lon decays and from lepton scattering experiments suggest spin one, but a final conclusion cannot yet be made. Confirmation should come from analysis of the jet angular distributions.

While it is important to confirm the existence of the gluon and to pin down its quantum numbers, another vital test is to search for evidence of a single gluon decaying into a gluon pair. This three-gluon coupling has no analogue in more familiar field theories, such as quantum electrodynamics, but is a necessary consequence of QCD.

This three-gluon coupling, which would be seen as a softening and broadening of gluon jets at high energy compared to the showers coming from quarks, provides a vital test of QCD.

All this will be helped by the availability of full energy (2 × 19 GeV) in PETRA next year, and the hunt for the gluon will soon be given another boost when experiments begin at the new PEP electron-positron ring at Stanford.

Exploiting muon spin rotation

Last year, some twenty per cent of the available beam time at the CERN 600 MeV synchro-cyclotron (SC) was taken up by studies using the technique of muon spin rotation (μSR).

The idea of muon spin rotation dates back some twenty years to the pioneer experiments on parity violation in weak decays, but it has only come into its own as an experimental technique in the 1970s.

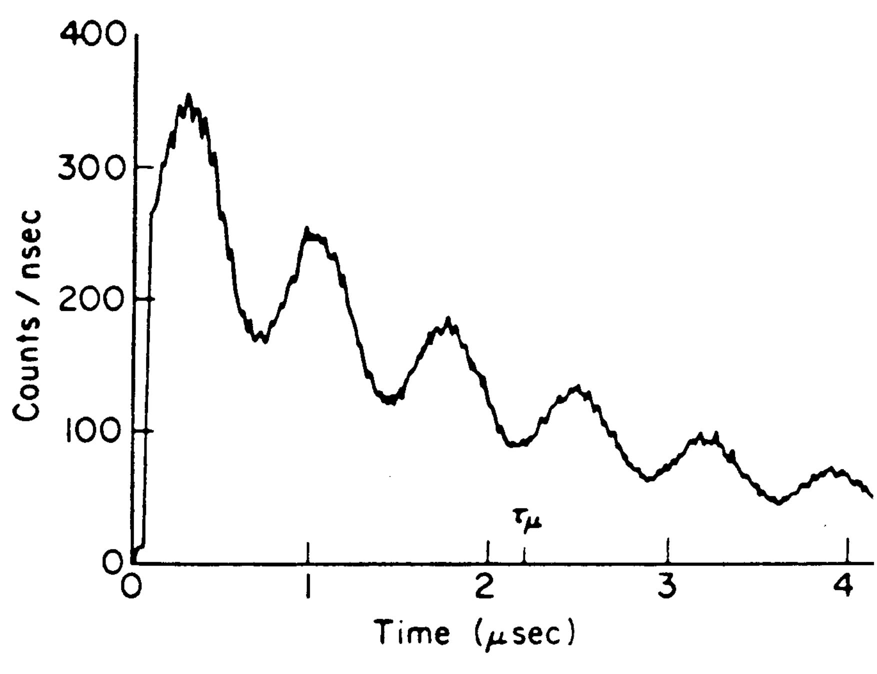
Polarized positive muons are brought to a stop in a target and precess in the local magnetic fields. (Negative muons are quickly captured by nuclei and are much less useful.) Because of parity violation, positrons from the decay of these positive muons are preferentially emitted in the direction of the muon spin.

This behaviour can be monitored by positron detectors which record the rate of muon decay and show the characteristic precession of the muons. In this way the stopped muons can be used to probe the inner structure of a wide range of materials.

Early experiments had shown that at sufficiently low temperatures, muons come to rest in metals and that the muon precession rates in ferromagnets can be used to measure internal magnetic fields at the muon sites. Early μSR applications at CERN were aimed at ferromagnetic materials.

However it was soon discovered that, first, much more had to be learnt about the way muons interact in metals, and in particular, what types of sites in the crystals the muon energies prefer.

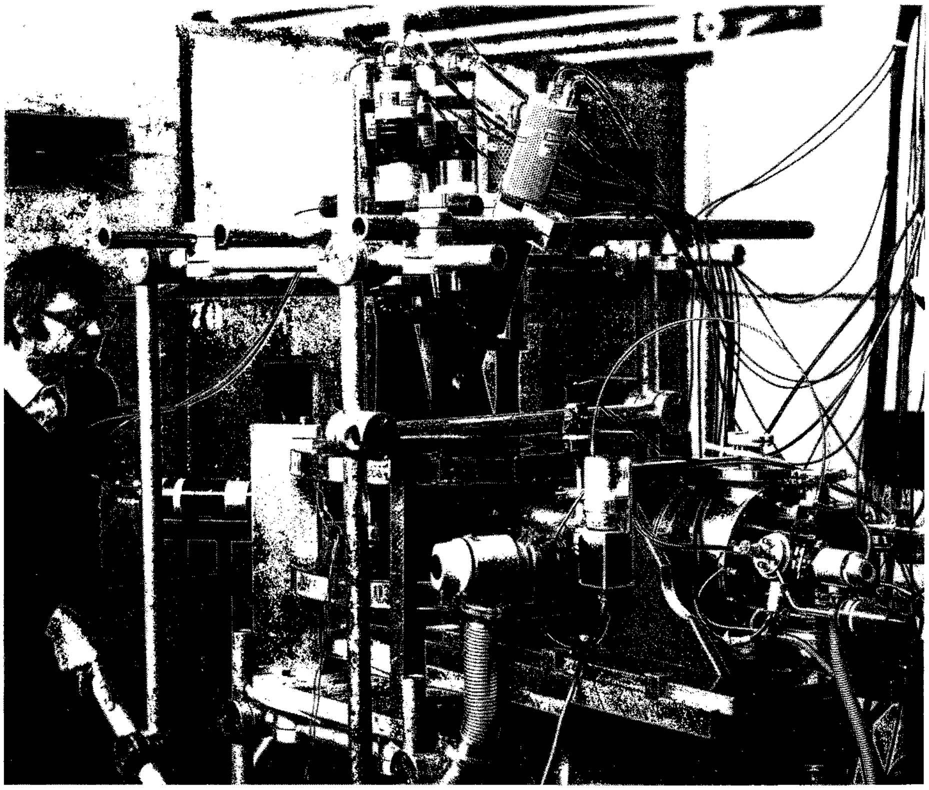
The importance of the electric field which the charged muons exert on the surrounding nuclei was first realized at CERN. Once this was understood, stopping sites could be confi-



Typical muon spin rotation signal showing the characteristic pattern due to the precession of the stopped muons in a sample. This technique is finding increasing application in physics, chemistry and biology.

Erik Karlsson with the experimental arrangement used at CERN for measuring muon spin rotation at temperatures down to 0.03K. These low temperatures are needed to reveal the quantum mechanical nature of muon diffusion in certain metals and semiconductors.

(Photo CERN 260.9.79)



dently determined from muon depolarization measurements in single crystals.

It was also found that while muons could be brought to rest in some metals with relatively little cooling, muons seemed to be mobile in others right down to a few degrees Kelvin. In many metals irregularities in the depolarization rate also showed up at certain temperatures.

The understanding of all these phenomena has been a major objective at CERN. In 1977, the first systematic studies of the effect of impurity content were carried out and its strong influence on muon mobility was clearly shown.

A model for 'trapping' and release of muons at impurities in metals was formulated. This can be related to corresponding behaviour in the metallurgically very important technique of hydrogen diffusion in metals. Muons have a great advantage over hydrogen in this respect as they can be studied at extremely low concentrations.

As a very light particle, the muon is prone to tunnel quantum mechanically through barriers in its path, in contrast with heavier particles which have to find their way over these obstacles.

This has opened up a new field of diffusion studies which is of interest to theoreticians as well as experimentalists, and provides new insights into the propagation mechanisms in disordered systems in general, such as electron propagation near the transition region between metals and insulators. Experiments at CERN have penetrated the temperature range from 2 down to 0.03 K and discovered many new and interesting phenomena.

These studies are still being pursued, but experimenters are now confident that they know enough about the influence of purity on the localization of muons to be able to re-embark on their original programme of ferromagnetic studies.

Another speciality involves subjecting the metallic samples to pressures of up to 7000 atmospheres to increase the electron densities in experiments on ferromagnetic substances. These studies complement those which measure the influence of temperature and impurity level on the localization of muons.

Muonium effects

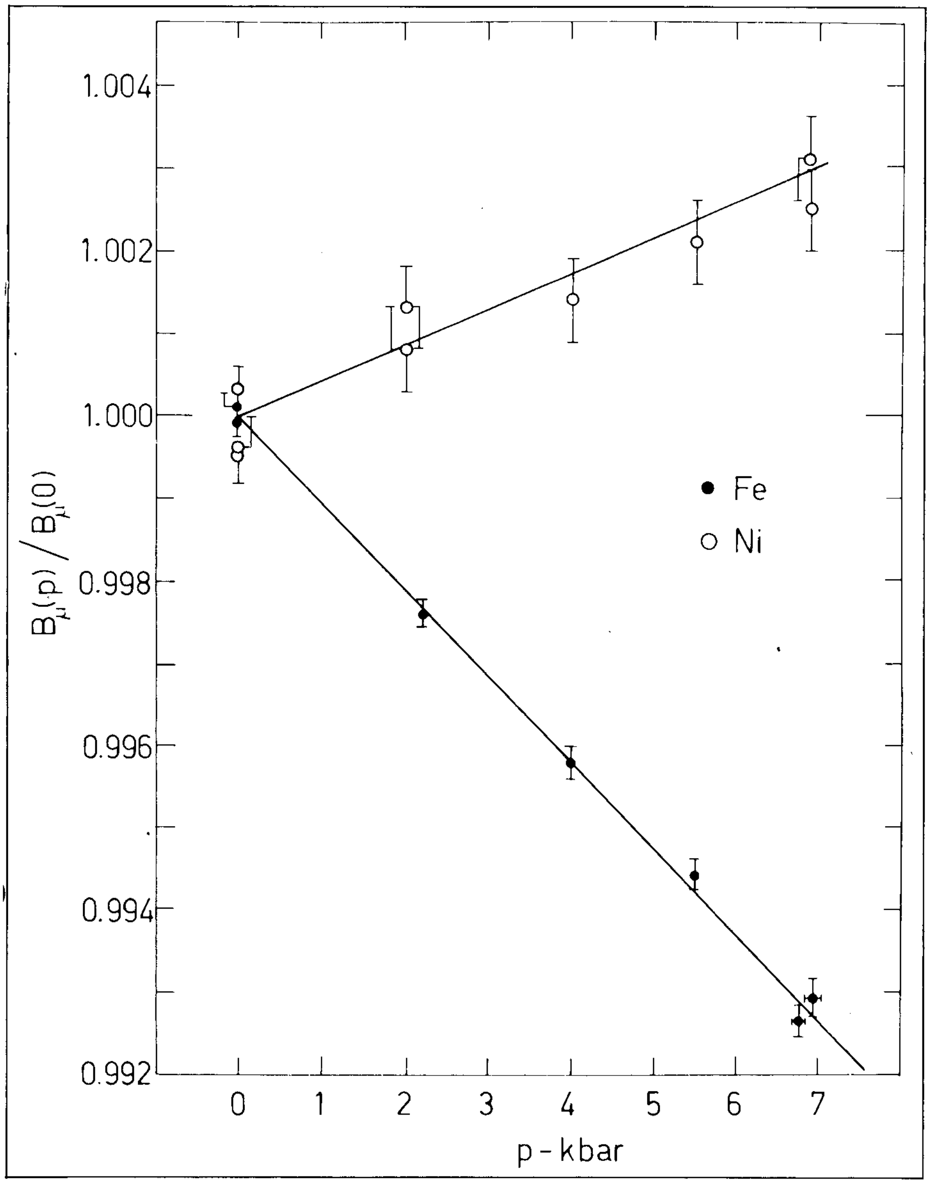
In metals, it is principally free positive muons which are stopped, as the conduction electrons which could pair with the muons are smeared out through the sample. Any hyperfine interactions between muons and conduction electrons are cancelled out by quantum mechanical exchange forces.

In insulators, this is not the case and the muons pair up with electrons to form muonium — a hydrogen-like atom with a positive muon, rather than a proton, as nucleus. Thus the inner structure of insulators can be studied through the hyperfine spectroscopy of muonium, as revealed by the muon spin rotation technique.

Of course, the boundary between free muons in metals and muonium in insulators is not clear-cut, and there is a transition through semimetals, such as arsenic, antimony and bismuth, which has been extensively studied at CERN.

The main aim in muonium studies in non-conductors is to hope that the muonium atoms with their single electrons could behave in certain respects like hydrogen atoms, and the technique could complement the results obtained directly from hydrogen.

Relative change of the local magnetic fields in nickel and iron with applied pressure, as measured in muon spin rotation experiments at CERN. The behaviour reflects the changes in the polarization of electron spins around the muons.



While in some cases this comparison with hydrogen is valid, the lightness of the muon also means that quantum mechanical tunnelling takes on an important role, so that other effects occur up to a hundred times faster with muonium than with hydrogen.

If an itinerant hydrogen atom meets a molecule, it may react or not. If it does not react, the atom moves on and must travel a distance comparable to its mean free path before encountering another likely molecular target.

However muonium tends to react with the first molecule it meets, so that reaction mechanisms are considerably faster. But the muon spin rotation technique enables much faster reaction rates to be studied (down to 5 ns) than with other methods.

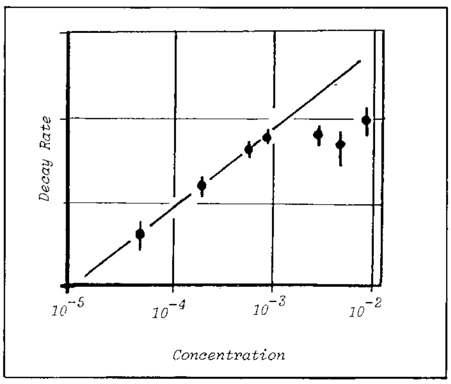
Again optimistic initial studies to explore the behaviour of biomolecules encountered the same sort of general problems as were found with metals, and experimenters first had to go backwards and investigate how muonium was formed in these materials before making important progress.

In complex biological molecules, such as DNA, the transient radicals are expected to exist on a timescale which can be probed by µSR, and recent results at CERN have shown evidence for such radicals containing muonium.

The reaction rates of muonium have been studied not only with complex biomolecules but also with model molecules such as benzene. This work has shown how the resulting radicals can be detected and their electronic configurations probed.

From a radiobiological viewpoint, the most interesting outcome of the DNA studies using muonium is that all of DNA's four molecular bases react strongly with the hydrogen-like atom. The focus is now on understanding the evolution of these

Results (below) from experiments on the formation of muonium atoms in water and their subsequent reaction with DNA bases. The decay rate of the muonium signal is found to rise in proportion with the solute concentration up to a certain point, when a plateau is reached. Work done at CERN on both biological and model molecules in this region has shown that muonium radicals are formed as the first reaction products.



Physics monitor

muonium-base radicals. These studies, and others on complex polymers, could give important insights in molecular chemistry and biology.

At CERN, the study of the hyperfine interactions in muonic radicals in liquids proceeds along with studies on insulating or semiconducting crystals. In particular, the properties of muonium in semiconductors at low temperatures are being investigated.

An important development in the μSR camp at CERN revolves around the use of wire chambers as detectors. In principle, this will be able to monitor the precessions of muons at many different sites and could speed up the analysis considerably.

With widespread applications, muon spin rotation is now a powerful new technique in physics, chemistry and biology which is only just beginning to show its worth.

Looking for the neutron's electric dipole moment

An experiment now being prepared by a Grenoble / Harvard / Munich / Oak Ridge / Rutherford / Sussex collaboration to run at the research reactor at the Institut Laue-Langevin, Grenoble, will use new techniques to search for an electric dipole moment of the neutron.

The magnetic dipole moment of the neutron was first measured in 1940 at the Berkeley cyclotron by Luis Alvarez and Felix Bloch, but any electric counterpart has yet to be seen.

The existence of an electric dipole moment in this neutral particle would provide the first evidence for the violation of time reversal symmetry outside the world of the neutral kaon.

While the total electric charge inside the neutron is of course zero, the constituent positive and negative charges (the quarks in the neutron are charged) might be distributed so that the positive and negative regions are permanently displaced. This could produce an electric dipole moment.

Any such dipole moment would have to point along the direction of the neutron's spin axis. Because the neutron has spin, any separation of electric charge away from the spin axis would be averaged out by the rotational motion, and only a separation of positive and negative charge along the spin axis would be detectable.

Applying a time reversal operation to a neutron flips the spin direction — a film of any object spinning right-handedly, when run backwards, shows the object to be spinning left-handedly.

However a time reversal operation has no effect on electric charge. Thus, if initially the electric dipole moment and the spin axis point in the same direction, after a time reversal operation they will point in opposite directions. This is a violation of time reversal symmetry — a film of a neutron, when run backwards, would no longer look like a neutron.

(Unlike an electric dipole moment, a magnetic dipole moment does switch direction under a time reversal operation, so for the magnetic moment, time reversal symmetry is good.)

Neutron experiments have already established that if an electric dipole moment exists, it must be less than 3×10^{-24} e cm (e being the electronic charge). To go beyond this limit requires neutrons which can be kept under observation for a long time, and this requires special techniques.

Very slow neutrons were first used in this type of experiment by a group working at the Institute for Nuclear Physics in Leningrad, but the experiment now being prepared at Grenoble plans to 'bottle' these unhurried neutrons to further increase the observation time.

As the energy of a neutron wave-packet falls, so its wavelength increases according to the Planck law. For more energetic neutrons, a solid appears as a lattice of nuclei through which the particles can filter. As the energy falls and the wavelength increases, the solid eventually becomes a continuous barrier which the particles cannot easily penetrate. This phenomenon is analogous to the total internal reflection of light in a glass prism, and was predicted by Enrico Fermi in 1945.

Thus when neutrons are slowed down past this critical energy (when they are said to be 'ultra-cold'), they can be trapped and stored in a