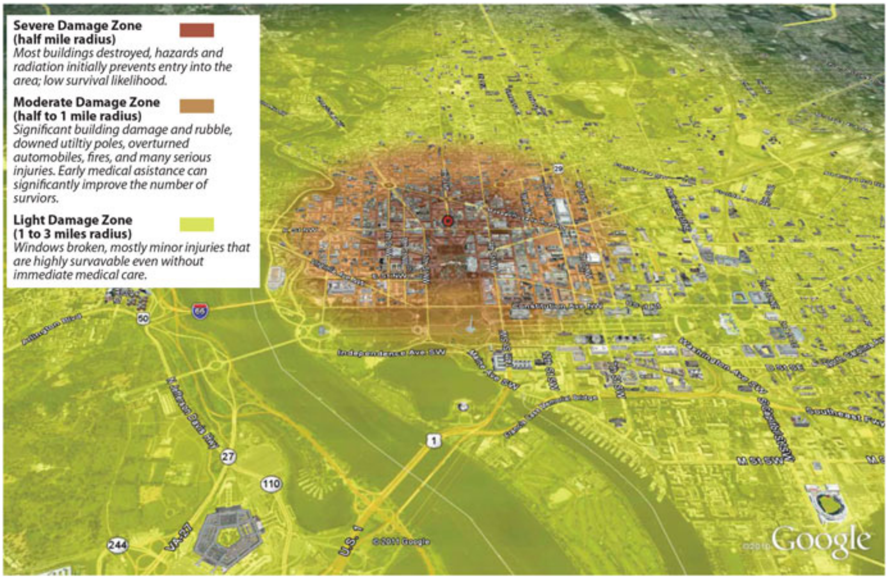


Fig. 1.4 Summary of prompt damage expected from a hypothetical 10-kt nuclear explosion in Washington, DC. Reproduced from Ref. [8]

1.3 The Role of Policy in Nuclear Security and Arms Control

It is a well-known fact that global nuclear security, especially its nonproliferation aspect, has relied on an evolving policy framework established by a growing international consensus. The basis for this framework are several key international treaties, which are succinctly introduced here.

The *Nonproliferation Treaty* (NPT) is an abbreviated form of the *Treaty on the Non-Proliferation of Nuclear Weapons*. NPT is first of the major treaties put into place in an effort to prevent the spread of nuclear weapons and the associated technology, as well as promote cooperation on the peaceful uses of nuclear energy. NPT has another ambitious and synergistic goal, and that is to promote nuclear disarmament and general and complete disarmament. The treaty was opened for signature in 1968 and became effective in 1970, and was ultimately signed by 191 states as of 1991. Notably, the known nuclear powers of India, Pakistan, and Israel have not joined the NPT, along with South Sudan. The case of North Korea is special in that is joined in 1985, but then withdrew in 2003 after conducting its first nuclear test. The NPT formally defines the nuclear-weapons states (United States, Russia, United Kingdom, France, and China). It further requires all other signatory states to agree never to acquire nuclear weapons; in exchange, the NPT nuclear-weapon states pledge to share the benefits of peaceful nuclear technology and to pursue nuclear disarmament aimed at the ultimate elimination of their nuclear arsenals (http://disarmament.un.org/treaties/t/npt/text, 1968). A common interpretation of the NPT is to consist of three major pillars: nonproliferation, disarmament, and the right to use nuclear technology for peaceful purposes.

The treaty requires ratification by the respective legislators and this has been the case with only 40 signatories to date, albeit they include the important powers of United States, Russia (ratified as Soviet Union), and United Kingdom. The NPT has been considered a wide success, not only because of being the most widely embraced arms control treaty in history, but also because of its quantifiable performance. Namely, despite the predictions of the wide adoption of nuclear weapons at the time the treaty was put forward, the list of additional states that acquired nuclear weapons since is relatively short and can in large part be credited to global efforts articulated through the NPT.

The NPT was augmented by two other major instruments that can be considered highly related to the original treaty. First, in the aftermath of the Indian nuclear test in 1974, the *Nuclear Suppliers Group* (NSG) was founded to further curtail the export of material, equipment, and technology that could find use in construction of nuclear weapons (http://www.nuclearsuppliersgroup.org/en/, 1975). The group is sometimes referred to as the *London Club* because it held a series of meetings in London. Today, NSG has 48 signatory states. NSG implements two sets of additional guidelines for nuclear and nuclear-related exports, with sensitive items constituting the so-called *Trigger List*.

The second major supplement to the NPT was introduced by the IAEA in 1993 and is referred to as the *Additional Protocol*. The objective of this program is to extend and strengthen the nuclear safeguards, which improves the ability of IAEA to uncover undeclared nuclear activities, especially those that have no clear connection to civilian applications. Under the Additional Protocol, more information on nuclear and nuclear-related activities is provided to the IAEA, the right of access of IAEA inspectors are greatly enhanced (for example, by shortening the inspection notice to 2 h and granting automatic visa renewals), and development of safeguards is deemed to be state-specific. The Additional Protocol was signed and brought into force by the vast majority of NPT signatories.

A major recent development related to NPT is the international agreement termed the *Joint Comprehensive Plan of Action* or the *Iran deal*, which was adopted in 2015 by Iran, the permanent members of the United Nations Security Council plus Germany, and the European Union. In this landmark recent agreement, Iran will take steps to limit the capacity of its uranium enrichment facilities, eliminate its medium-enriched uranium, reduce the stockpile of low-enriched uranium, and delay the construction of any heavy-water facilities, in return receiving a relief of the economic sanctions imposed in the wake of Iran's nuclear activities. The Iran deal has seen significant criticism and remains the subject of intense international attention, one of the critical components being the mechanism of its verification.

There are several major arms control and disarmament efforts treaties that went into effect over the past several decades, significantly reducing the deployed nuclear stockpiles. The *Strategic Arms Limitation Talks* (SALT) started in 1969 and consisted on two rounds (SALT I and SALT II). As a result of SALT I, the *Anti-Ballistic Missile Treaty* was signed in 1973 and terminated in 2002. While SALT II aimed to reduce the number of strategic nuclear forces to 2250 delivery vehicles and was agreed upon in 1979, it was not ratified amidst international tensions surrounding Afghanistan and expired in 1985. The *Strategic Arms Reduction Treaty* (START, also START I) between Soviet Union and the United States was signed on 1991 and went into force (with Russia) in 1994, limiting the signatories to 6000 deployed nuclear warheads on 1600 inter-continental ballistic missiles and bombers. The START I expired in the 2009, and in 2010 a follow-up treaty was signed (*New START* implementing further reductions by a factor of two. While the START II was negotiated, it has not come into force, and the START III treaty has not been negotiated yet.

In the area pertaining to nuclear tests, the landmark multilateral agreement has been the *Comprehensive Nuclear-Test-Ban Treaty* (CTBT), which prohibit all nuclear explosions regardless of purported application. CTBT was adopted in 1996 and signed by 183 countries and ratified by 166 of them. Notably, eight major countries with nuclear capability, including China, India, Pakistan, North Korea, and the United States, have not signed or ratified the treaty.

A key component of any international treaty related to nonproliferation and arms control is the implementation of a solid verification regime. The goal of a verification regime is to monitor and verify nuclear reduction agreements and detect violations of treaties and other nuclear nonproliferation commitments. To do, measures are developed and deployed to ensure verifiable compliance with treaties and other international agreements, implement regimes to reduce nuclear weapons, and detect and dismantle undeclared nuclear programs (https://nnsa.energy.gov/aboutus/ourprograms/nonproliferation-0/npac/verification, 2017).

There are many technologies that have been developed and put into use over the years to support the objectives of treaty verification, and they follow the principle of *trust, but verify* attributed to a Russian proverb and used by President Ronald Reagan in 1987, and now also used as a motto of the Defense Threat Reduction Agency's On-Site Inspection Agency (https://www.legistorm.com/stormfeed/view_rss/254149/organization/31751.html, 1995). The technologies used for verification measurements are diverse and include satellite imagery, telemetry, electro-optical and radar senors, space-based sensors, seismic and infrasound monitoring for suspected nuclear explosions, on-site inspection, and air sampling.

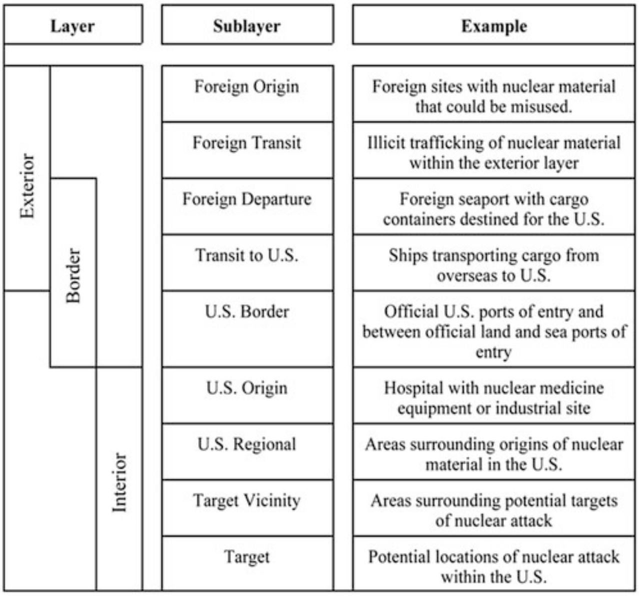
In the recent period, the U.S. Department of Energy's National Nuclear Security Administration (NNSA) has stepped up effort to integrate the U.S. academic community into its effort to maintain and improve on the treaty verification regime. Since 2014, NNSA has provided a substantial and coordinated support to a group of universities and national laboratories to engage in a combination of education and research at the intersection of science, technology, and policy. The goal of this effort is not only to provide future workforce proficient in the current methods of verification, but also to advance the fundamental research into science and technology that could support current and future verification challenges. This framework has been led by the University of Michigan under the *Consortium for Verification Technology* (https://cvt.engin.umich.edu, 2014).

1.4 Institutionalized Efforts to Curb Nuclear Terrorism

While the extensive policy framework has evolved over decades in response to a major buildup of nuclear weapons and means of their delivery by nation-states, the problem of nuclear terrorism requires a different set of measures and programs. It is certain that the arms control reductions have had a positive impact on the efforts to prevent nuclear terrorism by the virtue of material reductions and implementation of better security and verification measures. The complementary measures to prevent nuclear terrorism are arguably significantly easier to agree upon in the broad international community, since they are seen to pertain to non-state actors.

The problem of nuclear terrorism is seen to be of persistent nature and of limited, albeit significant local impact (see Sect. 1.2). It has also been seen to be an example of a *rare event*, associated with a low probability of occurrence and a sparse historical record from which to develop predictive models based on past statistics [9]. It has been a conclusion of numerous assessments that terrorist groups have the ambition to acquire, and possibly use, unconventional weapons such as improvised nuclear explosive devices and radiological dispersal devices.

The problem of domestic nuclear terrorism in the United States has been addressed primarily by the Domestic Nuclear Detection Office (DNDO), an organi-



Layer	Sublayer	Example
Exterior	Foreign Origin	Foreign sites with nuclear material that could be misused.
	Foreign Transit	Illicit trafficking of nuclear material within the exterior layer
Border	Foreign Departure	Foreign seaport with cargo containers destined for the U.S.
	Transit to U.S.	Ships transporting cargo from overseas to U.S.
	U.S. Border	Official U.S. ports of entry and between official land and sea ports of entry
Interior	U.S. Origin	Hospital with nuclear medicine equipment or industrial site
	U.S. Regional	Areas surrounding origins of nuclear material in the U.S.
	Target Vicinity	Areas surrounding potential targets of nuclear attack
	Target	Potential locations of nuclear attack within the U.S.

Fig. 1.5 Layers of the global nuclear detection architecture. Reproduced from Ref. [10]

zation established in 2005 within the department of Homeland Security to centralize the coordination of the federal government's response and to prevent nuclear terrorism by continuously improving capabilities to deter, detect, respond to, and attribute attacks, in coordination with domestic and international partners (http://www.dhs.gov/domestic-nuclear-detection-office, 2017). The SAFE Port Act (https://www.congress.gov/bill/109th-congress/house-bill/4954, 2006) established DNDO and passed to it the specific statutory responsibilities to protect the United States against radiological and nuclear attack, including the responsibility to develop a *global nuclear detection architecture* (GNDA) [10].

The GDNA (Fig. 1.5) is envisioned to consist of three partially overlapping areas and nine sublayers, and therefore has a broad scope and international character. The *exterior layer* comprises the foreign origin, foreign transit, and foreign departure sub-layers. DNDO improves upon radiological and nuclear material detection abroad through efforts that encourage foreign nations or regions to develop and enhance their nuclear detection architectures. The *interior layer* of the GNDA includes all areas within and up to, but not including, the U.S. border. The interior layer focuses on increasing nuclear detection capabilities across the maritime, air, and land pathways and addresses a wide array of potential threats. Finally, the *transit and border layer* is composed of transit to the U.S. from a foreign port of departure or non-port of departure, as well as passing through the U.S. border prior to entering the U.S. interior. This represents the last opportunity to detect radiological or nuclear materials prior to their arrival onto U.S. territory, and initiatives in this layer emphasize maritime domain awareness related to preventive radiological/nuclear detection (https://www.dhs.gov/global-nuclear-detection-architecture, 2017).

GNDA architecture encompasses other programs, such as the *DNDO GRaDER Guidance for Users*, which provides a continuous means of independently testing and evaluating commercially available radiological and nuclear (Rad/Nuc) detection equipment against ANSI N42 performance standards to ensure that only the best radiation detector capabilities are funded by government procurement and grant programs. GRaDER provides performance and operationally relevant technical information on these systems to Department components, other federal agencies, and state, local and tribal governments and first responders. Also, as a part of GNDA, DNDO support cross-cutting efforts, which focus on programs and capabilities spanning multiple layers and pathways of the GNDA. Efforts undertaken in this layer provide the basis for time-phased deterrence and detection strategies. These elements streamline existing capabilities, improve overall coordination, and ultimately seek to enhance radiological and nuclear detection at the federal, state, territorial, tribal and local levels (https://www.dhs.gov/global-nuclear-detection-architecture, 2017).

DNDO work is supported by the activities of the Department of Defense, Department of Energy, Department of Justice, and Department of State, as well as the U.S. Nuclear Regulatory Commission and the Office of the Director of National Intelligence, in coordination with state, local, and tribal authorities, international partners, and private entities. Together, programs supporting the GNDA create a multi-layered defensive network to detect and assist interdiction of radiological and nuclear materials out of regulatory control.

Examples of efforts supporting the GNDA include the radiation portal monitors, which scan for radiological and nuclear materials at international border crossings, employment of radiation detectors by law enforcement and public safety personnel to protect special events, and the use of radiation detection equipment by the U.S. Coast Guard teams when boarding vessels (https://www.dhs.gov/global-nuclear-detection-architecture, 2017).

Similar to the NNSA's efforts in verification, DNDO has been making a significant investment to engage the U.S. academic community in the basic and applied research in the area of detection for homeland security applications, such as prevention of nuclear terrorism. To support this engagement, an Academic Research Initiative program has been established, which provides the necessary education and training to graduate students in the areas of advanced radiation detection and measurement while engaging them in basic, high-risk and potentially high-payoff research in this area.

A *Second Line of Defense* initiative has also been developed under the name *Megaports Initiative*, which is of international character. The program is the part of the Office of International Material Protection and Cooperation within the NNSA. The main idea behind the Megaports Initiative is to enhance the security of the international maritime shipping network (containerized traffic) by equipping the major international seaports with radiation detection equipment and alarm communication systems. Also, the initiative provides comprehensive training for foreign personnel, short-term maintenance coverage, and technical support to ensure the long-term viability and sustainability of installed radiation detection systems [11]. The Megaports Initiative is a joint effort of NNSA, DHS, and the Department of State.

International efforts to prevent nuclear terrorism and ultimately led by the IAEA, but a number of national entities and organizations has emerged to support this mission. For example, the Stanton Foundation has provided support to spearhead the US-Russia Initiative to Prevent Nuclear Terrorism and includes prominent institutions such as the Center for International Security, Institute for World Economy and International Relations, Russian Academy of Sciences in Russia and the Nuclear Threat Initiative (US).

The umbrella program of the European Union in the area of nuclear power is the *Euratom* (https://ec.europa.eu/programmes/horizon2020/en/h2020-section/euratom, 2017). Within the Euratom program, the Joint Research Center of the European Commission supports the development and qualification of nuclear forensics methods and techniques to fight against illicit trafficking and provide operational support to member states and international organizations. The European Commission has further established the European *Nuclear Security Training Centre* (EUSECTRA), which aims to improve member states' capabilities to address the threats associated with illicit incidents involving nuclear or other radioactive materials by providing hands-on training using real nuclear materials to front line officers, their management, trainers, and other experts in the field (https://ec.europa.eu/jrc/en/european-nuclear-security-training-centre-eusectra/about, 2017).

In Japan, the Japan Atomic Energy Agency has established the *Integrated Support Center for Nuclear Nonproliferation and Nuclear Security* (https://www.jaea.go.jp/04/iscn/index_en.html, 2017) to contribute to the improvement of the nuclear material management and strengthening of international nuclear nonproliferation. The mission of this organization includes the development of technologies for nuclear nonproliferation, measurement, detection, and forensics of nuclear material, and support to capacity building and infrastructure development.

1.5 Overview of the Active Interrogation Method

Active interrogation (AI) has become one of the most active areas of research and development in nuclear security and nuclear detection worldwide [12]. The intense focus on this topic by the international scientific community has been motivated not only by the increased level of attention and support by the main stakeholders, such the U.S. federal agencies, but also by the realization that the recent advances in the component technologies such as sources, detectors, and algorithms may allow a significant rate of progress to be realized. It is worth mentioning that, since many of the AI approaches employ advanced concepts, the AI research has been able to attract an impressive cadre of researchers with experience in fundamental sciences to work on the practical problem of detection of illicit nuclear materials.

The most challenging and urgent problem that demands the development of AI technology is the detection of special nuclear material, i.e. material that could be employed to construct nuclear weapons, with focus on ^{235}U and ^{239}Pu. The problems here include rapid clearing of objects such as containers in transit from nuclear threats, standoff detection of nuclear materials at kilometer-scale distances, and improved methods to material accountancy, quantification, safeguards, and verification. The main physics limitations associated with the use of conventional methods of detection are the very low spontaneous rate of characteristic signature generation (γ rays and neutrons), especially in the case of uranium, and the relative ease with which those spontaneous signatures can be shielded. To add to the complexity of this problem, almost all scenarios include the presence of relatively intense, complex, and variable radiation backgrounds.

The simplest method to address the problem of detection and characterization of nuclear material is *passive detection*. In this method, the objective is to reduce the minimum detectable amount of material or improve upon quantitative measurements by the use of sufficiently sensitive and selective radiation detectors, systems, measurement approaches, and algorithms. Some of the key technologies and performance metrics include radiation imaging, high-resolution spectroscopy, and background rejection. Unfortunately, it has been found that the passive detection methods frequently fail due to the aforementioned physics limitations.

The second widely employed possibility that could enable detection of special nuclear material is the use of probing radiation and transmission imaging. This type of measurement is usually referred to as *radiography* or *transmission radiography*. This method is well-developed and used in a wide range of applications, including security, medical, industrial, and basic research. Regrettably, nearly all radiographic methods (with the exception of specialized techniques such as nuclear resonance fluorescence radiography, fast neutron resonance radiography, and associated particle imaging) are only sensitive to the atomic structure along the propagation of the probe radiation. As a result, the radiographic techniques have been limited to imaging the gross distribution of material, the approximate atomic number, and, at best, identifying the locations where high-Z (high atomic number) materials such as uranium may be found. This is complementary to detection of special nuclear material, but in itself has insufficient selectivity.

The third, and the most promising, method that could enable detection of special nuclear material in challenging configurations, such as shielded highly enriched uranium, is referred as *active interrogation*. The key aspect of AI is that the probing radiation strongly interacts with the atomic nuclei to provide characteristic and significantly more intense signatures than in passive detection. To this end, probing radiation in the form of neutrons and energetic photons (X rays or γ rays) holds the greatest promise, although more exotic probes such as protons and muons have also been considered. The characteristic radiation emitted and detectable is in the form of γ rays and neutrons, and suitable detector systems need to be developed and optimally integrated to detect characteristic radiation in an AI environment, which is frequently associated with high radiation field.

One important characteristic of AI is that it establishes a definitive time structure of the expected signature signal. If the probing radiation can be pulsed, the time evolution of the emitted radiation may serve as an additional discriminant for special nuclear material and can help to further reduce the component of the background that overlaps with the signal in time. Such pulsed techniques thus rely on measurements within some coincidence window, or may apply the time-of-flight technique.

Directionality of the probing radiation may also be used to improve the detection sensitivity in AI. If the probing radiation is directed towards a small area, it may be possible to localize the threat by distinguish its characteristic response from the surrounding areas. While only few types of sources may offer inherent directionality, collimator arrangements may be used in conjunction with virtually all of them.

AI systems thus comprise several key components, all of which are discussed in more detail in the remainder of this book: sources, detector systems, and detection algorithms. One special consideration is the radiation dose delivered in AI, which has to be kept to a minimum to minimize the effects on stowaways and sensitive materials in the path of the interrogation beams.

It is tempting to consider the AI as a solution to the standoff detection problem. While AI may be able to provide a future path to gaining such capability, several remaining challenges must be addressed. First, there is a stringent requirement on source directionality (a component of source *brightness*). Second, the attenuation of the interrogating radiation on the way to the interrogated object and of the signature signal returning back to detector (preferably located near the source) must be considered. Finally, the characteristic signature radiation emitted by the interrogated object is emitted nearly isotropically, which limits the efficiency with which it can be collected at a standoff. Regardless of these limitations, it may be possible to establish ambitious (but realistic) goals for the use AI in standoff detection.

1.6 Synopsis of the Book

The organization of this book is as follows. Following the introductory remarks in this chapter, in Chap. 2 we turn our attention to the general characteristics of measurements in nuclear security. We introduce the material of interest, identify the characteristic signatures for detection and their backgrounds, and focus on their origins and the physics of their production. We also consider the methods that allow the statistical limits for their detection to be established.

In Chap. 3 we turn our focus on passive measurements as a baseline for subsequent discussion of the AI techniques, discussing issues such as strength of characteristic signatures, the general method with which passive measurements are performed, we introduce the associated technology, and consider the limitations that are encountered in passive measurements.

Chapter 4 provides the foundations of the detection approach via AI. A considerable attention is given to the impact of active measurements on the detectability of SNM and a synopsis of the AI technology is provided. We further discuss the modeling and simulation in the context of AI and which limitations arise in implementation of actual AI measurements.

Chapter 5 is focused on one of the key technological components of any AI system—the generation of the probing radiation. The principle of operation of linear accelerators, cyclotrons, and novel laser-driven sources is discussed, along with the review of radioisotope sources and the use of natural radiation for AI.

The next important component of an AI system are detectors, which are discussed in detail in Chap. 6. After discussing the general detector characteristics we devote special attention to photon and neutron detectors that may find use in AI as well is in any associated radiographic measurements.

In Chap. 7 we consider the various aspects of data acquisition and processing systems. In addition to introducing the more general aspects of those systems, we provide some discussion of the enabling techniques which may enable high rates in AI measurements, as well as methods that can allow the neutron from photon interactions with detectors to be distinguished from each other.

Chapter 8 discusses how the data generated by an AI system may be interpreted. Here we introduce the associated planar and tomographic radiography, principal component analysis, methods to unfold the signatures from measurements performed with detectors, and the use of algorithms to extract useful information from distributed detection systems.

We highlight some of the prototype systems that have reached a reasonable level of integration and testing readiness in Chap. 9. This includes the Nuclear Carwash, the Pulsed Neutron Fast Analysis system, the advanced scanner developed by Passport Systems, and the prototype laser-based scanner based on inverse Compton scattering.

Radiation dose is a major concern in all AI measurements, and the relevant aspects of dose deposition, measurement, and mitigation are discussed in Chap. 10. In Chap. 11 we introduce an effort to create a technical standard for AI systems, and summarize the main conclusions in Chap. 12.

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Chapter 2
Overview of Signatures and Measurement Needs

Mitaire Ojaruega and Anna S. Erickson

Abstract The Atomic Energy Act of 1954 defined special nuclear material (SNM) as plutonium or uranium enriched in the isotopes ^{233}U or ^{235}U, or any materials the U.S. Atomic Energy Commission determines to be SNM. With the current state of affairs, a key technical challenge on a quest to combat illegal use of SNM is detecting heavily shielded highly enriched uranium. For the purpose of this anthology the above definition holds. Active interrogation is the intentional bombardment of an object using ionizing radiation in order to induce nuclear reactions producing distinct, energetic emissions, hence making the target more readily detectable. This method further allows the detection of SNM quantity and other material properties. Traditionally, this technique uses ionizing radiation such as neutrons, muons, and γ rays as a probe. Combating this challenge has resulted in various government entities investing their substantial resources.

2.1 Overview of Signatures of SNM

For the past two decades, detection of SNM in all its forms has been an issue of significant importance. A number of techniques have been developed over the years to help address this challenge. The most promising approach for identifying the mass and other features of shielded SNM is active interrogation (AI), which involves introducing ionizing radiation to penetrate a cargo and other shielding. The interaction of different types of radiation with nuclear materials produces unique signatures. The main signatures used to identify the SNM within a cargo are delayed

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neutrons, delayed γ rays, prompt neutrons, and prompt γ rays, because of their penetrating power [1].

For the detection and characterization of shielded SNM, fission is the most important and most studied nuclear reaction process in AI detection techniques to date. In AI applications, the neutrons and γ rays emitted as part of the fission process can yield information about the following characteristics of SNM: yield from induced fission, energy, and half-life of the decaying nuclides produced in fission.

Fission fragments do not need another name. Usually the daughter products are the results of the fission fragments radioactive decay mostly beta (then gamma) and in very few cases via neutron emission. In addition to fission fragments, two to three prompt neutrons and about eight prompt γ rays are emitted within a very short time (on the order of 10^{-14}–10^{-12} s). Fission fragments are highly unstable and subsequently tend to undergo β decay, introducing comparatively long decay times (on the order of a second or longer), which is the origin of the delayed signature for on average fission. These delayed signatures are unique for SNM when using AI and yield six to seven γ rays and 0.01–0.02 neutrons per fission. The process of fission and the emission of associated particles is illustrated in Fig. 2.1.

The cross section is an important consideration when discussing fission-based SNM detection and characterization since it is a representation of probability of an interrogating radiation to cause fission or photofission in the given nuclear material. In general, the microscopic cross section, which is an inherent property of the isotope, increases with decreasing neutron energy. Cross sections for ^{235}U are shown in Fig. 2.2 and range from 600 b for thermal neutrons to about 1.2 b for 2.2-MeV neutrons [2], making thermal neutrons ideal candidates to cause fission in ^{235}U. As the energy of the neutron increases, the region of resonances can be observed. Resonances correspond to neutron energies that produce final states that coincide with compound nuclear energy levels. Since the level widths are rather small, the resonances are sharp and grow closer together as the kinetic energy of the neutron increases. At some point, resonances can no longer be resolved, and the cross section drops off sharply. For low-energy neutrons, the fission and radiative capture cross sections follow a $1/\sqrt{E}$ scaling with neutron energy (E), indicating that the probability of reaction is proportional to the time the neutron spends near the nucleus. Based on fission cross sections, one might predict that thermalized neutrons are best for AI. Unfortunately, interrogation with low-energy neutrons is by itself, in many cases not practical due to the high probability of neutron absorption in shielding and other cargo materials before they have a chance to reach the SNM.

As shown in Fig. 2.2, the cross section also heavily depends on the type of probing ionizing radiation. Interrogation sources used in AI produce neutrons or x-rays of appropriate energies to induce fission. For photon interrogating beams, the photofission threshold is 5–6 MeV. The fission process gives rise to a range of signatures, which are summarized in Table 2.1.