

# A brief introduction to analytical methods in nuclear forensics

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**Abstract** Nuclear forensic (NF) techniques are critical in responding to both environmental releases of nuclear materials and illicit trafficking activities involving both nuclear and counterfeit materials. Despite rising need, however, significant barriers exist to the future success of such research. This subset of analytical chemistry contains unique concerns (e.g. chronometry and impurity signatures), a wide variety of preparatory/instrumental approaches, and is in need of innovative solutions to current problems both in and out of the lab. The present work introduces existing NF research, development challenges and notes potential areas for advancement by highlighting several key analytical approaches. Examples of concerns and techniques discussed in this review include: chronometry, reference materials, separations, counting spectrometry, mass spectrometry and more.

**Keywords:** Chronometry · Counting spectrometry · Ion exchange separations · Mass spectrometry · Microscopy · Nuclear forensics · Standard reference materials

## Introduction

Nuclear forensics (NFs) is the technical means used to characterize various nuclear materials and interpret the

resulting data [1]. This subset of analytical chemistry is critical in responding to suspect trafficking activities, deterring nuclear terrorism, and verifying that international treaties (e.g. Non-Proliferation Treaty [2]) are being upheld; identical methodologies are also used in responding to or tracking intentional/unintentional environmental releases of nuclear materials. Should a nuclear incident occur, a range of NF techniques will also be required to obtain key response information such as device type, material origin, route of travel, and likely/unlikely responsible parties. Such information could ultimately result in legal, civil, or even retaliatory actions and must be highly defensible.

Recent application of NF techniques has been discussed in several works [3–5]. Such reports, while sometimes involving hoaxes, highlight the field's rising significance in the face of increased illicit activities. According to the International Atomic Energy Agency (IAEA) [6], total confirmed trafficking incidents involving nuclear and non-nuclear/counterfeit materials increased by ~500 % between 1996 and 2006. Further details regarding illicit trafficking are illustrated in Fig. 1.

Despite the rising need, significant barriers exist to the future success of NFs research. The US NF capabilities were recently identified as having three large-scale challenges, including [1]:

- Development of enhanced international cooperation.
- Current and future availability of expert personnel.
- Research and development in key technical areas.

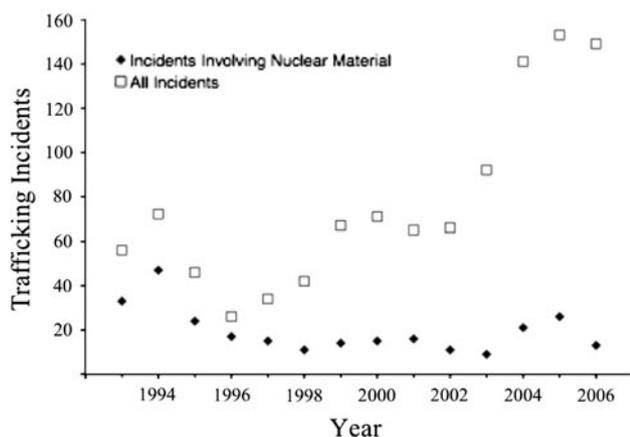
Addressing these challenges will be exacerbated by the sensitive nature of NFs research as well as national and international protocol considerations.

The present work introduces some of the challenges of modern NFs by briefly reviewing several analytical

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**Fig. 1** Incidents of illicit trafficking (involving nuclear and counterfeit materials) recorded by the IAEA. Adapted from Ref. [1]

methods used in the interrogation of nuclear materials. Discussed topics include key concepts and special concerns, separations, and frequently employed methods of instrumental analysis. Some comparison of complementary techniques is also provided throughout, as this consideration impacts the manner in which a collected sample is ultimately processed.

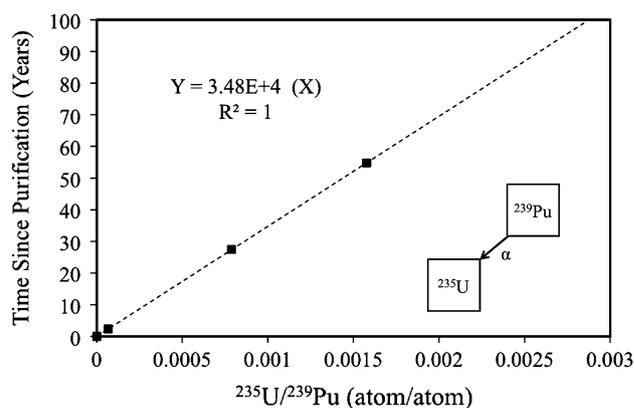
### Key concepts and special concerns

The intrinsic radioactive decay of nuclear materials is frequently used to garner information not always available in conventional forensics. Decay may also raise special concerns as a sample system can be changing rapidly and may not be as well characterized as desired. Hence, a thorough knowledge of several concepts and concerns is required to conduct NF investigations.

### Chronometry

The determination of a nuclear material's age is a critical tool in NF investigations. Dating techniques can be used to identify a material's source as well as procedures that may have been carried out on that material, such as reprocessing [4, 7, 8]. This information can be used to identify or exclude potential participants in the "life" of the material of interest.

Nuclides related through radioactive decay processes (e.g.  $^{234}\text{U}$  and  $^{230}\text{Th}$ ) will have relative sample concentrations that may be readily predicted using parent–daughter in-growth equations and relevant half-lives [9]. If a material has been radiochemically refined to remove daughter species, the time elapsed since purification can frequently be "back calculated" using radiochemical separation techniques in conjunction with analytical measurement of existing



**Fig. 2** Plot of the relationship between daughter/parent ratio and time elapsed since "perfect" radiochemical purification of  $^{239}\text{Pu}$

parent–daughter ratios. These concepts are illustrated in Fig. 2 for the  $\alpha$  decay of  $^{239}\text{Pu}$  to  $^{235}\text{U}$ , assuming perfect purification at time  $T_0$ ; this figure clearly illustrates the predictable relationship between in-growth of  $^{235}\text{U}$  and time elapsed since purification. Cases when this strategy may not apply involve parent–daughter pairs that achieve secular equilibrium<sup>1</sup> very rapidly or instances when the half-life of the daughter nuclide is significantly shorter than the time that has elapsed since purification (e.g.  $^{237}\text{Np} \rightarrow ^{233}\text{Pa}$ ) [9]. Additionally, for environmental samples, non-equivalent metal/ion transport for parents and daughter species may also complicate or invalidate the use of chronometric measurements.

Various useful age-dating relationships exist, including the commonly employed  $^{234}\text{U}/^{230}\text{Th}$  and  $^{241}\text{Pu}/^{241}\text{Am}$  chronometers [7, 8, 10]. Special application chronometers may also be used in the analysis of unique samples; the  $^{232}\text{U}/^{228}\text{Th}$  and  $^{233}\text{U}/^{229}\text{Th}$  ratios, for example, are valuable in age-dating certain uranium materials. Parent–granddaughter relationships can also be considered as special chronometry relationships. These ratios may be particularly valuable in uncovering efforts to intentionally make nuclear materials look older through the addition of daughter nuclides [9].

The concept of chronometry embodies one barrier to fully characterizing nuclear materials: *the composition of nuclear material changes as samples are prepared and analyzed*. This consideration can be substantial for species that decay quickly and/or whose daughter product(s) put forth spectral interferences. As an example, the decay of  $^{233}\text{U}$  ( $t_{1/2} \sim 1.6 \times 10^5$  years) is rapid compared with many species (e.g.  $^{238}\text{U}$ ) and yields  $^{229}\text{Th}$ , which emits an  $\alpha$  particle that is nearly isoenergetic with the parent [11].

<sup>1</sup> Occurs when the activity associated with an isotope becomes essentially constant after a given time because of the continued decay of the parent isotope. At this point, parent and daughter activity values are approximately equal.

Confident nuclear materials characterization, therefore, tends to rely on the use of freshly prepared samples and complementary analysis methods, such as mass spectrometry (MS) and counting techniques that measure nuclides both directly (e.g. ions reaching the detector) and indirectly (e.g. decay particles reaching the detector), respectively [9]. However, species that decay exceptionally rapidly (e.g.  $^{232}\text{U}$ ,  $t_{1/2} \sim 32$  years) will not be measured by MS, but can readily be accounted for using decay counting techniques [9, 10].

The decay of nuclear samples makes rapid analysis methods highly desirable. Rapid analysis not only has the potential to dramatically simplify resulting data in a laboratory setting, but is also in-line with field response needs. Field response techniques, however, are lacking and there is a need for a new subset of automated, field-deployable instrumentation capable of characterizing NF materials on short order [1].

### Signatures and database availability

Determining the composition of a sample's key components (e.g. U, Pu and progeny isotopes) is clearly of central importance. However, analysis of material impurities can provide signatures, whether inherent or arising from processing, that can also provide key insights into an NF sample's history and clarify the nuclear material's expected function. Fabrication and reprocessing of nuclear fuel, for instance, are multistep processes that generate products containing a variety of informative impurities [12]. Examples of potentially present and valuable species may include: metals (e.g. Ba, Ca, Cs, Mg), transition metals (e.g. Cr, Fe, Mo, Ni), lanthanides (e.g. Eu, Nd) and more [4, 13, 14].

Lead isotopic signatures have proven an excellent example of useful impurities in NF investigations. Several recent reports discuss the use of lead signatures in determining the origin of uranium samples [14–16]. Each of these works provides insight into the nature of the sample material based on the disruption of naturally occurring lead isotopic abundances; the lead isotopic distribution in uranium materials are dramatically different from common sources. Such efforts, however, are complicated by the need to account for natural variations in Pb content and concentration.

Though not technically an impurity, the measurement of oxygen isotopic ratios (i.e.  $^{18}\text{O}/^{16}\text{O}$ ) within actinide complexes may also point to the origin of an NF sample. This concept stems from the final steps of material production using waters from the fabrication region [17]; oxygen isotopic content in air and groundwater has been observed to vary by as much as 10 % with geography [18]. Recent

research demonstrated various instrumental approaches to the use of MS to determine material origins based on this sample parameter [19–21]. Some debate, however, remains as to what technique represents an ideal approach to the determination of oxygen isotopic ratios in NF samples.

A thorough understanding of an NF sample's impurities is invaluable. The importance of impurity signatures highlights the need for comprehensive NF databases. These databases, ideally, would be capable of describing the expected elemental compositions and isotopic ratios for nuclear materials from around the world and the variations in these parameters that would result from later processing. While several databases are maintained by US entities, as well as international organizations, these are not extensive enough to facilitate rapid data comparison [22, 23]. Unfortunately, given the obstacles to assembling such an information store, advances on this front will certainly need to be made outside of the realms of industry/academia and will likely never result in a widely accessible, comprehensive database.

### Reference materials

Certified reference materials, produced by national and international organizations, serve as critical standards in NF research. These are vital for instrument calibration, method validation, and analyte tracing, as seen in isotopic dilution measurements. Interagency groups, however, have found that there is a substantial lack of reference materials addressing NF priorities (e.g. terrorism/attribution, non-proliferation, and fuel cycle related issues) [24]. The need for new standards takes various forms, including:

- Environmental matrix reference materials with known actinide content.
- Isotopic dilution/ratio reference materials.
- Chronometry standards reflecting a known material age.

Ideally, numerous additional materials would also be available for special applications (e.g. uranium oxide standards with known oxygen isotopes), radiobioassay, and environmental research. Years of work will be required to identify/obtain appropriate source materials, prepare homogenized samples and certify the reference standards needed by the NF community.

### Separations

Chemical separation techniques are frequently used in NF research to reduce interferences and facilitate the measurement of low level radionuclides. Ideal purification

strategies will be capable of providing high levels of purification and rapid, as progeny in-growth begins immediately following purification. Some general types of radiochemical purification are briefly introduced below.

### Anion exchange

Anion exchange separation methods are widely used in the purification of actinides and actinide bearing materials [25]. The widespread use of these approaches can be attributed to their simplicity, versatility, and broad applicability. Useful resins are now available from a variety of vendors, including AG 1 resins from Bio-Rad, TEVA/UTEVA resins from Eichrom, DOWEX 1 resins from DOW and more. These resins, however, work on similar principles; anionic actinide complexes (e.g. nitrate or chloride complexes) are retained by anion exchange sites (e.g. quaternary ammonium) on the resin and neutral species pass through the column unretained. Then, if desired, retained species may be eluted from the column by conversion to a neutral complex, typically by changing the mobile phase(s) passed through the resin bed.

Anion exchange-based separations of actinides, while valued for simplicity and widely used [26–28], tend to be very time-consuming and are infrequently automated. Indeed, most are still carried out based on a gravity drip approach with manual mobile phase introduction. Efforts to expedite these processes have taken various forms, including the use of gas pressurized systems [29] and vacuum manifolds [30], and have met with some success. Such methods, however, tend to represent strictly mechanical approaches that expose additional equipment to potential contamination that may jeopardize future investigations. Hence, advances are still needed to prepare updated, rapid anionic exchange procedures that satisfy NF research priorities.

### Co-precipitation

Actinide isolation by co-precipitation is frequently used for samples of relatively large volumes to concentrate analytes and remove interferences. The most frequently used actinide carriers include iron hydroxides, lanthanide fluorides/hydroxides, manganese dioxide, and a few other species. Additional information on the co-precipitation of actinides can be found in the works of Katz et al. [31].

Several considerations exist for the use of co-precipitation techniques. These include variable recoveries for closely related carriers (e.g. ferrous vs ferric hydroxide), recovery rates that may be analyte concentration dependent [32], and the need to ensure uniform analyte oxidation state in the sample solution [31].

### Analysis

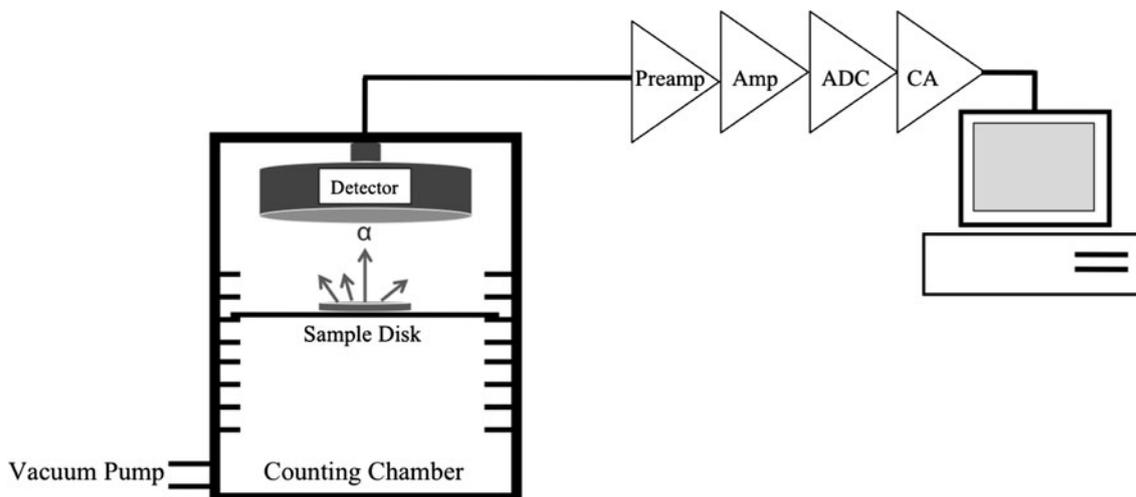
NFs, like classical forensics, uses a range of instrumental techniques. For species with short half-lives, radiometric counting techniques are valuable in detecting decay products associated with specific nuclides. For longer-lived species, inorganic MS is a powerful means of carrying out elemental analyses and determining valuable isotopic relationships. Microscopy approaches are also central to in-depth characterization of a nuclear material. These are discussed below, along with additional useful techniques.

### Counting techniques

Various counting techniques may be employed in the analysis of NF materials that emit decay species. Options include  $\alpha$ -,  $\beta$ -,  $\gamma$ -, and neutron counting approaches; the most frequently employed of these methods, however, are alpha and gamma spectrometry [9].  $\beta$  Counting is infrequently used because most short-lived  $\beta$ -emitters also give off characteristic  $\gamma$ -rays and produce very broad counting peaks. Neutron counters are rarely found in the analytical lab, partly in light of shielding concerns should such neutron emitters be introduced into a counting facility; neutron counting is, however, typically associated with sample receiving measurements.

### Alpha spectrometry

Alpha spectrometry measures the presence of radionuclides based on the emission of  $\alpha$  particles (i.e. helium nuclei) and is frequently used in NF investigations [33–36].  $\alpha$  Particles can be measured by a variety of detectors, including liquid scintillation counters, gas ionization detectors, and ion-implanted silicon semiconductor detectors [34]. Among these, the silicon semiconductor detectors are the most frequently used. Typical alpha spectrometers, illustrated in Fig. 3, have low backgrounds and measure particles ranging from 3 to 10 MeV; radionuclides that decay through  $\alpha$  emission tend to eject  $\alpha$  particles with discrete, characteristic energies between  $\sim 4$  and 6 MeV. However, the energies of these particles can be slightly attenuated as they pass through the layers of the sample. Upon impacting the detector element, these particles create a cascade of hole:charge pairs proportional to the energy of the impinging  $\alpha$  particle. Detector energy resolution, typically on the order of  $\sim 25$  keV [34], is impacted by both the spectrometer's performance and the source-to-detector geometry. Increased distance between the source and the detector tends to lead to improved resolution, but at the cost of decreased particle detection. Even at close geometries, large quantities of incoming  $\alpha$  particles can still go uncounted, as the detectors are only  $\sim 30$ – $40$  % efficient



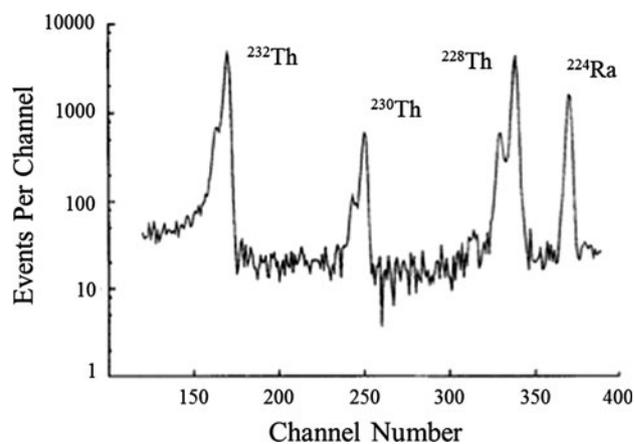
**Fig. 3** Representation of an alpha spectrometry system, including associated electronics and recording devices

[34]; overcoming this deficiency may require increased sample masses and/or extended counting times to achieve desired limits of detection.

The advantages of alpha spectrometry include relatively inexpensive equipment costs, low backgrounds, high selectivity, and good throughput capabilities with the use of multi-chamber systems. Alpha spectrometry is particularly valuable as a complement to MS methods to account for short-lived nuclides (e.g. species with  $t_{1/2} < 100$  a). Several disadvantages, however, are also associated with the method. Examples include:

- Significant sample preparation efforts to obtain useful alpha spectrometry sources (frequently stainless steel or platinum disks with a thin layer of analyte electrodeposited on one side) [37].
- Spectral interferences/artifacts from extensive preparation prior to counting. High purity acids are needed to ensure that minimal external metals are introduced and glassware must be acid treated to remove trapped uranium.
- Measurements may require relatively large quantities of material; these quantities, however, can lead to poor spectral resolution due to loss of energy as a particle travels through the “thicker” analyte layer.
- Undesirable spectral overlap of related isotopes (e.g.  $^{233}\text{U}$  and  $^{234}\text{U}$ ) and parent–daughter nuclides (e.g.  $^{233}\text{U}$  and  $^{229}\text{Th}$ ) [11].
- Analysis times may be long relative to various other methods; counting times can range from days to weeks.

An example of an  $\alpha$  decay spectrum is provided in Fig. 4 for the analysis of thorium-bearing materials. As shown, results are typically plotted as detector channel (assigned to discrete particle energy and increases proportionally) versus number of particles detected at a given energy. Figure 4



**Fig. 4** An example of an  $\alpha$  decay spectrum. Adapted from Ref. [36]

also highlights that isotopes of a given atom tend to be detected in reverse sequence with increasing  $\alpha$  particle energy. Gamma spectrometry (discussed below) provides results that are conceptually identical, but resulting peaks tend to be much sharper because of reduced energy attenuation.

#### Gamma spectrometry

Some radionuclides produce discrete  $\gamma$  rays between a few keV and 10 MeV that can be measured by gamma spectrometry without destroying the sample. Gamma spectrometry systems use a variety of detectors, with the most common being the semiconductor germanium detector [34]. These detectors are capable of providing energy resolution superior to that observed in alpha spectrometry measurements; typical high purity germanium detectors are capable of providing resolution of  $<2$  keV, but have absolute efficiencies of less than a few percent [34].

Information regarding the application of gamma spectrometry can be found in the work of Wolf [38], Sill [39], and others [40–42].

Gamma spectrometry, in general, is less sensitive than either alpha spectrometry or MS methods because of relatively low detector efficiency and high background [38]. Gamma measurements, however, can be made without time-consuming sample procedures and can occur in the field using portable detectors. Hence, gamma measurement techniques are recommended for on-site analysis of NF materials to identify bulk constituents [6].

### Mass spectrometry

MS techniques are indispensable in modern NF investigations. MS techniques are capable of accurately providing elemental and isotopic information for a variety of materials while requiring reduced sample mass relative to counting techniques. These methods also provide quantitation of nuclides of interest through the addition of a tracer; this is known as isotope dilution MS. One of the primary challenges with these approaches, however, is the need for distinguishing between highly similar analytes (e.g.  $^{235}\text{U}$  and  $^{236}\text{U}$ ) present in drastically different proportions; hence, excellent resolution/mass abundance, low backgrounds, and, in general, proper instrument functioning/programming are essential. Several options for carrying out this type of work are discussed below.

### Thermal ionization MS

Thermal ionization MS (TIMS) has been used for decades in the measurement of isotopic ratios of long-lived radio-nuclides. In TIMS, small quantities of highly purified analyte are deposited onto a clean metal filament, frequently made of either rhenium or tungsten. The sample is then heated in the vacuum of the ion source by passing a current through the filament; typical temperatures achieved range from 1,000 to 2,500 °C [9]. If the ionization potential of a given analyte is low enough, a portion of the analyte will be ionized by interaction with the hot filament surface. Ions are then directed down the flight tube and separated based on mass-to-charge ratios. Specificity in TIMS methods is achieved through the use of separations procedures prior to filament loading and refined filament temperature selection.

The major application for TIMS is the precise determination of isotopic ratios of various materials [43]; determined ratios frequently span numerous orders of magnitude. TIMS is capable of measuring these ratios using picogram levels of starting material [6]. In light of the high precision, sensitivity and resolution associated with TIMS, resulting measurements frequently serve as the

benchmark for comparing other isotopic analyses for a given material.

The major disadvantages of TIMS include the need for time-consuming sample preparation (e.g. separations and filament preparation) and relatively inefficient analyte ionization regardless of employed sample loading method. Hence, some interest has been shifting to the use of multi-collector inductively coupled plasma MS (MC-ICP-MS) techniques in modern NF investigations [9].

### Multi-collector inductively coupled plasma MS

MC-ICP-MS is frequently used in the determination of nuclear material isotopic ratios. In MC-ICP-MS, purified sample solutions are nebulized directly in a spray chamber prior to being aspirated into a plasma. The high temperature of the plasma leads to the dissociation of the sample solution and high efficiency ionization of the analyte. Ions then enter the mass spectrometer where mass discrimination typically relies upon a double focusing system. Ions of various masses are detected simultaneously by a bank of detectors similar to those used in TIMS (i.e. Faraday cups and ion counters that may both present within a single detector block).

ICP-MS, using more traditional detection setups, is also useful for surveying the elemental composition of materials of interest. These methods allow for the quantitation of various impurities of interest [15, 44], discussed above. Such methods, however, do not provide isotopic information.

MC-ICP-MS analysis may be performed rapidly, relative to TIMS, and does not require lengthy filament preparation procedures. Efforts to obtain high quality, defensible results, however, still tend to require extensive sample clean up and negate some of the time saved during analysis. Furthermore, Ar plasma ionization is inherently less stable than thermal ionization and the MC-ICP-MS system remains a relatively expensive instrument requiring a skilled operator. The potential for isobaric interferences (e.g.  $^{238}\text{UH}^+$  vs  $^{239}\text{Pu}$ ) is also a significant concern in the use of MC-ICP-MS, as the production of these species within the Ar plasma is well known [45].

### Secondary ion MS

Secondary ion MS (SIMS) is a micro-analytical technique valuable for three-dimensional analyses of a material's elemental composition and isotopic ratios. SIMS can be applied to the characterization of bulk materials with limits of detection in the low ppb range. Ion production in SIMS relies on the bombardment of solid samples with a focused beam of primary ions ( $\text{Ar}^+$ ,  $\text{Ga}^+$ ,  $\text{Cs}^+$ ,  $\text{O}_2^+$ ,  $\text{O}^-$ ) [9]. The sputtered, secondary ions are directed into the MS system

for measurement. These ions are the result of kinetic energy transfer from the primary ions, which penetrate into the solid sample to some depth. SIMS can be used to detect any element, but the sputtering process is highly matrix dependent and ion yields can vary greatly. Matrix-matched standards are, therefore, critical in conducting precise SIMS analysis. Proper standards strategies and multicollector instrumentation can allow for precisions of 0.002 % to be obtained [46].

#### Additional MS approaches

A full review and comparison of all MS techniques of potential value in NFs is well beyond the scope of the present work. Methods other than those discussed above include spark source MS, glow discharge MS, laser ablation ICP-MS, accelerator MS and many more. Additional information on the strengths and weaknesses of such methods can be found in [9, 43].

Resonance ionization MS (RIMS) methods should be briefly introduced as an alternative MS approach in light of recent renewed interest. RIMS is a highly selective and ultrasensitive means of characterizing NF materials that relies on a two-step ionization process [43]. A portion of a given sample is first excited/volatilized, and then one or more lasers are used to ionize the vaporized analyte. These lasers are tuned to the excitation energy of the analyte of interest and are the basis of selectivity in RIMS. While this approach is not new [47], the application of recent laser technologies may allow RIMS to play a greater role in future NF work. Advantages of the use of RIMS include: (1) isobaric suppression, (2) high ionization efficiency, (3) high overall sensitivity, (4) high isotopic selectivity, and (5) minimal sample preparation [48].

#### Additional NFs analysis methods

Numerous additional approaches may be employed in the interrogation of seized nuclear materials. For example, controlled potential coulometry [49], ceric titration [50, 51], and Davies and Gray titration [52] methods have all proven highly valuable means of determining sample actinide content with good precision. These methods have been employed for decades and are still used in several US national laboratories [53]. In contrast to the previously discussed methods, however, these approaches have received relatively little attention in recent years in terms of novel advancement and tend to require much larger quantities of sample (mg to g).

Further NF analysis methods can include: autoradiography, liquid scintillation counting, pycnometry, X-ray diffraction measurements, and more. Scanning electron

microscopy (SEM), X-ray fluorescence (XRF) and neutron activation analysis (NAA).

#### Secondary electron microscopy

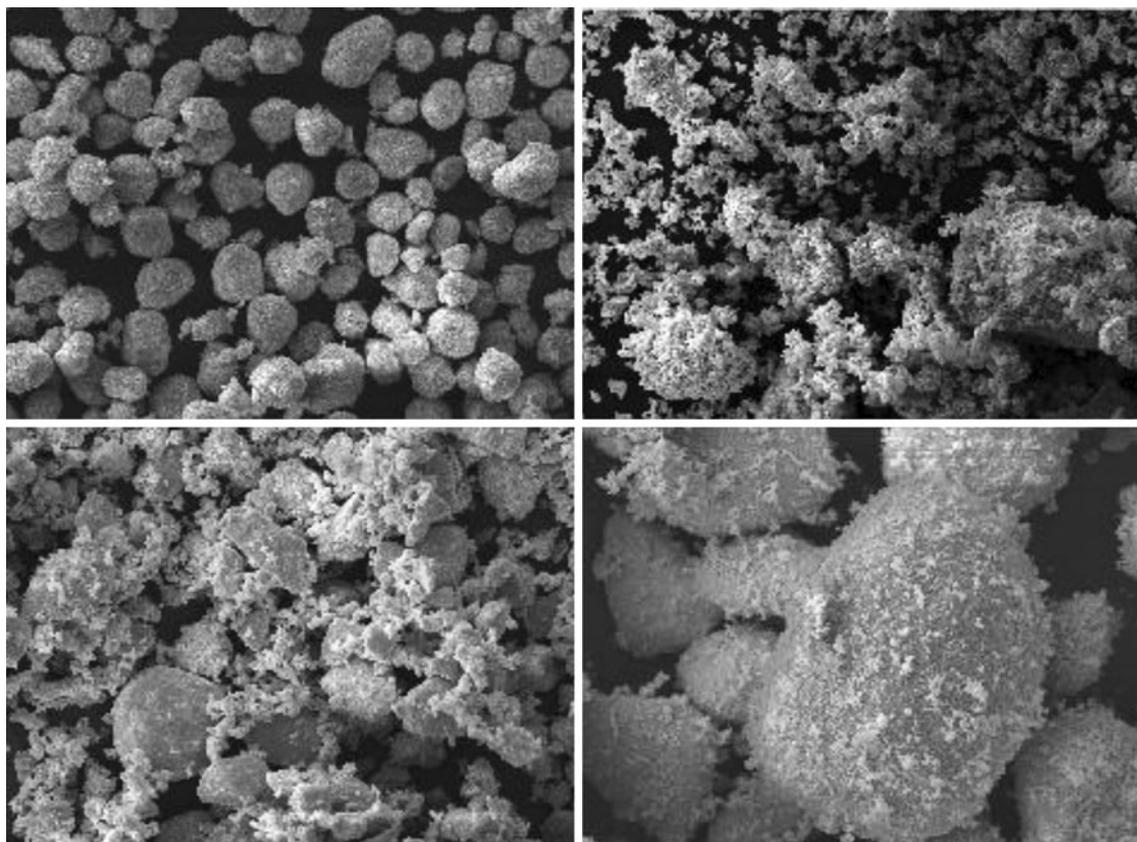
SEM can provide images of an object's surface at high magnification, up to 500 000 times, with resolution on the order of nanometers [6, 7]. In this technique, a focused beam of energetic electrons is scanned over the sample and electrons that are backscattered or emitted from the sample surface are detected. Images are constructed by measuring the flux of electrons from the sample surface as a function of the electron beam scanning position. This data may be useful in determining what process(es) may have been employed in the material's production and distinguishing between materials of differing origins. For example, the images shown in Fig. 5 illustrate the use of microscopy to clearly distinguish between four UF<sub>4</sub> samples produced by differing processes [54].

Both backscattered and emitted electrons provide valuable information about the sample surface. Backscatter measurements elucidate the average atomic number of the area being scanned. Emitted electrons, also known as secondary electrons, provide topological information. X-rays may also be emitted from the sample surface and can be used to determine the elemental content of the material; XRF is discussed more below and further information on SEM-XRF can be found in the work of Newbury et al. [55].

SEM is a relatively straightforward method to use, however image quality may be impacted by sample preparation procedures. Samples must be amenable to being under vacuum in the SEM chamber, may require pretreatment (e.g. conductive coating), and are limited in size by the dimension of the SEM chamber, typically on the order of inches.

#### X-ray fluorescence

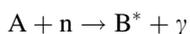
XRF is a valuable means of rapidly and non-destructively determining the elemental composition of a nuclear material based on the detection of characteristic X-rays. Direct sample irradiation allows for minimal sample preparation and portable XRF instrumentation is available for field deployment. The limits of detection for XRF are ~10 ppm [6]. This value is well above the limits of MS approaches that are also capable of providing isotopic data, but that require sample purification prior to analysis. XRF analyses tend to be hindered by matrix effects, which must be corrected for, and particle size distribution considerations. Additionally, the measurement of elements with low characteristic X-ray energies remains problematic.



**Fig. 5** Microscopy *images* for four  $\text{UF}_4$  samples of differing origins. Adapted from Ref. [49]

### Neutron activation analysis

NAA is a powerful, non-destructive means of analyzing elements of mid to high atomic number [56]. The method, which is also routinely used in the analysis of non-nuclear materials, combines excitation by nuclear reaction (i.e. neutron bombardment) and radiation counting techniques to detect various materials. The measurement of characteristic radiation, following bombardment completion, is indicative of the elements of interest. These steps can be summarized as:



where A is the starting analyte, n is the incoming neutron,  $B^*$  is the excited product, and  $\gamma$  is the detected radiation given off by de-excitation of the product species [57].

The advantages of NAA include multi-element analysis, excellent sensitivity, and high selectivity. NAA also does not require the use of time-consuming separations procedures, though they may be useful in some cases. However, practical disadvantages, such as requiring a nuclear reactor for sample preparation, make NAA analyses unlikely to ever be performed on a scale similar to MS or the other techniques discussed above.

### Conclusions

NFs is a burgeoning field in the face of increased illicit trafficking activities throughout the world. Future success in preventing and responding to nuclear events, and environmental releases, will rely heavily on the use of an extremely wide variety of analytical techniques, including separations, counting methods, MS, and numerous others. Significant work, however, is still needed to ensure that such methods are capable of providing critical information promptly, accurately, and with exceptionally low levels of material. Additionally, several special concerns (e.g. widespread availability of databases, appropriate standards, and lack of expert personnel) [1, 24] must be either resolved or circumvented in the near future.

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