Algorithms of data processing and controlling experimental equipment

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Abstract

In this article I would try to explain the princiles of magnetic resonance phenomena (*Nuclear Magnetic Resonance - NMR, Electron Spin Resonance - ESR*) and computer aplication to solve controlling and processing problems.

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1 Introduction

I take part in two departments' (Department of Quantum Magnetic Phenomena and Computational Physics Department of Physical Faculty) research program. The first research direction focused on investigation of Magnetic Resonance (Nuclear Magnetic Resonance - NMR) phenomenon for atom nuclei and for atom electrons (Electron Spin Resonance - ESR). On the other hand computational physics dealing with improve and analysis numerical calculations as applied to different branches of modern physics. And it's very promising that incorporating efforts of this directions have good perspective. According to these ideas, a portable ESR-spectrometer is being developed on Quantum Magnetic Phenomena Department. So, let's have a look to world of magnetic resonance and its application.

Magnetic resonance is an analytical technique based on a property of matter called spin. Magnetic resonance techniques include magnetic resonance imaging (MRI), nuclear magnetic resonance (NMR), electron spin resonance (ESR), and electron paramagnetic resonance (EPR). Magnetic resonance imaging is used by clinicians to produce tomographic images of the inside of the human body. MRI is also used by scienetists to study materials as it is a non-destructive imaging technique. Nuclear magnetic resonance is used by scientists to study the structure and dynamics of molecules. Electron spin resonance (ESR) and electron paramagnetic resonance (EPR) are used by scientists to study structure and reactions of free radicals. Magnetic resonance techniques are generally non-invasive and non-destructive.

The questions considered below imply that reader have elementary quantum physics background, but I tried to explain as much detailed as it's necessary and possible.

2 Physical principles and detecting methods

NMR is a non-invasive means of obtaining clinical images and of studying tissue metabolism in vivo. Bloch and Purcell independently discovered NMR in 1946 (Bloch (1946) [1], Bloch et al. (1946) [2] and Purcell et al. (1946) [3]. Six years later they were awarded the Nobel Prize for their achievements. Since then, the development of NMR spectrometers and NMR scanners has led to the opening up of whole new branches of physics, chemistry, biology and medicine.

2.1 Basic quantum physics principles

The main aim of this chapter is to provide an overview of the principles of NMR and ESR. For a more detailed account, refer to a book such as "NMR and its applications to living systems" by Gadian (1995) [4]. Many of the figures in this article are based on illustrations from "Basic Principles of MR Imaging", written by Keller (1988) [5].

Nuclei with an odd number of protons and neutrons possess a property called **spin**. In quantum mechanics spin is represented by a magnetic spin quantum number. Spin can be visualised as a rotating motion of the nucleus about its own axis. As atomic nuclei are charged, the spinning motion causes a magnetic moment in the direction of the spin axis. This phenomenon is shown in Figure 1. The strength of the magnetic moment is a property of the type of nucleus. Hydrogen nuclei (^{1}H), as well as possessing the strongest magnetic moment, are in high abundance in biological material.

Consider a collection of ^{1}H nuclei (spinning protons) as in Figure 2 (left). In the absence of an externally applied magnetic field, the magnetic moments have random orientations. However, if an externally supplied magnetic field B_0 is imposed, the magnetic moments have a tendency to align with the external field (see Figure 2 (right)).

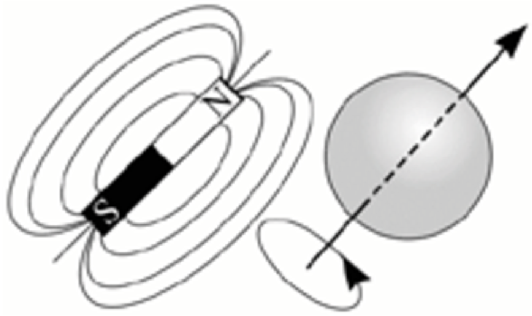

Figure 1: A charged, spinning nucleus creates a magnetic moment which acts like a bar magnet (dipole).

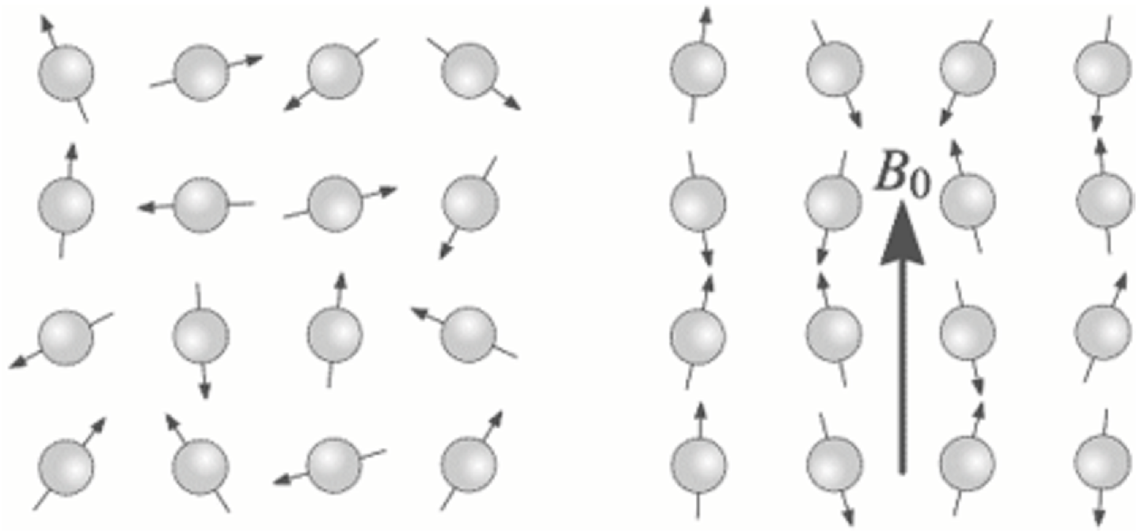

Figure 2: (left) A collection of ^{1}H nuclei (spinning protons) in the absence of an externally applied magnetic field. The magnetic moments have random orientations. (right) An external magnetic field B_0 is applied which causes the nuclei to align themselves in one of two orientations with respect to B_0 (denoted **parallel** and **anti-parallel**).

The magnetic moments or spins are constrained to adopt one of two orientations with respect to B_0, denoted **parallel** and **anti-parallel**. The angles subtended by these orientations and the direction of B_0 are labelled theta (Θ) in Figure 3 (left). The spin axes are not exactly aligned with B_0, they precess around B_0 with a characteristic frequency as shown in Figure 3 (right). This is analogous to the motion of a spinning top precessing in the earth's gravitational field. Atomic nuclei with the same magnetic spin quantum number as ^{1}H will exhibit the same effects - spins adopt one of two orientations in an externally applied magnetic field. Elements whose nuclei have the same magnetic spin quantum number include ^{1}3C, ^{19}E and ^{31}P. Nuclei with higher magnetic spin quantum number will adopt more than two orientations.

The **Larmor equation** expresses the relationship between the strength of a magnetic field, B_0, and the precessional frequency, F, of an individual spin.

$$F = \gamma B_0$$

The proportionality constant, γ, to the left of B_0 is known as the **gyromagnetic ratio** of the nucleus. The precessional frequency, F, is also known as the **Larmor frequency**. For a hydrogen nu-

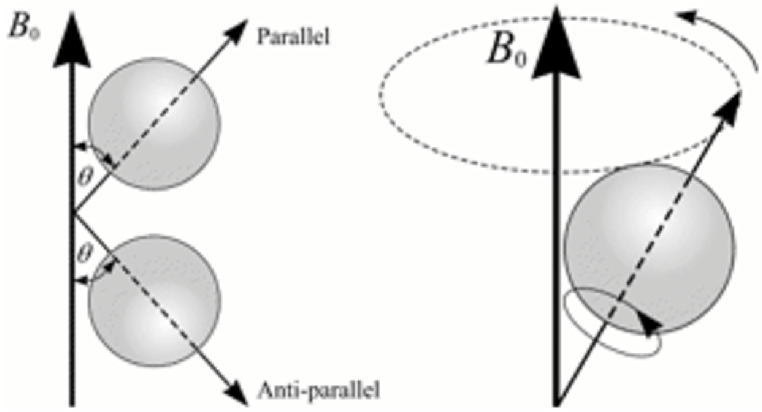

Figure 3: (left) In the presence of an externally applied magnetic field, B_0, nuclei are constrained to adopt one of two orientations with respect to B_0. (right) A magnetic moment precessing around B_0. Its path describes the surface of a cone.

cleus, the gyromagnetic ratio is 4257 Hz/Gauss. Thus at 1.5 Tesla (15000 Gauss), $F = 63.855$ MHz.

2.2 Radiofrequency field and MR signal

For a collection of ^{1}H nuclei, let the number of spins adopting the parallel and anti-parallel states be P_1 and P_2 respectively, with corresponding energy levels E_1 and E_2. E_2 is greater than E_1 causing P_1 to be greater than P_2. An obvious question is why do spins adopt the higher energy anti-parallel state? The answer is that spins of P_2 may move to P_1 if the exact amount of energy, $\Delta(E) = E_2 - E_1$ is supplied to the system. If the temperature of the system were absolute zero, all spins would adopt the parallel orientation. Thermal energy will cause P_2 to be populated. At room temperature in a 1.5 Tesla magnetic field, there will typically be a population ratio $P_2 : P_1$ equal to 100000:100006.

At any given instant, the magnetic moments of a collection of ^{1}H nuclei can be represented as vectors, as shown in Figure 4. Every vector can be described by its components perpendicular to and parallel to B_0. For a large enough number of spins distributed on the surface of the cone, individual components perpendicular to B_0 cancel, leaving only components in the direction parallel to B_0. As most spins adopt the parallel rather than the antiparallel state, the net magnetisation M is in the direction of the B_0 field.

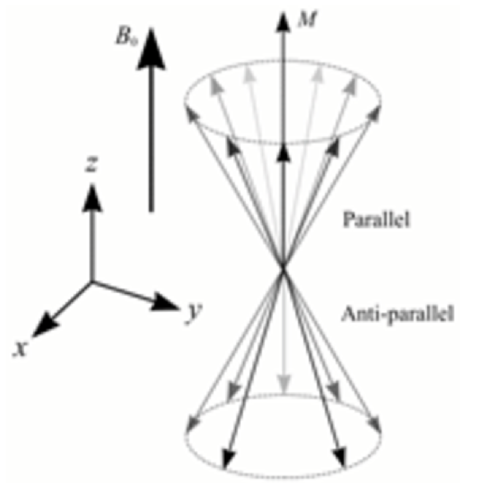

Figure 4: A collection of spins at any given instant in an external magnetic field, B_0. A small net magnetisation, M, is detectable in the direction of B_0.

Suppose the direction of B_0 is aligned with the z-axis of Euclidean 3-space. The plane perpendicular to B_0 contains the x and y-axes. In order to detect a signal from ^{1}H nuclei, radio frequency (RF) energy must be applied. RF energy at the Larmor frequency causes nuclear spins to swap between parallel and anti-parallel states. This has an oscillatory effect on the component of M parallel to the z-axis. RF energy, like all electromagnetic radiation, has electric and magnetic field components. Suppose the magnetic field component is represented by B_1 and lies in the x-y plane. The x-y components of M will be made coherent by the B_1 field giving a net x-y component to M and hence effectively cause M to tilt from the z direction into the x-y plane. This phenomenon is described further in Figure 5.

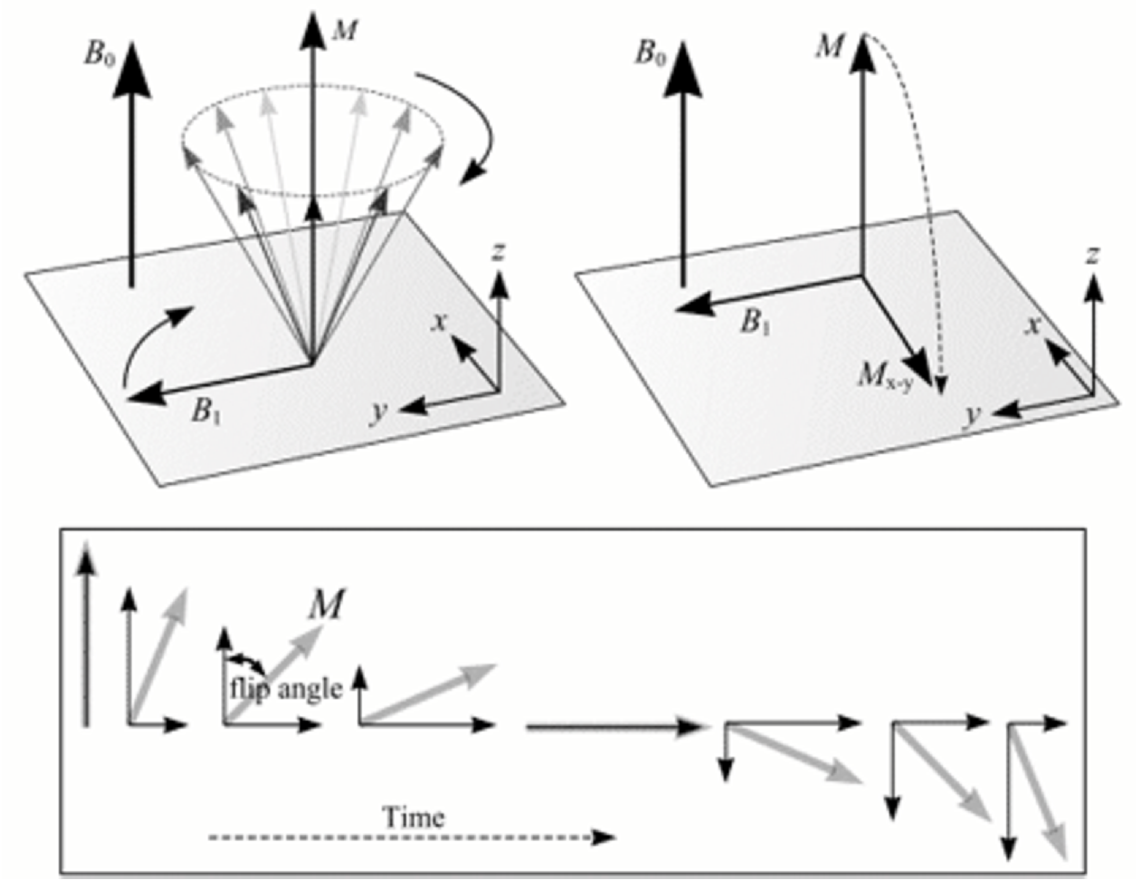

Figure 5: (top) The effect of RF radiation on the net magnetisation M is to produce a second magnetic field M_{x-y}. M is tilted from its original longitudinal z-axis orientation, along the direction of the external magnetic field B_0, into the transverse x-y plane. (bottom) An illustration of **flip angle**, which is the angle through which M has rotated away from the z-axis.

The angle through which M has rotated away from the z-axis is known as the **flip angle**. The strength and duration of B_1 determine the amount of energy available to achieve spin transitions between parallel and anti-parallel states. Thus, the flip angle is proportional to the strength and duration of B_1. After pulses of 90 degrees and 270 degrees, M has no z component and the population ratio $P_2 : P_1$ is exactly one. A pulse of 180 degrees rotates M into a position directly opposite to B_0, with greater numbers of spins adopting anti-parallel (rather than parallel) states. If the B_1 field is applied indefinitely, M tilts away from the z-axis, through the x-y plane towards the negative z direction, and finally back towards the x-y plane and z-axis (where the process begins again).

Figure 6 (left) shows the situation after an RF pulse is applied that causes the net magnetisation vector M to flip by 90 degrees. M lies in the x-y plane and begins to precess about the B_0 axis. M will induce an electromotive force in a receiver coil according to Faraday's law of magnetic induction. This is the principle of NMR signal detection. It is from this received RF signal that an MR image can be constructed. Figure 6 (right) shows a graph of the voltage or signal induced in a receiver coil verses time. Such a graph, or waveform, is termed a free induction decay (**FID**). The magnitude of the generated signal depends on the number of nuclei contributing to produce the transverse magnetisation and on the relaxation times (see next section).

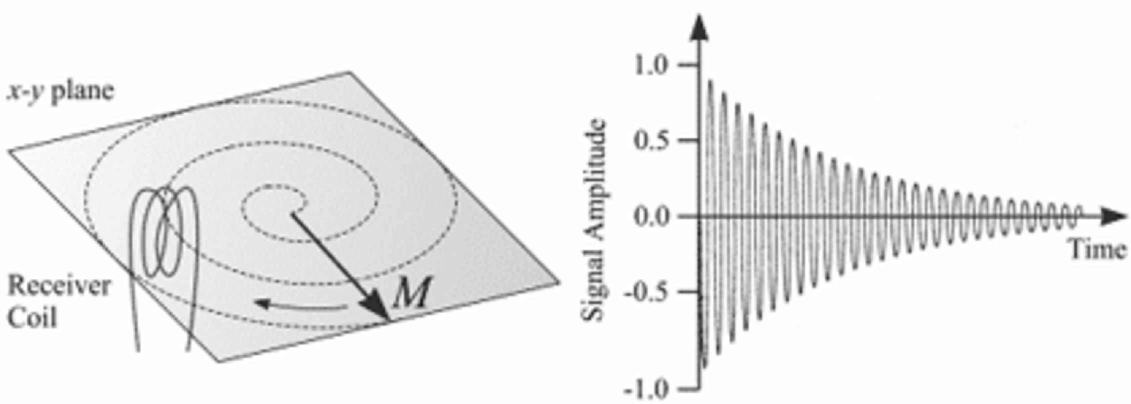

Figure 6: (left) After a 90 degrees RF pulse, M lies in the x-y plane and rotates about the z-axis. The component of M in the x-y plane decays over time. An alternating current, shown in Figure (right), is induced in the receiver coil.

2.3 Relaxationx Mechanism

The return of M to its equilibrium state (the direction of the z-axis) is known as relaxation. There are three factors that influence the decay of M: magnetic field inhomogeneity, longitudinal T_1 relaxation and transverse T_2 relaxation. T_1 relaxation (also known as spin-lattice relaxation) is the realignment of spins (and so of M) with the external magnetic field B_0 (z-axis). T_2 relaxation (also known as T_2 decay, transverse relaxation or spin-spin relaxation) is the decrease in the x-y component of magnetisation.

For NMR spectroscopy to be practical, an efficient mechanism for nuclei in the higher energy $-1/2$ spin state to return to the lower energy $+1/2$ state must exist. In other words, the spin population imbalance existing at equilibrium must be restored if spectroscopic observations are to continue. Now an isolated spinning nucleus will not spontaneouly change its spin state in the absence of external perturbation. Indeed, hydrogen gas (H_2) exists as two stable spin isomers: ortho (parallel proton spins) and para (anti-parallel spins). NMR spectroscopy is normally carried out in a liquid phase (solution or neat) so that there is close contact of sample molecules with a rapidly shifting crowd of other molecules (Brownian motion). This thermal motion of atoms and molecules generates local fluctuating electromagnetic fields, having components that match the Larmor frequency of the nucleus being studied. These local fields stimulate emission/absorption events that establish spin equilibrium, the excess spin energy being detected as it is released. This relaxation mechanism is called **Spin-Lattice Relaxation** (or **Longitudinal Relaxation**). The efficiency of spin-lattice relaxation depends on factors that influence molecular movement in the lattice, such as viscosity and temperature. The relaxation process is kinetically first order, and the reciprocal of the rate constant is a characteristic variable designated T_1, the spin-lattice relaxation time. In non-viscous liquids at room temperature T_1 ranges from 0.1 to 20 sec. A larger T_1 indicates a slower or more inefficient spin relaxation.

Another relaxation mechanism called **Spin-Spin relaxation** (or **Transverse relaxation**) is characterized by a relaxation time T_2. This process, which is actually a spin exchange, will not be discussed here. For more information about this type of relaxation see [7] "Relaxation Processes" section.

2.4 Nuclear Magnetic Resonance (NMR)

The following features lead to tne NMR phenomenon:

1. A spinning charge generates a magnetic field, as shown by Figure 1. The resulting spin-magnet has a magnetic momentum M proportional to the spin.

2. In the presence of an external magnetic field B_0, two spin states exist, $+1/2$ and $-1/2$. The magnetic moment of the lower energy $+1/2$ state is alligned with the external field, but that of the higher energy $-1/2$ spin state is opposed to the external field. Figures 2, 3 and 4.

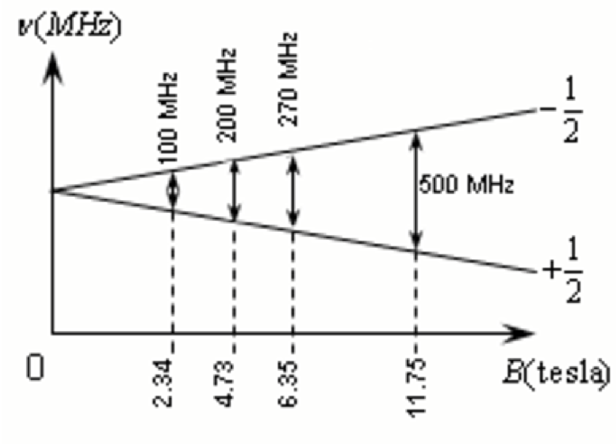

Figure 7: Proton Spin Energy Difference

3. The difference in energy between the two spin states is dependent on the external magnetic field strength, and is always very small. Figure 7 illustrates that the two spin states have the same energy when the external field is zero, but diverge as the field increases. At a field equal to B a formula for the energy difference is $\Delta E = \frac{M \cdot B}{I}$ (remember I = 1/2 and M is the magnetic moment of the nucleus in the field).

Strong magnetic fields are necessary for NMR spectroscopy. The international unit for magnetic flux is the tesla (T). The earth's magnetic field is not constant, but is approximately 10^4 T at ground level. Modern NMR spectrometers use powerful magnets having fields of 1 to 20 T. Even with these high fields, the energy difference between the two spin states is less than 0.1 $\frac{cal}{mole}$. To put this in perspective, recall that infrared transitions involve 1 to 10 $\frac{kcal}{mole}$ and electronic transitions are nearly 100 time greater. For nmr purposes, this small energy difference (ΔE) is usually given as a frequency in units of MHz (10^6 Hz), ranging from 20 to 900 Mz, depending on the magnetic field strength and the specific nucleus being studied. Irradiation of a sample with RF energy corresponding exactly to the spin state separation of a specific set of nuclei will cause excitation of those nuclei in the $+1/2$ state to the higher $-1/2$ spin state. Note that this electromagnetic radiation falls in the radio and television broadcast spectrum. NMR spectroscopy is therefore the energetically mildest probe used to examine the structure of molecules.

The nucleus of a hydrogen atom (the proton) has a magnetic moment $M = 2.7927$, and has been studied more than any other nucleus. Figure 7 displays energy differences for the proton spin states (as frequencies).

2.5 Pulsed Fourier Transform Spectroscopy

In a given strong external magnetic field, each structurally distinct set of hydrogens in a molecule has a characteristic resonance frequency (Figure 8, it is a distinct frequency of exponintial FID

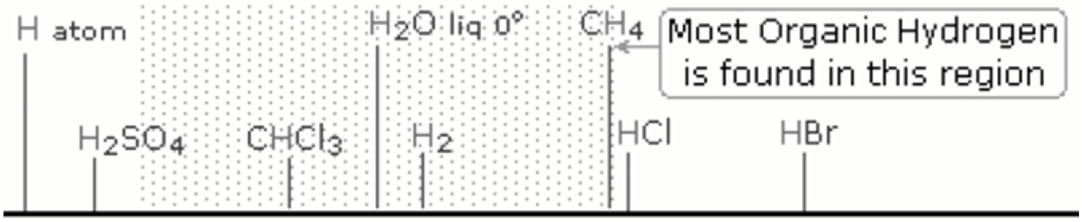

Figure 8: Hydrogen atoms has distinct resonance frequency for different molecules.

signal). We can make a comparation. To discover the frequency of a chime one can strike it and measure the sound emitted. This procedure can be repeated for each chime in the group so that all the characteristic frequencies are identified. An alternative means of obtaining the same information is to strike all the chimes simultaneously, and to subject the complex collection of frequencies produced to mathematical analysis. In the middle of Figure 9 you can see the complex summation wave that consists of 4 waves with different frequencies (ω_0, $2\omega_0$, $3\omega_0, 4\omega_0$). This is a straightforward conversion; and the reverse transformation, while not as simple, is readily accomplished, provided the combination signal is adequately examined and characterized.

It has proven much more efficient to excite all the proton nuclei in a molecule at the same time, followed by mathematical analysis of the complex RF resonance frequencies emitted as they relax back to the equilibrium state. This is the principle on which a pulse Fourier transform (FT) spectrometers operates. By exposing the sample to a very short (10 to 100 μsec), relatively strong (about 10,000 times that used for a CW spectrometer discribed in next section) burst of rf energy along the x-axis, as described above (2.2), all of the protons in the sample are excited simultaneously.

The overlapping resonance signals generated as the excited protons relax are collected by a computer and subjected to a Fourier transform mathematical analysis. As shown in the diagram on the left, the Fourier transform analysis, converts the complex time domain signal emitted by the sample into the frequency domain spectrum we are accustomed to seeing.

Since, the FID signal collected after one pulse, may be stored and averaged with the FID's from many other identical pulses prior to the Fourier transform, the nmr signal strength from a small sample may be enhanced to provide a useable spectrum.

Figure 9: This method based on the Fourier transformation that helps us to pick out distinct frequencies from complex wave.

2.6 Continuous Wave Method

This is important and well-established application of NMR spectroscopy method. To begin with, the NMR spectrometer must be tuned to a specific nucleus, in this case the proton. A CW NMR spectrometer functions by irradiating each set of distinct nuclei in turn, a process analagous to striking each chime independently. The actual procedure for obtaining the spectrum varies, but the simplest is referred to as the **continuous wave (CW) method**. A typical CW-spectrometer is shown in the Figure 11. A solution of the sample in a uniform glass tube is oriented between the poles of a powerful magnet. RF radiation of appropriate energy is broadcast into the sample from an antenna coil. A receiver coil surrounds the sample tube, and emission of absorbed RF energy is monitored by dedicated electronic devices and a computer. An NMR spectrum is acquired by varying or sweeping the magnetic field over a small range while observing the RF signal from the sample. An equally effective technique is to vary the frequency of the rf radiation while holding the external field constant. In other words, we use sweeping magnetic field H_1 to determine the sweeping of absorption spetral line amplitude dA. Thus, if one knows the varying value of function (A) and varying value of argument (H_1) hence the first derivative of spectral line is known. After experiment as a result we will have a spectrum in differential form. Obviously, it is necessary to use further mathematical analysis.

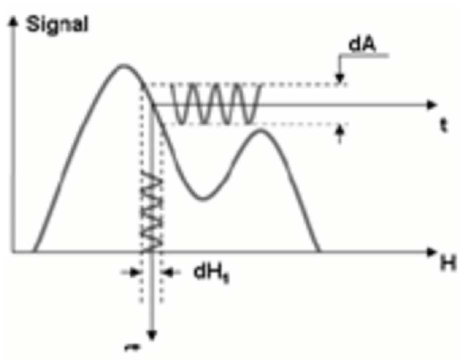

Figure 10: Sweeping magnetic field H_1 and the first dirivative spectral line acquiring process.

Next key feature of this method is a problem because of inhomogeneous magnetic field scan takes place. It means that if we are increasing the current through the coil (to increase external magnetic field B) by linear low external magnetic field will not increase by the linear low too (this phenomenon is called **hysteresis**). But nonlinear increasing low absolutely unacceptable in this method. This facts result in 2 cycles experiment division. The first is obtaining the low of increasing $B(t)$ depending on $I(t)$: $B(I(t))$ and the second is reverse transform of this function and getting function $I(B(t))$ where linear part is $B(t)$ rathe than $I(t)$.

As an example, consider a sample of water in a 2.3487 T external magnetic field, irradiated by 100 MHz radiation. If the magnetic field is smoothly increased to 2.3488 T, the hydrogen nuclei of the water molecules will at some point absorb RF energy and a resonance signal will appear.

Since protons all have the same magnetic moment, we might expect all hydrogen atoms to give resonance signals at the same field (frequency) values. Fortunately for chemistry applications, this is not true. It is not possible, of course, to examine isolated protons in the spectrometer described above; but from independent measurement and calculation it has been determined that a naked proton would resonate at a lower field strength than the nuclei of covalently bonded hydrogens. With the exception of water, chloroform and sulfuric acid, which are examined as liquids, all the other compounds are measured as gases.

Since protons all have the same magnetic moment, we might expect all hydrogen atoms to give resonance signals at the same field / frequency values. Fortunately for chemistry applications, this is not true. By clicking the Show Different Protons button under the diagram, a number of representative proton signals will be displayed over the same magnetic field range. It is not possible, of course, to examine isolated protons in the spectrometer described above; but from independent measurement and calculation it has been determined that a naked proton would resonate at a lower field strength than the nuclei of covalently bonded hydrogens. With the exception of water, chloroform and sulfuric acid, which are examined as liquids, all the other compounds are measured

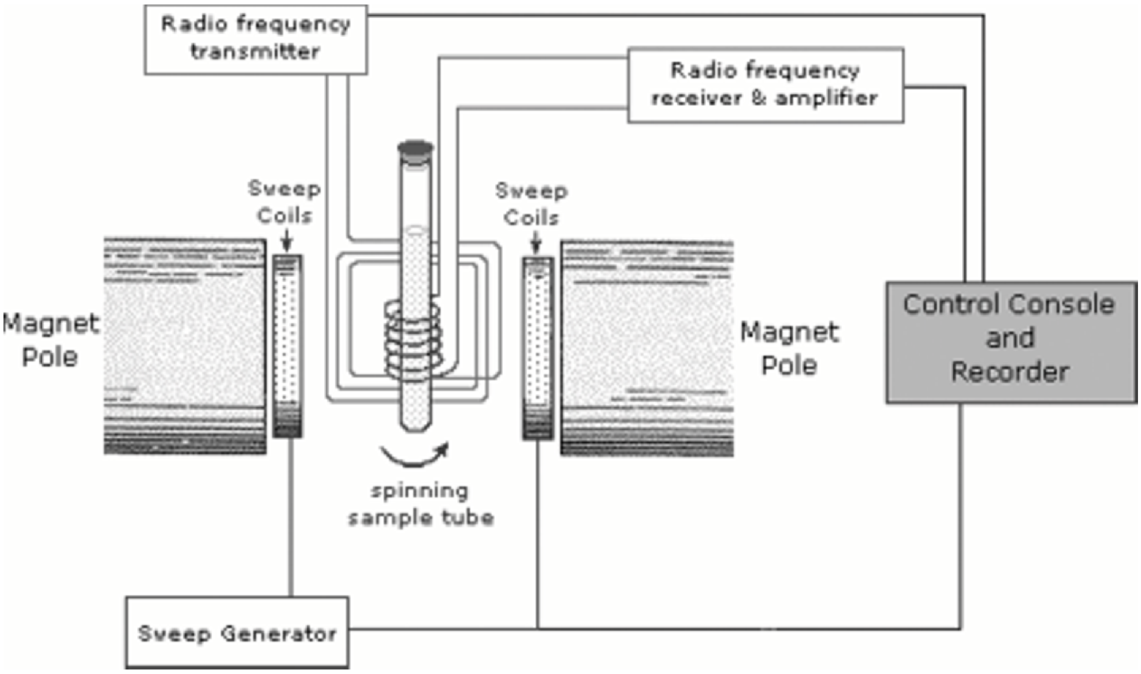

Figure 11: Typical CW NMR spectrometer.

as gases.

2.7 Electron Spin Resonance (ESR)

When the molecules of a solid exhibit **paramagnetism** [6] as a result of unpaired electron spins, transitions can be induced between spin states by applying a magnetic field and then supplying electromagnetic energy, usually in the microwave range of frequencies. The resulting absorption spectra are described as electron spin resonance (ESR) or electron paramagnetic resonance (EPR). Electron spin resonance has been used as an investigative tool for the study of radicals formed in solid materials, since the radicals typically produce an unpaired spin on the molecule from which an electron is removed. Particularly fruitful has been the study of the ESR spectra of radicals produced as radiation damage from ionizing radiation. Study of the radicals produced by such radiation gives information about the locations and mechanisms of radiation damage.

The interaction of an external magnetic field with an electron spin depends upon the magnetic moment associated with the spin, and the nature of an isolated electron spin is such that two and only two orientations are possible. The application of the magnetic field then provides a magnetic potential energy which splits the spin states by an amount proportional to the magnetic field (Zeeman effect [6]), and then radio frequency radiation of the appropriate frequency can cause a transition from one spin state to the other. The energy associated with the transition is expressed in terms of the applied magnetic field B, the electron spin g-factor g, and the constant μ_B which is called the **Bohr magneton** [6]. Magnetic potential energy of electron spin in magnetic field is expressed as $U = \mu \cdot B = \pm\frac{1}{2} g\mu_B B$, and accordingly energy difference is $\Delta E = g\mu_B B$.

If the radio frequency excitation was supplied by a klystron [1] at 20 GHz (you can compare this frequency with frequencies typical for NMR, 2.1 on page 3), the magnetic field required for resonance would be 0.71 Tesla, a sizable magnetic field typically supplied by a large laboratory magnet.

[1] High radio frequency generator.

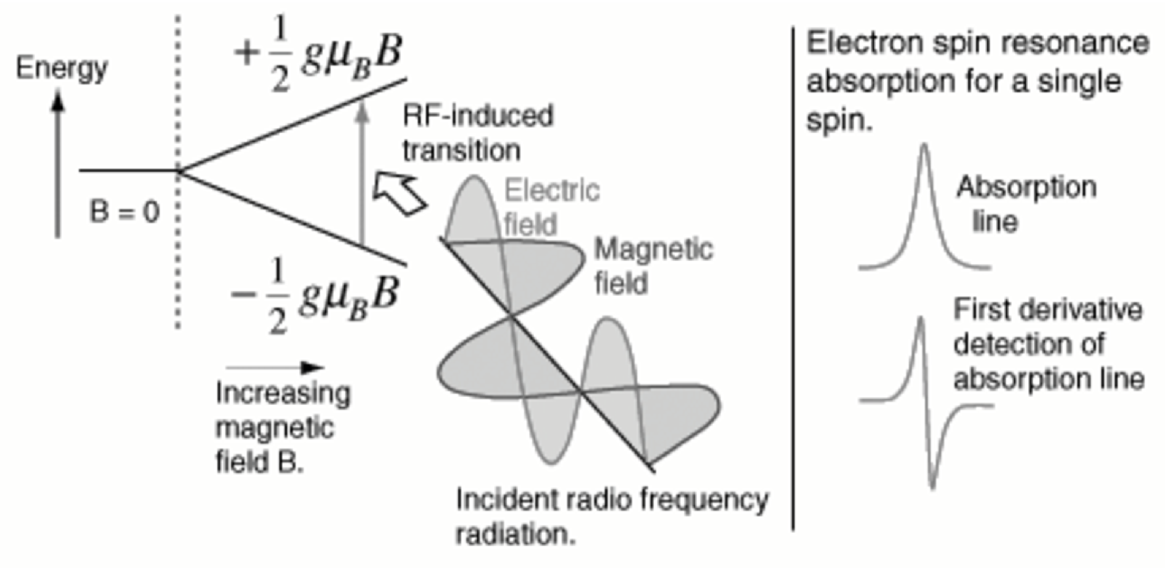

Figure 12: Key features and visual representation of ESR.

If you were always dealing with systems with a single spin like this example, then ESR would always consist of just one line, and would have little value as an investigative tool, but several factors influence the effective value of g in different settings. Much of the information obtainable from ESR comes from the splittings caused by interactions with nuclear spins in the vicinity of the unpaired spin, splittings called nuclear hyperfine structure. For further reading on this topic see [6].

3 Real Time Operating Systems (RTOS)

Real-time and embedded systems operate in constrained environments in which computer memory and processing power are limited. They often need to provide their services within strict time deadlines to their users and to the surrounding world. It is these memory, speed and timing constraints that dictate the use of real-time operating systems in embedded software.

3.1 Technical criteria

General-computing operating systems (GCOS) especially multi-users OS (e.g. UNIX) are directed on optimal computer's performances distributing between users and tasks (time sharing systems). But the main object of real-time operating system (RTOS) is providing guaranteed possibility to react on external interrupt in time. And the usage of RTOS is always premeditated.

Let's have a look on a usual process of developing real-time software and hardware complex. The first step is learning the requirements to our object and classification of object events. The next is choosing real-time critical events and events that require a definite reacting time (otherwise it is possible destroys of the object or negative profit). To every critical event is compared the critical time (duration). Then one should make a forecast of the worst object outcome (or outcomes took place at the same time). And only after these steps and hardware analysis we can start the developing of our software.

Events took place on the object usually is registered by sensors, and then this information from sensors transmit to Input-Output modules (interfaces) of a system. After receiving and handling, module generates the interrupt signal in controlling computer. On receiving the interrupt signal system must run event processing program. Time from the moment when an event on object appeared and up to the first program instruction will be executed is called as interrupt latency. This time interval consists of the following: time between event and generating interrupt signal (which doesn't depend on RTOS properties absolutely and determined by hardware) and time between signal and first instruction (define only by operating system and computer architecture).

The key difference between GCOS and RTOS is the need for deterministic timing behavior in RTOS. Formally, deterministic timing means that operating system services consume only known and expected amounts of time. In theory, these service times could be expressed as mathematical formulas. These formulas must be strictly algebraic and not include any random timing components. Random elements in service times could cause random delays in application software and could then the application randomly miss real-time deadlines - a scenario clearly unacceptable for a real-time embedded system.

Reaction time	**Suitable OS**
$< 10\ \mu s$	Only RTOS. It is a boundary condition between soft- and hardware solution
$10 - 100\ \mu s$	RTOS
$100 - 1000\ \mu s$	RTOS, RT-Linux, RT enhancements for Windows NT
$> 1\ ms$	For not hard real-time critical problems it's possible to apply Linux and Windows NT

Table 1: Reactivity requirements and suitable operating systems.

RTOS exhibit parallelism or in other words multi-tasking processing (moreover multi-processing, multi-threading) and negative profit of tasks switching time must be known. Time that system spends on passing of managing between tasks (processes, threads) is called context switch time. Besides, the possibility of creations systems without external (slow) memory storage, it means that RTOS must have a very small size of executing part and must completely locate in fast memory (cache or fast RAM). Just for example the kernel size of OS9 for MC68xxx microprocessors is 22 Kbytes, VxWorks – 16 Kbytes. One more important characteristic of RTOS is rebooting time. It becomes decisive when unexpectedly hang-up takes place. Some of modern advanced reliability operating systems have rebooting time less than 1 second, but for others this characteristic may be variable by changing booting sequence.

All RTOS may be divided on two parts, they are hard and soft real-time operating systems. And the key difference is that any delays and lateness of reactions on event for hard real-time systems absolutely unacceptable (because a result might have been useless, it might catastrophe be occurred or the cost of late might be very high) and soft real-time systems shouldn't be late with reaction on event (for example usual computer network, if the system doesn't have time to process next received information pocket, it just result in timeout on transmitting side and repeat of sending this pocket again).

3.2 RT mechanisms

Most RTOSs do their scheduling of tasks using a scheme called "priority-based preemptive scheduling." Each task in a software application must be assigned a priority, with higher priority values representing the need for quicker responsiveness. Very quick responsiveness is made possible by the "preemptive" nature of the task scheduling. "Preemptive" means that the scheduler is allowed to stop any task at any point in its execution, if it determines that another task needs to run immediately.

The basic rule that governs priority-based preemptive scheduling is that at every moment in time, "The Highest Priority Task that is Ready to Run, will be the Task that Must be Running." In other words, if both a low-priority task and a higher-priority task are ready to run, the scheduler will allow the higher-priority task to run first. The low-priority task will only get to run after the higher-priority task has finished with its current work.

Each time the priority-based preemptive scheduler is alerted by an external world trigger (such as a switch closing) or a software trigger (such as a message arrival), it must go through the following 5 steps:

- Determine whether the currently running task should continue to run. If not...
- Determine which task should run next.
- Save the environment of the task that was stopped (so it can continue later).
- Set up the running environment of the task that will run next.
- Allow this task to run.

These 5 steps together are called "task switching".

Also, tools dealing with timers are necessary for hard real-time operating system too. They enable possibility of the following:

- measuring and setting different time intervals (from $1\mu s$)
- generating interrupt signals at the end of time intervals
- creation single and cyclic alarms

3.3 Classes of RTOS

Executive RT systems. There is difference between platforms for developing and executing. RT applications are developed on host-computer, then put together with kernel and loaded to special executive system. As a rule, RT application is a one task and parallelism is achieved with threads. The key benefits of this kind of systems are speed and reactivity because of short context switching time between threads. These systems quite expensive and average prices are about $10000. For example, VxWorks.

RT kernels. Systems from this class, actually, modular, well structured, have the most developed real-time toolkit, compact and predictable. One of the distinctive features is scalability. It means that these systems have a great flexibility like LINUX kernel configuration and their size can be within very wide range (from Kbytes up to Mbytes). The most popular are OS9 and QNX.

RT UNIXes. Historically, the rapid UNIX developing was followed by such rapid RTOS creation and developing process. As a following many RTOS contain basic principle of UNIX systems. This way out was not very difficult because of open source kernels and other optional applications. Now as a result one got real time productive operating systems with perfect toolkit, compilers, and different ready application. Undersides are big kernel size and insufficient reactivity (in comparison with previous ones). System among these is LynxOS.

3.4 Summary

Real-time and embedded systems are used in many applications such as airborne computers, medical instruments and communication systems. Embedded systems are characterized by limited processor memory, limited processing power, and unusual interfaces to the outside world. RTOS kernels hide from application software the low-level details of system hardware, and at the same time provide several categories of services to application software. These include: task management with priority-based preemptive scheduling, reliable intertask communication and synchronization, and basic timer services. A number of RTOS implement these solutions in their compact high-performance kernels.

4 QNX

4.1 What is QNX?

The main responsibility of an operating system is to manage a computer's resources. All activities in the system - scheduling application programs, writing files to disk, sending data across a network, and so on - should function together as seamlessly and transparently as possible.

Some environments call for more rigorous resource management and scheduling than others. Realtime applications, for instance, depend on the operating system to handle multiple events within fixed time constraints. The more responsive the OS, the more "room" a realtime application has to maneuver when meeting its deadlines.

The QNX Operating System is ideal for realtime applications. It provides multitasking, priority-driven preemptive scheduling, and fast context switching - all essential ingredients of a realtime system.

QNX is also remarkably flexible. Developers can easily customize the operating system to meet the needs of their application. From a "bare-bones" configuration of a kernel with a few small modules to a full-blown network-wide system equipped to serve hundreds of users, QNX lets you set up your system to use only those resources you require to tackle the job at hand.

QNX achieves its unique degree of efficiency, modularity, and simplicity through two fundamental principles:

- microkernel architecture
- message-based interprocess communication

4.2 QNX's microkernel architecture

QNX consists of a small kernel in charge of a group of cooperating processes. As the following illustration shows, the structure looks more like a team than a hierarchy, as several players of equal rank interact with each other and with their "quarterback" kernel.

The *kernel* is the heart of any operating system. In some systems the "kernel" comprises so many functions, that for all intents and purposes it is the entire operating system!

But the QNX Microkernel is truly a kernel. First of all, like the kernel of a realtime executive, the QNX Microkernel is very small. Secondly, it's dedicated to only two essential functions:

- **message passing** the Microkernel handles the routing of all messages among all processes throughout the entire system
- **scheduling** the scheduler is a part of the Microkernel and is invoked whenever a process changes state as the result of a message or interrupt

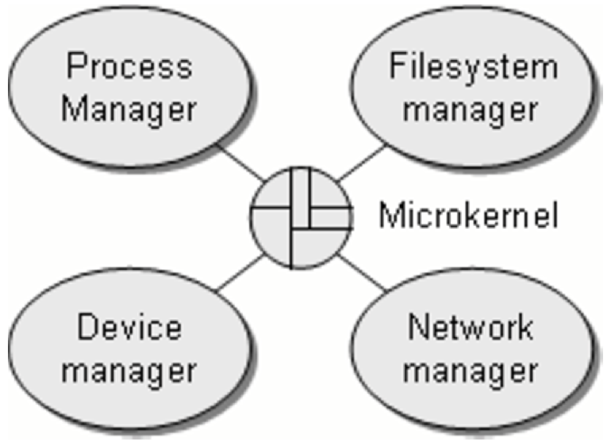

Figure 13: The QNX Microkernel coordinating the system managers.

Unlike processes, the Microkernel itself is never scheduled for execution. It is entered only as the direct result of kernel calls, either from a process or from a hardware interrupt.

4.3 System Processes

All QNX services, except those provided by the Microkernel, are handled via standard QNX processes. A typical QNX configuration has the following system processes:

- Process Manager (`Proc`)
- Filesystem Manager (`Fsys`)
- Device Manager (`Dev`)
- Network Manager (`Net`)

System processes are practically no different from any user-written program - they have no private or hidden interfaces that are unavailable to user processes.

It is this architecture that gives QNX unparalleled extensibility. Since most OS services are provided by standard QNX processes, it's a very simple matter to augment the OS itself: you just write new programs to provide new services!

In fact, the boundary between the operating system and the application can become very blurred. The only real difference between system services and applications is that OS services manage resources for clients.

Let's suppose you've written a database server. How should such a process be classified?

Just as a filesystem accepts requests (messages in QNX) to open files and read or write data, so too would a database server. While the requests to the database server may be more sophisticated, both servers are very much the same in that they provide a set of primitives (implemented by messages) which in turn provide access to a resource. Both are independent processes that can be written by an end-user and started on an as-needed basis.

A database server might be considered a system process at one installation, and an application at another. *It really doesn't matter!* The important point is that QNX allows such processes to be implemented cleanly, with no need at all for modifications to the standard components of the operating system.

Device Drivers Device drivers are processes that shield the operating system from dealing with all the details required for supporting specific hardware.

Since drivers start up as standard processes, adding a new driver to QNX doesn't affect any other part of the operating system. The only change you need to make to your QNX environment is to actually start the new driver.

Once they've completed their initialization, drivers can do either of the following:

- choose to disappear as standard processes, simply becoming extensions to the system process they're associated with
- retain their individual identity as standard processes

4.4 Interprocess Communication (IPC)

When several processes run concurrently, as in typical realtime multitasking environments, the operating system must provide mechanisms to allow processes to communicate with each other.

IPC is the key to designing an application as a set of cooperating processes in which each process handles one well-defined part of the whole.

QNX provides a simple but powerful set of IPC capabilities that greatly simplify the job of developing applications made up of cooperating processes.

QNX as a message-passing operating system QNX was the first commercial operating system of its kind to make use of message passing as the fundamental means of IPC. QNX owes much of its power, simplicity, and elegance to the complete integration of the message-passing method throughout the entire system.

In QNX, a message is a packet of bytes passed from one process to another. QNX attaches no special meaning to the content of a message - the data in a message has meaning for the sender of the message and for its receiver, but for no one else.

Message passing not only allows processes to pass data to each other, but also provides a means of synchronizing the execution of several processes. As they send, receive, and reply to messages, processes undergo various "changes of state" that affect when, and for how long, they may run. Knowing their states and priorities, the Microkernel can schedule all processes as efficiently as possible to make the most of available CPU resources. This single, consistent method – message passing – is thus constantly operative throughout the entire system.

Realtime and other mission-critical applications generally require a dependable form of IPC, because the processes that make up such applications are so strongly interrelated. The discipline imposed by QNX's message-passing design helps bring order and greater reliability to applications.

4.5 QNX as a network

In its simplest form, local area networking provides a mechanism for sharing files and peripheral devices among several interconnected computers. QNX goes far beyond this simple concept and integrates the entire network into a single, homogeneous set of resources.

Any process on any machine in the network can directly make use of any resource on any other machine. From the application's perspective, there is no difference between a local or remote resource - no special facilities need to be built into applications to make use of remote resources. In fact, a program would need special code to be able to tell whether a resource such as a file or device was present on the local computer or was on some other node on the network!

Users may access files anywhere on the network, take advantage of any peripheral device, and run applications on any machine on the network (provided they have the appropriate authority). Processes can communicate in the same manner anywhere throughout the entire network. Again, QNX's all-pervasive message-passing IPC accounts for such fluid, transparent networking.

4.6 Single-computer model

QNX is designed from the ground up as a network-wide operating system. In some ways, a QNX network feels more like a mainframe computer than a set of micros. Users are simply aware of a large set of resources available for use by any application. But unlike a mainframe, QNX provides a highly responsive environment, since the appropriate amount of computing power can be made available at each node to meet the needs of each user.

In a process control environment, for example, PLCs and other realtime I/O devices may require more resources than other, less critical, applications, such as a word processor. The QNX network is responsive enough to support both types of applications at the same time - QNX lets you focus computing power on the plant floor where and when it's needed, without sacrificing concurrent connectivity to the desktop.

5 Conclision: RTOS application for MR-spectroscopy

Let's put all information together and try to make a conclusion.

5.1 Real Time-critical problems in MR-spectroscopy

Now, when one have already known necessary information about magnetic resonance and RT operating systems let's try to pose a problem of usege these two theories combined. The main difficulty to be solved is obtaining correct results of measuring experiment using pulse method (high resolution fourier spectroscopy, see 2.5). For better comprehension of the experiment to be carried out we should pick out the critical points and real-time-critical features. As we remember, the average FID[2] time is $1\mu s - 1s$, and thus in order to have a real time spectrum on computer diplay one should thinking about choice of RT operating system. So, our experiment consists of the following steps (see Fig. 14):

1. According to the investigated substance FID-time computer generates and transmits to **smart pulse generator** pulse sequence (quantity and thier duration), in other words we make the order of experiment;

2. While smart pulse generator carrying out this experiment, and during the solitary FID the **receiver** is registring spin echoes of the sample. In this time ADC[3] is getting numerical values (e.g. 1K=1024, 2K, 4K, 8K or 16K measurements) and saving in its buffer memory[4]. And it's the most important and real-time-critical aspect, because for 1 numerical value (for 1 measurement) one have (even for 1-second FID duration) just $\frac{1\ second}{4K\ points} \sim 10^{-5}\ seconds$ And by the next pulse ADC already must have free buffer memory to collect next measuring sequence. It's a quite solvable problem for modern ADCs and receivers, but not for computers (in wide meaning, e.g. PC – with usual architecture).

[2] Free Induction Decay. See 2.2

[3] Analog-to-Digital Converter

[4] As distinct from CW-method (see 2.6), there is no need for internal memory in ADC, because the information stream is very slow and homogeneous

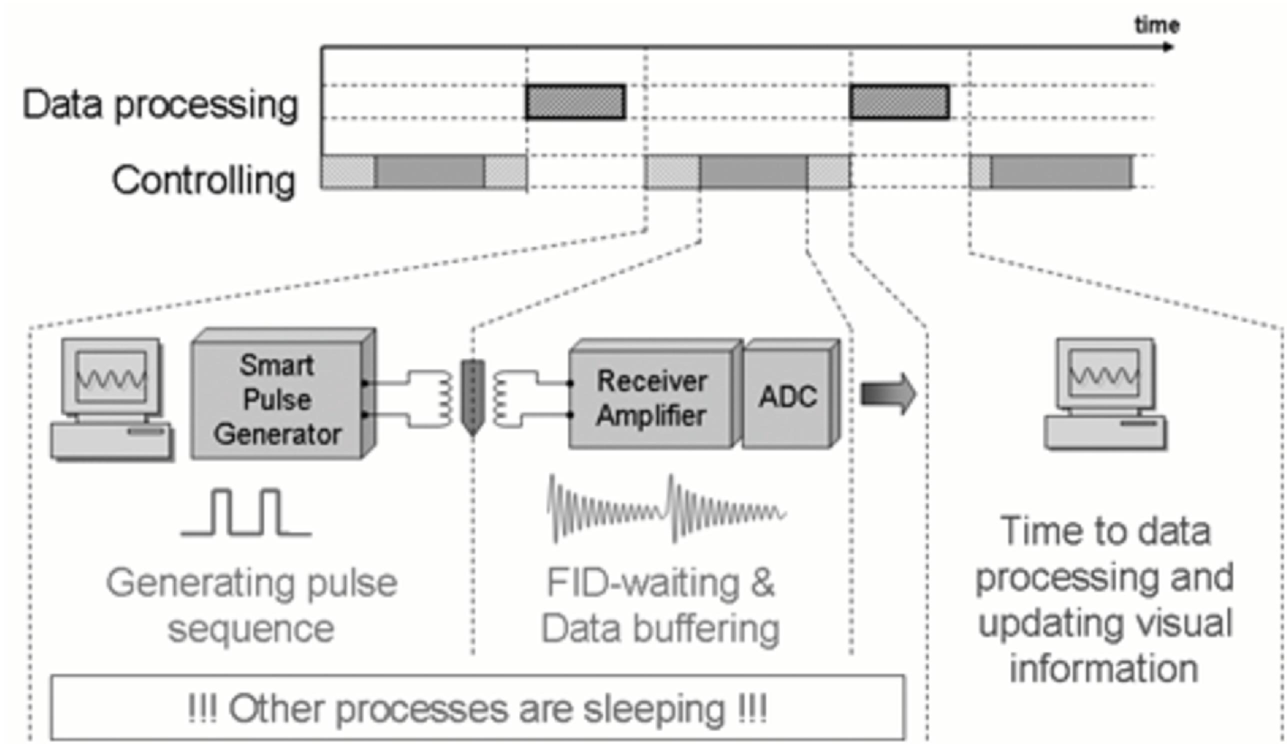

Figure 14: Order of the experiment

3. **Visualisation.** And at the same time with collecting and obtaining measure values we would like to see what is actually happening in the sample. Moreover we want to see the specral picture, it means that it must be applied some numerical algorithms like fast Fourier transform, approximations, single and double numerical integration and so on.

Well, it's quite possible to solve all these difficults by using RT operating systems that have guaranteed interrupt latency. QNX is one of the most famous real time operating system in the world and it have very rich development toolkit and supporting means. Perfect network realization as a single-computer model (see 4.6) lets the wide space for experiments with distributed systems for easier controlling ang parallel and fast computing a lot of data.

5.2 My ESR project

Today's my task consists of developing software for a very small portable ESR-spectrometr operating with CW-method (Stanislav M. Sukharzhevskiy is developing hardware of this spectrometer). There is no need of using RT operating system hence it will quite enough to write processing part and simple controlling part with possibility of magnetic field scan linearization (see 2.6).

6 Special thanks

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- Assoc. Prof. Andrei V. Komolkin

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