Neutrons With A Twist!

Intreerede

door

Prof. C. Pappas
© Delft, 2010

Niets uit deze uitgave mag worden verveelvoudigd en/of openbaar gemaakt door middel van druk, fotokopie, microfilm of op welke andere wijze ook, zonder voorafgaande schriftelijke toestemming van de copyrighthouder.
Mijnheer de Rector Magnificus,
Leden van het College van Bestuur,
Collagae Hoogleraren en andere leden van de universitaire gemeenschap,
Zeer gewaardeerde toehoorders,

Dames en heren.

Aangezien ik nog niet zo lang in Nederland woon, en mijn Nederlands daarom nog niet zo goed is, wil ik mijn intreerede graag in het Engels houden. Ik hoop dat u hier geen bezwaar tegen heeft.

The beginning of the 20th century was revolutionary, in arts, music, politics and in particular in science, where quantum mechanics and relativity theory were introduced. With the discovery of the negatively-charged electron by Thomson in 1897 and of the positively-charged proton by Rutherford in 1918 it was possible to understand the atomic structure and the chemical bonds. The disparity, however, between atomic numbers and atomic masses, brought Rutherford to assume that a neutral particle with a mass similar to that of a proton could exist. The detection of such a particle was very difficult, because all methods available detect only charged particles – a quest similar to that of dark matter nowadays. Rutherford often discussed the existence of neutrons with his fellow Chadwick and it is reported that they very often suggested ‘silly’ experiments to discover them.

Figure 1: A photo of "Chadwick’s neutron chamber".
The breakthrough came in 1928 when Bothe in Germany found a highly energetic radiation of strong penetrability, which, as reported by the Joliot-Curies, ejected protons from paraffin. It was widely assumed that this was some kind of highly energetic gamma-rays but Rutherford and Chadwick were convinced that these were neutrons. Chadwick worked literally day and night to prove it: he built the so-called “Chadwick’s neutron chamber”, a chamber in vacuum with aluminum windows containing a polonium alpha particle source and a beryllium target. He assumed that the nuclear reaction between beryllium nuclei and alpha particles leads to the formation of carbon with the release of one neutron:

\[ \frac{9}{4}\text{Be} + \frac{4}{2}\text{He} \rightarrow \frac{12}{6}\text{C} + \frac{1}{0}\text{n} \]

Neutrons, however, cannot be detected because they have no charge. Even today we do not detect neutrons directly. What we detect is the result of a nuclear reaction when a neutron dies, when it is absorbed by a specific nuclei such as \(^{10}\text{B}\), \(^{235}\text{U}\) or \(^{3}\text{He}\).

Figure 2: Schematic view of Chadwick’s experiment after cambridgephysics.org.

In his experiments Chadwick showed that unlike gamma rays, neutrons do not eject electrons from a material but protons. Protons are charged and could be easily detected. The neutron assumption explained all experimental findings – but there was no direct evidence. Chadwick published his results in 1932 and received the Nobel Prize just 3 years later, in 1935.

This story illustrates very well the potential of neutrons as well as their limitations: their interaction with matter is weak. This implies high penetration depths but also low interaction probabilities and low intensity.

Today we know that neutrons consist of three quarks and are unstable outside the nuclei. Fortunately their life-time is about 15 min, which for particles is almost eternity and leaves plenty of time for any possible experiments and manipulations. A most important detail: neutrons have a spin \(\frac{1}{2}\) and a magnetic moment. So if we cannot manipulate them with electric fields, as all other charged particles, we can manipulate them with magnetic fields!
Only 5 years after the discovery of neutrons, in 1937, a team under Otto Frisch produced the first polarized neutron beam in Copenhagen and demonstrated Larmor precession. It is remarkable that the next experimental realization of Larmor precession with neutrons took place almost 30 years later, in 1969 by Drabkin at Gatchina, close to Leningrad.

This pioneering experiment remained unnoticed for long time, because of what happened afterwards. It was the discovery of the neutron that completed the atomic model and opened the way for the discovery of nuclear fission in 1938. Frisch was the nephew of Lise Meitner and both had to flee Nazi Germany. Their work was decisive in the discovery of the nuclear fission by Otto Hahn, who stayed in Berlin. I worked over several years at the Hahn-Meitner Institut in Berlin, named after Lise Meitner and Otto Hahn. Also the Reactor Institut Delft has a Meitner seminar room next to the one dedicated to Fermi – one of these little things that make you immediately feel at home.

Back to Larmor precession, which will be a focus of this talk. Just like in nuclear magnetic resonance, the easiest way to describe Larmor precession is by assuming point-like classical particles with an arrow-like spin and magnetic moment. An external magnetic field exerts a torque on this magnetic moment leading to Larmor precession, with a frequency proportional to this magnetic field.

This picture of a tempting simplicity but it is in strong contrast with quantum mechanics, where there are no point-like particles. Wave functions describe the spatial and the spin behavior and the spin is not an arrow with a defined direction.

Figure 3: Classical representation of Larmor precession.

What we call Larmor precession results from the energy splitting, the Zeeman splitting, of the eigenstates |+> and |-> by the magnetic field. The neutron wave function is the coherent superposition of these two eigenstates.
This been said, neutron scientists view neutrons either as waves or as particles depending on the experiments. We will do the same and if several theories give the same results we will chose the simplest one.

The fathers of modern neutron scattering, neutron diffraction – for structure determinations – and inelastic scattering – for dynamical studies – Cliff Shull and Bert Brockhouse shared the Nobel price in 1994 for introducing a technique, which literally tells where the atoms are and what the atoms do.

![Nobel Prize in Physics 1994](image)

**Figure 4: The poster of the 1994 Nobel Prize in Physics.**

We have seen that neutrons have a large penetration power and go through even thick materials and metals. This movie of an engine in function was recorded at the neutron tomography instrument in Berlin. The large penetration power led recently the “US Homeland Security Program” to plan on putting $^3$He based neutron detectors in all US ports and borders. The goal is to scan all cargo containers entering the US searching for nuclear weapons. This US plan has now caused a world-wide shortage in $^3$He.

Back to the movie: the interesting aspect of it is that neutrons don’t see the metal but the hydrogen of the lubricant!

Neutrons are scattered by the nuclei, not by the electrons and the element they see the best is hydrogen. Also they distinguish between different isotopes, in particular between hydrogen and deuterium.

This is at the origin of some very important applications, where one component may be highlighted when hydrogen is substituted by deuterium.
Figure 5: Snapshot of a movie with an engine in function and a comparison of the scattering cross sections for neutrons and X-rays (courtesy N. Kadjilov, HZ Berlin).

The degree of isotopic substitution can be controlled so that the scattering strength in one part of a structure is the same as the one in the surrounding medium, rendering it invisible, whereas another part stands out in contrast. Neutrons therefore are vital for anything containing hydrogen, from watery biological materials to hydrogen storage.

In fact, neutrons see all light elements, such as Li (e.g. in battery materials) or nitrogen. This slide is a nice illustration of their scattering power, the difference between the x-rays, on your left side, and neutron diffraction on the right side comes from the strong neutron scattering power of nitrogen.

.... why neutrons?
neutrons see the nitrogen
perovskite structure: Ce₃InN

Figure 6: Comparison of X-ray and neutron powder diffraction spectra.
The so-called “thermal” or cold neutrons have wavelengths comparable to the distances between atoms and energies comparable to the energies in solids and liquids. If we consider different radiations, with a wavelength of 0.2 nm, which is comparable to distances between atoms, the differences in energies is overwhelming: from 70 MK for X-rays, 400 000 K for electrons and only about room temperature for the massive neutrons. We have therefore a microscopic probe that interacts with all kind of systems, penetrates deeply in matter and is soft enough not to destroy even the frail biological substances.

Neutron scattering: waves and particles

Diffractometers – Structures

Neutron as a plane wave
Christiaan Huygens:
every center re-emits radiation
=> interference

Spectrometers – Dynamics

Neutron as a particle
Newton’s laws - change of energy detected

Figure 7: Overview of the capabilities of neutron scattering.

Neutron scattering is in many respects not too different from light or X-ray scattering. It is therefore possible to apply principles familiar from classical optics. In other words all interference phenomena can be treated in the way, which was introduced by Christiaan Huygens more than 300 years ago. Huygens, one of the founders of modern science, was the first to assume that light consists of waves and his approach to interference was fundamental in understanding the wave-particle duality in quantum mechanics. And when you will get out of this building, the street on your right is named after him.

Slow motions can be seen by real time modulation of the beam, just like the engine in function seen by neutron radiography. Fast motions of the atoms and molecules lead to energy exchange: the neutrons loose or gain energy from the sample and these changes can be measured with very high accuracy. Due to their magnetic moment neutrons interact with magnetic fields also at the microscopic level. They can see magnetic structures and spin dynamics.
length scales

Figuur 8: Length scales covered by neutrons.

And the dynamic information spans from the microscopic times, typically $10^{-13}$ s to almost the μs, typical times for slow motions of proteins or polymers.

Neutrons do not do everything – but they do a lot, and they often give the decisive hint to solve a puzzle. Neutron scattering has a continuously increasing impact in science and society.

energy - time scales

Figure 9: Energy and time scales seen by neutrons
However, most of us do not use neutrons in our work!

The reason is that neutron sources, typically research reactors, are expensive to build and run and their number around the world is small. Also we often need large samples, more neutrons, better sources.

The basic scattering principle is simple and in practice it can be realized in many different ways. For example, Bragg scattering from single crystals filters a particular wavelength out of the incoming beam. This secondary beam is scattered by the sample and can be directly detected to reveal the microscopic structure of the specimen. This is the same simple generic set-up as the one used by Shull in 1945 to demonstrate neutron diffraction and the wave-particle duality principle for neutrons.

Bert Brockhouse, went a step further. He analyzed the energy of the scattered neutron beam with a second crystal after the sample and he was able to measure the energy change of neutrons due to the vibrations of the atoms, due the phonons or the magnons.

In neutrons, just like in optics and X-Rays, resolution is closely related to the way we define the beam. These conventional methods determine the energy and direction of the incident and scattered neutrons separately and the resolution depends on how precisely these quantities may be defined. High resolutions imply prohibitively high beam collimations and monochromatisations. With increasing resolution more and more particles are discarded and the number of those reaching the sample goes down dramatically. At high resolutions it would take ages to perform a single experiment.

**Spin Echo**

**NMR spin echo**

**Erwin Hahn 1950**

\[
\frac{d\vec{S}}{dt} = \gamma \vec{S} \times \vec{B} = \vec{S} \times \vec{\omega}_L
\]

High resolution requires methods that go beyond these conventional approaches.

Figure 10: Schematic illustration of NMR spin echo
A solution is in the neutron spin. When it precesses in a magnetic field, it accumulates a phase, which labels the trajectory of each individual neutron. Larmor precession can give us the information we look for.

The idea is simple and very similar to NMR spin echo, introduced by Hahn in 1950: precessions start after a $\pi/2$ rotation, then a $\pi$ flip marks the inversion point and all magnetic moments focus again at the echo point.

It is like runners, who run with different speeds. After a while they are far from each other, but if they run back with the same speed they all meet again at the starting point.

Neutron Spin Echo, introduced by Feri Mezei in 1972, is very similar to NMR Spin echo with the only difference that neutrons are not steady as the nuclei in NMR: but propagate. In the reference frame of the neutron the sequences are experienced as sequences in time just like in NMR.

In the frame of the laboratory, however, the flips take place at different positions along the neutron trajectory. We can even get rid of the $\pi$ flip and just reverse the magnetic fields before and after the sample. We can also have more complex pulse sequences — exactly like in NMR. And exactly like in NMR, this method can be used for a wide variety of problems, to study the dynamics and the structure.

**Spin Echo**

**NMR spin echo**

*Erwin Hahn 1950*

**Neutron spin echo**

*Ferenc Mezei 1972*

$$\frac{d\vec{S}}{dt} = \gamma \vec{S} \times \vec{B} = \vec{S} \times \vec{\omega}_L$$

Figure 11: NMR and Neutron Spin Echo
As I mentioned at the beginning there are several ways to see Larmor precession, in a more classical or more quantum mechanical way. Both give the same result: we have a highly symmetric set-up and the symmetry is broken by the sample. What we measure is a loss in coherence seen as the loss in the amplitude of the Larmor oscillations. The higher the magnetic fields, the more precessions take place and the higher is the resolution with which we can detect how the sample modifies the neutron beam. The resolution is therefore completely decoupled from any beam characteristics, it is only a function of the magnetic field.

The idea of Larmor Labeling is of stunning simplicity. However, one should mistrust simple ideas as they often turn out to be extremely complex in their details. The very first Neutron Spin Echo coils built by Feri Mezei were small and had a mechanical accuracy of 0.3 mm. The instruments, which followed in Grenoble or Berlin, had mechanical accuracies of 30 to 10 microns over distances of 4 m. The next generation of instruments will require mechanical accuracies of the order of some micrometers and will reach Fourier times beyond 1 μs.

Long Fourier times are needed to see the motion of large objects, nanoparticles, proteins, polymers. As an example, the only direct confirmation of De Gennes’ reptation model for polymer motion came from neutron spin echo spectroscopy, when Fourier times as long as 400 ns, corresponding to energies as low as 2 neV, became accessible for the first time.

**Larmor labeling encodes trajectories**

**SESANS Theo Rekveldt 1996**

![Diagram](image)

*Figure 12: The principle of SESANS*
Innovative and inventive applications of Larmor labelling belong to the most important recent methodological and instrumental developments in neutron scattering. In this field the TU Delft occupies a prominent position with the first implementation of Spin Echo Small Angle Neutron Scattering or the introduction of Larmor diffraction by Theo Rekveldt. These techniques expand the use of Larmor labelling to structural studies. Similarly to classic Neutron Spin Echo, they break the resolution limits of conventional diffraction, while keeping the high intensity advantage of a poorly monochromatised and collimated beam. Spin Echo Small Angle Neutron Scattering – in short SESANS - is similar to conventional Neutron Spin Echo, with the exception of the inclined boundaries of the magnetic fields. This special magnetic field configuration is particularly sensitive to the neutron trajectories. In the symmetric case, echo is recovered. Any scattering by a sample deflects neutrons and reduces the amplitude of the echo.

Figure 13: Artist’s view of the planned European Spallation Source.

The very first instrument of its kind was built and it is still operational at the Reactor Institute Delft. A next project was a co-operation with the British neutron source ISIS at Oxfordshire. New, highly flexible Larmor labeling components were conceived and built here. They were shipped and installed at ISIS about one year ago and started producing first results last summer. One of the first experiments was the direct observation of gravity on a neutron beam, which illustrates the power and the potential of the method: the incoming neutron beam had a kinetic energy of $2 \times 10^{-2}$ eV. The Zeeman energy due to the applied magnetic field was seven orders of magnitude smaller. The effect of gravity was well beyond that, almost 11 orders of magnitude weaker than the energy of the incoming neutrons. This effect was nevertheless clearly seen on the spectra!

These were the very first results. In the process of commissioning the resolution has been further improved.

What is in the future?
Neutron scattering is an intensity-limited technique, also because the power of research reactors levels off since the early seventies. The substantial increase in neutron brilliance witnessed in the last years, results from a better use of the existing neutron sources with improved neutron optics, advanced instruments and, we have seen, some intelligent ideas.

The future is in spallation sources, where accelerators generate pulses of highly energetic protons. These hit a target of heavy nuclei releasing neutrons. Spallation sources open up a new era, similarly to that of synchrotrons in X-Rays. The slide shows the neutron sources in Europe, SINQ in Switzerland, the ILL in Grenoble and LLB in Saclay, France, ISIS in United Kingdom, the Reactor Institute in Delft or the reactors in Munich and Berlin in Germany. The future European Spallation Source will be built in Lund, Sweden and will be the most intense source in the world. With the ESS the intensity barriers will be broken and neutrons will access the large scientific communities, giving unique and direct answers to the questions of the future. The ESS will be an impressive microscope giving a new view to nature.

Figure 14: The European neutron scattering landscape with the planned European Spallation Source.

In this process, Larmor labeling will play an important role. It is a technique with future and we are in it. We now know better how to manipulate the neutron spin, how to twist it and make it roll through our samples and experimental setups. We can use it to see the structure and movements of our materials. We can also use it to study the fundamental questions of quantum mechanics and gravitational interactions.
Wolfgang Pauli, Niels Bohr

and a spinning Top!

May 31 1951

opening of the new institute of physics at the University of Lund

We, here in Delft have the knowledge and I am happy to contribute to this process merging my background of classical neutron scattering and neutron spin echo with the competences of the section. I very much enjoy the lively and open discussions with the colleagues and look forward to closer contacts with the students.

The future? In the section we have lots of ideas for new instruments including Larmor labeling, which will be important at the European Spallation Source.

Was that something Pauli and Bohr could think of when they admired a spinning top and the opening of the institute of physics at the university of Lund in 1951?

Ik heb gezegd.