Science and technology are intimately related, and advances in science often become possible with the availability of new instrumentation. This has certainly been the case in mass spectrometry, which is used in so many scientific disciplines. Originally developed as an instrument for research in physics it was used in the discovery of isotopes, their recognition as the fundamental species comprising the elements, and the investigation of elemental isotopic composition. Isotope ratio mass spectrometry is a metrological technique of the highest order, and has been widely used in chemical, biochemical, cosmochemical, environmental, geological, physical, and nuclear research. Mass spectrometry presently plays a key role not only in scientific research, but also in industrial operations.

This paper highlights the role that Alfred Otto Carl Nier played in bringing mass spectrometry into the mainstream of science. Nier’s career spanned a remarkable period in science, and he made crucial contributions to atomic weights, geochronology, isotope geochemistry, nuclear physics, and space science. He is widely viewed as the ‘father of modern mass spectrometry’, because of his genius with instrumentation, his innovations, and the generosity with which he shared his ideas and designs. It is timely to remember his fundamental work in mass spectrometry, particularly the development of the sector field mass spectrometer, which is still the instrument of choice for many isotope scientists some 66 years after its first appearance in 1940. Copyright © 2006 John Wiley & Sons, Ltd.

**KEYWORDS:** Alfred Nier; gases; isotopes; mass spectrometry; sector field

**INTRODUCTION**

The power and versatility of mass spectrometry lies in the fact that it measures isotope abundances in gaseous, solid, and liquid samples. There are only 92 chemical elements, but these elements comprise some 272 stable isotopes and a multitude of radioactive isotopes of varying half-lives. Thus isotopic science has a vast array of stable and unstable isotopic species that are capable of providing information to unlock the secrets of nature, and to be used in numerous applications.

In 1912, Joseph Thomson at the Cavendish Laboratory at Cambridge University examined the positive ray parabolas formed from the excitation of Ne. His observations suggested that Ne could exist in two chemically indistinguishable forms. Thomson encouraged Francis Aston to design and build a succession of mass spectrographs with increasing resolution, incorporating both magnetic and electric fields, which provided velocity focusing to the ion beams. These instruments enabled Aston to measure the isotopic composition of many chemical elements and to establish the binding energy curve, which became the basis for an early model of the nucleus.1

An alternative approach to mass spectrometry was taken by Arthur Dempster in 1918 at the University of Chicago, who designed a mass spectrometer with directional focusing, in which a beam of monoenergetic ions, after traversing a 180° magnetic field, was deflected in a circle to focus on the detector.2 Another American physicist – Kenneth Bainbridge, then in Pennsylvania, built a high-precision mass spectrometer that combined a Wien filter with a 180° magnetic analyser based on the Dempster design, to prove the Einstein mass-energy equation by measuring the masses of the isotopes in the nuclear reaction:3

\[ ^1\text{H} + ^7\text{Li} \longrightarrow 2 \times ^4\text{He} + Q \]

In the mid-1930s a fifth person appeared on the mass spectrometer scene – a person destined to have an enormous

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influence not only in mass spectrometry instrumentation, but also in pioneering the applications of that instrument in a number of scientific fields. In 1935, Alfred Nier, a young physicist from the University of Minnesota, graduated with a PhD under the supervision of John Tate. Over 70 years have elapsed since Nier reported the discovery of a rare, new isotope – $^{40}$K – which was radioactive, and later became the basis of the K-Ar geochronological decay scheme. Of these five pioneers of mass spectrometry, Professor Nier was unique in that he revolutionised mass spectrometry by constructing a sector field mass spectrometer, of deceptively simple design, which enabled new fields of scientific endeavour such as geochronology, isotope geochemistry, nuclear physics, space physics, atomic weights, meteoritics and extra-terrestrial studies to be developed. Even more impressive was that he was an active participant in all these endeavours. His ability to design and construct mass spectrometers of all shapes and sizes was a major factor in giving mass spectrometry the status and universality that it enjoys today. Kiser has given a comprehensive account of the early history of mass spectrometry.

Mass spectrometers that were utilised up to 1940 were large, cumbersome instruments, which used 180° magnets, and required enormous effort to build and maintain. In 1940, Nier designed a revolutionary new mass spectrometer, based on a 60° sector field magnet, in which the ion source and detector were removed from the influence of the electromagnet. This simple design not only reduced the power consumption of the electromagnet (and fabrication costs), but was superior in operation to the earlier mass spectrometers without any decline in resolution. Another feature of the Nier spectrometer was the use of electronic measurement of the ion beams, in contrast to the photographic measurement techniques used in the earlier mass spectrographs.

In 1947, Nier published details of a modified version of the 1940 sector field mass spectrometer, taking advantage of the technological developments which had occurred in vacuum technology and electronics during World War II. This instrument, which is shown in Fig. 1, represented a pivotal point in the history of mass spectrometry; rather than being restricted to research in physics, isotope science became available to scientists from other disciplines. Aston had predicted the diminution of the importance of mass spectrometry, but he did not foresee the explosion in the applications to which this versatile instrument was to be put over the next half-century. Alfred Nier has been called the ‘Father of modern mass spectrometry,’ because the sector field mass spectrometer has become one of the most widely used instruments in science. In fact, it is doubtful if any other analytical instrument has had such a significant impact in so many fields of science. Nier made a major contribution by developing the first sector field mass spectrometer, but also making his extensive knowledge available to anyone who needed help.

THE AGE OF THE EARTH

Modern geochronology of ancient rocks and minerals is dominated by the U,Th-Pb technique which is based on the decay of $^{235,238}$U to $^{207,206}$Pb and $^{232}$Th to $^{208}$Pb, respectively. This technique is the most versatile and inherently the most accurate of all the geochronological decay schemes. The basis of the U,Th-Pb method was established in the 1930s, and as the first of the modern isotopic geochronological techniques, it has been in use for approximately 70 years. It was the work of Nier that established the theoretical framework of this technique by analyses of the isotopic composition of Pb in a number of Pb ores.

Nier was fortunate to receive a National Research Foundation Fellowship at Harvard University in 1936 with Professor Bainbridge, where sufficient funds were available to build a 180° mass spectrometer with greatly improved resolution, which enabled him to accurately measure the isotopic composition of heavy elements such as U and Pb. Theodore Richards of Harvard had earned a Nobel Prize for developing a chemical method to determine atomic weights. Richard’s successor as Professor of Chemistry was Gregory Baxter, who was more than willing to provide Pb samples to Nier so that he could measure their isotopic composition, and hence their atomic weight, so that the values determined by this ‘physical’ method could be compared to those of the traditional ‘Harvard’ methodology. To Baxter’s surprise, Nier found that the isotopic composition of Pb in these ore samples varied depending on the relative amounts of U and Th, as well as the age of the samples, whereas the Harvard chemists always measured a constant atomic weight of 207.21. Baxter was understandably sceptical of these isotopic
results, because the prevailing opinion of the day was that atomic weights were invariant in nature, in the same way that the velocity of light in vacuo is an absolute constant. However, Baxter came to realise that Nier’s isotopic methodology was superior to the Harlow method. Thus, mass spectrometric-derived determinations for atomic weights began the demise of the chemically derived values.

An important outcome of Nier’s mass spectrometric analysis of the Pb ores (such as galena) was the hypothesis that Pb extracted from these minerals consisted of two components – a radiogenic component of fixed isotopic composition which had existed since the formation of the Earth, and a radiogenic component that was generated by the decay of $^{238}$U and $^{232}$Th. Thus, the present-day abundances of the isotopes of Pb depend on the age and chemical composition of the ore. Nier showed that U-rich ores were enriched in $^{206}\text{Pb}$, while Pb derived from Th-rich ores were enriched in $^{208}\text{Pb}$. The fourth stable isotope of Pb is $^{204}\text{Pb}$, which is purely of primeval origin since it is not the end-point of any nuclear decay process. It can therefore be used to calculate the primeval amounts of the measured $^{206}\text{Pb}$/$^{208}\text{Pb}$ values. Nier showed that age determinations based on the radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ ratio were inherently more reliable than either the $^{208}\text{Pb}/^{238}\text{U}$ or the $^{208}\text{Pb}/^{232}\text{Th}$ – derived ages, which were more readily affected by chemical and/or thermal alteration.

The landmark paper by Nier et al. not only demonstrated the great age of the Precambrian, but also provided an accurate set of isotopic data from which the age of the Earth could be calculated. The true age of the Earth had been a controversial topic among geologists for over a century, and the age of 3550 $\times 10^6$ years derived by Holmes was the first determination based on reliable experimental data. In addition to his work on the U, Th-Pb technique, Nier also demonstrated the validity of the K-Ar geochronological technique with Tom Aldrich – based on his paper in 1935.4 Aldrich then went from Minnesota to the Department of Terrestrial Magnetism at the Carnegie Institute, where he was instrumental in developing the Rb-Sr method of geochronology. Geologists were among the first to recognise the power of this instrument in geochronology, and the sector field instrument has played an essential role in the initiation of many other geochronological techniques over the years.

Not only did Nier lay the foundations for U, Th-Pb geochronology by his investigation of Pb samples, but he also measured the isotopic composition of U. His reported value for the abundance ratio $^{238}\text{U}/^{235}\text{U}$ of 139 $\pm$ 1 has stood the test of time10 as has most of his published data, which is remarkable considering the huge advances in measurement technology. He also measured the abundance of the previously unknown isotope $^{234}\text{U}$, and calculated the half-lives of the three isotopes of uranium.10 Ludolf Schultz relates an interesting interchange with scientists at the National Bureau of Standards in Washington, in which he informed them that a recent measurement of the isotopic composition of $^{20}\text{Ne}/^{22}\text{Ne}$ was slightly lower than the accepted value. National Bureau of Standards replied by saying that the accepted values had been measured by Nier and could not possibly be changed, as it was well-known that Nier ‘never made a mistake’.

STABLE ISOTOPE GEOCHEMISTRY

During the time he worked on Pb isotopic variations, Nier also demonstrated that the carbon isotopic composition varied in natural samples. Nier and Gulbransen showed that the $^{12}\text{C}/^{13}\text{C}$ ratio varied by up to 5%.14 These C isotopic variations were later shown to be caused by physicochemical equilibrium reactions which resulted in the isotopic fractionation of $^{12}\text{C}$ from $^{13}\text{C}$, thus proving that the isotopic composition and hence the atomic weight of at least some elements, other than those associated with radioactive decay processes, varied in nature. In 1947, Harold Urey gave a theoretical explanation for isotope fractionation based on Quantum Mechanics.19 The experiment by Nier and Gulbransen laid the foundation for the field of stable isotope geochemistry.

On his return to the University of Minnesota in 1938, Nier became interested in isotope separation, because of the potential value of isotopically enriched C as tracers in biochemical and medical applications. Together with John Bardeen (later to win two Nobel Prizes), Nier used a thermal diffusion column 74 feet in length and employed methane to enrich the $^{12}\text{C}/^{13}\text{C}$ abundance ratio by a factor of ten over naturally occurring carbon.16 Nier and his colleagues used the enriched $^{13}\text{C}$ in numerous biochemical applications.22

The sector mass spectrometer proved to be the ideal instrument for measuring the isotopic composition of gases such as $\text{H}_2$, $\text{CO}_2$, $\text{O}_2$, $\text{N}_2$, and $\text{SO}_2$ which became the basis of stable isotope geochemistry. In measuring these light gases, a dual-inlet system was developed to allow gas to flow from two reservoirs into the ion source, so that the sample gas and a reference gas could be alternately measured. This technique enabled accurate determination of small differences between the sample gas and the standard and is still widely used today. Each light element has its own reference material, so that stable isotope geochemists express the isotope ratio differences relative to those standards. Isotope fractionation of these elements was found to occur through a variety of physicochemical processes whose rates or equilibrium states are mass dependent. Physical, chemical and biological processes that are mass fractionating lead to measurable changes in isotopic composition both from equilibrium and kinetic fractionation effects. Stable isotope geochemistry rapidly grew into an important field in the earth sciences and has had a major impact on environmental, hydrological, oceanographic and atmospheric studies.

NUCLEAR PHYSICS AT MINNESOTA

No discussion of Nier’s contributions to science would be complete without some account of his crucial experiment on the fissionable characteristics of uranium. During his post-doctoral Fellowship at Harvard, Nier had measured the isotopic composition of U, and on his return to the University of Minnesota, he developed an interest in isotope separation and constructed a sector field mass spectrometer that possessed sufficient resolution to analyse the isotopes of U. At the time when Niels Bohr discussed the discovery of nuclear fission at the American Physical Society in 1939, it was not known which of the two isotopes of U was fissionable. The
Bohr–Wheeler 'liquid drop' model suggested that the lighter isotope was probably the fissionable component of U, but a definitive experiment was needed to confirm the theoretical prediction. John Dunning and Eugene Booth at Columbia University conceived the idea of bombarding samples of $^{235}\text{U}$ and $^{238}\text{U}$ with neutrons produced in a cyclotron, to distinguish which was the fissionable isotope. Unfortunately, no separated isotopes of U existed at that time. Dunning therefore approached Alfred Nier to see if he could provide the necessary samples, and Enrico Fermi followed this up in a letter dated October 28, 1939 (Fig. 2).

Nier was probably the only person who had both the background knowledge in U analyses and an available instrument with sufficient resolution to separate the U isotopes. He was only able to produce nanograms of $^{235}\text{U}$ due to electrical discharge in the ion source of his sector field mass spectrometer with large ion beams. The problem could have been solved by an additional vacuum pump, but no money was available for its installation – which is quite remarkable considering the total cost of the Manhattan Project, and the vital importance of this isotope separation experiment. As it turned out, the minute amounts of separated isotopes were sent by mail to New York, where the $^{235}\text{U}$ sample was bombarded with thermalised neutrons from the Columbia cyclotron, using an ionisation chamber as detector.\(^1\) The experiment 'strongly supported the view that $^{235}\text{U}$ is the isotope responsible for slow neutron fission'.\(^1\)

The results confirmed the importance of isotope separation in the investigation of possible chain reactions in $^{235}\text{U}$. A few months later, Nier separated larger amounts of the U isotopes, which confirmed the earlier results for $^{235}\text{U}$ thermal neutron fission, and also enabled the team to show that $^{238}\text{U}$ undergoes fast fission only.\(^1\) This information was used by Fermi in his calculations to determine the feasibility of a self-sustaining chain reaction in the first man-made nuclear reactor at Chicago. Details of Nier’s contribution to the Manhattan Project can be found in the excellent paper by Grayson,\(^2\) and in the reminiscences of Nier.\(^2\)

The impact of Nier’s work in showing that the isotopic composition and hence the atomic weight of some elements such as Pb and C were not 'constants of nature' has already been discussed. However, Nier was destined to make other important contributions. One problem in mass spectrometry is that the measured isotope ratios of an element are affected by a number of processes in the instrument itself, which have the net effect of modifying these 'relative' isotope abundances from their 'true' or 'absolute' values. Thus, in order to obtain the absolute isotopic composition of an element, it is necessary to calibrate the mass spectrometer by a gravimetric mixture of at least two isotopically enriched isotopes of that element.

In 1949, Nier prepared some isotopically enriched batches of Ar, and used these to calibrate two sector field mass spectrometers, thus enabling him to correct the measured isotopic composition of Ar into 'absolute' values.\(^2\) The astonishing outcome of this historic experiment is that the isotopic composition and atomic weight of Ar determined by Nier are still the accepted values, 56 years after the measurement was undertaken. Furthermore, Nier’s value for the atomic weight of Ar is still an essential input parameter for the determination of the Universal Gas Constant, \(R\). This fundamental constant is determined by measuring the velocity of sound \(c_0\) in Ar at the triple point temperature of water, using an acoustic interferometer. The value of

Dr. Alfred O. Nier
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Dear Nier:
Since our discussion last spring in Washington on the possibilities of using a mass spectograph separation of the uranium isotopes for deciding whether the slow neutron fission is or is not due to 235 isotope, I have convinced myself that this is actually the best way to decide the question, which is of a considerable theoretical and possibly practical interest.

I understand that you have lately undertaken such a separation, and I should very much like to know whether and how this work is progressing.

Please give my best regards to Professor Tate.

Yours sincerely,

E. Fermi
Department of Physics
Columbia University
in the City of New York.

**Figure 2.** The letter Enrico Fermi wrote to Nier on October 28, 1939 requesting him to endeavour to separate the uranium isotopes to establish which was the fissionable isotope of U.
was constructed by Nier and his colleagues at Minnesota. The Nier–Johnson mass spectrometer incorporated an electrostatic analyser symmetrically and a magnetic analyser asymmetrically, which provided second order direction focusing while allowing a large divergence angle for the ion beam. This instrument enabled atomic mass measurements with unprecedented accuracy to be made. In order to minimise fluctuations in the magnetic field and the ion deflecting voltage, a small auxiliary flight tube was deployed in the same magnetic field as the main instrument. A double collector system coupled to a differential amplifier was used, with 50% of the ion beam going to each collector plate. Under these circumstances, the differential amplifier would give a null reading. Changes in the accelerating voltage or magnetic field would produce a shift in the ion beam, and hence a signal on the differential amplifier, which would be fed back to the accelerating voltage to produce a compensating voltage to restore the ion beam to its original ion path. The ‘slave’ tube therefore corrected for fluctuations in the ‘master’ tube since both tubes obtain their deflection potentials and ion-acceleration potentials from a common voltage divider. The net effect was that fluctuations in the mass spectrometer were minimised, thus enhancing the quality of the measured atomic masses. The ion currents were measured electronically, as were the differential ion beams in the mass doublet. This eliminated the subjectivity of visual matching, and because the digital signals are integrated over a period of time, the signal to noise ratio is increased.26 Relative atomic masses are known with an accuracy of one part in 10^8, and are one of the best sets of fundamental constants. Much of the credit for this can be attributed to Nier and his colleagues at the University of Minnesota.

EXTRA-TERRESTRIAL MATERIALS AND THE NOBLE GASES

Alfred Nier had a special affinity for measuring the isotopic composition of the rare gases. His early interest in the separation of ^3He by thermal diffusion led to an investigation of variations in ^3He/^4He ratios between the atmosphere and terrestrial well gases, the first documentation of natural helium isotopic variations, where ^4He is produced by the U and Th decay chains.27 The study of the noble gases in terrestrial materials is now an important research field in mantle and crustal processes. Nier’s interest in the rare gases led to a seminal paper in which isotopic variations in Ar, Ne, and He in the iron meteorite Grant were investigated with Peter Signer.28 Meteorites are fragments of planetary bodies, most commonly from the asteroidal belt, which have survived their passage through space for up to 2.3 × 10^6 years before landing on the Earth’s surface. Exposure to cosmic rays in space produced noble gas spallation products in the iron meteorites, which because of shielding, varied with depth from the sample’s surface.

In the early 1960s, Nier embarked on a new research career by exploring the composition of the Earth’s upper atmosphere and planetary atmospheres. The transition from large mass spectrometers used to measure atomic masses with unprecedented accuracy to building miniaturised, lightweight but robust mass spectrometers designed to
withstand the rigours of space was on the surface a
seamless one. It is no surprise that the program managers at
NASA were sceptical about sending mass spectrometers
on spacecraft. Many did not believe it was possible
to accommodate the power requirements with a limited
payload, and doubted it would be possible to get useful data,
given the difficult conditions. Nier convinced the sceptics by
building a battery-operated sector field mass spectrometer
in a briefcase, carrying it by hand to a meeting at NASA
headquarters, and measuring the atmospheric composition
in real-time (Fig. 3). This was quite a technological feat for
the mid-1960s, but was one of many for Nier. A series of
Atmosphere Explorer Satellites each carried as part of its
payload an open-source neutral mass spectrometer, which
provided important information on the chemically active
species atomic O and N, and how solar radiation affected the
gas densities of the upper atmosphere.  

The Viking mission to Mars was the vehicle that
demonstrated the value of these small yet sensitive mass
spectrometers in space. Working with Michael McElroy
from Harvard University, Nier was assigned the task of
measuring the elemental and isotopic composition of the
Martian atmosphere during the descent of the Viking lander.
In this situation there was no room for mistakes, as the
measurements would be performed while the spacecraft
transited the atmosphere to crash on the surface. The mass
spectrometer performed its task without fault. The results
included the discovery that $^{15}$N is significantly enhanced
relative to the more abundant isotope $^{14}$N, due to the
preferential escape from the planet of the lighter isotope.  
This fractionation of Martian N was later used to prove that
a small number of meteorites actually originated from the
surface of Mars by comparison with the isotopic composition
of Nier’s experiment.

Nier was also asked by NASA to assist in the gas
cromatograph mass spectrometer on the Viking lander,
which was experiencing some design difficulties. Needless
to say, the instrument was successfully deployed, and
provided important results. Nier enjoyed his role as team
leader, and later went on to measure the composition,
temperature profile, and homopause altitude on Venus.  
The Venus experiment was a joint German–American project
of which Ulf von Zahn was the Principal Investigator. For his
involvement in the exploration of Mars and Venus, NASA
honoured Professor Nier for his contribution to national
science programs.

It was characteristic of Nier that his retirement from
the University of Minnesota did not mean retirement
from research. His space science experience in building
miniturised mass spectrometers enabled him to return to
his love of noble gas analyses by adapting this design
to build a small, gas source mass spectrometer of high
sensitivity. With this instrument he was able to measure the
isotopic composition of He and Ne from tiny interplanetary
dust particles (IDPs) and lunar grains using stepped-heating
techniques. This enabled the thermal history of these particles
to be deciphered and to distinguish between cometary
and asteroidal origins. Nier and Schlutter examined the
helium release patterns for 12 IDPs by stepped-heating, and
compared the release patterns with those of 14 lunar soil
samples. The similarity of these two sets of release patterns
indicated that the IDPs did not suffer extreme heating during
atmospheric entry. These IDPs are approximately 15 µm in
size and the amount of He in any one particle is around
$10^{-10}$ cm$^3$ STP, and the amount of $^3$He is about $10^{-4}$ of
the total He content. The magnitude of the task would
be daunting for a younger scientist, but Professor Nier,
with the assistance of a gifted technician in D. J. Schlutter
made important contributions to this new field of extra-
terrestrial fluxes to the earth’s surface. His colleagues have
continued this project, notably Robert Pepin at Minnesota.
Professor Nier’s last paper, published posthumously in 1994,
reported the isotopic abundances of these noble gases in
lunar ilminites of different antiquities.

![Figure 3. Al Nier’s ‘mass spectrometer in a briefcase’, constructed in the mid-1960s, and used to convince NASA officials that it was possible to include such instrumentation on spacecraft.](image)
Figure 4. Alfred Otto Carl Nier, May 28, 1911–May 16, 1994. The photo shows the glass mass spectrometer, he used to make measurements relating to uranium fission, taken in 1940. At right, Al Nier in 1991 holding an Antarctic rock sample that had been analysed using techniques he pioneered.

CLOSING REMARKS

Professor Nier died on May 16, 1994, at the age of 82, after a car accident on his way home from his laboratory at the University of Minnesota where he spent most of his academic career. In 1966, the University recognised his important scientific contributions by naming him Regents Professor of Physics, and in 1980 awarding him an Honorary Doctor of Science. Figure 4 shows two photographs of Professor Nier, one taken in 1940 and the second in 1991. The Manhattan Project was a clear demonstration of the role that science could play in achieving national objectives, and its success was a major factor in the support for basic science in the United States after World War II. In this respect Professor Nier played an important role by determining that \(^{235}\text{U}\) produced fission, and by contributing substantially to the success of the gaseous diffusion separation effort. Professor Nier was honoured by the Atomic Energy Commission for his contribution to the Manhattan Project.

Alfred Nier once described himself as ‘more of a gadgeteer than most physicists’. However, he was well-known to his colleagues for his remarkable modesty. He was a brilliant experimentalist who applied his skills to designing and constructing mass spectrometers both large and small, using the latest technological advances of the time. He was especially proficient in electronics, presumably because of his early education in electrical engineering, and he was largely responsible for mass ‘spectrographs’ becoming mass ‘spectrometers’.

Professor Alfred Otto Carl Nier was a giant in mass spectrometry for a period of some 60 years. His greatest achievements were arguably the construction of the sector field mass spectrometer, which he designed for ‘isotope and gas analysis,’ and his ability to pioneer new fields of science. His lifelong passion was in the isotopic analysis of gases, including samples from Mars and Venus. At the time of his death he was analysing the noble gases contained in IDPs. During his professional career Professor Nier received many prizes and awards, especially from the chemical, geochemical, geological, geophysical, and meteoritical communities, who benefited so much from his work. The Los Alamos National Laboratory organised a number of Symposia named in his honour, and it was at one of these that John Reynolds paid tribute to Professor Nier, in the following words:

‘His own work in mass spectrometry for more than 50 years has resulted in monumental contributions to nuclear physics, nuclear energy, isotopic geochemistry, and space physics. Offshoots of his leadership in the field have revolutionised Earth Science and Meteoritics. His eternal youth and enthusiasm have inspired us all.’

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