

**DISCOVERER AND METHODOLOGIST: ALFRED O. C. NIER AND THE MID-20<sup>TH</sup> CENTURY  
INSTRUMENTAL REVOLUTION IN GEOCHEMISTRY**

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**Abstract**

During the mid-20<sup>th</sup> century, geochemistry—one of the core Earth sciences—underwent a spectacular transformation as a result of the introduction of electronic instruments based on physical principles. In this process, mass spectrometry became the workhorse analytical technique in isotope geochemistry. This essay concerns the dynamic relationship between discoveries of isotope systems and the variations in their relative abundances, on the one hand—discoveries that became the foundation of isotope geology—and the development of mass spectrometry, on the other. This relationship is illustrated by the career of physicist and instrument-builder Alfred O. C. Nier, who was based at the University of Minnesota in Minneapolis. Nier's 60°-sector mass spectrometer design of 1940 endowed the instrument with powerful new capabilities, as well as facilitated its adoption outside the nuclear physics community. In the course of developing and applying the instrument, Nier also made important discoveries about the relative abundances of isotopes that paved the way for geochemical research on the deep past. My thesis is that Nier's early career, spanning the 1930s and '40s, illustrates a dynamic relationship in which science and technology co-evolved synergistically. This pattern of research spread beyond Nier—who largely moved on from this research after the 1940s—to develop into a research tradition, initially based at the University of Chicago's Institute for Nuclear Studies and then spreading to other institutions, notably Caltech and the University of California, San Diego. This tradition made crucial contributions to historical geology, including paleoclimate, solar system history, and the tectonics revolution.

The following abbreviation is used: NP, Alfred O. C. Nier Papers, University of Minnesota Archives.

## 1 Introduction

Geochemistry spectacularly transformed scientists' ideas about the Earth and its history during the latter decades of the 20<sup>th</sup> century. Instrumental methods in geochemistry helped 20<sup>th</sup>-century scientists better understand the planetary movement of carbon, global lead pollution, plate tectonics, processes of mineral formation relevant for prospecting and mining, the history of the solar system, and the global hydrological cycle, on geological timescales. All of this has become central to our understanding of the Earth, and how humans can live upon it productively and sustainably.<sup>1,2</sup>

Evidence that supported many of these new ideas came from geochronology, the branch of geochemistry that exploits the constancy of the rate of radioactive decay to measure time.<sup>3</sup> Building upon models of radioactive decay developed in nuclear physics, geochronologists in the middle decades of the 20<sup>th</sup> century learned to determine the absolute age of various materials by interpreting isotopic ratios. By measuring samples of earthly minerals, meteorites, and even materials that had formerly been alive—like wood, bone, or coal—scientists could better reconstruct the history of these samples. The changing ratio of carbon-13 to carbon-14 in the atmosphere showed it was the burning of ancient coal and oil, not changes in current living things, that most significantly increased the greenhouse gases causing climate change.<sup>4</sup> Measuring the ratio of isotopes produced by the decay of uranium and thorium into lead enabled Claire Patterson in 1955 to calculate the age of the Earth as 4.56

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<sup>1</sup> (a) Peter J. Bowler, *The Earth Encompassed: A History of the Environmental Sciences* (London: W. W. Norton & Co., 2000). (b) Naomi Oreskes, *The Rejection of Continental Drift* (Oxford: Oxford University Press, 1999). (c) Spencer R. Weart, *The Discovery of Global Warming* (Cambridge, MA: Harvard University Press, 2008). (d) Sarah Dry, *Waters of the World* (Chicago: University of Chicago Press, 2019). (f) Matthew Shindell, *The Life and Science of Harold C. Urey* (Chicago: University of Chicago Press, 2019). (g) Ronald E. Doel, "Constituting the Postwar Earth Sciences: The Military's Influence on the Environmental Sciences in the USA after 1945," *Social Studies of Science* 33, no. 5 (2003): 635-666. (h) Naomi Oreskes and Ronald E. Doel, "The Physics and Chemistry of the Earth" in *The Modern Physical and Mathematical Sciences*, ed. Mary Jo Nye (Cambridge, UK: Cambridge University Press, 2002).

<sup>2</sup> (a) William M. White, "History of Geochemistry," in *Encyclopedia of Geochemistry*, ed. William M. White (Cham: Springer, 2018), 670-683. (b) Rhodes W. Fairbridge, "History of Geochemistry," in *Geochemistry. Encyclopedia of Earth Science*, eds. Clare P. Marshall and Rhodes W. Fairbridge (Dordrecht: Springer, 1999). (c) Eville Gorham, "Biogeochemistry: Its Origins and Development," *Biogeochemistry* 13, (1991): 199-239.

<sup>3</sup> William M. White, *Isotope Geochemistry* (Oxford, John Wiley & Sons: 2015).

<sup>4</sup> Edward A. G. Schuur, Ellen R. M. Druffel, and Susan E. Trumbore, eds., *Radiocarbon and Climate Change* (Switzerland: Springer, 2016).

billion years. For rocks less than 10 million years old, like those produced by geologically recent volcanic activity, the radiogenic isotopes of argon decay on the right timescale. Measuring these isotopes in samples from the bottom of the Atlantic Ocean provided key evidence for sea floor spreading, the mechanism that helped convince many geologists of the reality of continental drift.<sup>5</sup>

Digging deeper, it's clear that understanding how these seismic intellectual changes occurred requires understanding the history of the scientific instruments used to make these measurements. Mass spectrometry was the workhorse analytical technique in isotope geochemistry. One of the most important figures in the development of mass spectrometry as a tool for geochronology was University of Minnesota physicist and instrument-builder Alfred O. C. Nier. Between 1935 and the 1970s, Nier developed a series of influential mass spectrometer designs optimized for measuring the isotopic ratios of various elements; that is, machines good for answering different kinds of research questions. When Nier began his career, mass spectroscopy was the province of physicists, without geological expertise and professional interest in geological questions. During the late 1930s, Nier pioneered the application of mass spectrometry to geochronology, showing how the instrument could be used to measure lead isotope ratios connected to the uranium-thorium-lead decay chain. Nier's 60°-sector mass spectrometer design of 1940 endowed the instrument with powerful new capabilities, as well as facilitated its adoption outside the nuclear physics community. During World War 2, Nier built prototype mass spectrometers for the Manhattan Project that were produced in volume by General Electric, thus exposing the instrument's capabilities to a greater number of scientist and engineers, including Nier's supervisor, Harold Urey. Nier's early career shows how scientists have worked as instrument-makers to create tools tailored to their research questions—an example of the synergistic evolution of instrumentation and discovery.<sup>6</sup> This pattern spread

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<sup>5</sup> (a) Allan Cox, ed., *Plate Tectonics and Geomagnetic Reversals* (San Francisco: W. H. Freeman, 1973). (b) Naomi Oreskes, ed., *Plate Tectonics* (Boulder: Westview Press, 2003).

<sup>6</sup> Historian and philosopher of science Hasok Chang's notion of an 'epistemic activity' will be helpful for understanding Nier's contribution. Chang defines an epistemic activity as 'a coherent set of mental or physical actions (or operations) that are intended to contribute to the production or improvement of knowledge in a particular way, in accordance with some discernible rules.' Epistemic activities are generally practiced in relation to others, forming what Chang calls a 'system of practice.' A set of epistemic activities forms such a system when they are performed with a view to achieving certain aims. The system is coherent when the constituent activities

beyond Nier—who largely moved on from geochronology research after the 1940s—to develop into a research tradition, whose early epicenter was the University of Chicago’s Institute for Nuclear Studies, and which then spread to other institutions, notably Caltech and the University of California campuses at Berkeley and San Diego. This tradition made crucial contributions to historical geology, including studies of paleoclimate, solar system history, and the tectonics revolution.

This paper aims to make three interventions into the historiography. First, it aims to elevate Nier’s profile as a significant figure in the history of science. Nier’s career has received considerable attention from mass spectroscopists and geochemists.<sup>7</sup> But when historians of science have paid attention to isotope geochemistry, they have generally focused on post-war developments interpreted through Cold War lenses. These studies briefly mention Nier’s role as an instrument inventor, while focusing on the work of people like Harrison Brown, Claire Patterson and Harold Urey.<sup>8</sup> This paper shows the considerable debt these later and more celebrated geochemists owed to Nier—not just for his instrument designs, but also for showing how expertise in mass spectroscopy could be fruitfully applied to geological questions. While

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combine effectively to achieve the aims of the system. Applying these notions to Nier’s career, I argue that he showed how mass spectroscopy and geochronology could be combined to effectively achieve the aim of age determination. In so doing, and to the extent his approach was adopted, geochronology was transformed into a technologically-driven endeavor. Hasok Chang, “Compositionism as a Dominant Way of Knowing in Modern Chemistry,” *History of Science* 49 (2011): 247-268, on 250-251.

<sup>7</sup> For a very rich oral history, see (c) interview by Michael A. Grayson and Thomas Krick at the University of Minnesota, Minneapolis, Minnesota, 7-10 April 1989 (Philadelphia: Chemical Heritage Foundation, Oral History Transcript # 0112), highlights of which are reported in (d) Michael A. Grayson, “Professor Al Nier and His Influence on Mass Spectrometry,” *Journal of the American Society of Mass Spectrometry*, 3 (1992): 685-694 (e) John H. Reynolds, *Alfred Otto Carl Nier, 1911-1994* (Washington, D.C.: National Academies Press, 1998) (f) Konrad Mauersberger, “Alfred O. C. Nier (28 May 1911 – 16 May 1994),” *Proceedings of the American Philosophical Society*, 143, no. 4 (1999): 686-691. (g) Michael A. Grayson, *Measuring Mass*, (Santa FE: American Society for Mass Spectrometry, 2002). (h) John De Laeter and Mark D. Kurz, “Alfred Nier and the Sector Field Mass Spectrometer,” *Journal of Mass Spectrometry*, 41 (2006): 847-854. (i) Keith A. Nier, “Alfred Otto Carl Nier,” in *The Encyclopedia of Mass Spectrometry, Volume 9: Historical Perspectives, Part B: Notable People in Mass Spectrometry*, ed. Michael L. Gross and Richard M. Caprioli (Amsterdam: Elsevier, 2016), 167-169.

<sup>8</sup> (a) Ana Caneiro and Marianne Klemun, eds., “Seeing and measuring, constructing and judging: instruments in the history of the Earth sciences. Special issue.” *Centaurus*, 53 (2011). (c) Matthew Shindell, “From the End of the World to the Age of the Earth: the Cold War development of Isotope Geochemistry at the University of Chicago and Caltech.” In *Science and Technology in the Global Cold War*, ed. Naomi Oreskes and John Krige (Cambridge, MA: MIT Press, 2014). (d) Ronald A. Doel, “The Earth Sciences and Geophysics” in *Companion to Science in the Twentieth Century*, ed. John Krige and Dominique Pestre (New York: Routledge, 1997), 391-416.

Nier did not have the courage (or perhaps hubris) to pursue the use of mass spectrometry as far as it could be taken in geochemistry, his intellectual lineage did.

Second, this paper aims to make connections with the literature on the Instrumental Revolution in chemistry. My treatment of Nier's career may also be contrasted with Carsten Reinhardt's seminal book on this episode, *Shifting and Rearranging*.<sup>9</sup> Reinhardt focuses on the role of "method makers" in the transfer of physical theory and instrumentation to new fields. Reinhardt shows, for the case of chemistry, that this process involved the adaptation of the theory and instrumentation to the needs, knowledge and practices of the importing field, and so was hardly a mere case of "applied physics." For this reason, he and others have also emphasized the role of industry in mediating the transfer. Though Nier was a good candidate for a "method maker," my focus will be on the epistemic pre-requisites for a system of practice to come together rather than on the problem of knowledge transfer. Partly for this reason, my focus will be on academic developments, though Nier and the scientists he influenced were clearly indebted to industry for certain technical advances.

Third, and most broadly, this paper contributes to a needed debate about the degree of continuity in the Earth sciences between the pre- and post-World War 2 eras. Excellent scholarship has amply documented the tremendous transformations in the Earth sciences during and after World War 2. The perceived needs of militaries and national security policy makers during World War 2 and then the Cold War led to a vast increase in funding, increased access to distant and extreme environments, the creation of new institutions, and a new availability of expensive new tools and instruments. Scientists put these resources to work in fields like ranging from geophysics and space science to oceanography, meteorology, seismology. Scientists investigated new parts of the Earth, including the deep seas, upper atmosphere, and terrains that could now be bored and cored.<sup>10</sup> Scientists certainly asked new questions and reoriented what they considered worth studying, sometimes all but abandoning previous questions that had been central to their disciplines.<sup>11</sup> But, as Mary Jo Nye argues in

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<sup>9</sup> Carsten Reinhardt, *Shifting and Rearranging*, (Sagamore Beach: Science History Publications, 2006). See also the seminal collection of papers on this topic in Peter J. T. Morris, ed., *From Classical to Modern Chemistry: The Instrumental Revolution*, (London: Science Museum, 2002).

<sup>10</sup> John Cloud, ed. *Social Studies of Science* 33, no. 5 (2003). Special issue on Earth sciences in the Cold War.

<sup>11</sup> Naomi Oreskes, *Science on a Mission*, (Chicago: University of Chicago Press, 2021).

*Before Big Science*, “[f]or all this seemingly radical change [between pre- and post-WWII science], much remained continuous with the past. Most of the basic presuppositions and fundamental explanatory systems in chemistry and physics changed very little from those of the prewar period, even while postwar instrumentation, much of it computer-driven, became bigger, faster, and more complex.”<sup>12</sup> Nier’s career suggests that there were important continuities in pre-war and post-war geochronology. Nier developed the fundamentals of the instrumentation central to isotope geochronology before direct US involvement in the war. Focusing on Nier’s early career thus balances studies that focus on the impact of WWII and the Cold War on the development of geochemistry.

This paper begins by tracing Nier’s career. Nier’s education in electrical engineering prepared him to improve on existing mass spectroscopy apparatus, and as a graduate student he produced a novel kind of mass spectrometer that could measure low abundance isotopes. As a post-doc at Harvard, Nier shifted his focus to geochronology, becoming a significant contributor to research in that field.. During World War 2, Nier’s innovative mass spectrometers developed for the Manhattan Project were built in significant numbers, contributing to the “black boxing” of mass spectrometry and the instruments’ becoming accessible to a wider range of users. After the war, Nier spent the final decades of his career disseminating mass spectrometry across the sciences, working in geochemistry, biochemistry, and space exploration. The paper next explores how mass spectrometers were used in post-war geochemistry. Nier’s methodological descendants made key discoveries, propagating a Nierian tradition of research. The paper concludes by comparing changes in geochemistry to broader changes in chemistry during the period, the so-called “Instrumental Revolution,” and reflecting on Nier’s significance in the history of science.

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<sup>12</sup> Mary Jo Nye, *Before Big Science*, (Cambridge, MA: Harvard University Press, 1996), 226.

## 2 Early Academic Career

### 2.1 From Engineering to Physics at Minnesota, 1927-1936

Alfred Nier was born in 1911 in St. Paul, Minnesota to a family of German immigrants. As a youth, he exhibited an interest in electronics.<sup>13</sup> After graduating high school in 1927, he earned both a bachelor's (1931) and master's (1933) degree in electrical engineering at the University of Minnesota. Nier later recalled that he mainly took physics courses for the master's degree due to the very slim graduate offerings in electrical engineering at the time.<sup>14</sup> His master's thesis was devoted to an analysis of how the magnetic flux changes in an iron bar when the latter is placed inside a variable magnetic field.<sup>15</sup> Nier showed how equations previously used to model current in an electrical transmission line could be applied, by analogy, to the magnetic flux changes. He also criticized previous investigators who "evidently did not realize all of these facts [pertaining to the application of the equations to flux] and consequently applied equations blindly."<sup>16</sup> This knowledge of the interplay between theory and apparatus would serve Nier well when he switched disciplines, but stayed on campus, to pursue a Ph.D. in physics at the University of Minnesota.

Nier joined the lab of Professor John T. Tate. Though a physicist, Tate had become interested in mass spectroscopy as a means for studying electron impact phenomena like the ionization potentials of atoms and molecules. The Tate lab had developed expertise in the construction of apparatus, as well as in high vacuum techniques, thus distinguishing it from other academic labs because, as Nier recalled later, at the time "very few people in the academia [*sic*] had good vacuums."<sup>17</sup> As part of its broad concern with instrumentation, the lab

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<sup>13</sup> Grayson, "Professor Al Nier," (ref. 7d), 685.

<sup>14</sup> Nier, Grayson-Krick interview (ref. 7c), 7.

<sup>15</sup> This phenomenon is related to the Barkhausen effect, the noise produced in wires of certain materials when they are placed inside a varying magnetic field. The noise arises from discontinuous changes in the magnetic flux as the field is varied. This effect can be exploited to assess the quality of materials. See K. J. Sixtus and L. Tonks, "Propagation of Large Barkhausen Discontinuities", *Physical Review*, 37 (1931): 930-959, cited in Alfred O. C. Nier, "The Magnetic Transmission Line," Master's Thesis (Minneapolis: University of Minnesota, 1933), NP, Box 10, Folder 21.

<sup>16</sup> Nier, "The Magnetic Transmission Line," (ref. 15), 24.

<sup>17</sup> Nier, Grayson-Krick interview (ref. 7c), 15, 34, 56. According to Nier, these techniques were more widespread in industry at the time.

had made a few key improvements in the mass spectrometer that would be key to the eventual success of Nier's own instruments.

Nier's first physics paper reported the invention of a device to stabilize the magnetic field of a mass spectrograph. Nier recalled that

it was at this point that my engineering background and connections came in...It occurred to me that, since the mass that you collect is proportional to the square of the magnetic field divided by the accelerating voltage, why don't you fool the instrument by monitoring the magnetic field, and changing the ion accelerating voltage so that you stay on the peak ... The result was, the ions didn't know the difference, so the trajectory was stable. I could work with heavy ions where you needed high resolution.

Here Nier was describing an instance of feedback control, a novel concept in electrical engineering at the time. The instability was due to a motor generator that was used to produce the large amount of power, 5 kW, required to run the solenoid. Nier credits the idea for a key component of the device to his master's advisor, H. E. Hartig.<sup>18</sup> Nier did not see a sharp distinction between science and engineering, commenting that "it's so interesting how these things [engineering and experiment] overlap. It isn't quite clear which is which, you see."<sup>19</sup>

From the beginning of his physics career, Nier's approach consisted of pushing the instrumentation to its limits in order to detect extremely low abundance isotopes or abundance variations. Nier's dissertation research involved building an improved mass spectrometer and using it to study low abundance isotopes. He sought to make possible "accurate quantitative measurements on the relative abundances of isotopes of a given element."<sup>20</sup> Nier felt that previous mass spectroscopic apparatus was not sensitive enough to detect weak isotopes, and was prone to contamination from water and hydrocarbons present in wax and grease in the joints and stopcocks of the apparatus. To address this problem, Nier first built a new mass spectrometer and published its design in 1935..

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<sup>18</sup> See Alfred O. Nier, "Device to Compensate for Magnetic Field Fluctuations in a Mass Spectrograph," *Review of Scientific Instruments*, 6 (1935): 254-255, and Nier, Grayson-Krick interview, (ref. 7c), p. 17.

<sup>19</sup> Nier, Grayson-Krick interview (ref. 7c), 17-18.

<sup>20</sup> Alfred O. Nier, "A Mass Spectrographic Study of the Isotopes of Argon, Potassium, Rubidium, Zinc, and Cadmium," Doctoral Thesis (Minneapolis, University of Minnesota: 1936), p. 2.

The 1935 machine combined Nier's feedback control mechanism to stabilize the magnetic field, with five improvements that had previously been developed by member of the Tate lab. First, graduate student Walker Bleakney had figured out a method for creating ions by bombarding the sample with electrons of controlled energy, known as the "electron impact" method. Descendants of this method are still widely used today. Second, Tate and graduate student P. T. Smith had come up with a novel design that isolated the ionization process from the mass analyzer section of the instrument. This design made it possible to construct instruments with larger magnetic analyzers, which made higher mass resolution possible. Third, the use of larger analyzers required the use of larger magnets, and it so happened that Nier was able to take advantage of a larger solenoid magnet, which had been constructed for unrelated cloud chamber studies. The larger magnet also contributed to enhanced resolving power. Fifth, graduate student Merrill Distad and post-doc John Williams had designed and constructed a novel detector, consisting of an electrometer vacuum tube amplifier of extremely high sensitivity.<sup>21</sup> Nier's 1935 machine used a modified 180° magnetic sector instrument design previously used to study ionization potentials ("sector" here refers to the sector of the circle described by the ion flight path; see Fig. 2). The result was an instrument with exceptionally high stability, resolution and sensitivity, and which enabled Nier to make an important discovery that top mass spectroscopists of his day had been unable to make.

Though Nier initially applied the instrument to the study of organic compounds, he quickly moved to that of isotope abundances, which were of growing interest in nuclear physics, itself an increasingly popular field. Tate, as editor of *Physical Review*, was keenly aware of this trend and interested in getting into it himself. So Nier decided to turn his attention to the study of argon and potassium isotopes. Potassium was of particular interest because of its observed, but unexplained, radioactivity. (It's the reason bananas make a Geiger counter click.) Nier later recalled thinking "[w]ell, this is just made to order, because if I'm going to get attention around here, I need to be in nuclear physics, and here it fit in."<sup>22</sup>

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<sup>21</sup> Alfred O. Nier, "Some Reflections on the Early Days of Mass Spectrometry at the University of Minnesota," *International Journal of Mass Spectrometry and Ion Processes*, 100 (1990): 1-13.

<sup>22</sup> Nier, Grayson-Krick interview, (ref. 7c), 14, 20-25.

Nier was able to detect the extremely low abundance  $^{40}\text{K}$  isotope that was suspected to be the source of the radioactivity.<sup>23</sup> Earlier analyses of the potassium isotopes by the pioneering mass spectroscopists Arthur Dempster, Francis Aston and Keith Bainbridge had not detected  $^{40}\text{K}$ . This isotope would become the basis for one of the pillars of geochronology, the K-Ar dating method (section 4).

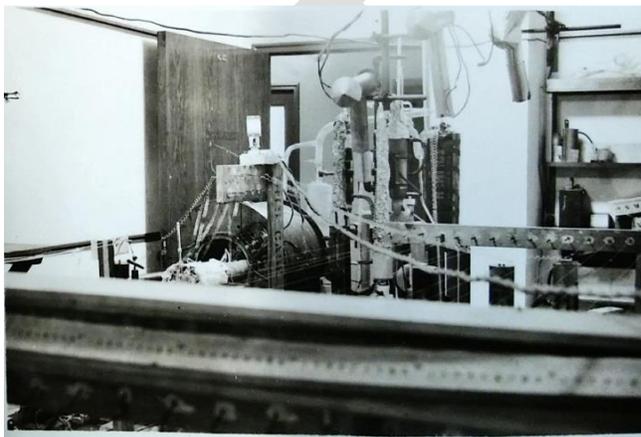
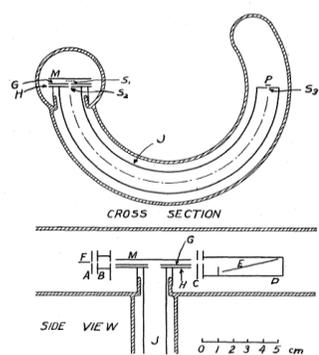


FIG. 1. Diagram of apparatus used for the study of potassium, rubidium, zinc and cadmium. Slit  $S_1=0.25$  mm; Slit  $S_2=0.15$  mm; Slit  $S_3=0.15$  mm for K, 0.07 mm for Rb, Zn and Cd.

Figure 1. The left-hand image is a schematic of Nier's 1935 instrument. The cross section is of the mass analyzer. Note the  $180^\circ$  path. The diagram below it illustrates the electron-impact method of ionization. From Alfred O. Nier, "A Mass-Spectrographic Study of the Isotopes of Argon, Potassium, Rubidium and Zinc," *Physical Review*, 1936, 50: 1041. Despite Nier's use of the term 'mass-spectrographic,' this instrument had an electrometer detector. The photograph on the right is from NP, box 34, folder 4, courtesy of University of Minnesota Archives and is labelled "1935 MS of AOCN." The cylinder on the left is the magnet; the mass analyzer sits inside.

## 2.2 Geochronology at Harvard, 1936-1938

While a graduate student, however, Nier had not yet become interested in geochronology. This came during his subsequent post-doc in the Harvard laboratory of Keith Bainbridge from 1936 to 1938. On graduating in 1936, Nier won a coveted National Research Council Fellowship in physics, one of two awarded that year. Nier's graduate work had attracted considerable attention due to the power of his technique. Bainbridge thought Nier's precision measurement of isotope abundances could complement his on-going research, and offered Nier \$5000 (1936 dollars) in lab funds, free access to what Nier describes as excellent facilities and shop-work, and freedom of research. Nier accepted.<sup>24</sup>

<sup>23</sup> Alfred O. Nier, "Evidence for the Existence of an Isotope of Potassium of Mass 40," *Physical Review*, 48 (1935): 283-284; and Nier, "Some Reflections," (ref. 21), for Nier's account of the background to, and his design of, the 1935 instrument.

<sup>24</sup> Grayson, "Professor Al Nier," (ref. 7d), 688.

Bainbridge was a respected physicist who, according to Nier, “was in mass spectrography in the business of measuring precise masses” and “had built this beautiful double focusing machine.”<sup>25</sup> The latter would provide crucial inspiration for Nier’s 60° sector-field design of 1940 (*vide infra*). At the time, Harvard was the world leader in precision atomic weight measurements by chemical analysis. The Chemistry Department was home to Gregory P. Baxter, who carried on the “Harvard method” of making such measurements developed by his predecessor T. W. Richards.<sup>26</sup> The atomic weights measured by Richards, Baxter and others had revealed a difference between the atomic weights of what was called “common” or “ordinary” lead, on the one hand, and radiogenic lead from uranium and thorium ores, on the other. Common lead is lead found in non-uranium or -thorium ores, and is so-called because it is found in more common ores like galena. Nevertheless, uranium and thorium ores were often contaminated with this lead. It was thus recognized that the atomic weight difference could be used for dating purposes, namely by correcting the age of a sample for contamination by common lead. As will be explained in the next two sections, however, such correction would only work if one knew the isotopic composition of common lead, and until 1938 it was assumed that the composition was constant. Nier would show this assumption to be false.

### 2.2.1 State of isotope geochronology in the mid 1930s

When Nier went to Harvard, mass spectrometry was only just starting to be applied to geological questions. The discovery of isotopes in the early 20<sup>th</sup> century opened the way for the development of isotope geochronology, or the dating of processes and events by measuring relative isotope abundances. Ernest Rutherford (1906) was the first to propose that the proportion of radioactive atoms that disintegrate in a given time interval is an unvarying constant and therefore a potential clock. A particularly important kind of radioactive decay, in the early 20<sup>th</sup> century, was that of uranium into lead. Several scientists tried to exploit this process to develop an absolute geological timescale and establish estimates of the age of the

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<sup>25</sup> Nier, Grayson-Krick interview, (ref. 7c), 39.

<sup>26</sup> For accounts of this method, see: Arthur F. Scott, “Critique of the Harvard Method for Determining Atomic Weights,” *Analytical Chemistry*, 33, no. 9 (1961): 23A-31A, and Keith Nier, “The Transformation of Atomic Weight: New Instrumentation and Objective Progress,” in *5<sup>th</sup> International Conference on the History of Chemistry — “Chemistry, Technology and Society” — Proceedings*, ed. Isabel Malaquias, Ernst Homburg, M. Elvira Callapez (Aveiro : Sociedade Portuguesa de Quimica, 2005), 231-240.

Earth.<sup>27</sup> In order to measure the age of a sample, the quantities of both the residual ‘parent’ atom (e.g. uranium) and the decay product or ‘daughter’ atom (e.g. lead) had to be measured. Until the 1930s, this was done solely by bulk chemical techniques, involving chemical analysis of the sample followed by gravimetric or volumetric measurements.

The character of the task of radioactive dating was radically transformed by the recognition of the range and complexity of isotopic differences among the elements. In 1919, Aston used a mass spectrograph to show that ordinary neon, a nonradioactive element, is composed of two isotopes of different abundances with masses 20 and 22 respectively, resulting in the chemical atomic weight of 20.2. During the following two decades, Aston and other scientists, notably Arthur Dempster, continued to apply mass spectroscopy to identify the isotopic composition of elements across most of the periodic table. In 1929, Francis Aston at the University of Cambridge had used a mass spectrograph to detect isotopes of lead in radioactive bröggerite.<sup>28</sup> In articles from that same year, using Aston’s data, Rutherford estimated the age of the Earth while the geophysicists Fenner and Piggot postulated the first isotopic mineral ages.<sup>29</sup> It became clear that one could no longer hope to simply measure the uranium and lead contents of a sample in order to get an accurate age. Age measurements based on radioactivity would require the measurement of isotopes, not just bulk chemical analysis of the radioactive parent element and its daughter, and this would require mass spectroscopy. In particular, since both parents and daughters might consist of isotopes, each with its own decay properties, it was necessary to be able to accurately measure their relative abundances. In the uranium-lead case, for example, it was necessary to distinguish between two different processes, the decay of <sup>238</sup>U and that of <sup>235</sup>U. Moreover, uranium ore samples were contaminated with “common” lead, which consisted of both radiogenic and non-

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<sup>27</sup> For accounts of these efforts, see: (a) C. L. E. Lewis and S. J. Knell, eds. *The Age of the Earth: from 4004 BC to AD 2002* (London: The Geological Society, 2001); (b) Patrick Wyse Jackson, *The Chronologers’ Quest* (Cambridge, UK: Cambridge University Press, 2006).

<sup>28</sup> F. W. Aston, “The Mass-Spectrum of Uranium Lead and the Atomic Weight of Protactinium,” *Nature*, 123, no. 3096 (1929): 313.

<sup>29</sup> (a) E. Rutherford, “Origin of Actinium and Age of the Earth,” *Nature*, 123, no. 3096 (1929): 313-314. Nier summarized Rutherford’s article on an undated sheet (NP, Box 3, folder “Age of earth; computations, 1937, 1941, 1948, & n.d.”). (b) C. N. Fenner and C. S. Piggot, “The Mass-Spectrum of Lead from Bröggerite,” *Nature*, 123, no. 3108 (1929): 793-794.

radiogenic isotopes. Though traditional gravimetric methods were initially used to sort some of these isotopic complications out, their inherent sensitivity limits restricted the accuracy of this approach.

### 2.3 Ordinary Lead: Not So Ordinary

Cambridge, MA was also home to Alfred Lane, a professor emeritus at Tufts. Lane was chairman of the National Research Council Committee on the Measurement of Geological Age, and was excited at the possibility, raised by Nier's graduate work, of accurate isotope measurements of lead samples. Nier considered Lane "one of the very few persons in this country interested in quantitative geological age measurements" at the time, as opposed to qualitative methods based on sequences of rock strata and fossils.<sup>30</sup> In a letter from 1976, Nier recalled that Lane was "intensely interested in the geological age question" and credited him with providing moral support during the post-doc.<sup>31</sup> The extent of Lane's influence is also suggested by Nier's recollection that the former "was very interested in my work, and tried to promote it, getting samples and things for me to work on. So I spent most of my time, or a very large part of it, working on things related to geochronology."<sup>32</sup> Nier's papers contain an agenda for a 1937 meeting of Lane's committee in Boston in which various radioactive decay dating methods were to be discussed alongside the "[i]mportance of work of A.O. Nier."<sup>33</sup> Lane's letters to Nier also exhibit enthusiasm about his results.<sup>34</sup> These sources suggest that Lane's enthusiasm and expertise had a major impact in spurring on Nier's work.

It was in this context that, with Bainbridge's assistance, Nier designed an improved mass spectrometer with higher resolution, thus enabling accurate abundance measurements on lead, uranium, and other heavy elements (resolution is mass-dependent). To improve the resolution relative to the 1935 instrument, Nier decided to double the radius of the mass analyzer and increase the strength of the magnetic field. This modification required a much larger magnet. According to Nier, the use of a larger solenoid would have been impractical, and so he and

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<sup>30</sup> Nier, Grayson-Krick interview (ref. 7c), 54.

<sup>31</sup> Alfred O. C. Nier to Henry Faul, 3<sup>rd</sup> November 1976, NP, Box 3, Folder 21.

<sup>32</sup> Nier, Grayson-Krick interview, (ref. 7c), 54.

<sup>33</sup> NP, Box 11, Folder 5.

<sup>34</sup> Alfred Lane to Alfred O. C. Nier, 7<sup>th</sup> January and 10<sup>th</sup> March 1939, and 13<sup>th</sup> May 1940, Box 3, Folder 30.

Bainbridge decided to replace it with a two-ton electromagnet, with the analyzer now sandwiched between the poles.<sup>35</sup> This modification produced a field approximately four to five times stronger than the solenoid without increasing the power requirement, though the latter (5 kW) remained high. This field was “very high for that time,” which “pushed the whole thing [spectrometer] up to something that was different.” The magnet was still unstable due to the power needed and the stabilizing device Nier had invented in Minnesota would not work with the new design. So Nier had to invent a new compensating device that stabilized the power supply to the magnet rather than the field itself, an approach that was actually facilitated by the switch to an electromagnet.<sup>36</sup> (I mention these details because they are important for understanding the design of the later, seminal 60° sector instrument).

Initially, Nier focused on measuring the isotope abundances of several elements, justifying his research by appeal to the growth of nuclear physics and the power of his instrument for discovering rare isotopes and measuring relative abundances.<sup>37</sup> Under the influence of Baxter and Lane in particular, and with encouragement from Bainbridge, Nier shifted towards applying the new spectrometer to geochronology.<sup>38</sup> As a result of the work of Richards, Baxter and colleagues, the Harvard chemistry department had accumulated a large number of lead samples of high purity, which Baxter made available to Nier. Baxter’s willingness to help Nier can be understood by considering the state of radioactive dating at the time. The latter was dependent on chemical atomic weight determinations to estimate isotopic composition, which limited the accuracy of the technique. For example, it was assumed at the time that common lead is of constant isotopic composition, because its atomic weight was

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<sup>35</sup> Nier, “Some Reflections,” (ref. 21), 9.

<sup>36</sup> Nier, Grayson-Krick interview, (ref. 7c), 50-51. In 1935, Nier had not deemed direct stabilization of the power supply feasible.

<sup>37</sup> (a) Alfred O. Nier, “The Isotopic Constitution of Osmium,” 52 (1937): 885; (b) Alfred O. Nier, “A Mass-Spectrographic Study of the Isotopes of Hg, Xe, Kr, Be, I, As, and Cs,” *Physical Review*, 52 (1937): 933-937; (c) Alfred O. Nier, “The Isotopic Constitution of Calcium, Titanium, Sulphur and Argon,” *Physical Review*, 53 (1938): 282-286; Alfred O. Nier, “The Isotopic Constitution of Strontium, Barium, Bismuth, Thallium and Mercury,” *Physical Review*, 53 (1938): 275-278.

<sup>38</sup> Nier, Grayson-Krick interview, (ref. 7c), 53ff. In the latter, Nier states that Bainbridge introduced him to Baxter. He sometimes makes it sound as if Bainbridge might have suggested geochronology as a potential application. See (a) Alfred O. Nier, “Some Reminiscences of Mass Spectrometry and the Manhattan Project,” *Journal of Chemical Education*, 66, no. 5 (1989): 385-388, on 385; and (b) Nier, “Some Reflections,” (ref. 21), 9. In his letter of November 3, 1976 to the geologist Henry Faul, Nier “suspected” it had been Bainbridge who had informed him of the possibility of working on lead at Harvard: Nier to Faul, 3<sup>rd</sup> November 1976, NP, (ref. 31).

always found to have a value very close to 207.21 and because the U or Th content in its ores was negligible. In order to determine the age of a sample of a uranium ore, the atomic weight of the lead in it was measured, and the amount of common lead contamination estimated in light of the result. For instance, the closer the weight approached 206, the greater the purity of the sample in  $^{206}\text{Pb}$ . This method was less than optimal, however, both because it is an indirect measure of isotopic purity, and also because the chemical methods employed were time-consuming. In contrast, the mass spectrometric approach potentially offered a direct measure, as well as faster through-put. According to Nier, "I could do in an hour for which [sic] the chemists, in making atomic weight measurements, needed weeks." Baxter appears to have been especially excited by the speed of the mass-spectrometric analysis.<sup>39</sup>

For historical studies in isotope geology, three key results came out of Nier's research with this new and improved mass spectrometer. In July, 1938, Nier disclosed that common lead consists of a mixture of isotopes the relative abundance of which varies by sample source. This was a great surprise, given all the previous atomic weight determinations, and given that that constancy is not to be expected if the relative abundances vary. These variations are caused by the addition of radiogenic lead, from uranium and thorium that had decayed long ago and was no longer present in the ore, to a "primordial" or "primeval" lead, of fixed isotopic composition, present at the time of formation of the Earth. Nier's discovery had three important consequences for geochronology. First, it showed that U-Pb dating would have to be corrected for the isotopic composition of the specific common lead that is co-present in a given sample of uranium ore lead. Second, the variations gave insight into the history of the different lead ores. Most importantly, they permitted an accurate calculation of the age of the Earth, provided that one could find a sample of primordial lead (*vide infra*). Thirdly, it showed that mass-spectrometric measurements were superior to chemical methods for detecting small variations in isotope abundances.<sup>40</sup>

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<sup>39</sup> Nier, Grayson-Krick interview, (ref. 7c), 55-56 and Nier, "Some Reminiscences of Isotopes, Geochronology, and Mass Spectrometry," *Annual Review of Earth and Planetary Science*, 9 (1981), 1-17, on 5-6.

<sup>40</sup> Alfred O. Nier, "Variations in the Relative Abundances of the Isotopes of Common Lead from Various Sources," *Physical Review*, 60 (1938): 1571-1576; helpful explanations of the significance of the variations can be found in Nier, "Some Reminiscences of Isotopes," (ref. 39), 1-17 and in Nier, Grayson-Krick interview, (ref. 7c), esp. 53-63.

In January 1939, Nier followed up the common lead work with a pair of seminal publications on “The Isotopic Constitution of Radiogenic Leads and the Measurement of Geological Time,” perhaps his most important foray into geochronology. His results revealed the diverse relations of the four isotopes of lead and showed how their ratios and their relations to thorium and uranium could be used to measure geological time with unprecedented precision. He made the most precise measurements of the decay constants of  $^{235}\text{U}$  and  $^{238}\text{U}$  to date. He also measured the abundance ratio of the two isotopes. This latter quantity allowed him to develop an “internal” method for dating radiogenic lead samples that dispensed with the need to measure the absolute quantities of uranium and lead (*vide supra*). Instead, the age of a sample could be inferred from the ratio of  $^{206}\text{Pb}$  to  $^{207}\text{Pb}$ .<sup>41</sup> This method obviated the need for chemical analysis and was less susceptible to mineral alterations over time than the U/Pb or Th/Pb methods. In addition, Nier showed that mass spectrometric data could be used to compute ages from the decay of  $^{238}\text{U}$  to  $^{206}\text{Pb}$  and from that of thorium to  $^{208}\text{Pb}$ , thus yielding three independent methods for determining the age of a sample. He calculated that certain minerals were over two billion years old, which challenged various prior estimates of the age of the Precambrian, the Earth’s time of formation and even the beginnings of the universe itself.<sup>42</sup>

Nier, however, decided not to pursue geochronology as far as his new instrument might take him. Studying variations in common lead would have “opened up a whole new area,” then, as Nier lamented in 1989, “but unfortunately, I didn’t exploit it.”

If I had followed up on that I’d have been generations ahead of other people, because nobody else had instruments as good as I did for many years. I could have done much more, and could have come up with the age of the solar system...But...I didn’t know

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<sup>41</sup> J. L. Rose and R. K. Stranathan (“Geologic Time and Isotopic Constitution of Radiogenic Lead,” *Physical Review*, 50 (1936): 792-796) were the first to suggest this method, but without a mass spectrometer had to determine the abundance ratio indirectly, leading to less accurate results.

<sup>42</sup> (a) Alfred O. Nier, “The Isotopic Constitution of Uranium and the Half-Lives of the Uranium Isotopes. I,” *Physical Review*, 55, (1939): 150-153; (b) Alfred O. Nier, “The Isotopic Constitution of Radiogenic Leads and the Measurement of Geological Time. II,” *Physical Review*, 55, (1939): 153-163. The results in (b) were amplified a few years later in Alfred O. Nier, Robert W. Thompson and Byron F. Murphey, “The Isotopic Constitution of Lead and the Measurement of Geological Time. III,” *Physical Review*, 60 (1941): 112-116. In (b), Nier cites (on 163) Arthur Holmes’ *The Age of the Earth* (London: Thomas Nelson & Sons Ltd, 1937), according to which the universe was thought to be no more than 2 billion years old at the time (on vi).

enough about geology, and was kind of advised by some people that I shouldn't stick my neck out on things that I didn't know much about.<sup>43</sup>

Whoever those people were, Nier chose not to be explicit to historians. Thus, though Nier saw the potential of his discoveries for geochronology, he largely left it to others to connect the ages of individual minerals to the larger context, e.g. the ages of planets and the solar system.

Instead of pursuing radiogenic isotope geochemistry, in 1939 Nier made an important contribution to *stable* isotope geochemistry, of fundamental importance for the study of climate history. Together with Earl Gulbransen, an instructor at Tufts University, Nier recognized that the ratios of the two stable isotopes of carbon,  $^{13}\text{C}$  and  $^{12}\text{C}$ , vary by up to 5 percent depending on the sample source, with limestone-derived samples having the largest amount of  $^{13}\text{C}$  and plant-derived the least. They suggested that the variation may be related to the process of formation of the sample.<sup>44</sup> Though Nier and Gulbransen were not the first to observe stable isotope variations—variations in the oxygen isotopes had been discovered by bulk density measurements a few years before<sup>45</sup>—this work demonstrated the discriminating power of mass spectrometry for measurement. Indeed, in addition to theoretical anticipations of carbon variations, testing the power of the technique seems to have been part of the motivation for the study.<sup>46</sup> This potential was later recognized by chemist and Nobel laureate Harold Urey. In his 1947 paper, “The Thermodynamic Properties of Isotopic Substances”, Urey developed a statistical mechanical theory to show why, on theoretical grounds, isotope fractionations (the term for changes in isotope ratios arising from some chemical or physical process) could be expected. In the course of developing this theory, Urey also suggested that these fractionations could provide useful geologic information. Nier's carbon studies provided some of the initial empirical evidence for Urey's theory.<sup>47</sup> Moreover, on the basis of these

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<sup>43</sup> Nier, Grayson-Krick interview (ref. 7c), 259-260 (see also 60-61). Earlier, Nier made a similar remark in a letter to Henry Faul (ref. 31).

<sup>44</sup> Alfred O. Nier and Earl A. Gulbransen, “Variations in the Relative Abundance of the Carbon Isotopes,” *Journal of the American Chemical Society*, 61 (1939): 697-698.

<sup>45</sup> Malcolm Dole, “The Relative Atomic Weight of Oxygen in Water and in Air,” *Journal of the American Chemical Society*, 57 (1935): 2731 and “The Relative Atomic Weight of Oxygen in Water and in Air,” *Journal of Chemical Physics*, 4 (1936): 268-275.

<sup>46</sup> Nier, “Some Reminiscences of Isotopes,” (ref. 39), 7-8.

<sup>47</sup> Besides the work with Gulbransen, in 1941 Nier published a paper, co-authored with graduate student Byron Murphey, confirming and extending the 1939 results with the newly invented 60° sector instrument. See Byron F.

results, Urey suggested that Nier's 60° sector spectrometer could be used to measure oxygen isotope ratios, and that the latter would allow the temperature at which the samples were formed to be inferred.<sup>48</sup> Urey would go on to pioneer paleoclimate studies at Chicago, using mass spectrometers based on Nier's design.<sup>49</sup>

At the end of his post-doc, Nier took up an assistant professorship back at the University of Minnesota. Though the discoveries Nier made in graduate school and his post-doc were certainly important empirical contributions to isotope geology, it was upon his return to Minnesota (1938) that he made his most important *instrumental* contribution to the field.

#### 2.4 Mass Spectrometry for the Masses, 1938-1940

On his return to Minnesota, Nier became interested in the preparative separation of isotopes in the context of a collaboration with biologist John Bardeen, who needed carbon enriched in <sup>13</sup>C for biological tracer studies. For preparative purposes, however, more mass spectrometer capacity would be required than for measurement.<sup>50</sup> Nier's previous Harvard magnet design was impractical for the capacity needed, both due to its heavy weight and its exceptional power requirements, and so Nier set out to develop a more economical system. In 1936, Bainbridge had published the use of a 60° sector magnet as a component of a mass spectrograph built for the precision determination of atomic masses.<sup>51</sup> Bainbridge's design yielded high resolution, which was especially important for the measurement of atomic masses, but it did not work well with electrical detection, which was an important feature for the accurate measurement of isotope ratios (*vide supra*). Nier recounted having the following insight, which also illustrates the constraints imposed on designers by the available technology:<sup>52</sup>

Theoretically, any angle would do. If it wasn't for the fringing fields, you could have a 1-degree sector. It seems like the question is if you're going to do this, what angle should

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Murphey and Alfred O. Nier, "Variations in the Relative Abundance of the Carbon Isotopes," *Physical Review*, 59 (1941): 771-772.

<sup>48</sup> Harold C. Urey, "The Thermodynamic Properties of Isotopic Substances," *Journal of the Chemical Society* (1947): 562-581, especially 576-578.

<sup>49</sup> For a comprehensive study of Urey's career, see Shindell, *Harold C. Urey*, (ref. 1f).

<sup>50</sup> Nier, "Some Reflections," (ref. 21), 11-12.

<sup>51</sup> Kenneth T. Bainbridge and Edward B. Jordan, "Mass Spectrum Analysis. 1. The Mass Spectrograph. 2. The Existence of Isobars of Adjacent Elements," *Physical Review*, 50 (1936): 282-296.

<sup>52</sup> Peter Galison, *Image and Logic*, (Chicago: The University of Chicago Press, 1997).

you choose? And I thought about this a little bit, and choose 60 degrees...because the 60-degree deflection worked so well in the Harvard machine of Bainbridge's...When I thought about other angles, it turns out that it would have taken quite a bit more magnet for 90 degrees. If you stop to think of it, going from 60 to 90 is quite a bit more. Also, if you were going to have a flattened [metal flight] tube that you fit between the poles, it was a lot easier to bend something through 60 degrees, rather than 90. Flattening tubes isn't the easiest thing in the world...you see, if you want to use an electromagnet, you had to have a narrow air gap to exploit it. So, there wasn't room for a glass tube.<sup>53</sup>

Such a change in angle would greatly reduce magnet size, since the latter is partially determined by the length of the ion flight path through the field, and reduce its power consumption. So, he combined the 60° sector feature of the Bainbridge design with the electrometer tube amplifier feature of Nier's Harvard instrument. The result was a new instrument with greatly reduced magnet and energy source size, power requirements, and cost, and of simpler design, but with comparable resolution and sensitivity (Fig. 3).<sup>54</sup> For comparison, whereas the earlier magnet weighed 4000 pounds and required a large 5 kW generator, the new instrument's magnet weighed a few hundred pounds and could run on 25 W from "a couple of automobile storage batteries."<sup>55</sup> The low power requirement further dispensed with the need for a special stabilizing device.

The title of Nier's report on the instrument was "A Mass Spectrometer for Routine Isotope Abundance Measurements". Nier's inclusion of the adjective "routine" truly reveals the significance of the design because it allowed the mass spectrometer to become more accessible to non-specialists. Reflecting back on this aspect of the instrument design, Nier later commented that "if you could make these tools available to other people, who didn't

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<sup>53</sup> Nier, Grayson-Krick interview, (ref. 7c), 84-85. See also Nier, "Some Reflections," (ref. 21), 11-12. Here it is appropriate to acknowledge the "hidden labor" that made Nier's career possible. In his recollections, Nier repeatedly acknowledges his debts to the technicians and facilities at Minnesota and Harvard (e.g., Grayson-Krick interview, (ref. 7c), 45, 49, 88-90). For example, the precision machine work for the 60° prototype was done by a machinist, R. B. Thorness, who Nier described as "an utter genius." They would even co-author several papers in the '50s and '60s. Space does not permit going further into the social relations of the laboratories in which Nier worked. For classic discussions of these issues, see Steven Shapin, "The Invisible Technician," *American Scientist*, 77 no. 6, (1989): 554-563 and Robert E. Kohler, "Moral Economy, Material Culture, and Community in *Drosophila* Genetics," in *The Science Studies Reader*, ed. Mario Biagioli (New York: Routledge, 1999), 243-257.

<sup>54</sup> Alfred O. Nier, "A Mass Spectrometer for Routine Isotope Abundance Measurements," *The Review of Scientific Instruments*, 11 (1940): 212-216.

<sup>55</sup> Nier, "A Mass Spectrometer," (ref. 54), p. 212 and Nier, Grayson-Krick interview, (ref. 7c), 85.

necessarily have to know how a mass spectrometer worked, but could use it, they could apply it to problems in their fields. I think that this is one of the very important developments of our time.”<sup>56</sup> This pay-off was crucial for the widespread adoption of mass spectrometry in geology. Indeed, the development of isotope geology as a discipline independent of physics, i.e. one that was pursued by specialists rather than physicists with an interest in geology, depended on having instruments that were simple and reliable enough to be black-boxed for use by non-specialists. Moreover, the compact magnet made it more feasible to increase magnet size in future studies, thereby facilitating progress in resolution. At the same time, it also made miniaturization more feasible, a feature Nier would exploit in his later work on space exploration.

The coming of World War 2 focused Nier’s research on uranium, and transformed Nier’s mass spectrometers from bespoke research instruments into standardized tools used at industrial scale.

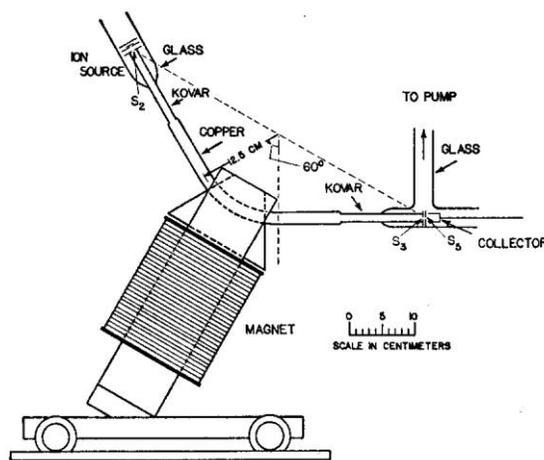
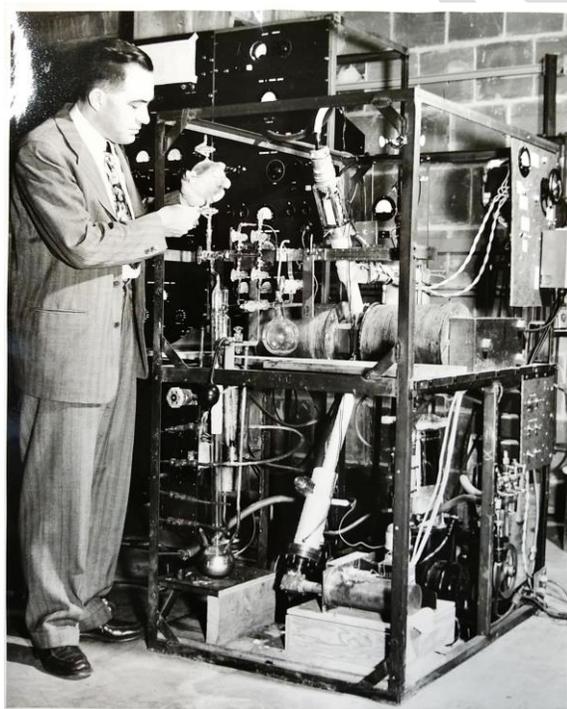


Figure 1. At left: Alfred Nier in the late 1940s, working at a version of his 60-degree sector field mass spectrometer. Note the 60° inflection of the mass analyzer tube as it passes between the poles of the magnet at the center of the photograph. Unlabelled photograph from the NP, box 34, letter box 1, courtesy of University of Minnesota Archives.

<sup>56</sup> Nier, Grayson-Krick interview, (ref. 7c), 267.

*At right: a schematic of the original 60-degree design of 1940. Note the sector indicated by the "60°". Nier, "A Mass Spectrometer," (ref. 54), p. 213.*

### 3 Nier and the Manhattan Project

Nier's expertise and instruments contributed to the development of the atomic bomb. Like many American physicists, Nier's defense related work began even before the United States formally entered the war.<sup>57</sup> In February 1940, Nier used a 180° analyzer instrument, similar to the one he used at Harvard, to separate <sup>235</sup>U from <sup>238</sup>U, permitting the identification of <sup>235</sup>U as the source of fission.<sup>58</sup> As part of the Manhattan Project, Nier was supervised by Harold Urey as part of the wartime effort to produce enriched uranium. In 1941, the Office of Scientific Research and Development commissioned Urey's uranium program to construct mass spectrometers for uranium analysis. In the following year, Nier's group built seven new 60° instruments specifically for the uranium effort. At the same time, several methods for the preparative separation of <sup>235</sup>U were being considered, and Nier's group established the effectiveness of the gaseous diffusion method. The famous K-25 separation plant in Oak Ridge, Tennessee was constructed to put the method into effect.

Nier built two prototype mass spectrometers for the Oak Ridge plant. One was a leak detector, a portable and extremely sensitive mass spectrometer used to ensure air was not leaking into the uranium separation process. General Electric made many hundreds based on Nier's prototype. Engineers carried them about to check the integrity of the plant's miles of pumps and diffusion barriers. The other prototype was a recording mass spectrometer that could monitor the progress of isotope separation throughout the process stream. General Electric built over 100 of these instruments to create a system for monitoring the separation process in over 50 locations throughout the enormous plant. The recording output of each instrument was transmitted to a central control room, where it could be monitored by a single person (Nier mentions engineers).<sup>59</sup>

Nier's mass spectrometers were among many scientific instruments whose significance was transformed by standardization and substantial manufacturing during World War 2. In

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<sup>57</sup> Daniel J Kevles, *The Physicists: The History of Scientific Community in America* (Cambridge, MA: Harvard University Press, 1995), Chs. 8 and 9.

<sup>58</sup> Nier, Grayson-Krick interview, (ref. 7c), pp. 73-82.

<sup>59</sup> Nier, Grayson-Krick interview, (ref. 7c), pp. 107-124; Grayson, *Measuring Mass* (ref. 7g), 16-17.

some cases, as Yakov Rabkin has described for infrared spectrophotometers, an existing technique was given a standardized instrumental form and put into commercial production by government order.<sup>60</sup> In other cases, like the Pauling oxygen meter, expected military needs led to a focused effort to invent and manufacture a new class of instrument. Nier's mass spectrometers were black-boxed, mass-produced and, in the case of the recording spectrometer, partially automated for the war effort. The war exposed more scientists and engineers to mass spectroscopy. As Matthew Shindell observes, mass spectrometers

had existed before the [Second World War], but only a few laboratories had had sufficient expertise to build and maintain them. Wartime development of mass spectrometers by US industries under military contract and postwar tinkering by interested engineers, scientists, and oil companies effectively black-boxed the technology (although a trained technician was still required to operate it), increased its precision dramatically, and put it within reach of any university department willing to pay for the still relatively expensive instrument.<sup>61</sup>

Scientists like Harold Urey witnessed the flexibility and capability of mass spectrometer, and would put that capability to use in path-breaking research after the war.

Nier's work sheds light on the scholarly debates about continuity and change between pre- and post-World War II science mentioned in the introduction. Although the Instrumentation revolution in chemistry had begun before the war, the usage and availability of instruments was greatly advanced by standardization, bulk production, and the US government's role in promoting their use by different research groups. Both the leak detector and the recording spectrometer were novel instruments. Nevertheless, all the instruments built by Nier for the war were based on the 1940 sector design which was the fruit of Nier's research in the 1930s. For Nier, as an instrument inventor and research scientist, rather than a manufacturer, it was the pre-war work that truly made mass spectroscopy an accessible tool. "It was not until the late 1930's, when high vacuum and electronic techniques became an

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<sup>60</sup> Yakov Rabkin, "Technological Innovation in Science: The Adoption of Infrared Spectrometry by Chemists" in Morris, *From Classical to Modern* (ref. 9), 3-28.

<sup>61</sup> Shindell, "From the End of the World" (ref. 8c), 109. See also Doel, "Constituting the Postwar," (ref. 1g) and "The Earth Sciences," (ref. 8d), 412, Oreskes and Doel, "The Physics and Chemistry," (ref. 1h), on 539, 552-557.

essential part of physics laboratory work, that mass spectroscopy became a tool which could serve scientists in a variety of disciplines,” he wrote in 1966.<sup>63</sup>

#### 4 Nier’s Postwar Career

After the war, Nier initially returned to geochronology. In 1948, Nier and his graduate student L. T. Aldrich showed that  $^{40}\text{K}$  decays to  $^{40}\text{Ar}$ , and suggested that this phenomenon “might become extremely useful in the measurement of geological time.”<sup>64</sup> This demonstration was based on Nier’s earlier discovery of  $^{40}\text{K}$  while in graduate school (section 3.1). The K-Ar method would be developed by others and become one of the pillars of geochronology. Besides continuing to work on the K-Ar dating system, Nier’s post-war work in this field largely consisted of collaborations with geologists, like the eminent geologist and pioneer of geochronology Arthur Holmes at the University of Edinburgh or Samuel Goldich at Minnesota, in which Nier’s role was to build instrumentation and conduct isotopic analyses. A 1946 letter from Holmes gives a sense of the importance of Nier’s work:

Ever since your isotopic analyses of ore-leads was published I have hoped that it would be possible to calculate from the results the time that has elapsed since the earth’s primaeval lead began to be contaminated by radiogenic lead. The acquisition of a calculating machine a few months ago has now made possible the somewhat formidable calculations and I have just completed the work. The age works out at about 3000 million years by various sets of solutions, the range being about 2750 to 3150 and the average of the best set of solutions ... being 3015. We can, however, afford to neglect the odd 15.! [sic] This looks like being the first really reliable estimate of the age of the earth and I should like to salute your work as the means of making it possible.<sup>65</sup>

Holmes had been working on the problem of the earth’s age since the beginning of the century. Though Holmes’ 1946 estimate was supplanted a decade later by the currently accepted age of 4.56 billion years, provided by Claire Patterson and colleagues, this subsequent

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<sup>63</sup> Alfred O. Nier, “Mass Spectroscopy—An Old Field in a New World,” *American Scientist*, 54, no. 4 (1966): 359-384. For the early use of the technique in the petroleum and chemical industries, see Carsten Reinhardt, “The Chemistry of An Instrument: Mass Spectrometry and Structural Organic Chemistry,” in Morris, *From Classical to Modern Chemistry* (ref. 9), 229-247.

<sup>64</sup> L.T. Aldrich and Alfred O. Nier, “Argon 40 in Potassium Minerals,” *Physical Review*, 47, no. 8 (1948): 876-877.

<sup>65</sup> Arthur Holmes to Alfred O. C. Nier, 16<sup>th</sup> February 1946, NP, Box 3, Folder 50.

revision remained dependent on the techniques and data that Nier pioneered and to which Holmes gives so much credit. Moreover, Holmes is considered the father of the modern geological time scale, which assigns absolute dates to geologic time periods. His early versions of the scale relied on Nier's data.

Over time, Nier shifted to disseminating mass spectrometry across the sciences, making further design improvements, and applying the technique to atmospheric and space exploration, as well as atomic weight determination.<sup>67</sup> For example, he returned to tracer work and published an improved design of his 1940 spectrometer that was subsequently manufactured by the Consolidated Electrodynamics Company for biochemical research. Whereas the 1940 design was aimed at light elements (C, N, O), the 1947 version could be modified to study masses up to 400.<sup>68</sup> The miniaturization of the spectrometer was an important contribution from this period, for it was essential for sending spectrometers into flight.<sup>69</sup> Overall, his research approach consisted in leveraging and enhancing his ability to measure isotope variations in order to study the composition of various objects, such as meteorites or the atmospheres of the Earth, Mars and Venus. Similar in this respect to Nier's early study of carbon isotope variations, these investigations continued to be of historical relevance because they provided information on the origin and mode of formation of their objects, as indicated by a report he co-authored titled the "Isotopic Composition of Nitrogen: Implications for the Past History of Mars' Atmosphere," which discussed results from the Viking mission.<sup>70</sup>

It is worth noting that Nier's topical shift was accompanied by a shift in the sources of funding. As determined from his publications, before the war, Nier was funded by the University of Minnesota, the Milton fund (a Harvard bequest fund), the Rockefeller Foundation and the National Research Council (NRC). After the war, his papers acknowledge the Office of Naval Research (ONR), the Atomic Energy Commission (AEC), and the Committee on Growth of

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<sup>67</sup> J. R. De Laeter, "Al Nier's contribution to atomic weights," *International Journal of Mass Spectrometry*, 178 (1998): 1-7.

<sup>68</sup> Alfred O. Nier, "A Mass Spectrometer for Isotope and Gas Analysis," *The Review of Scientific Instruments*, 18, no. 6 (1947): 398-411. See also Nier, Grayson-Krick interview, (ref. 7c), pp. 86-87.

<sup>69</sup> Nier, Grayson-Krick interview, (ref. 7c), 177-215.

<sup>70</sup> Co-authored with Michael B. McElroy and Yuk Ling Yung. *Science*, 194 (1976): 70-72.

the NRC, which was a funding arm of the American Cancer Society (ACS). For obvious reasons, the ONR was interested in projects relating to nuclear physics, and Nier's work on spectrometers for precision measurements of atomic masses was relevant.<sup>71</sup> The ACS funding was motivated by the use of isotopes as tracers for biological studies.<sup>72</sup> Nier's work on atmospheric and space exploration would receive funding from NASA and the NSF.<sup>73</sup>

The shift in funding may help to explain the topical shift. Nier himself attributed the shift to the intervention of the war and his involvement in the Manhattan Project, which followed on the alleged advice, mentioned above, against venturing further into geology. He also described himself as having a limited attention span. But he also seems to have been motivated by a desire to leverage his instruments, by applying them in "areas where there's interesting things to do." And he did so in a way that made him more than a mere dabbler: As his interviewer Michael Grayson has observed, "[a]fter doing seminal work Nier would move on to another area."<sup>74</sup>

## 5 The Nierian tradition in isotope geology

Even though Nier's own research shifted away from geochemistry, his instrument design, as well as his method of coupling a tailored mass spectrometer to measuring particular isotopes or isotope pairs, produced compelling discoveries in geochemistry during the post-war decades. When mass spectrometrist John Reynolds eulogized Nier for the National Academy of Sciences in 1998, he wrote: "one can categorize a large part of the worldwide geochronological effort as a pyramid of workers with AI at its apex. The Nier pyramid would be all encompassing with respect to geochronologists, if using magnetic sector instruments were the defining category, which is much the case." According to Reynolds, Nier's scientific descendants "frequently acknowledged their debt to the facilities Nier invented and the example he set in their use."<sup>75</sup> They also learned how to take the ancient Earth's temperature, gave the planet a new

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<sup>71</sup> Nier, Grayson-Krick interview, (ref. 7c), 142, 230.

<sup>72</sup> *Ibid.*, 156.

<sup>73</sup> *Ibid.*, 233.

<sup>74</sup> Nier, Grayson-Krick interview, (ref. 7c), 60-61, 134, 259-260, 275-276; Grayson, "Professor AI Nier," (ref. 7d), 693.

<sup>75</sup> Reynolds, *Nier* (ref. 6e), p. 10.

birthdate, found a traumatic period in the Moon's past, and provided key evidence for a mechanism that could cause continental drift, among other applications.

This process was mediated by connections Nier had made through the Manhattan Project. There, Nier came to know one Mark Inghram, a graduate student at the University of Chicago who had studied under Arthur Dempster, the pioneering mass spectroscopist. Inghram was sent to Minnesota to learn as much as possible from Nier about the instrument and the methods of analysis. Inghram was then sent on to Columbia with two of Nier's instruments to work on uranium enrichment.<sup>76</sup> After the war, Inghram became a physics instructor at the University of Chicago. There Inghram was able to work with some of Nier's 60° sector instruments, which were managed by the Argonne National Laboratory under the auspices of the university.<sup>77</sup> After the war, the university had founded the Institute for Nuclear Studies (INS), which was led by Manhattan Project alumni Harold Urey, Harrison Brown, Arthur Compton and Willard Libby, and attracted a number of students who would become prominent figures in isotope geochemistry. During the late 1940s and throughout the 1950s, Inghram supervised or worked with a number of these students, including Clair Patterson, Gerald Wasserburg, John Reynolds, George Wetherill, George Tilton, and others. According to Reynolds, "Ingram's [*sic*] skills in having good mass spectrometers were a real important—and perhaps unique—aspect for Chicago's being ... a good platform [for geochronology]."<sup>78</sup> These students would go on to set up their own labs and train further generations of students. Their contributions were made possible by a deep knowledge of mass spectrometry, combined with a strong interest in applying it to geological problems. In the next four subsections, I will briefly describe some of the contributions of the INS scientists, focusing on the personal and scientific connections to Nier and his work that made those contributions possible.

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<sup>76</sup> On these moves of Inghram and the instruments, see Nier, Grayson-Krick interview, (ref. 7c), 98 and Reynolds, *Nier*, (ref. 6e), 8 and 10.

<sup>77</sup> Nier, Grayson-Krick interview, (ref. 7c), 126 and Albert Parr and Roger Stockbauer, "Mark G. Inghram," in *Encyclopedia Part B* (ref. 7i), 124-125.

<sup>78</sup> John H. Reynolds, interview by William Glen. Berkeley, California. January 30, 1978. Bancroft Library, University of California, Berkeley, on 13.

## 5.1 Harold Urey invents a clam thermometer

Urey's pioneering work on paleoclimate history was indebted to Nier. As previously noted, Urey claimed that past temperatures could be inferred from oxygen isotope ratios in 1947. He also suggested that a Nier-type spectrometer could provide the requisite data. In the late 1940s, however, the commercial production of a Nier-type spectrometer was still in development, so Urey decided to build his own. To this end, Urey recruited two young scientists with experience in mass spectroscopy. One was an electrical engineer, Charles R. McKinney, who had maintained Nier's spectrometers at Oak Ridge during the war. Another was Samuel Epstein, a Canadian post-doctoral fellow who had worked as a graduate student with the Canadian mass spectroscopist Harry Thode. By February 1949, Urey's group had constructed two mass spectrometers based on Nier's design. Urey, who had supervised Nier on the Manhattan Project, was in communication with him during this time.<sup>79</sup> Their work with these instruments resulted in a series of foundational papers in paleoclimatology. Epstein, McKinney and other members of Urey's group tested Urey's idea for inferring temperature from oxygen isotope ratios by growing mollusks in water of various temperatures. They discovered an empirical relationship, the carbonate-water temperature scale, that allowed the temperature, at which a shell had grown, to be inferred from the relative O<sup>18</sup> abundance in the calcium carbonate in it.<sup>80</sup> This work required the optimization of the Nier 60° sector instrument for the measurement of the very small isotope effects involved in fractionation: "the greatest mass spectroscopist in the world [Nier] had just built a new spectrometer and it was not good enough," Epstein recalled later.<sup>81</sup> One of the first papers in the series was devoted to describing these improvements.<sup>82</sup>

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<sup>79</sup> Shindell, *Harold C. Urey*, (ref. 1f), 131-136.

<sup>80</sup> J. M. McCrea, "On the Isotopic Chemistry of Carbonates and a Paleotemperature Scale," *The Journal of Chemical Physics*, 18, no. 6 (1950): 849-857; H. C. Urey et al., "Measurement of Paleotemperatures and Temperatures of the Upper Cretaceous of England, Denmark, and the Southeastern United States," *Bulletin of the Geological Society of America*, 62 (1951): 399-416; Samuel Epstein et al., "Carbonate-Water Isotopic Temperature Scale," *Bulletin of the Geological Society of America*, 62 (1951): 417-426; and Samuel Epstein et al., "Revised Carbonate-Water Isotopic Temperature Scale," *Bulletin of the Geological Society of America*, 64, (1953): 1315-1326.

<sup>81</sup> Samuel Epstein, interview by Carol Bugé. Pasadena, California, December 19 and 26, 1985, and January 10, 1986. Oral History Project, California Institute of Technology Archives, on 22-23.

<sup>82</sup> C. R. McKinney et al., "Improvements in Mass Spectrometers for the Measurement of Small Differences in Isotope Abundance Ratios," *The Review of Scientific Instruments*, 21, no. 8 (1950): 724-730.

## 5.2 Clair Patterson and Harrison Brown Age the Earth

Clair Patterson's first experience with mass spectrometry was on the Manhattan Project, working on uranium separation at Oak Ridge, though in a different plant than Nier. After the war, Patterson undertook a Ph.D. at the University of Chicago, finishing his degree in 1951. His advisor there was the nuclear chemist Harrison Brown, who had published a design for a mass spectrometer in 1941 that cited Nier's 1940 design.<sup>83</sup> Brown had also worked at Oak Ridge, on the separation of plutonium in the same plant as Nier.<sup>84</sup> Patterson's Ph.D. work focused on determining the lead isotopic composition of zircons, a kind of crystal, found in granite, that is free of non-radiogenic lead. He collaborated with fellow Brown graduate student George Tilton, who was charged with determining the uranium contents of zircons. According to an interview Patterson gave in 1995, the amounts of lead in zircons were 1,000 times smaller than anything that had been measured before.<sup>85</sup> The attempt to meet this sensitivity requirement revealed to Patterson that his samples were being contaminated by exogenous lead, a discovery that forced him to develop new methods for avoiding such contamination, notably the use of a rigorously decontaminated "clean lab," which was a novelty at the time.<sup>86</sup>

He put these techniques to good use in his post-doc, also with Brown, when he determined the age of the Earth based on the comparison of lead isotope ratios in meteorites and terrestrial samples. In the 1940s, Arthur Holmes, Erich Gerling of the Radium Institute of the Academy of Sciences of the USSR, and F. G. Houtermans at the University of Göttingen had independently estimated the age of the Earth based on data Nier had published in his pre-war research.<sup>87</sup> All three arrived at an age of about 3 billion years. For his own work, Patterson

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<sup>83</sup> It is worth noting that Nier's designs and geochronological results, discussed in sections 2-4, are routinely cited in the work discussed in this section.

<sup>84</sup> I am not aware of any contact between them there.

<sup>85</sup> Clair C. Patterson, interview by Shirley K. Cohen. Pasadena, California, March 5, 6 and 9, 1995. Oral History Project, California Institute of Technology Archives, on 14 and 17.

<sup>86</sup> *Ibid.*, 19. See also Doug MacDougall, *Nature's Clocks*, (Berkeley: University of California Press, 2008), 110. George R. Tilton, Claire Patterson, Harrison Brown, Mark Inghram, et al., "Isotopic Composition and Distribution of Lead, Uranium, and Thorium in a Precambrian Granite," *Bulletin of the Geological Society of America*, 66 (1955): 1131-1148 provide a detailed description of the procedures used.

<sup>87</sup> G. Brent Dalrymple, "The Age of the Earth in the Twentieth Century: A Problem (Mostly) Solved," in *The Age of the Earth: from 4004 BC to AD 2002*, ed. C. L. E. Lewis and S. J. Knell (London: The Geological Society, 2001), 205-222, on 211-212.

depended on a mass spectrometer developed by Inghram and colleagues at Argonne National Laboratory, a modified version of Nier's 60° sector design.<sup>88</sup> These techniques together were essential for allowing Patterson to settle the question of the Earth's age. Inghram was co-author on the initial communication of the calculation.<sup>89</sup> Brown and Patterson also planned their approach to calculating the age of the Earth around Nier's discovery that common lead is a mixture of primordial and radiogenic lead, recalled Patterson in 1995: "Now, there's a bunch of equations that these atomic physicists—Al [Alfred] Nier, for example—calculated. It's so marvelous how they worked all this stuff out. And if we only knew what the isotopic composition of primordial lead was in the earth at the time it was formed, we could take that number and stick it into this marvelous equation we had. And you could turn the crank and, *blip*, out would come the age of the earth."<sup>90</sup>

### 5.3 John Reynolds and Plate Tectonics

The Nier tradition also made an important, albeit indirect, contribution to the plate tectonics revolution. John Reynolds was a student of Inghram's who accepted an assistant professorship in the physics department at UC Berkeley in 1950. He began his career there by improving the technique of potassium-argon dating. Reynolds built an all-glass, 60°-sector spectrometer that could be iteratively baked at high temperature in an oven to release contaminants, and then pumped down. Previous designs did not permit placement in an oven, thus precluding comprehensive baking. This procedure allowed extremely minute amounts of radiogenic argon to be measured very accurately, an essential requirement for dating rocks younger than 10 million years. The Reynolds spectrometer was then used by Garniss Curtis and Jack Evernden, of the Berkeley geology department, in collaboration with Reynolds' graduate student Joseph Lipson, for the dating of young volcanic rocks. Their data, together with those of other researchers, would allow changes in the polarities of volcanic rocks to be dated. The reversals of polarity would provide key evidence for the reality of sea-floor spreading. Isotope measurements using the Reynolds spectrometer were crucial for establishing the chronology of

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<sup>88</sup> Patterson, Cohen interview (ref. 88), 21; Tilton et al., "Isotopic Composition," (ref. 89), 1137-1138.

<sup>89</sup> (a) C. Patterson, G. Tilton and M. Inghram, "Age of the Earth," *Science*, 121, no. 3134 (1955): 69-75. (b) Claire Patterson, "Age of Meteorites and the Earth," *Geochimica et Cosmochimica Acta*, 10, (1956), 230-237.

<sup>90</sup> Patterson, Cohen interview (ref. 88), 16.

the sequence of reversals. By 1966, this chronology allowed for the precise identification and correlation of the patterns of remnant magnetism in the ocean floors, allowing for the documentation of the movements of oceanic crust outward from mid-oceanic rifts and ridges. Starting in 1970, the dating of samples, independently of their magnetism, from deep cores showed that oceanic crust is older the farther it is from the mid-ocean rift and ridge yet none of it dates from before the Mesozoic era.<sup>91</sup>

I will mention two more of Reynolds' contributions. In 1963-1964, Reynolds and colleagues set up a K-Ar laboratory at the University of São Paulo, the first geochronology lab in South America. Using his spectrometer, the group measured ages of Brazilian rocks that fit with age patterns seen along the coast of Africa. This provided evidence that South America had separated from Africa. Among geochemists, however, Reynolds is perhaps best known for the discovery of extinct radioactive nuclides. In 1960 Reynolds discovered evidence of extinct <sup>129</sup>I in the form of an anomalous excess of <sup>129</sup>Xe in a meteorite. He again used his spectrometer design, which is suitable for noble gases in general. This discovery proved important for reconstructing the history of the early solar system.<sup>92</sup>

#### 5.4 Gerald Wasserburg and the Lunatic

Gerald Wasserburg may serve as a final example of the kind of research pattern Nier pioneered. Wasserburg earned a PhD in geology in 1954 at Chicago under the joint supervision of Inghram and Urey.<sup>93</sup> He then went on to champion geochronology at Caltech. In the late 1960s, he and his colleagues invented a new 60° sector mass spectrometer, the "Lunatic I", partially in anticipation of the analysis of lunar samples. This instrument was fully digital, which allowed the magnetic field to be changed rapidly via computer programming. Doing so greatly reduced the error induced by ion beam instability. In his 1986 award speech for the Crafoord Prize, awarded by the Royal Swedish Academy to scientists in the Earth sciences, Wasserburg claimed that "[m]y own ability to carry forward the new instrumental design and development

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<sup>91</sup> The role of Reynolds and his spectrometer in confirming the theory of plate tectonics is described in detail in William Glen, *The Road to Jamarillo*, (Stanford, Stanford University Press: 1982).

<sup>92</sup> For background see Alan P. Dickin, *Radiogenic Isotope Geology*, 3rd ed., (Cambridge: Cambridge University Press, 2018), ch. 15.

<sup>93</sup> G. J. Wasserburg, "Isotopic Adventures—Geological, Planetological, and Cosmic," *Annual Review of Earth and Planetary Science*, 31 (2003): 1-74.

are a direct consequence of the training I received in the laboratory of M. G. Inghram III.”<sup>94</sup> This technique then permitted measurement of extremely small isotopic differences on very small samples of many elements. Wasserburg applied this capability *inter alia* to the study of solar system history. For example, the Lunatic I was used to determine the ages of lunar rocks from the Apollo missions and the Soviet Luna 16 and 20 missions. These studies established the time scales for lunar evolution. One remarkable discovery, inferred from a combination of U/Pb and Rb/Sr measurements, was of evidence for a so-called “terminal lunar cataclysm,” a large-scale bombardment of the Earth-Moon system by small planetary bodies that might have occurred 500 million years after the formation of that system due to disturbances in the asteroidal belt.<sup>95</sup> In his 2003 memoir, Wasserburg recalled that, when he was looking for an assistant professorship in the mid-1950s, Inghram connected him with Nier, who then championed his candidacy at Minnesota.<sup>96</sup> His first paper, on  $^{40}\text{Ar}/^{40}\text{K}$ , was based on dates by Nier.<sup>97</sup> R. Lawrence Edwards, a student of Wasserburg’s in the 1980s, went on to develop the Lunatic I system, and related techniques, for U/Th dating, which he then used to study climate history, leading to greater insight into the causes of ice age terminations, as well as techniques for calibrating  $^{14}\text{C}$  ages, among other discoveries.<sup>98</sup> In a personal communication to me, Edwards corroborated Reynolds’ pyramid metaphor and emphasized Inghram’s role in disseminating knowledge of how to use Nier-type spectrometers among the geochronologists at Chicago.

Though I have focused on Nier’s influence via scientists based at the University of Chicago, other threads could be pursued, such as the disseminating role of L. T. Aldrich at the Carnegie Institution, mentioned by John Reynolds.<sup>99</sup> The role of Paul Gast, a colleague of Nier’s at Minnesota and collaborator of Aldrich’s, who contributed to the extension of radiogenic isotope studies beyond geochronology to the evolution of the Earth’s internal structure, would

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<sup>94</sup> G. J. Wasserburg, “Isotopic Abundances: Inferences on Solar System and Planetary Evolution,” *Earth and Planetary Science Letters*, 86, (1987): 129-173, on 136.

<sup>95</sup> Fouad Tera, D. A. Papanastassiou, and G. J. Wasserburg, “Isotopic Evidence for a Terminal Lunar Cataclysm,” *Earth and Planetary Science Letters* 22 (1974), 1-21.

<sup>96</sup> Wasserburg, “Isotopic Adventures,” (ref. 93), on 10. The candidacy was ultimately unsuccessful.

<sup>97</sup> G. J. Wasserburg, R. J. Hayden, “The Branching Ratio of  $\text{K}^{40}$ ,” *Physical Review*, (1954): 645.

<sup>98</sup> On  $^{14}\text{C}$ , see, for example, Hai Cheng et al., “Atmospheric  $^{14}\text{C}/^{12}\text{C}$  changes during the last glacial period from Hulu Cave,” *Science*, 362, (2018): 1293-1297. On ice age terminations, see, for example, Hai Cheng et al., “Ice Age Terminations,” *Science*, 326, (2009): 248-252.

<sup>99</sup> Reynolds, *Nier*, (ref. 7e), 10.

also be worth investigating.<sup>100</sup> That said, enough has been said to show that the post-war period was a time of exciting advances in geochronology and geochemistry, and that Nier's descendants played a major role in making them. Their research displays a common pattern, the adaptation and extension of the capabilities of mass spectrometry to make new kinds of isotopic measurements in order to answer questions of geological structure and history. Beyond the common approach, moreover, there was a good deal of personal and instrumental continuity, involving the transmission of instrumental expertise via individuals like Inghram or the Manhattan Project experience, and of instrumental design in the form of the 60° sector template. The testimony I have cited from Reynolds, Epstein, Patterson, Wasserburg and Edwards, though admittedly retrospective, suggests that the Nier “pyramid” was the result of conscious admiration and emulation. For these reasons, I think it is reasonable to speak of a Nierian “tradition,” as opposed to weaker forms of dependence, like mere use of his data or instrument designs.

## 6 Conclusion: An Instrumentation Revolution in Geochemistry

Alfred Nier and his intellectual descendants were part of a bigger change sweeping chemistry during the middle decades of the 20<sup>th</sup> century. The “instrumental revolution” began in the 1930s, picked up steam in the 1940s and had stabilized by the late 1960s.<sup>101</sup> In this period, electronic instruments, many of them based on physical principles, transformed the work practices of analytical chemistry. Like Nier's mass spectrometers, these instruments enabled new ways to analyze materials that largely replaced the practices of wet chemistry, volumetric analysis, and chemical separation. The instrumental revolution in geochemistry multiplied how minerals could be distinguished. In addition to chemical and structural properties, scientists could now analyze a mineral's atomic characteristics (e.g., absorption and

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<sup>100</sup> (a) White, *Isotope Geochemistry* (ref. 3), 161. (b) Claude Allègre, *From Stone to Star* (Cambridge, MA: Harvard University Press, 1992), 187. (c) C. J. Allègre and S. R. Hart, eds., *Trace Elements in Igneous Petrology* (Amsterdam: Elsevier, 1978), Preface.

<sup>101</sup> George Borg, “On ‘the Application of Science to Science Itself:’ Chemistry Instruments and the Scientific Labor Process,” *Studies in History and Philosophy of Science*, 79 (2020): 41-56; José A. Chamizo, “About Continuity and Rupture in the History of Chemistry: the Fourth Chemical Revolution (1945–1966),” *Foundations of Chemistry*, 21, no. 1, (2019): 11-29; Apostolos Gerontas, “Creating New Technologists of Research in the 1960s: The Case of the Reproduction of Automated Chromatography Specialists and Practitioners,” *Science and Education*, 23, (2014): 1681-1700; Morris, *From Classical to Modern* (ref. 9).

emission spectra) and nuclear characteristics. In the decades since Nier's pioneering work, geochemists have developed numerous specialized forms of mass spectrometry tailored to particular isotopic pairs. This led to a corresponding expansion of the questions that could be answered empirically, of which those concerning early solar system history, climate change or plate tectonics are but a few particularly spectacular examples.<sup>102</sup>

Nier helped establish a system of practice in isotope geochronology by developing new instruments and showing how they could be useful in the field. I use the term 'system of practice,' rather than just 'technique,' because modern geochronological studies are based on two intertwined streams of activities: the development of mass spectrometry, on the one hand, and the development of geochronological techniques, on the other. Geochronologists typically talk of dating by means of a specific target system—an isotope pair, or a type of mineral or element—as a “method,” coupled with mass spectrometric techniques: measuring uranium-lead or potassium-argon with Gas Source Mass Spectrometry, or <sup>14</sup>C with accelerator mass spectrometry. Besides the instruments and the target systems there are, in addition, techniques of data analysis and a wealth of geochemical background knowledge that are necessary for applying the instruments and interpreting their outputs. In short, creating knowledge in modern geochronology requires an unusual combination of knowledges from many disciplines. Nier was among to develop this combination. In the 1930s and '40s, he built a succession of spectrometers, each one improving on the other, and culminating in a design that could routinize isotope abundance measurements. Concurrently, he used these instruments to make discoveries of great significance for the emerging field of isotope geochemistry. He was able to engage in this interplay because he was uniquely positioned to combine multiple lines of research and kinds of knowledge: atomic and nuclear physics; radiometric dating; chemical analysis (though he did not perform the analyses himself); mass spectroscopy, and

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<sup>102</sup> (a) Philip J. Potts, “Geoanalysis: Past, Present and Future,” *Analyst*, 122 (1997): 1179-1186. (b) Philip J. Potts et al., “Advances in Analytical Technology and its Influence on the Development of Modern Inorganic Geochemistry: a Historical Perspective,” in *Magmatic Processes and Plate Tectonics*, eds. H. M. Prichard et al. (London : Geological Society, 1993). (c) James M. Mattinson, “The Geochronological Revolution,” in *The Web of Geological Sciences: Advances, Impacts, and Interactions*, ed. Marion E. Bickford (Boulder: The Geological Society of America, 2013). (d) Clark M. Johnson et al., “Smaller, Better, More: Five Decades of Advances in Geochemistry,” in Bickford, ed., *The Web of Geological Sciences*, (ref. 102c).

spectrometry in particular; electrical engineering; and vacuum technology. In this sense he illustrates a noted pattern of scientific innovation, creatively integrating ideas and practices from multiple fields.<sup>103</sup> But it was necessary that particular lines of research and kinds of knowledge were sufficiently developed so that someone at “the right place at the right time” could combine them effectively, something Nier keenly recognized about his work.<sup>104</sup> Indeed, instrument development tends to be especially holistic.<sup>105</sup> In brief, instruments embody knowledge of different kinds—such as theoretical or practical knowledge (e.g., glass-blowing skills)—produced by different practices and fields, like theoretical physics and electrical engineering. It is rare for one person to master all the different kinds of knowledge required to construct a particular instrument. He acquired an unusual skill set that combined mastery of physical theory, experimental techniques, and engineering know-how.<sup>106</sup> This skill set corresponded well to the holistic requirements of instrument development. Moreover, he grasped the geochronological problem sufficiently well to be able to apply that skill set. Finally, the basic design principle of mass spectroscopy, which Nier inherited, proved versatile enough to allow an extended series of variants to be derived from it, a crucial feature for meeting geochemical needs.<sup>107</sup>

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<sup>103</sup> Oren Harman and Michael R. Dietrich, *Dreamers, Visionaries, and Revolutionaries*, (Chicago: The University of Chicago Press, 2018), 9-10.

<sup>104</sup> Nier, Grayson-Krick interview (ref. 7c), 18.

<sup>105</sup> George Borg, “Discovery and instrumentation: how surplus knowledge contributes to progress in Science,” *Perspectives on Science*, 27 no. 6, 861-890 and “Science, Labor, and Scientific Progress” (PhD dissertation, University of Pittsburgh, 2020), ch. 8.

<sup>106</sup> In this sense, he resembles the figure of the engineer-scientist identified by Matteo Valleriani as a historiographical key for studying the interactions between theoretical and practical knowledge. See *Galileo Engineer*, (Dordrecht: Springer, 2010).

<sup>107</sup> In this sense, it provided a particularly fruitful *scaffold*, a concept I discuss in the works cited in footnote 105.

Minnesota's School of Physics and Astronomy for showing me the Nier instruments in their collection, and Larry Edwards, of the Department of Earth and Environmental Sciences, for a helpful conversation about Nier's work and legacy. I also thank the friendly and efficient staff of the University of Minnesota Archives for their help during my visit to the Nier Papers. I thank the Science History Institute for hosting the project.

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