Physics in Perspective

From Natural History to the Nuclear Shell Model: Chemical Thinking in the Work of Mayer, Haxel, Jensen, and Suess

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In 1949 the nuclear shell model was discovered simultaneously in the United States and Germany. Both discoveries were the result of a nuclear scientist looking at geochemical and nuclear data with the eyes of a chemist. Maria Goeppert Mayer in the United States and Hans Suess in Germany both brought a chemist's perspective to the problem; the theoretical solution was subsequently supplied independently by Mayer and Hans Jensen.

Introduction

The nuclear shell model, a highly successful scheme for accounting for the characteristics of many stable nuclei, is of fairly limited usefulness to most branches of chemistry. It has its origins, however, in chemistry and geochemistry. The data that provided the starting point for the shell model were supplied by geochemists, as was described recently by Helge Kragh.[1] Here I take the argument one step further and look at the role that chemical reasoning, as well as chemical data, played in the independent and simultaneous discoveries of this model in the United States and Germany. As an example of the fruitfulness of interdisciplinary investigations, this story illustrates the importance of bringing different philosophical perspectives to disciplinary work.

In the Bohr model of the *atom*, one electron experiences a potential produced by the atomic nucleus and all of the other electrons in the atom. Combined with the Pauli principle, this explains why certain atoms with filled electron shells are particularly stable. The *nucleus*, by contrast, may be conceived in two different ways. It may be treated as a homogeneous mass of material, such as a liquid drop, or, in analogy to the Bohr atom, it may be treated as a collection of discrete particles. In the latter case, the individual nucleons – neutrons and protons – are considered to be independent particles with independent spins and energy levels, each moving in a potential well produced by

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the action of all of the other nucleons. This is the basis of the nuclear shell model, in which the interaction energy between individual nucleons is negligible compared to the energy of the central nuclear potential. Again by analogy to the Bohr atom, the primary evidence for the nuclear shell model was that nuclei with certain specific numbers of protons or neutrons – 2, 8, 20, 28, 50, 82, or 126 – are particularly stable. Data collected from nuclear-binding energies, radioactive-decay energies, and isotopic abundances established this pattern, which suggested that nucleons fill nuclear-energy levels similar to the way in which electrons fill atomic-energy levels. The numbers of nucleons occupying filled shells, however, turned out to be different from those that the usual methods of quantum mechanics predicted for standard central potentials.

In 1949 Maria Goeppert Mayer in the United States, and independently Hans Suess, Hans Jensen, and Otto Haxel in Germany discovered the solution to this puzzle. The key was the assumption of a strong spin-orbit interaction that splits the energy levels of the nucleons. This interaction also occurs for electrons in an atom, but the energy splitting is negligible compared to the total electron-binding energy except for very heavy atoms. Until 1949 nuclear physicists assumed that the same was true for nucleons.

The nuclear shell model thus has two essential features: first, the identification of the shell structure itself, based on the evidence for nuclear stability and leading to the basic assumption that the nucleus can be described by a single-particle model; and second, the assumption of a strong spin-orbit interaction among nucleons, accounting for the splitting of their energy levels. I will show how Maria Goeppert Mayer and Hans Suess arrived at the first feature by looking at chemical, geochemical, and nuclear data as chemists.

Early History of the Shell Model

When the successful explanation of nuclear shells was published in 1949, the shell model already had a sixteen-year history that was closely linked to the history of nuclear systematics. Although the study of nuclear stability as a function of mass number and proton number went back to the 1920s, the first true shell model of the nucleus was worked out by Walter Elsasser, in conjunction with Kurt Guggenheimer, in 1933–1934. Elsasser was an atomic theorist, and Guggenheimer was a physical chemist. Both were refugees from Nazi Germany. They met in Paris in 1933, shortly after James Chadwick's discovery of the neutron, and found that they shared an interest in studying the internal structure of nuclei by examining nuclear-binding energies.

Guggenheimer took a chemist's approach to the problem: He sought to identify periodicities in terms of the numbers of protons and neutrons in nuclei in the hope that he could construct a nuclear analog to the periodic table of the elements. He based his analysis on nuclear-binding energies (calculated from mass measurements) and on isotopic abundances. By plotting the known stable nuclides as a function of proton number Z and neutron number N, he demonstrated that certain values seemed to confer unusual nuclear stability, and hence suggested closed shells. In this way he identified marked discontinuities at $N = 28, 50$, and 82. The evidence for discontinuities at $Z = 50$ and 82 was less compelling, and Guggenheimer saw it merely as a coincidence that these same values appeared for both neutrons and protons.[2]

Elsasser, at the same time, was trying to formulate a successful theory of nuclear structure that would account for the apparent nuclear shells observed by James H. Bartlett in light nuclei with nucleon numbers 2, 8, 18, and 32.[3] Then, after the publication of Guggenheimer's identification of $N = 50$ and 82, Elsasser extended his theory to include heavier nuclei as well. He started by searching for a suitable modification of the central nuclear potential that would enable him to use quantum mechanics to predict higher numbers of particles per shell than the numbers predicted for electrons in a Coulomb potential. He first used a finite square well to bring the higher angular-momentum levels down to lower energies, and then tried an infinite spherical potential well with perturbations in an attempt to account for the higher occupation numbers. Unfortunately, it seemed that *any* nuclear potential predicted nuclear shells at 2, 8, and 20 nucleons, while *none* could predict the higher shell numbers.[4]

The strongest objection to the nuclear shell model came from Niels Bohr, who articulated it while developing his compound-nucleus model. Essentially, Bohr argued that all measurements of the nuclear force suggested that it exhibits saturation; that is, the force between any two nucleons is of the same order as the force between the entire nucleus and a single nucleon. Thus, Bohr argued, it is not possible to treat individual nucleons independently, and to assign individual values of spin-angular momentum and energy to each nucleon, so that the concept of nuclear shells is invalid. Bohr went on to adapt George Gamow's liquid-drop model of the nucleus to his compound-nucleus model, in which the excitation of a nucleus is attributed to "some quantised collective type of motion of all the particles."[5]

Bohr's compound-nucleus model, particularly as mathematized by Gregory Breit and Eugene Wigner,[6] when wedded to Gamow's liquid-drop model, led three years later to an understanding of nuclear fission,[7] which terminated attempts to formulate a nuclear shell model. Thus, for more than a dozen years, from 1936 to 1949, nuclear physicists generally operated on the assumption that nuclei could not have a genuine shell structure (although independent-particle models were used regularly as calculational devices to estimate nuclear forces and energies).[8]

Maria Goeppert Mayer's Route to the Shell Model

Maria Goeppert (1906–1972, figure 1) was raised in Göttingen and completed her doctoral degree there at the Georgia Augusta University under the direction of Max Born in 1930. Her initial approach to physics was influenced strongly by Born's style of mathematical analysis. In her doctoral thesis, she extended P.A.M. Dirac's theory of the emission and absorption of single photons by an atom to the case of double-photon absorption and emission – work that had no practical applications until after the development of lasers in the 1960s. In 1930 Maria Goeppert came to the United States with better training in quantum mechanics, particularly matrix mechanics, than most American physicists, and a very formal mathematical approach to physics.

Goeppert left Germany in the company of her new husband, American chemist Joseph Mayer. Mayer, a physical chemist who had studied under G. N. Lewis at the University of California at Berkeley, had been working with James Franck in Göttingen as a Rockefeller Fellow. Like most American chemists in the 1920s, he was essentially an

Fig. 1. Maria Goeppert Mayer (1906–1972). *Credit:* American Institute of Physics Emilio Segré Visual Archives, Physics Today Collection.

experimentalist, but he had a stronger interest in theory than many of his peers. He and Maria went to Baltimore, Maryland, where he had an appointment in the chemistry department at The Johns Hopkins University. Maria had no appointment at Hopkins, but over the course of nine years there, she worked collaboratively with several colleagues. As a mathematical physicist, her strength was in the application of mathematics to physical puzzles; she worked mostly on questions posed by colleagues who enlisted her help in solving mathematical problems that arose in their particular areas of research. Since those who seemed most interested in soliciting her help were in chem-

istry and chemical physics, her work diverged from the atomic physics and quantum mechanics in which she was trained and became oriented toward the more complex systems of interest to chemists.[9] She wrote several papers with her husband, and several more with the chemical physicist Karl Herzfeld. She became best known, however, for a paper written with Alfred Sklar in 1938 in which they used group theory and the Hund-Mulliken method to calculate the expected energy levels of the benzene molecule.[10] By 1940 Goeppert Mayer was generally regarded as a theoretical spectroscopist, and many in the scientific community assumed she was a chemist.

This perception was enhanced by Goeppert Mayer's work with the Manhattan Project during World War II. By that time she and her husband had moved to New York, where Joe had a position at Columbia University and Maria again had no formal appointment in physics. She worked during the war with Harold Urey's group studying methods of uranium separation. Her major contribution was a theoretical analysis of the spectra of various uranium compounds. The group she worked with was composed almost entirely of chemists.

After the war Goeppert Mayer and her husband accepted invitations to join the Institute for Nuclear Studies at the University of Chicago, where she had her first opportunity to work in the field of nuclear physics. While collaborating with Edward Teller on a theory of the origin of the elements, she discovered the phenomenon that we know by the picturesque name of "magic numbers" – that certain numbers of neutrons or protons (2, 8, 20, 28, 50, or 82) in a nucleus confer unusual stability. (This term was invented by Eugene Wigner to indicate his skepticism about the phenomenon.) This pattern repeated in a wide variety of different isotopes, and Goeppert Mayer collected evidence for it by analyzing nuclear-binding energies, radioactive-decay energies, and isotopic abundances provided by the geochemist Victor Goldschmidt (see below). She tried to understand the observations in terms of nuclear-energy levels, or shells, but could not make the usual techniques of quantum mechanics, which worked so well for predicting atomic-energy shells, yield the correct numbers of nucleons. Frustrated by the lack of an adequate theory, she nonetheless continued to collect supporting data, which she published in *The Physical Review* in August 1948.[11]

Goeppert Mayer brought to her study of the nucleus her skills in quantum mechanics and a useful unfamiliarity with many of the commonly held assumptions of nuclear physicists in 1947. Unlike her colleagues in the nuclear-physics community, who were familiar with Bohr's arguments against the possibility of nuclear shells, she felt no such restriction. She was so familiar with the phenomenology of the magic numbers that when, early in 1949, Enrico Fermi suggested that she consider the possibility of a spin-orbit coupling effect in the nucleus, she immediately recognized that this could explain her magic numbers. If the spin-orbit effect for protons and neutrons in the nucleus were much stronger than the electronic spin-orbit effect in the larger atom, then the relative energies of the nucleon states would be altered enough to change the occupation numbers for closed nuclear shells; this could account for her magic numbers. Of more importance to nuclear physicists, the shell model also could account for many of the recently measured values of nuclear spins and nuclear magnetic moments. She published her solution to the problem of the magic numbers in a Letter to the Editor of *The Physical Review* in June 1949.[12]

From Geochemistry to Nucleons: Goldschmidt, Suess, Jensen, and Haxel

Goeppert Mayer had been reluctant to publish her solution to the puzzle of nuclear shells because before she wrote up her Letter, she had seen a manuscript posing a different solution to the problem. Not wanting to take advantage of this knowledge, she asked that her Letter be published in the same issue of the journal as the manuscript she had already seen. Because of this delay, her Letter appeared two weeks after one written by Otto Haxel, Hans Jensen, and Hans Suess. Like Goeppert Mayer's, it had its origins in the work of the Swiss-Norwegian geochemist Victor Moritz Goldschmidt. Goldschmidt (1888–1947) was born in Zurich and studied chemistry, mineralogy, and geology at the University of Christiania (Oslo). His professional career was spent in Oslo and Göttingen, where from a series of analyses of the abundance and distribution of geochemical elements he developed the basis of the science of geochemistry. Goldschmidt's work was prompted initially by Norway's need to locate Norwegian sources of chemicals that had been imported prior to World War I. In his capacity as chairman of the (Norwegian) Government Commission for Raw Materials, Goldschmidt began to formulate laws for the geochemical distribution of chemical elements based on the measurement of a wide range of physical parameters for their abundances.

Goldschmidt's work, particularly his application of crystallography to the study of geochemical abundances, went well beyond the questions we are concerned with here.[13] Recognized as the leading geochemist of his day, he accepted the directorship of the Mineralogical Institute at the University of Göttingen in 1929. As a Jew, he was forced to give up his chair in 1935 and return to Norway. He continued his mineralogical investigations there and in 1937 published the ninth and last monograph in his series of *Geochemische Verteilungsgesetze der Elemente*.[14] This volume, which he referred to as his Ninth Symphony, was devoted to a tabulation of elemental and isotopic abundances. In it he turned from his usual interest in strictly elemental abundances to a recognition of the role of the atomic nucleus in the relative abundances of specific isotopes. To determine the rules governing the distribution of the elements, he said, one must consider not only the abundances of the elements but also the relative abundances of the individual isotopes of the elements. His abundance data included isotopic-mass data (as determined by Francis W. Aston), data from the analysis of meteorites, and astrophysical measurements from spectral analysis. Ten years later, in 1948, his collection of isotopic-abundance data was still the best available. By plotting isotopic abundance as a function of atomic number Z, Goldschmidt found that certain elements have much lower abundances than their neighbors, both for terrestrial and nonterrestrial sources. Hence, he concluded, the abundances must be a consequence of nuclear structure, and not the result of chemical reactions.

One of Goldschmidt's major innovations was to classify isotopes by their proton number Z and neutron number N in addition to the standard classification by mass number A. From this observation it emerged that maxima in abundance could be seen at $Z = 28, 40, 50, 74, 82,$ and 90, and $N = 30, 50, 82,$ and 108. These values could not have led Goldschmidt to a recognition that these "special numbers" were the same for neutrons and protons, but his conviction that abundances could provide a clue to nuclear structure led to the shell model when the chemist Hans Suess encountered his data.
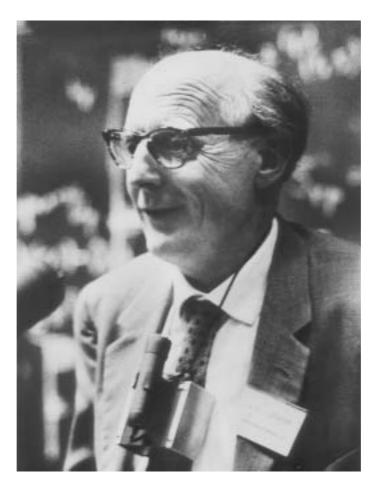
Fig. 2. Hans E. Suess (1909–1993). *Credit:* Glasheen Collection, Mandeville Special Collections Library, University of California at San Diego.

Hans E. Suess (1909–1993, figure 2) was born in Vienna, the son of a well-known professor of geology at the University of Vienna. He chose to continue the family tradition and study the origin of the earth, but from the chemical rather than geological standpoint. Suess completed his doctoral degree at the University of Vienna under Philipp Gross in 1936, and from 1937 to 1950 was at the University of Hamburg as a member of the Institut für Physikalische Chemie. Suess's earlier work, in Vienna, involved chemical reactions in heavy water. His research in Hamburg in the late 1930s was primarily in experimental nuclear chemistry and chemical kinetics, particularly with radioactive bromine compounds – work that was suggested by Paul Harteck, a colleague in Hamburg.

With the outbreak of war in 1939, Suess was involved in the German uranium project along with Harteck. As a result of his earlier research, Suess suggested the use of heavy water as a moderator for a fission pile. This, in turn, led him to the Norwegian heavy-water plant at Vemork, where he served as a consultant for the uranium project. On several of his routine trips to Norway in 1942, he met with Goldschmidt and was infected with Goldschmidt's curiosity regarding elemental and isotopic abundances.

Suess and Goldschmidt were joined in these discussions by a nuclear theorist, Johannes Hans Daniel Jensen. Hans Jensen (1907–1973, figure 3) attended the Uni-

Fig. 3. J. Hans D. Jensen (1907–1973). *Credit:* American Institute of Physics Emilio Segré Visual Archives, W.F. Meggers Gallery of Nobel Laureates.

versities of Hamburg and Freiburg and completed his doctoral degree in theoretical physics under Wilhelm Lenz at Hamburg in 1932. He became a *Privatdozent* in 1937 and remained at Hamburg until 1941, when he was appointed as professor of theoretical physics at the Technische Hochschule in Hannover. During the 1930s he had visited Bohr's institute in Copenhagen several times, and was familiar with the efforts there to formulate a general theory of the nucleus. His work during these years included crystal-lattice theory and extensions of the Thomas-Fermi theory of the atom.

By the time the war ended, Suess had spent enough time looking at Goldschmidt's isotopic-abundance data to be convinced that the data were not distributed randomly. They were evidence of some pattern. As a research topic, this was particularly good for Suess – he had a long-standing interest in the origin of the elements, and Goldschmidt had provided all of the data necessary for at least a preliminary consideration of this

question. Conditions for scientific research in Germany during and shortly after the war were extremely limited, and productive research topics were difficult to find in a situation where there was no funding for experimental apparatus. German scientists mostly found themselves limited to "side issues" in physics.[15] Fortunately for Suess, who was not a theorist, he managed to engage Jensen's interest in the subject.

Suess eventually published his efforts to account for the patterns in the abundance data in a two-part paper in 1947 in which he thoroughly described the systematics of abundances and developed, in detail, some rules for nuclear stability based on extensive graphical analysis of the isotopic-abundance data.[16] This work was an excellent illustration of his predilection for graphing empirical results in every possible configuration. Joseph Mayer summed it up by commenting: "Hans is a 'plotter.' He plots everything against everything else and examines every hump, kink or dip. I say this not derisively but with deep admiration."[17] This approach to experimental data enabled Suess to recognize what he called the "special numbers" for nuclei. In graphs of cosmic isotopic abundances as a function of odd and even mass number, and proton number, he came to see his results in terms of nuclear stability and identified the *ausgezeichneten Zahlen*:

N: 20   28   50 (58)   82
Z: (20) 26 or 28   50   74   82

This was the first clear suggestion that stability conditions might be the same for neutrons and protons. As Suess said later, "I was so impressed I couldn't sleep for many nights."[18]

Suess credited his colleague Otto Haxel with helping him to identify the "special numbers," particularly 28. Haxel (1909–1998, figure 4) studied at the Technische Hochschule in Munich and the University of Tübingen and received his doctoral degree under Hans Geiger at Tübingen in 1933. He remained there until 1936, when he became an assistant at the Technische Hochschule in Berlin. In 1946 he went to Göttingen as an assistant to Werner Heisenberg. Haxel's background was in experimental nuclear physics (measurements of nuclear reactions and spectra), and he had recognized the special nature of the *ausgezeichnete Zahlen* based on nuclear, rather than geochemical data. In discussions with Suess, it became clear that the two were talking about the same numbers. Haxel also had discussed the same questions independently with Jensen, then in Hannover.

Haxel and Suess continued to discuss possible reasons for the special numbers. Because this problem concerned them both; because they were in different cities (Göttingen and Hamburg); and because they seemed to be drawing similar conclusions from different perspectives, they made a pact concerning publication. They agreed that if either had an idea about the meaning of the special numbers, he would publish under both of their names. This made a great deal of sense for long-distance collaboration. At that time the German postal service was inadequate, and other modes of communication that we take for granted today were unavailable.

Both Haxel and Suess tried to convince Jensen that their "special numbers" were some sort of key to nuclear structure, but he seemed reluctant to pursue the issue. He

Fig. 4. Otto Haxel (1909–1998). *Credit:* Physik Journal.

saw absolutely no theoretical way to account for the regularities. Then, in August 1948, Maria Goeppert Mayer's paper appeared in *The Physical Review*,[19] setting out extensive evidence for the same numbers that Haxel and Suess were so excited about, and referring to those numbers as "magic numbers." Jensen read Goeppert Mayer's paper while visiting in Copenhagen and was inspired to give a seminar at Bohr's institute, discussing the results of Mayer, and Suess and Haxel. Bohr's reaction surprised him: "Niels Bohr listened very attentively and threw in questions which became more and more lively."[20] It was evident that Bohr was familiar with Mayer's paper and had given the subject a great deal of thought. Bohr's enthusiasm for the possibility of a shell structure encouraged Jensen to take the matter more seriously.

Suess found a way to produce the magic numbers, although he could not justify his method theoretically:

So I started playing with these numbers and found that they were indeed magic – I mean all kinds of things could be done with them, such as deriving mathematical progressions of these numbers. Next I simply looked up in a textbook the solutions

of the Schrödinger equation for the three-dimensional harmonic oscillator. (I did not go through the mathematics, because it could be looked up in any textbook.) Then I wrote down the levels one gets, sorted them in sequence according to the angular momentum, and used the Pauli principle to see how many particles would fit into each level. This gave the wrong numbers, but all one had to do was to reverse the usual sequence of spin values, and to start with the highest spin. If one includes the highest value in the previous shell, one gets precisely the magic numbers.[21]

Suess did not realize it, but he had introduced a spin-orbit effect when he divided each angular-momentum l-value into its constituent j-values ($l \pm {}^1/_2$), and assumed that their energies are sufficiently different to produce distinct energy levels. He used harmonic-oscillator energy levels simply because those were what he had found in the textbook.
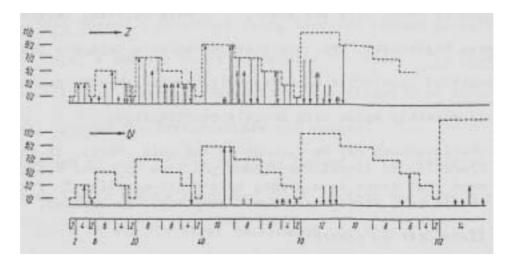
Suess found a way to check the order of spin levels that he derived from his procedure. Recalling a paper by Theodore Schmidt from the 1930s that suggested that the spin of a nucleus is due to the spin of the last (odd) nucleon,[22] Suess plotted the experimental spin-values for odd-even and even-odd nuclei against nucleon number. The result is shown in figure 5.[23] The stepwise horizontal dotted line in each plot indicates the expected spin value of the nucleus for a harmonic-oscillator energy-level scheme in which the j-values ($l \pm {}^1/_2$), are separated, assuming that the total nuclear spin depends only on the last (odd) nucleon. The direction of the vertical arrow in each case indicates the parity of the level (parallel or antiparallel spins), which should be determined by the orbital angular momentum, and is calculated empirically from the nuclear magnetic moment. Although the fit, particularly for odd-neutron nuclei, is not excellent, it was "an indication that this model is meaningful, one way or another."[24] Suess was struck by the small number of cases in which the measured spin-value exceeds the predicted value, one of which was Mn^{55}.

With this new and suggestive evidence, Suess again went to Jensen and showed him his plots of nuclear spins, hoping for an explanation of the curious rearrangement of the spin values.

> So I had to wait until Jensen showed up because I didn't know what this could mean. He said "I have to plot this myself" … and he drew exactly this but he … wanted to do it himself so he knew what it was meaning. I remember when he came to manganese which has a spin 5/2 and a plus parity, he said, "That's all nonsense."[25]

Suess's "plotting" had finally done the trick, and Jensen saw that there clearly was something to this scheme. The theoretical explanation did not take long after that. Steven Moszkowski recalled that Jensen once told him that he had first thought of spin-orbit coupling while he was shaving one morning.[26] Suess described the circumstances this way:

> The following day he came to me and said, "Well, if there is something to it – if the scheme you drew up means something – it would mean that there is a strong spin-orbit coupling." I asked why there should be a strong spin-orbit coupling. He replied, "Das hat der liebe Gott so gemacht."[27]

Fig. 5. Suess provided the following caption: "Empirical spin values of nuclei with odd proton number (above) and odd neutron number (below), plotted against the total number of protons (above) and neutrons (below) in the nucleus. An arrow pointing upward means parallel and downward antiparallel spin angular momentum. Where there is no arrow, this indicates that the magnetic moment is unknown." See Suess, Haxel, and Jensen, "Zur Interpretation" (ref. 23), p. 154.

The first note written by Jensen and Suess was rejected by *Nature*, with the criticism that they were playing with numbers rather than doing physics. They were more successful with *Die Naturwissenschaften*, which eventually published a series of three papers on the subject. Before the first paper was submitted, Suess recalled his agreement with Haxel, and the paper was published under all three names, with Haxel's listed first according to the convention of alphabetical order.[28] Hoping to publish in English as well, Jensen and Suess also sent a brief note to *The Physical Review*, which appeared in that journal two weeks before Maria Goeppert Mayer's note on the same subject.[29]

The nuclear shell model was rapidly accepted by nuclear physicists as a useful tool for understanding the behavior of stable nuclei. Together, Maria Goeppert Mayer and Hans Jensen developed the theoretical aspects of the model, setting them out in their book, *Elementary Theory of Nuclear Shell Structure*, published in 1955.[30] They were jointly awarded half of the Nobel Prize in Physics for 1963, only three years after Maria Mayer finally became a paid professor, at the University of California at San Diego.

Conclusions

In each case, American and German, these discoveries were prompted by the examination of isotopic-abundance data, along with nuclear data, with the eye of a chemist. How is this different from the way in which a physicist would look at the same data?

Physics and chemistry in the 20th century were closely linked and often overlapped. They were characterized, however, by identifiably different philosophical perspectives or, as Ian Hacking termed it, "styles of scientific reasoning."[31] This distinction is not necessarily obvious. Auguste Comte's traditional positivist hierarchy held that physics is the most fundamental science, and that all others, including chemistry, are derivative from it. More recently, the two disciplines have been distinguished naively by their subject matters. This assumes that they depend on the same methods and analytical tools, but that chemists rule the realm of molecules, while physicists hold sway among atoms, nuclei, and elementary particles, as well as stars and galaxies. Another distinction can be made in terms of the role of experiment in each discipline: Historically, chemistry has been more dependent on the laboratory than physics. These differences are relatively superficial, however, and do not tell us much about the fundamental approaches, or styles of scientific reasoning, practiced in the two disciplines.

We could distinguish physics and chemistry by their origins. Chemistry grew out of both alchemy and natural history. Natural history, the description and study of the origins and interrelationships of natural objects, inspired 18th and early 19th-century chemists to aspire to a system of chemical nomenclature and classification modeled on the Linnaean system of taxonomy for plants and animals, the goal being to identify and organize the variety in nature. Physics, by contrast, was called natural philosophy in the 19th century. The natural philosopher, taking cues from the ancient Greek philosophers, sought to explain natural phenomena with the smallest possible number of fundamental principles. Historically, unification and reduction have been the goals of physics, rather than tabulation of the complexity of nature.

This is a useful philosophical distinction, but by the 1940s few physicists or chemists probably were conscious of the philosophical roots of their daily practices. Looking at physics and chemistry in the first half of the 20th century, though, we find that the distinction between natural philosophy and natural history manifested itself in ways that are particular to the scientific methodologies of the 20th century, and yet consistent with the older philosophical positions. For example, chemists were far more likely to accept the legitimacy of semiempirical methods of deriving theories, while physicists tended to find such methods insufficiently rigorous; if the theory were correct, it should contain within it the necessary numerical results. The two disciplines also held very different attitudes toward the role of theory. Because physicists saw themselves as discovering universal and fundamental principles of nature, two different and equally successful theories for the same phenomenon constituted a theoretical crisis. Chemists, by contrast, were much more pragmatic in their approach to theory, and would not have said that one theory represented the "truth" more than another equally successful one.

Mary Jo Nye, who has studied the growth of theoretical chemistry, and the ways in which it differs from physics, has written:

> Physicists have focused on the "corpuscle" and principles common to all corpuscles, whether electrons, atoms, or molecules. In contrast, the chemist most often has reveled not so much in the discovery or justification of uniformities in nature as in the discovery or creation of what is different and marvelous.[32]

Thus, chemists had as their goal the characterization of the complexity of nature, and

the creation of new compounds. Physicists, by contrast, were interested in complexity only when its details supported or conflicted with their theories.

This distinction is evident in the two paths followed to the nuclear shell model. In the case of Suess, Jensen, and Haxel, the role of the natural historian was played by Suess, who was trained as a chemist, and regarded the accumulation and organization of physical data as having priority over first principles or physical theory. His conviction that the data were worth trusting eventually persuaded Jensen and Haxel to take them seriously as well. In the case of Maria Goeppert Mayer, the interactions were more complicated. Because of her intellectual history, she combined the skills of a theoretical physicist with the tendency to look at data with the eye of a chemist, and effectively played both roles herself. As she herself acknowledged, the chemist in her poured over the isotopic-abundance data even when the physicist in her could not find a satisfying theoretical explanation for it.[33] What is clear in both cases is that the natural historian was essential in recognizing the patterns that led to the theory of the nuclear shell model.

Acknowledgements

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