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Perspectives on nuclear physics over the past 100 years

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Perspectives on nuclear physics over the past 100 years

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Abstract. An attempt is made to review a small fraction of what has happened in Nuclear Physics after Rutherford, some milestones and the shifting focus of the field. In a hundred years enormous progress had been made, but there is still a great deal about the properties of hadronic matter that we do not understand, matter that makes up virtually all of the visible mass in our Universe.

1. Introduction
In the 19^{th} and 20^{th} centuries, humanity made enormous progress in understanding the way the physical world works. In this talk I was asked to summarize what has happened in nuclear physics in the past 100 years. The original talk consisted of a number of images, and not all of these could be reproduced here, but they are available on the web*.

Rutherford's discovery of 100 years ago, shown in Figure 1, was the key that opened the way to our modern understanding of the physical world. He established that the core of the atom was a very dense chunk of matter, a nucleus, and in fact nuclei constitute most of the mass of the visible Universe. But to understand this discovery required new rules of physics. Quantum mechanics arose as a direct consequence of Rutherford's work, defining fundamentally new basic rules to guide physics through the next century.

In the two-three decades after the existence of the nucleus was established, there was an initial series of seminal discoveries that are summarized in Table I.

I comment only on a few of these. Bohr's first paper on quantum mechanics shown in Figure 2 changed the foundations of our conception of the physical world. It arose directly from Rutherford's work. While most of us know this generally, I, for one, had not realized how close the link was until I saw the original papers. Bohr, in fact, had spent a sabbatical year at Manchester in 1912, and his 1913 manuscript that started quantum mechanics not only acknowledges Rutherford and the first reference is to Rutherford's paper, but the manuscript was communicated to the Philosophical Magazine by Rutherford. The neutron was discovered by Chadwick *[Image 6]* – and this new particle had much more of an impact – people were not so used to exotic forms of matter as we are now. Some of the other items in Table I will be discussed further in this talk.

*The images from the original talk are available as supplementary material for this article, or at http://www.nuclear.manchester.ac.uk/rutherford/, or http://www.phy.anl.gov/docs/Rutherford_talk_schiffer.pdf. Specific images that could not be included as figures in this manuscript will be referred to throughout the text as *[Image xx]*. References to the original papers are in the figures on the images.

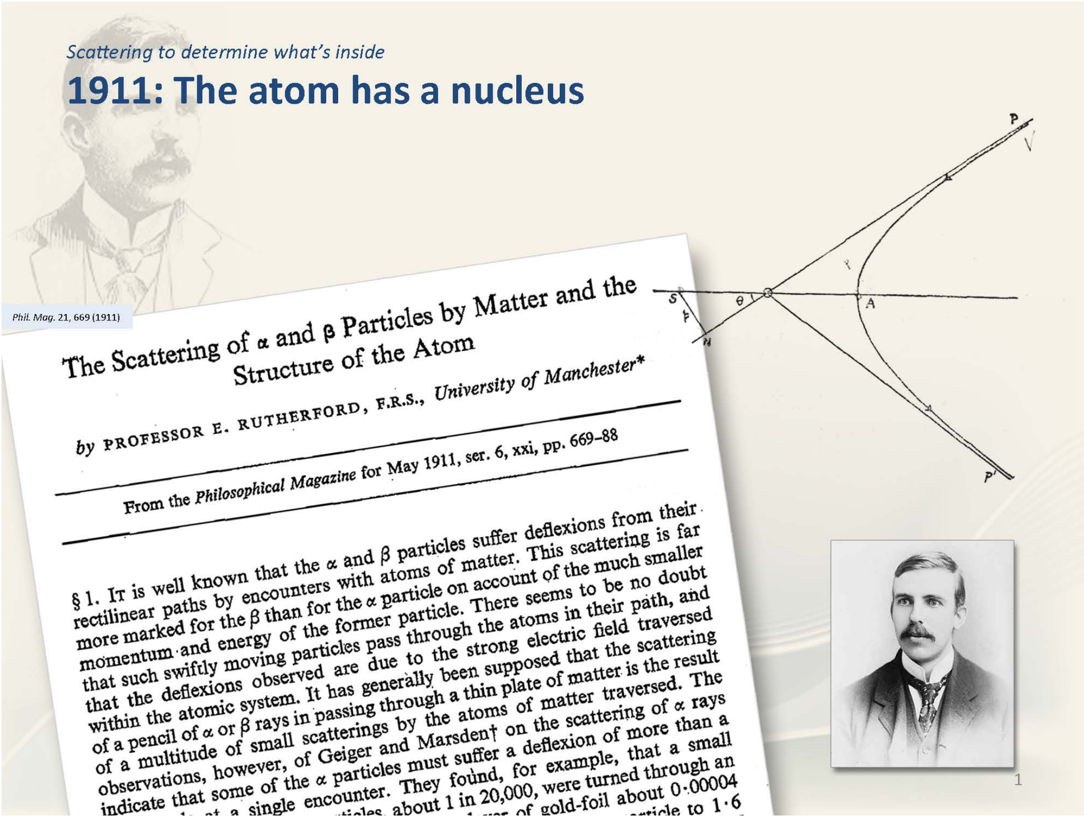

Figure 1. The discovery of the atomic nucleus.

Table I. Initial Wave of Discovery 1912-1939

1913	*Bohr*	*Quantum mechanics* and all that followed
1913	*Moseley*	X-ray sequence and charge of nuclei
1917	*Rutherford*	Nuclear *transmutations*
1919	*Aston*	Discovery of *isotopes*
1928	*Dirac*	Theory of the *electron*
1930	*Pauli*	Suggestion of *neutrino*
1932	*Chadwick*	Discovery of the *neutron*
1932	*Anderson*	Discovery of the *positron*
1934	*Yukawa*	Theory of *nuclear force* -- pion
1935	*Fermi*	Theory of *beta decay*
1938	*Hahn & Meitner*	Discovery of *fission*

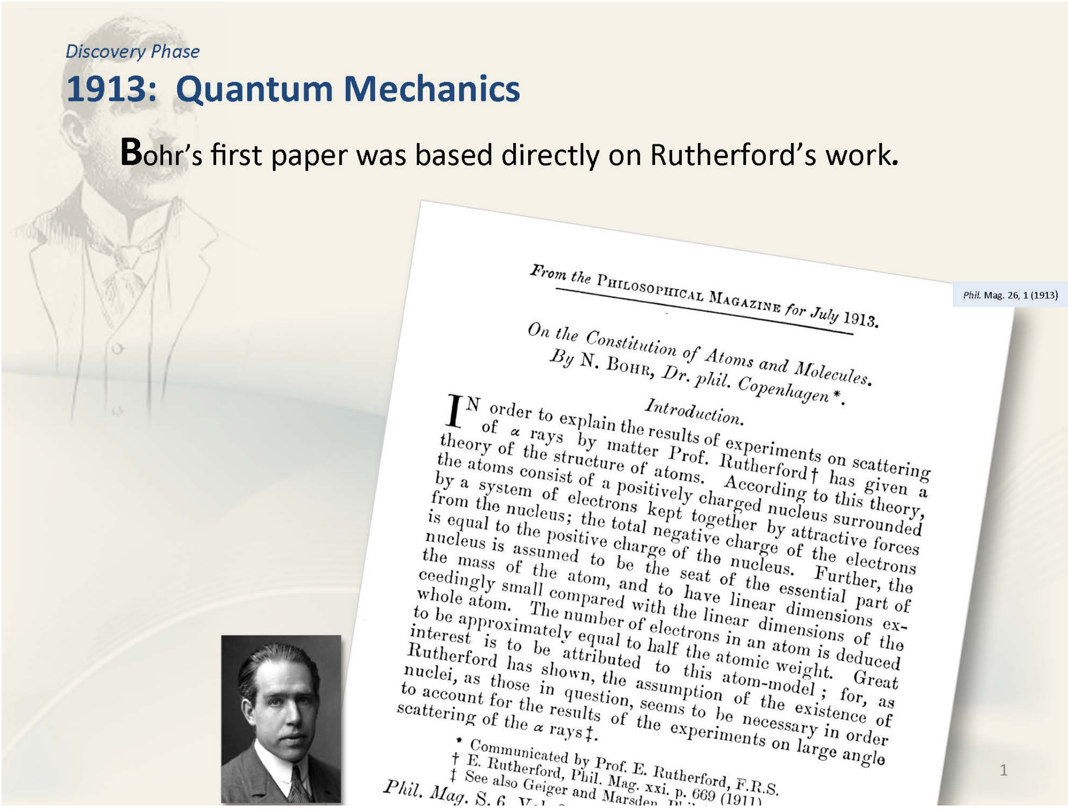

Figure 2. The birth of quantum theory, derived from the existence of the atomic nucleus.

2. Threads

Doing justice to the discoveries and developments of the past century is clearly impossible in this talk. I would like to go through a few threads that originate in one way or another from Rutherford's work.

2.1. Scattering to determine what is inside

Rutherford's work established that the positive core of the atom was small, but the technique has been extended repeatedly. His original work could only place a limit on the size of a compact nucleus, set by the energies of the alpha particles. But the onset of reactions, and the dependence on the charge of the target atoms gave a first indication. As the implications of quantum theory for barrier penetration became evident, Gamow *[Image 9]* showed the modifications to be made on these limits. Of course deviations from the Rutherford formula, when this became possible, also showed evidence for the size of the nucleus.

It became increasingly evident that some other source of energetic projectile was needed for studying nuclei. Rutherford made this known – and Cockroft and Walton at the Cavendish Laboratory were working on an electrostatic solution. It is remarkable that four schemes for producing energetic particles were proposed, the electrostatic solutions by Cockroft and Walton, and by Van de Graaff, and the radiofrequency ones by Wideroe and Lawrence, within a few years of each other, as shown in Figure 3.

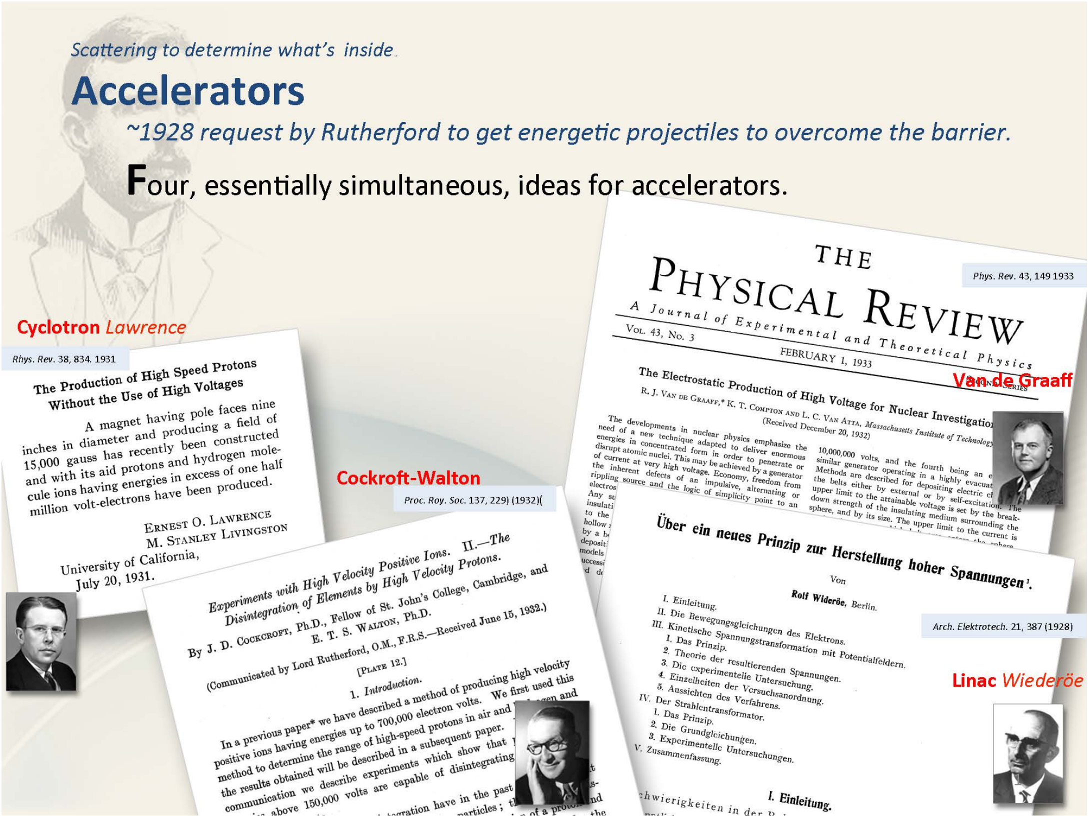

Figure 3. The start of accelerators.

On the theoretical side, to explain the short-range force that was required to hold a nucleus together, Yukawa *[Image 11]* proposed what today we know as the pion.

Some 40 years after Rutherford, Hofstadter, shown in *[Image 12],* used essentially the same technique with electrons, to deduce the size and shape of nuclei and of the proton itself, by precision measurements of electron scattering at a few hundred MeV. As more energetic accelerators became available, Friedman, Kendall, and Taylor *[Image 13]* again used electron scattering, and found that there were small constituents inside the proton – the quarks. But the basic idea in these experiments remains very similar to this day, when the difference between the electric and magnetic shapes of the proton finally seems to be known, making use of scattering of polarized particles as shown in *[Image 14].*

2.2. Structure and symmetries

Initial ideas about nuclear structure before the discovery of the neutron were strange. The first textbook on nuclear physics perhaps was the one by Rutherford, Chadwick and Ellis that was published in 1930. In it *[Image 17]* it is stated that

> "*.. the α particle is of primary importance as a unit of the structure of nuclei in general and particularly of the heavier elements ... probably in lighter elements, the nucleus is composed of a combination of α particles, protons and electrons*."

After the neutron was discovered this view changed drastically and the possibility of shells, in analogy with electron shells in atoms was considered. The 1936 review of Bethe and Bacher (the "Bethe Bible"), discusses various models, and considers the possibility the periodicities that seemed to indicate possible shells in nuclei up to ^{40}Ca. But then they say:

"*it is necessary to give a strong warning against taking the shells too*

> *literally … this has been done too frequently in the past with the effect of discrediting the whole concept of shells among physicists.*"

It took another 12 years for Maier and Jenssen to find that a strong spin-orbit interaction can account for all the "magic numbers" as shown in *[Image 19]*.

Heisenberg suggested an important symmetry about nuclei almost immediately after the discovery of the neutron – in effect that protons and neutrons be simply regarded as different states of the same particle, the isospin symmetry. There was some concern about this, because the Coulomb force acts on protons but not on neutrons, so especially in heavy nuclei the validity of the symmetry was questioned. But 20 years later there was more and more information on light nuclei to show that this symmetry was indeed very good, and in 1963 when isobaric analog states were discovered it became evident that the Coulomb force, because of its long range, played a rather minor role in breaking this symmetry. This is summarized in Figure 4.

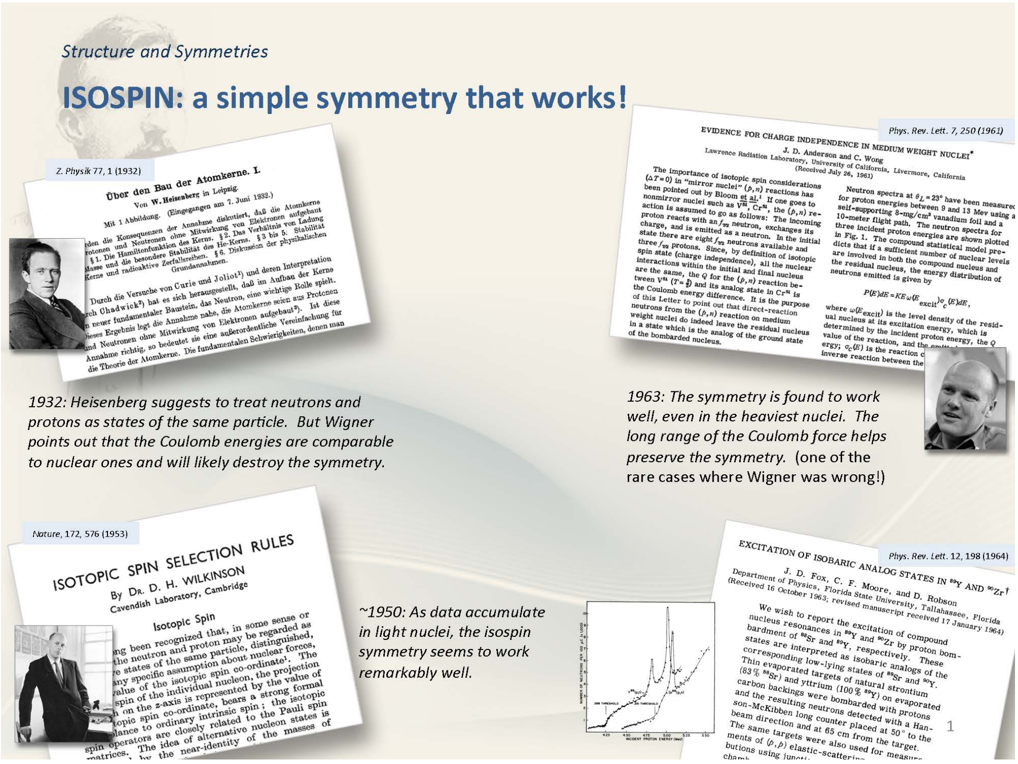

Figure 4. Some milestones in the history of the isospin symmetry in nuclei.

An important feature of nuclei was a mode in which protons oscillate against neutrons, the Dipole Giant Resonance of Goldhaber and Teller that was evident in the absorption of photons by nuclei, see *[Image 21]*. Shortly thereafter, a static collective property, the quadrupole deformations of nuclei was noted by A. Bohr and Mottelson *[Image 22]*. They also pointed out that, as a consequence, nuclei exhibit whole families of rotational bands and vibrations. This was followed by a class of less obviously geometrical, group-theoretical symmetries, in the Interacting Boson Model of Arima and Iachello *[Image 23]* that also had amazing successes in classifying a number of nuclear excitations.

But to gain this understanding, a great deal of experimental information had to be accumulated and the necessary tools were nuclear reactions. The discovery of the neutron was quickly followed by the observation of enormous fluctuations in neutron-induced nuclear reactions – and these were then understood in terms of resonances and the concept of long-lived intermediate states. The average properties of such complex systems were then parameterized in terms of the optical model, that tied in nicely with the concept of the transparency of nuclei that is implicit in the shell model. More or less in parallel, the concept of fast, quasi-elastic 'direct' reactions was developed, and with these insights the experimental arsenal for the study of nuclei was well prepared. All this is summarized in Figure 5.

Such reactions for instance give us the essential information on the single-particle structure underlying the ordering of nuclei as shown in *[Image 25]*, and allow us to explore the beautiful symmetries exhibited in the nuclear many-body system as is displayed in *[Image 27]*, together with some of the modern tools of gamma-ray spectroscopy.

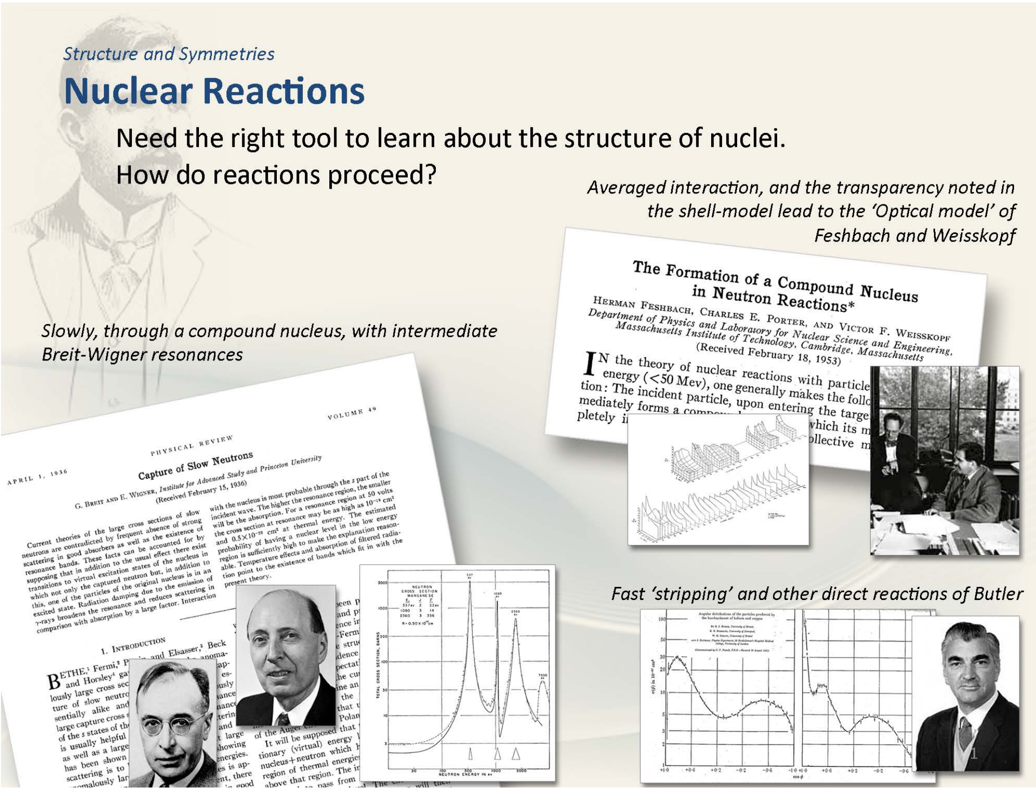

Figure 5. Understanding nuclear reactions.

2.3. Applications of nuclear physics

The largest impact of nuclear physics on society arose from the discovery of fission in 1939. The resultant Manhattan Project made the point rather forcefully that physics was relevant, whether for good or bad. The success of the Manhattan Project had an enormous impact on the support of all of physics by societies the world over in the second half of the 20th century. There is not time to give a complete review of societal applications of nuclear physics here, but just to mention a few:

- Nuclear energy, another application of fission, showed great promise – but society seems reluctant − perhaps because of the tie to weapons. It would be interesting to see whether 50-100 years hence whether this attitude will have changed.
- Nuclear fusion may or may not be a practical source of energy.
- Nuclear medicine is enormously successful and used extensively – it somehow has avoided the onus of being 'nuclear'.
- Accelerators, developed for nuclear physics, are used widely around the world, there are an estimated 10,000 used in medicine, 20,000 more in industry.

Nuclear physics and techniques developed in nuclear physics have found many applications in other sciences:

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- The Mössbauer effect, shown in *[Image 32]*, with primary applications in material science;
- ^{14}C and other isotopes in archeology, geology, history and oceanography;
- Accelerator Mass Spectrometry, traps, etc. with similar applications;
- Isotopes in a variety of ways in biology, chemistry, etc.;
- Rutherford back scattering in planetary science;

We can be proud of the many ways our science and our scientists have found ways to connect to other human endeavors.

2.4. Neutrinos, *a nuclear physics story*

One of the intriguing stories that ties a great deal of physics together is that of the neutrino. The fact of a continuous energy spectrum for beta rays was a puzzle in early nuclear physics. The Rutherford, Chadwick, and Ellis text explained in 1930 *[Image 34]* it in terms of mysterious α' particles – α particles with very tightly bound electrons that were thought to exist inside the nucleus whose disintegration involved a multibody decay and a broad energy spectrum. In the same year Pauli suggested that there might be a neutral light particle (with mass at least less than 0.01 times the proton and spin 1/2) that could account for the observed features, and also the spin statistics. He suggested that this particle be called 'neutron' – but that name was later used for Chadwick's 'real' neutron. It is interesting that Pauli suggested this in a letter to a meeting he could not attend, and never published the suggestion further. In 1934 Fermi built up the modern theory of beta decay – renaming the particle 'neutrino' but it was only in 1953 that Reines and Cowan actually detected the neutrino directly (Figure 6).

The nature of the electron and the existence of its anti-particle, the positron had already been predicted by Dirac in 1928, but the neutrino caused Majorana to speculate whether a neutral spin-1/2 particle would also have an anti-particle, as shown in *[Image 36]*. Majorana's suggestion remained a footnote for half a century. When in 1957 Lee and Yang suggested parity non-conservation in beta decay, C. S. Wu and coworkers quickly confirmed it experimentally in the beta decay of ^{60}Co, and Goldhaber and coworkers showed the neutrinos carried corresponding helicity as shown in Figure 7. Since by then it was widely assumed the neutrinos had zero mass it was thus taken as likely that this 'chirality' was an intrinsic property that distinguished neutrinos from anti-neutrinos.

But in the early 1960-s, a nuclear chemist, Ray Davis, started looking for neutrinos from the Sun, collaborating with John Bahcall who calculated the expected neutrino intensity; see Figure 8. The number of neutrinos was sharply lower than expected. The result was greeted with general skepticism – but eventually was confirmed. Today we know that neutrinos indeed oscillate because the have finite rest mass and the different kinds of neutrinos differ in mass. Thus the neutrinos reaching Davis's detector are a mixture of different species of neutrinos and the oscillation has by now been mapped out in detail by terrestrial measurements as shown in *[Image 39]*.

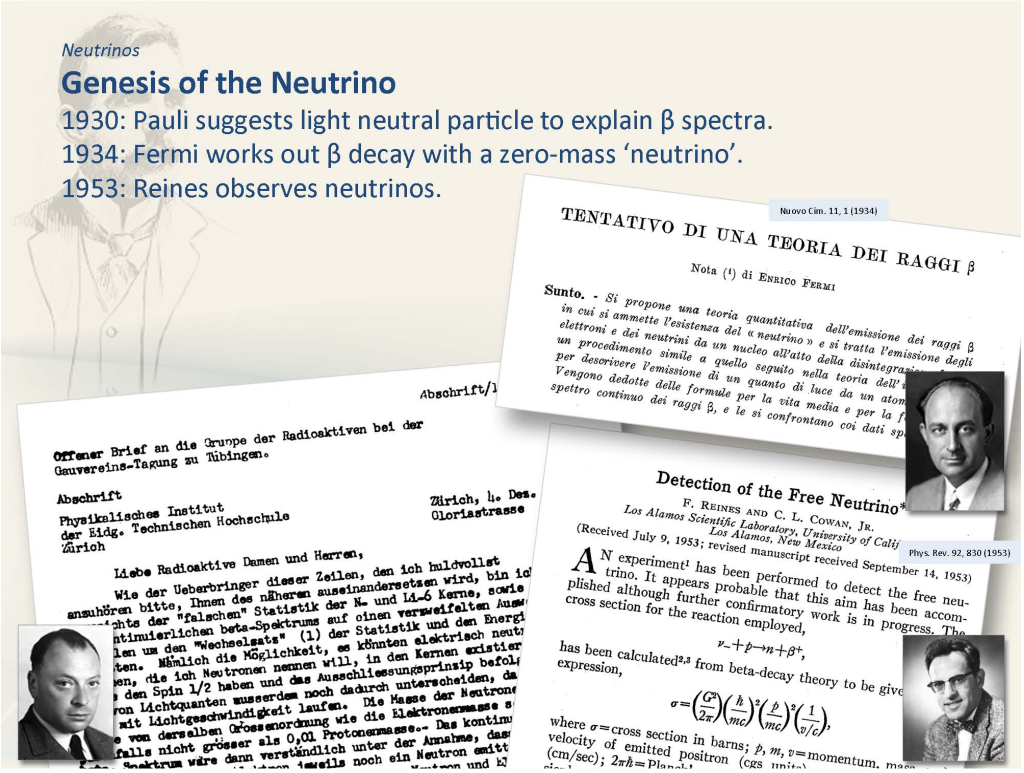

Figure 6. The beginnings of the neutrino and of beta decay.

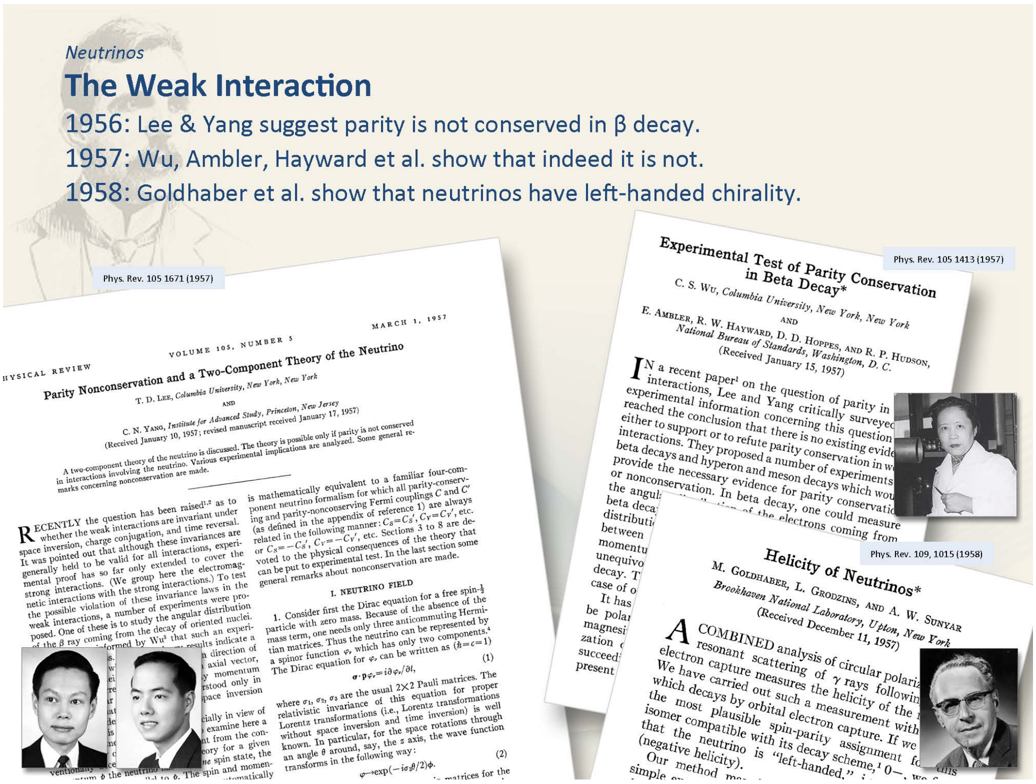

Figure 7. Parity non-conservation in beta decay, and the chirality of neutrinos.

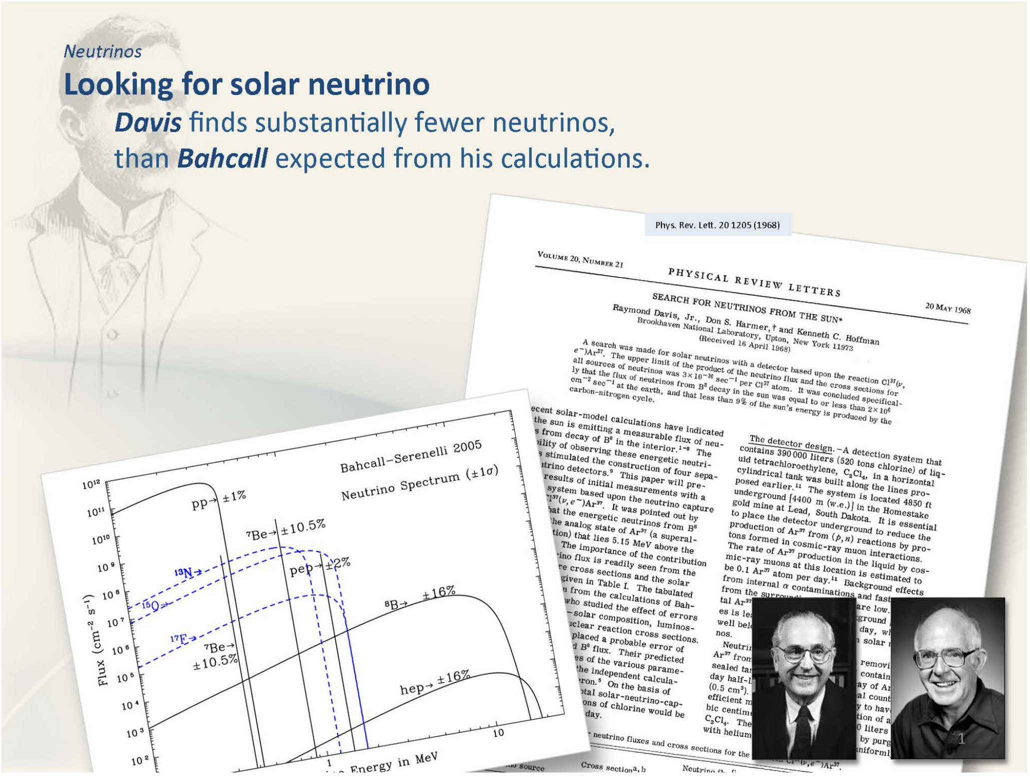

Figure 8. The discovery that neutrinos have mass and oscillate.

This brings us back to the question posed by Majorana. Once neutrinos have mass, chirality is not an intrinsic property, and it becomes much more plausible that a massive, neutral neutrino might be its own anti-particle. The only test on the horizon is the nuclear process of neutrinoless double beta decay that can only happen if Majorana was right. Perhaps the next decade will resolve this fascinating issue that digs at the foundations of physics and is outside the scope of the Standard Model, which just takes the nature of the neutrino as input.

2.5. *The Origin of Elements, the Fuel of Stars*

Nuclear reactions fuel the Sun and provide the energy that makes life possible on our planet. In fact, the Big Bang left the Universe with hydrogen, and a very low abundance of the lightest elements. It took the processes in stars to first burn this hydrogen into elements like carbon and oxygen, and later into all the heavy elements of which our visible universe is made. The work of Bethe, of Fowler and others [*Image 41]* provided the major insights and we are still trying to understand this better by a combination of theory, measurements, and observations.

2.6. *New forms of matter (fascination with things that may or may not exist)*

Searches for exotic nuclei, particles, or new forms of matter have motivated work in nuclear physics in a variety of ways. In Figure 9 the search for new elements is summarized. The transmutation of elements, the dream of alchemists has been a motivation of science since the Middle Ages. Rutherford actually succeeded in this, and many of his talks made this point. But the discovery of new elements started with Fermi, who actually thought he had discovered transuranic elements in the neutron bombardment of uranium, and suggested the names Ausenium and Hesperium for them. He received his Nobel Prize for this – and while he richly deserved the recognition for a number of other contributions, that the discovery was a mistake. Seaborg was the first to produce transuranic elements, a discovery that had to wait five years before publication, because of World War II. After this the groups at Berkeley and Dubna produced a number of new elements and at present the thrust has moved to GSI, Dubna, and recently RIKEN in Tokyo. We now have some 25 new elements beyond uranium, and more are being added.

For a chemist, adding one more proton is exciting – it produces a new chemical element. But for a physicist adding neutrons is much the same. With powerful fragmentation facilities many new isotopes can be made in one shot, as is shown in Figure 10. Of course the real interest will be in determining the detailed structural properties of these new species – and this is likely to take decades and is one of the major new areas for our field.

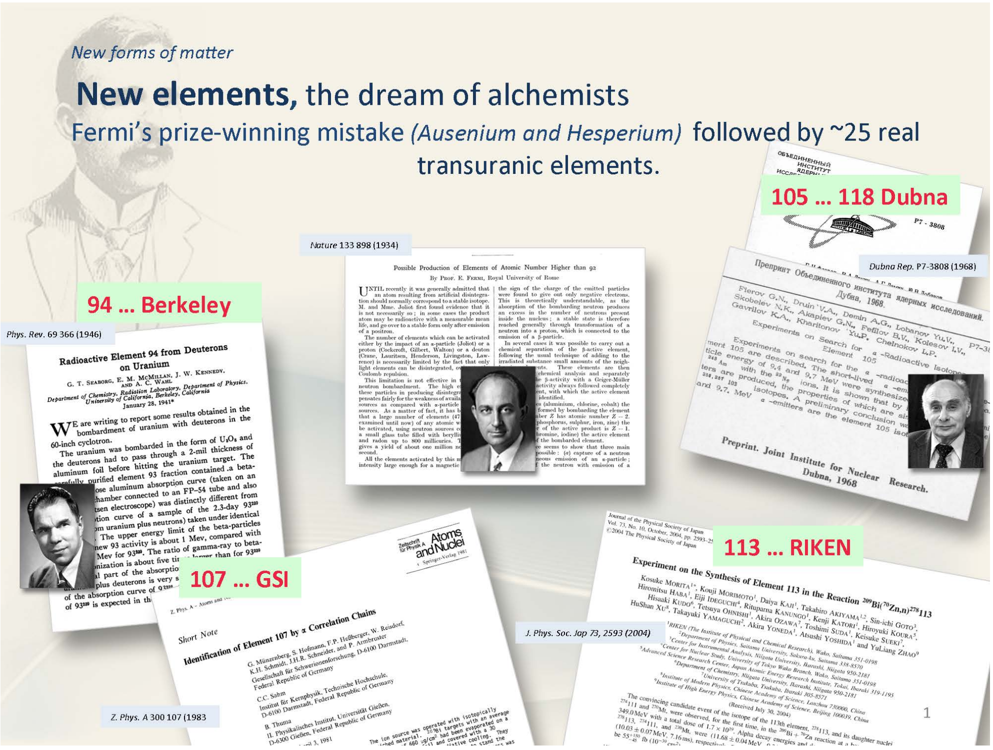

Figure 9. The continuing search for new elements.

Another exotic search was the investigation of what happens to matter in the limit of high energy density. The individual hadrons indeed melt, and a deconfined quark-gluon plasma becomes evident, as is shown in *[Image 45]*. It has recently been suggested that the properties of this weakly coupled plasma may form a connection to string theory – and this would be one of the few contacts string theory has with experimental observations.

3. Reflections

The world concentrates the visible matter of which we are made almost entirely into nucleons that are then cooked in stars into nuclei. It behooves us to strive to understand this better.

Some see nuclear physics as mired down in messy effects that get in the way of the essential simplicities of nature. Nuclear physicists try to understand why and how our world is the way it is, why quarks and gluons appear ***only*** as these 'messy' hadrons, how these hadrons form nuclei that then show beautiful simplicities. Perhaps what seems 'messy' and what is 'fundamental' is a reflection of the limitations of our understanding.

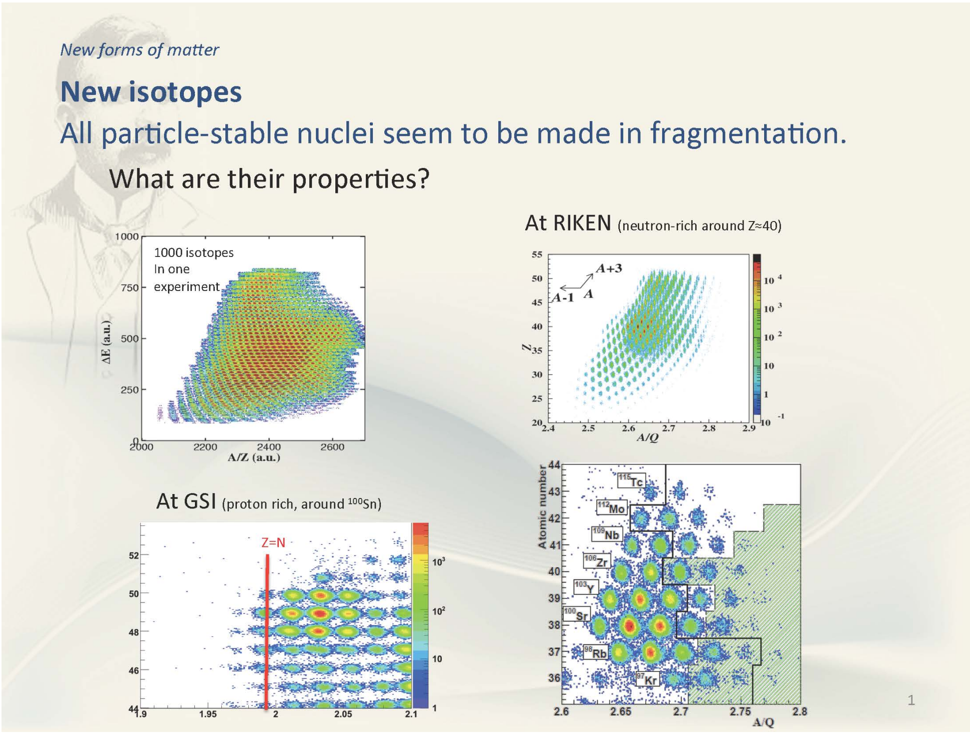

Figure 10. The profusion of new isotopes revealed in fragmentation.

Many questions remain, I mention just a few:
It is amusing that high-energy physics split off from nuclear physics some 50 years ago to study the properties of hadrons. Hadrons turned out to have structure, thus not 'elementary', and were returned to nuclear physics. Electrons determine most properties of atoms, yet they contain only ~0.1 % of the mass. Their binding lowers the mass. Quarks determine most properties of protons and hadrons, yet they contain only ~1% of the mass: their binding (their intrinsic confinement) *increases* the mass by about two orders of magnitude and dominates the mass. We are just beginning to gain some possible insights into the question:

Why is the mass and structure of hadrons what it is?

The Standard Model has been very successful but we still have no understanding of the very specific numbers: masses, mixing angles, etc. that describe the elementary particles. Higher and higher energies will perhaps shed light on these issues, but nuclear physics has contributed much – on neutrinos and on other issues – and this is likely to continue.

Why do we have the specific masses and mixing matrices for quarks and leptons?
Are neutrinos Majorana's neutrinos: are they their own antiparticles?

Nuclei are complicated, yet show remarkable emergent simplicities.

How do the symmetries in nuclei emerge?
What are the properties of exotic short-lived nuclei at the limits of binding?
How do these properties influence the formation of elements?

There are fashions in physics, as in other fields of human activities. We all want to work on the same questions as our colleagues. These questions are not necessarily settled before they go out of fashion. In Figure 11 I have attempted to indicate very qualitatively how trends in different aspects of nuclear physics and facilities changed. It is remarkable that in the 1970-s and 80-s there were perhaps a 100 laboratories around the world with large tandems or sector-focused cyclotrons suitably equipped for precision nuclear structure studies with light ion beams. Today there are almost no such facilities left, and last one in the US at Yale has just been closed, and only one remains in Europe. While it is probably true that there were too many of these facilities thirty years ago, having none is absurd. It is as if biologists declared that a microscope was outdated technology, and research with microscopes should not be supported.

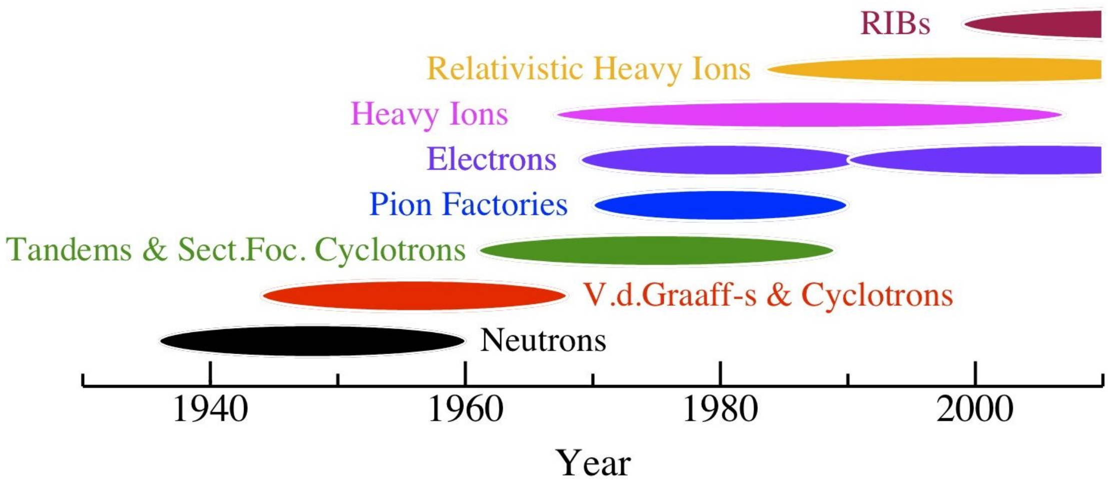

Figure 11. A very schematic indication of the changing fashions in nuclear physics.

4. Conclusions

Rutherford's discovery of 100 years opened a window on the nucleus, with all the marvelous interactions, symmetries and rules that manifest themselves in 'nuclear' phenomena. Nuclear matter accounts for most of the visible, accessible mass in our experience; its interactions produce the energy that makes life possible. We must continue the quest to better understand the rules that govern our world. Applications of nuclear physics have had major impacts in medicine, on many aspects of society, and on other sciences. Even nuclear weapons have helped shape the history of the latter part of the 20th century and (arguably) may have forced governments to be realistic, and reject another major war as a viable option.

Our species has an insatiable curiosity that has served it very well in the evolutionary process. Science, enabled by relatively stable societies, is a modern manifestation of this very basic human trait. We, practicing scientists in the last 100-200 years, are privileged to be participating in unique advances in human knowledge and understanding. We hope it will continue -- if only our species can also learn to use its intellect to control some of its other evolutionary drives. Stable rational civilizations are essential to enable science, the human quest for knowledge and understanding, to continue and flourish.

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