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Abstract: The idea of non-destructive elemental composition analysis is reviewed. The term non-destructive has many definitions in many different fields, as well as different definitions within a single field. The definition of non-destructive is discussed for several different fields: archaeology, paleontology, forensics, space science, geochemistry. Activation analysis techniques, claimed to be used non-destructively in many fields, are used as a lens to provide a unique perspective on what non-destructive means. A list of criteria was created to create a broad, general definition of non-destructive. Finally, photon activation analysis is discussed as a potential non-destructive technique for bulk elemental composition analysis of large samples.

Keywords: Non-destructive analysis, elemental composition analysis, chemical composition analysis, photon activation analysis, non-consumptive analysis

1. Introduction to Non-Destructive

Activation analysis techniques provide a unique lens through which the idea of non-destructive can be defined. In many fields, activation analysis is considered to be non-destructive. At times this includes some of the fields where no damage to the sample is highly sought after: archaeology and forensics.

Non-destructive techniques are highly valued in many different fields. A survey of the literature shows a wide array of working definitions. This paper intends to discuss definitions in various fields and try to start a discussion to create a consensus definition. The paper will also focus on the unique questions activation analysis imposes on the discussion of non-destructive and introduce photon activation analysis (PAA) as a possible non-destructive technique for broad spectrum elemental analysis. PAA offers unique capabilities to do bulk analysis of large, inhomogeneous samples. In addition, various other commonly used “non-destructive” techniques will be evaluated based on the criteria specified by our definition of non-destructive.

Every field has information that is scientifically important. Historically, archaeology has been mostly concerned about the external, physical characteristics of samples. Space science, the analysis of extraterrestrial rocks, dusts, etc. has been mainly interested in the chemical compositions. Paleontology has three main pathways of information: external morphology, internal structure, and chemical composition (Riquelme, Ruvalcaba-sil, & Alvarado-Ortega, 2009). These differing views of what is considered interesting, has lead to the evolution of many definitions of non-destructive. Chemical composition has become increasingly more important in archaeology (Biró, 2005). As the interesting information in a field evolves, so should the definition of what constitutes a non-destructive analysis.

2. Definitions from different fields

Non-destructive techniques are used and coveted in many fields of science. This discussion will focus on three major groupings of fields: rare items, environmental, and forensics. The group of rare items includes fields such as archaeology, paleontology, and space science. These fields tend to have samples that are irreplaceable, unique, one of a

kind, etc. Environmental encompasses analysis of rocks, soils, air particulates and other environmentally relevant samples. Finally, forensics is a broad field where non-destructivity is of the utmost importance. This can include fields such as crime, illegal and fraudulent trade, nuclear treaty verification, terrorist attribution, etc.

Standard definitions of non-destructive are hard to find for each field. The definitions given herein are either definitions found in specific works, or definitions inferred by the authors from a survey of field-specific literature concerning applications of non-destructive analysis.

The discussion will start with forensics, as this field has stringent requirements and consequences for non-destructive analysis. Forensics is a broad field with many questions to be answered through analysis. All of these applications however share the need to preserve evidence completely, making non-destructive testing of paramount importance (Houck, 2016). Forensics is also unique as a standard definition can be found in the Encyclopedia of Forensic Science (Bell, 2008): “A test that does not alter or damage the sample”. Non-destructive analysis is also useful to establish a baseline that can be used to compare subsequent destructive analyses after splitting the sample between the prosecution and defense (Houck, 2016). A related field, Non-Destructive Testing (NDT) (Cawley, 2001), has another definition, which is essentially, a test that maintains the serviceability of the sample. Non-destructive analysis is ideal for forensics, in reality, though; it is not often possible; so destructive techniques are commonly acceptable if enough of the sample is left for further testing; however, this can cause much inaccuracy if the sample is inhomogeneous.

By contrast, the field of environmental analysis is much less stringent. Samples tend to be reproducible and much more abundant. Techniques such as X-Ray Fluorescence (XRF) are considered non-destructive, even though alteration of the sample into a fine powder is typically required (Stremtan, Ashkanani, & Tykot, 2013). Laser ablation (LA) combined with inductively coupled plasma mass spectrometry (ICP-MS), where a small area of the surface is removed and destructively analyzed, is also considered non-destructive (Keighley, Mcfarlane, & Luo, 2013).

Finally, the field of rare items encompasses many fields and many definitions. The definition we have inferred from Paleontology papers is that non-destructive means

preserving the macroscopic physical attributes (external morphology, internal structure). Some consider just the act of removing a fossil from its deposit to be destructive (Ndo, Hen, Yodo, Ori, & Ugiyama, 2000). Others consider it non-destructive if no damage is done to the region of interest, but other parts of the sample can be damaged (i.e. given an insect preserved in amber, altering the amber to study the insect is non-destructive) (Popovski, McKellar, & Barbi, 2016). In addition ion beam techniques are considered non-destructive (Riquelme et al., 2009). This is similar to space science, where many studies “non-destructively” analyzed meteorites using activation analysis (Quandt & Herr, 1974; van Zelst, 1972).

Archaeology, likewise, has used neutron activation analysis for many years and it is considered non-destructive (Beauchesne, Barrandon, Alves, Gil, & Guerra, 1988; Gordus, 1970). Some definitions of non-destructive in the field include a procedure that leaves no visible effect and allows additional tests to be performed (Jakes, 2002). Or from (Ciliberto & Spoto, 2000): "allow analytical information to be obtained with no damage whatsoever to the sample or in some cases, the object in question. All visible alterations are avoided, and the object remains aesthetically unimpaired." From Archaeological Chemistry (Goffer, 2007): "... neither require sampling nor physically damage or impair the integrity of the objects studied."

3. What techniques are out there for elemental composition analysis?

X-Ray Fluorescence (XRF) has many variations, but they all share the same common principle. Low energy photons are used to stimulate the atoms in a sample by knocking out an electron (ionizing). Once these atoms are stimulated, they will decay to their non-stimulated (ground) state, giving off a characteristic set of photons that can be detected. Detection limits are typically around parts per thousand. The low energy of the stimulating photons only allows a low penetration into the sample, making this useful as a non-destructive surface technique. If analysis of more than just the surface is desired, grinding of the sample into a fine powder is required.

Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA ICP-MS) uses a laser to evaporate off a small area. Light from the heated area can be used to determine some concentrations, a technique known as Laser-Induced Breakdown Spectroscopy (LIBS). For LA ICP-MS, the particles are collected and sent to an ICP-MS machine for

destructive analysis. These techniques can have detection limits of approximately the parts per million level, depending on the element and other factors. This technique is also limited as a surface analysis technique. It is often considered to be non-destructive, but the fact that material is removed, albeit a small amount, and subsequently destroyed makes this a tenuous claim.

Particle (Proton) Induced X-Ray Emission is similar to XRF, except it uses particles, often protons, instead of photons. Ionization is induced and characteristic photons can be used to identify elements and calculate concentrations. Detection limits can be, under favorable conditions, around 1 ppm for thin foils, and become less sensitive with increasing sample thickness (Johansson & Campbell, 1988). This technique is also best for surface analysis of homogeneous materials.

Activation analysis is a set of techniques that differ by which particle is used to induce reactions in the material, much like the difference of XRF and PIXE. These techniques are similar to XRF and PIXE, except they use a higher energy incident particle. These particles include charged particles, such as protons and helium, (CPAA), neutrons (NAA), and photons (PAA). Instead of ionizing the atom, they stimulate the nucleus of the atom, causing protons and neutrons (or combinations of these) to be ejected from the nucleus. This transmutes the atom into a different, often times radioactive, element, which eventually decays, giving off characteristic photons that can be detected. This transmutation, as well as the induced radioactivity, gives a unique outlook on what is non-destructive. These techniques are considered non-destructive in many fields despite this.

CPAA and NAA have low penetrating depth. These are mostly useful as surface techniques or for small samples. PAA, however, has much better penetration depth, making it useful for bulk analysis of large and small samples, as well as homogeneous and inhomogeneous samples. PAA has been used in many fields with great success (Segebade, Starovoitova, Borgwardt, & Wells, 2017), but is still less well known and underutilized. PAA isn't suitable for organic materials. PAA is a great probe for the proton-rich side of the valley of stability, whereas NAA is a great probe for the neutron-rich side. The consequence of this is that many of the transmuted isotopes in PAA decay via positron emission to reach a stable isotope. These positrons annihilate with the electrons in sample. For organic materials, the molecular bonds are the result of shared electrons, so once these are destroyed, the bond is severed, damaging the sample. For

samples with a solid crystal structure though, there is negligible damage to interior structure, as long as the energy and current are not too high (Thompson, 2005).

4. Generalized Definition

Overall, the term non-destructive has many meanings to different people. These different definitions are typically influenced by what is considered to be important scientific information for the given field and application. Thus far, several fields have been discussed. From this, a general definition can be constructed based on the following characteristics for a technique:

- Requires no “sampling” (i.e. removing part of the sample)
- Requires no alteration of the sample (i.e. grinding into a powder)
- Alters the elemental content a negligible amount
- Alters the external characteristics a negligible amount
- Alters the internal characteristics (including crystal structure, bonds, etc) a negligible amount
- Induces a negligible amount of radioactivity after 1 month of cooling
- Able to re-/further analyze the sample and use the sample in its intended manner

A broad definition can be given as: a technique, including sample preparation, that allows further analysis without impacting any future results or use. Future results needs to be clarified further. This means the technique will not alter any characteristic of the sample that may be measured by the same or a different technique in the future. For example, a chemical composition technique shouldn't alter the crystal structure, external morphology, chemical composition, etc.

This definition is the ideal for non-destructive analysis; however, that also makes it unrealistic. A generalized definition this stringent is likely to not find acceptance in any field. So we propose using a minimally destructive definition instead. This is defined as a technique that is non-destructive in the context of the field in which it is applied. More simply put, any damage resulting from the analysis doesn't affect characteristics that are of interest to the field. It won't meet the above definition of non-destructive, but will be practically non-destructive for the specific application.

The above elements of non-destructivity should allow a more systematic definition of non-destructive to be developed, and subsequently used, for any field. Though a definition can be constructed for a field, some foresight needs to be applied as well. The best example of this is found in the field of archaeology. For the majority of the time the field has existed, physical attributes have been the sole, important source of information. As that source of information has been exhausted, chemical composition has found an importance in the field (Biró, 2005). Thus, if tests to measure physical properties had been performed and altered the chemical composition, they would have been considered non-destructive at the time, but as the field evolved, they would have been shown to have altered valuable information.

5. Photon Activation Analysis (PAA)

PAA is a technique with much potential for many fields (Segebade et al., 2017) where non-destructive testing is required. NAA has been the main tool for provenance studies in archaeology (Glascock & Neff, 2003) for a few decades, but access to research reactors is decreasing over time (Tykot, 2002). PAA, being similar to NAA and only needing some standard equipment such as detectors and a linear accelerator, could be a useful replacement, as recent work (Borgwardt, Wells, Pagnac, Sun, & Segebade, in press) has shown some potential. NAA is also considered unique and non-destructive in forensics, because it requires no “blank” (Sudersanana, Kayasth, Pant, Chattopadhyay, & Bhattacharyya, 2002). PAA offers this, as well as many of the other benefits of NAA. It can routinely analyze 30+ elements in a sample with typical detection limits being in the ppm range. In some cases, detection limits to ppb levels and below are achievable (Schulze & Segebade, 2005). The accuracy of the technique has been shown to be similar or better than NAA (Randa, Kucera, Mizera, & Frana, 2007). In addition to these, PAA offers the unique advantages to do whole sample analysis. The penetration depth of photons allows large samples to be easily measured. The total composition of inhomogeneous samples is easily measured. This is particularly useful for fields like archaeology, where the surfaces of samples tend to undergo various processes that will affect the composition (Caneva & Ferretti, 2000). To overcome this, other techniques require sampling of the object or abrasion of the surface, making it a destructive analysis. Even if one accepts this destructive analysis, the sample may be inhomogeneous, thus the analysis may not be as beneficial as it could be.

In terms of our criteria for non-destructiveness, PAA as typically applied is non-destructive for many applications. PAA can analyze samples with masses on the order of kilograms. Larger samples can also be accurately analyzed by using a collimator and scanning sections at a time. Therefore, there is no need for sampling or alteration of the sample. Typical irradiation times (< 5 hours) and power (~kW) induce a negligible

amount of damage externally and internally for samples that are solid, non-organic. This also alters around 1 ppb or less of the elemental content. All of this allows the sample to be re-analyzed with negligible difference caused by the analysis with PAA. The induced radioactivity is the main issue. If the sample is too active, in most cases it cannot be used in its intended manner. The activity in the sample depends on many things including the irradiation conditions, the content of the sample, and the amount of time the sample has cooled.

6. Conclusion

At the moment the term “non-destructive” analysis is used very loosely and subjectively. We have proposed a framework of criteria for creating a more standardized usage of the term. Many techniques are generally non-destructive, but only in certain situations limited by sample size, detection limits, etc. A more critical analysis needs to be done before claiming a technique is non-destructive in specific research. The criteria presented here should aid in this type of analysis. Although no technique is truly non-destructive in all situations, a critical analysis can help to generate a field-specific, or minimally destructive, definition for use. The intent of this paper is to raise awareness and generate discussion on the issue to make the term less subjective and more consistent than it currently is.

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Public interest statement:

Non-destructive elemental analysis is vital in a variety of fields, including forensics, paleontology, archaeology, and space science. A plethora of techniques is available for elemental analysis, each with its own particular strengths and weaknesses. Despite the indispensable utility of non-destructive analysis, the term itself is used in a very subjective and inconsistent manner. This paper aims to show this subjectivity and inconsistency by reviewing definitions from the aforementioned fields. After this, the physical principles of several commonly used “non-destructive” techniques are discussed to highlight some important considerations one must take note of when using the term. From this, a general set of guidelines is proposed to aid in the development of more standard definitions and usage of the term. Lastly, photon activation analysis is briefly discussed as a potentially non-destructive technique with some unique characteristics making it potentially suitable for fields where non-destructivity is important.

About the authors:

The photonuclear physics research group at South Dakota School of Mines and Technology is focused on applying photonuclear physics to a variety of interesting problems, including elemental analysis and medical isotope production. In particular, photon activation analysis is the main tool for exploring interesting applications in a variety of fields. Thus far, provenance studies in paleontology have been conducted, medical isotope feasibility studies have been performed, and an impurity analysis and exploratory study has been performed for an absolute neutrino mass experiment. Applying photon activation analysis to paleontology created discussions about non-destructivity and what issues need to be considered. This coupled with work towards using photon activation analysis as a forensics tool has created a unique perspective, showing a need to create and apply a more rigorous, consistent definition. The current paper is to be viewed as a first step towards that goal. In the authors' minds, a better understanding will lead to unique applications for photon activation analysis in paleontology, forensics, and beyond.