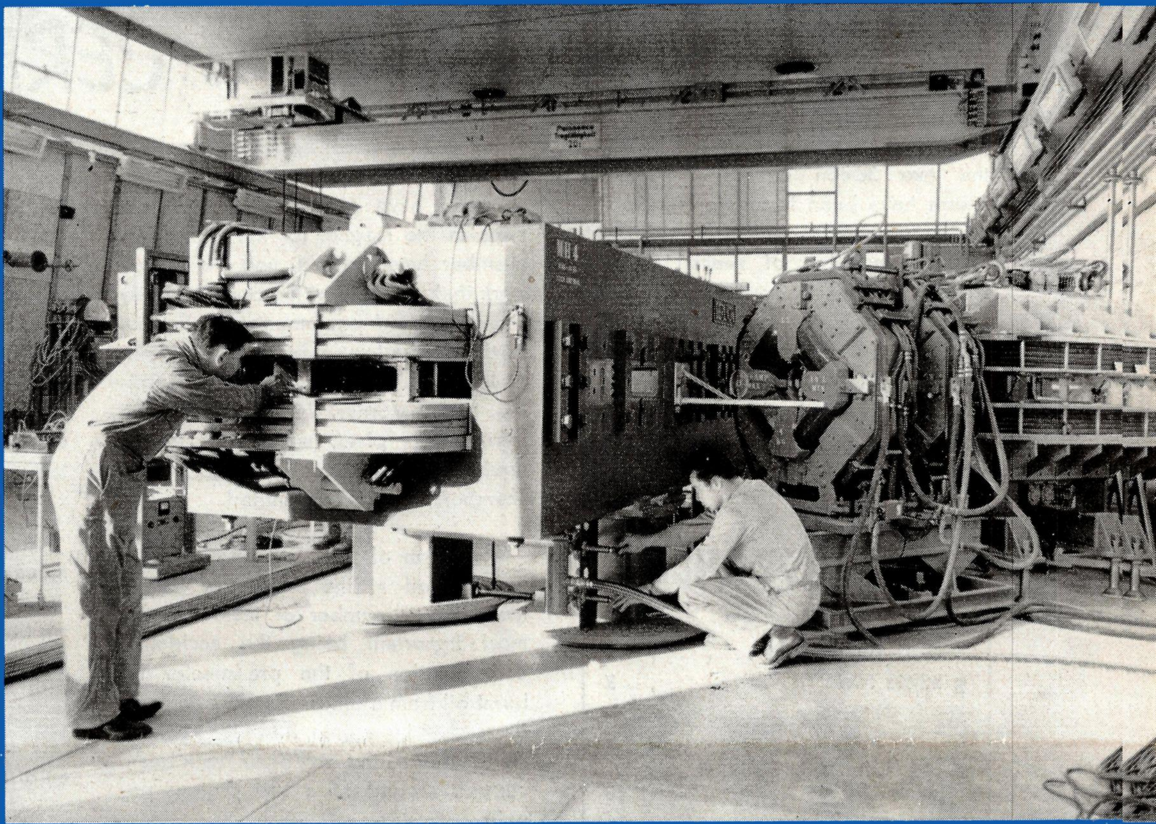
CERN COURIER



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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Last month at CERN

In the **East bubble-chamber building** the two 30-ton overhead travelling cranes have been tested for safety and are in use for assembling equipment. These cranes are of special interest, since they are operated entirely by compressed air — a safety feature in a building where large quantities of hydrogen will be employed.

The yoke and coils of the magnet for the 1.5-m British hydrogen bubble chamber have now been assembled. Parts of the magnet for the CERN 2-m chamber have arrived, and the framework that will support the chamber body and associated equipment is being assembled on a temporary support of concrete blocks in the centre of the building. In one corner, the large hydrogen refrigeration plant, which will supply liquid hydrogen continuously to the chambers, is being assembled.

Operation of the **proton synchrotron** was marred at the beginning of the month by a number of incidents, the most important being the accidental contamination of the pre-injector by burnt oil from a diffusion pump. Towards the end of the month, however, the machine was running well again, with beam currents around 3.5 x 10^{11} protons per pulse.

Greater precision in changing **targets** will now be possible, with the completion of a template enabling this to be done with an accuracy of ± 2 mm.

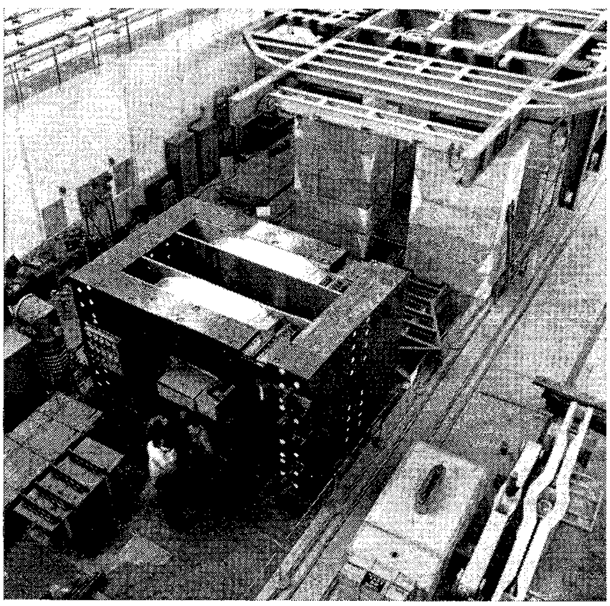
Beam sharing between two point-source targets, to give a short burst of low intensity and a long burst from the rest of the beam, has been studied during the last three months. The principle used was to drive the beam momentarily into betatron oscillations of suitable amplitude, by exciting the radio-frequency knockout system with a definite off-resonance frequency, giving one beat of the required duration. A 500-microsecond burst consuming 5 to 10 % of the circulating beam has been obtained from a beryllium target 3 mm x 4 mm x 38 mm.

The **Wilson Cloud Chamber** was moved on 7 March from its old position in the South hall to a new one intercepting the neutral beam v_1 (see CERN COURIER for February, p. 9). Successful runs were made later in the month, using the chamber in conjunction with a separate target taking one pulse in every 60 of the machine.

The CERN **32-cm hydrogen bubble chamber** has been moved out of the North hall, and has been replaced by the **1-m heavy-liquid chamber** belonging to the École Polytechnique, Paris.

After finishing their current experiments at the synchro-cyclotron and the

Continued on p. 12



This photograph, taken from the gallery in the East bubble - chamber building, shows the massive nature of the magnet for the 1.5-metre British chamber. Behind it, the supporting framework for the CERN 2-metre chamber is now being assembled.

Contents

The cover photograph shows B. Nicolai (left) and J. Schneuwly engaged on setting up the 6-metre magnet for the (g-2) experiment (see story on p. 3).

Photo credits : All photos by CERN/PIO, except p. 7 - CERN/SIS. Figs. 1, 2, 3, 5 and 7 for the (g-2) article by Marcel Bron.

CERN COURIER

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g minus two

The anomalous magnetic moment of the muon

One of the puzzles of present-day physics is that of the existence of the muon. An experiment recently completed at CERN has done much to clarify the problem, although the basic puzzle still remains. This article attempts to show as simply as possible why the experiment was done, some of the difficulties that were faced, and the answers that were obtained.

Early in 1961 a scientific communication from CERN [1] announced that the 'anomalous magnetic moment' of the muon had been measured directly for the first time, and had been found to confirm theoretical predictions to within 2 %. This result showed, contrary to what many had hoped, or even expected, that the muon was indeed very similar to the electron, in spite of being some 200 times heavier.

During the year, the experiments were refined and continued, and recently a new result has been published [2], confirming the similarity with even greater accuracy. Treating the muon as a simple 'Dirac particle', that is just as a heavy electron, its anomalous magnetic moment is calculated from the theory of 'quantum electrodynamics' as 0.001165. This latest experimental result shows the value to be 0.001162 ± 0.000005.

The (g-2) experiment, as it has come to be called, was begun here at CERN in 1958. Laboratories in the U.S.A. and U.S.S.R. have been working on similar experiments and will, it is hoped, eventually provide independent corroboration of the CERN result. Why has so much effort been put into the measurement of this property and why are physicists so interested in the results? What does it all mean?

For a start, it must be recalled that matter is made up of a number of 'elementary', or 'fundamental' particles. Some kind of explanation has been found for the existence of most of these, but there seems to be no reason at all for the particle that was originally called the **mu-meson** and is now generally called the **muon.** It is produced by the 'decay' of a pion, has a mass just over 200 times that of the next-smallest particle, the electron, and decays into an electron in a few millionths of a second. Like the electron, it exists in two forms, negative and positive *, and has the same interactions with other particles. In fact, except for its larger mass and short life the muon resembles the electron very closely.

[1] G. Charpak, F. J. M. Farley, R. L. Garwin, T. Muller, J. C. Sens, V. L. Telegdi and A. Zichichi. 'Measurement of the anomalous magnetic moment of the muon'. *Physical Review Letters* Vol. 6, pp. 128-132 (1 February 1961).

[2] G. Charpak, F. J. M. Farley, R. L. Garwin, T. Muller, J. C. Sens and A. Zichichi. 'A new measurement of the anomalous magnetic moment of the muon'. *Physics Letters,* Vol. 1, pp. 16-20 (1 April 1962).

* Many 'elementary particles' (including 'antiparticles') exist in three forms, one carrying a single negative electric charge, one a single positive charge, and one no charge (neutral). There is no evidence for a neutral form of the electron or of the muon.

This is one of the great puzzles of elementary-particle physics. Every other particle has at least one characteristic, *apart from its mass,* which distinguishes it from all the others, but so far no adequate reason has been discovered for the muon's separate existence. At one time it was possible to speculate that it might have some properties as yet unknown, but the accurate measurement of the anomalous magnetic moment has now shown this to be much less likely.

MAGNETIC MOMENTS

How is this so? To explain this, it is first necessary to say what is meant by 'anomalous magnetic moment', and indeed by 'magnetic moment'. In classical physics, the magnetic moment is a measure of the strength of a magnet: a compass needle, the earth's magnetism, the magnetic effect produced by a circulating electric current. A charged particle, like a tiny sphere spinning on its axis, also produces a magnetic field and has a corresponding magnetic moment.

g-factor

The magnetic moment of such a spinning charged ball is proportional to its 'angular momentum' or 'spin'. The factor by which one multiplies the spin to obtain the magnetic moment can be calculated from classical electromagnetic theory, but experimentally it was found that elementary particles have a different value. An extra factor has to be used to arrive at the true value for these particles, and this has come to be known as the 'g-factor'. For an electron, this factor was found at first to have a value of 2, and one of the early triumphs of Dirac's theory of the electron was its prediction of just this value.

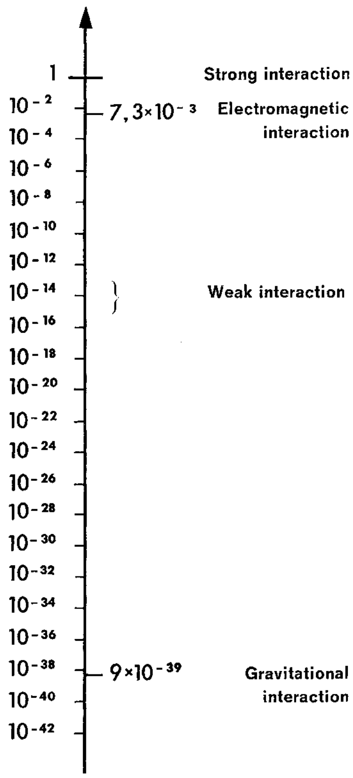
Pion clouds

If the theory were applicable to all particles, the g-factor would have the value 2 for *any* particle with a spin 'quantum number' of $1/2$, for example protons as well as electrons. The proton, however, has a magnetic moment that implies a g-factor of over $5^1/2$, so that obviously the theory is not strictly applicable. The proton and the electron are fundamentally different particles. The prediction and subsequent discovery of the meson, a particle which helps to hold atomic nuclei together, went a long way towards explaining this difference, since it can be assumed that the proton continuously emits and reabsorbs pi-mesons (pions). These are 'virtual', in the sense that they cannot escape from their parent particle under normal circumstances, but at the same time they produce observable effects. In particular they produce an extra magnetic moment which is in addition to the Dirac value. This additional part is called the **'anomalous magnetic moment'.**

Anomalous magnetic moment of an electron

Because the interaction between protons and pions is 'strong' the anomalous magnetic moment is large compared to the normal moment. An electron does not have any strong interaction, but it does have the much weaker 'electromagnetic' interaction (see fig. 1) with **photons** (the 'particles' of light or electromagnetism). This gives rise to a much smaller anomalous magnetic moment, due to the emission and reabsorption of virtual photons. The g-factor for the electron is not exactly equal to 2 but is greater by about 1 part in a thousand.

Fig. 1. This scale shows the relative strengths of the different kinds of interaction known to exist. Note that the scale is logarithmic, each position marked being 100 times smaller than the one next above.



To understand, how this 'anomaly' arises, it is useful to recall that a magnetic moment, or even a magnet, has no meaning by itself. It is only apparent by its effects, or interactions. The magnetic moment of a particle can only be found by introducing it into a known magnetic field and measuring what happens. If the particle changes its properties while it is in the magnetic field, the results may well be different to those expected.

To take a greatly simplified analogy, imagine that a lorry loaded with boxes is driven around and periodically passes over some apparatus that records its weight. Normally, the same reading would be obtained each time, but a man on the lorry amuses himself by occasionally throwing a box in the air and catching it again. Sometimes a box is in the air when the lorry passes over the weighing machine. The result is that the average weight obtained from all the readings is a little less than it would otherwise have been (provided the weighing machine is sufficiently sensitive to detect the difference). This 'experimental' value, though correct in the circumstances, does not confirm the 'theoretical' one obtained, for instance, by adding the separate weights of the lorry and its contents. However, even if the progress of the lorry could not be constantly observed, it might be possible to deduce how often a box was thrown and hence the probability that it would be in the air when the weight of the lorry was measured. Thus a correction could be made to the 'theoretical' value of the weight, and the more accurate the deduction the greater the agreement between the corrected value and the 'experimental' one.

In a similar way, in its interaction with the magnetic field the electron can be thought of as sometimes 'whole', sometimes without one photon temporarily, sometimes without two, or perhaps even more. Some of the possibilities are shown in fig. 2: the solid line is the electron, 'hitting' the magnetic field where the bend is shown; the dotted lines are photons. Using the relatively new theoretical developments called **quantum electrodynamics,** the value of the anomalous magnetic moment can be calculated, although the computation is long and involved. Accurate measurements of the electron g-factor have confirmed the theoretical value to a high degree of accuracy.

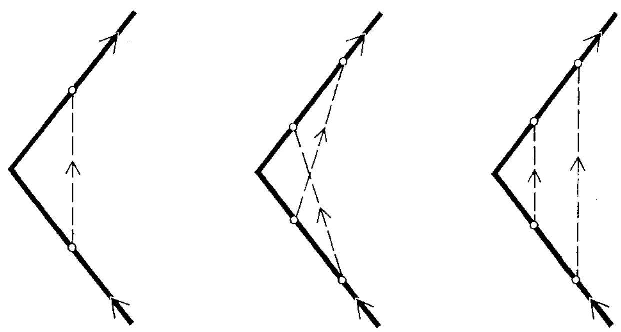


Fig. 2. One or two 'virtual' photons (dotted lines) sometimes miss the interaction (bend in solid line) of an electron or muon with the magnetic field.

The muon anomaly

What about the muon? Early measurements showed that its g-factor was rather more than 2, as for the electron; it therefore had an anomalous moment. As the properties of the muon became known in more detail and it seemed more and more to be like a heavy electron it became equally more interesting to measure the g-factor precisely, to see if there was some departure from the 'theoretical' value calculated in the same way

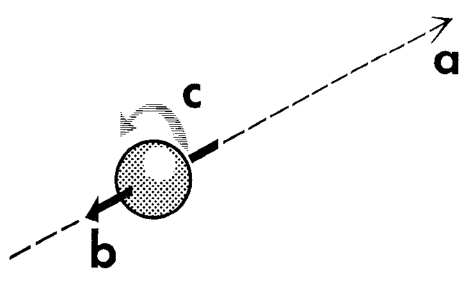


Fig. 3. The muon spins (c) as it travels along, and has a 'spin axis' (b) that starts off pointing backwards along its line of travel (a).

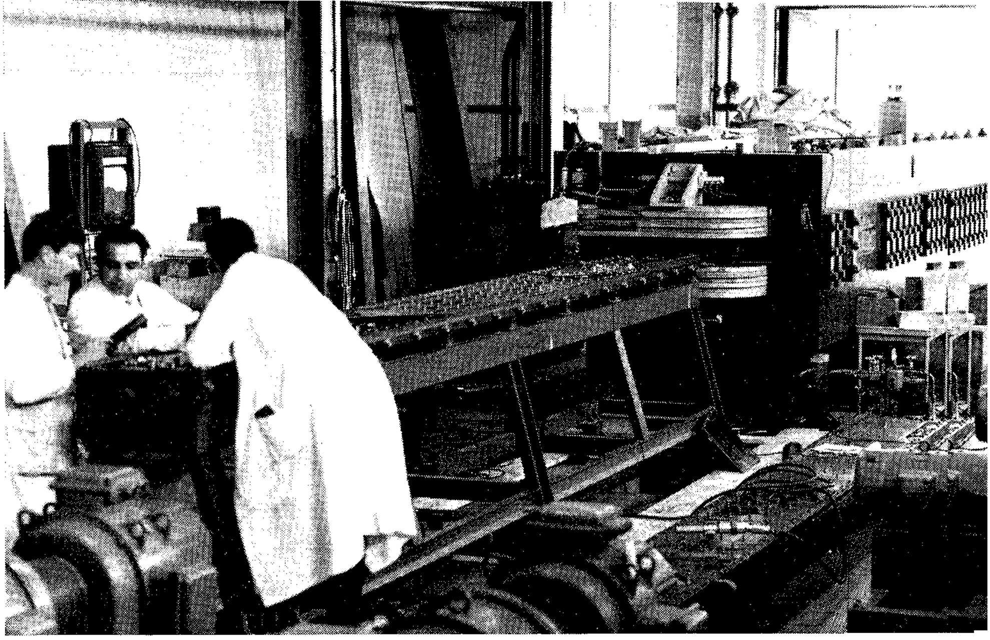


Fig. 4. Some 300 kg of steel strips, mostly 0.5 mm thick but sometimes as thin as 0.03 mm, were used to build up the flat pole pieces of the 6-metre magnet so as to get the right 'shape' for the magnetic field. R. Bouclier (left), **A. Zichichi, and J. C. Sens** (back to camera) **are here engaged on setting up these 'shims' outside the magnet.**

as that for the electron, that is by assuming only the existence of virtual photons but allowing for the different muon mass.

A major difficulty stood in the way, however. To compare an experimental value of the magnetic moment with theoretical predictions, a knowledge of the mass of the muon is required, and although it was possible to carry out an experiment on the magnetic moment with the required degree of accuracy it remained most unlikely that the muon mass could be measured to the same degree.

A way round this difficulty was to measure not the magnetic moment, and hence g itself, but the anomaly, defined as $\frac{1}{2}$ (g-2), which could be considered as arising from the following causes:

— emission and reabsorption of one virtual photon, value + 0.001161
— emission of a virtual photon that temporarily materializes into an electron-positron pair before being reabsorbed value + 0.000006
— other small effects, such as the emission and reabsorption of two virtual photons *, value — 0.000002

total + 0.001165

In this way it would be possible to find a departure at least from the first component by means of an experiment accurate to 1% (0.00001 compared to 0.00116), instead of the one part in a hundred thousand (0.00001 compared to 1.00116) required by measuring g itself.

* If two things each have 1% chance of happening separately, the probability that they will happen together is roughly 1% x 1%, that is 0.01%.

PRINCIPLES OF THE (g-2) EXPERIMENT

In principle, such an experiment could be done; it was already in progress for an accurate evaluation of g for free electrons.

When a positive muon is produced by the decay of a pion, it spins anticlockwise about its line of flight, and the spin axis is said to point backwards (fig. 3). If the particle is travelling in a magnetic field, say between the poles of a large electromagnet, two things happen simultaneously:

1. Because of its electric charge, the particle is deflected by the magnetic field. If the field is 'uniform' (with the same value everywhere) and the particle moves with constant speed, it will travel in circles with a definite frequency (some hundreds of millions of revolutions per second). The spin is in principle not affected by this, and the axis would remain pointed in the original direction if there were no magnetic moment.

2. Because of its magnetic moment, there is an interaction of the spinning particle with the field, which causes the spin axis to revolve in the same sense as the particle orbit. The frequency of the latter rotation is such that the spin axis revolves in space g times for every 2 revolutions made by the particle (see fig. 5)*.

* A further factor is involved for particles moving at relativistic speeds, but this has been ignored here.

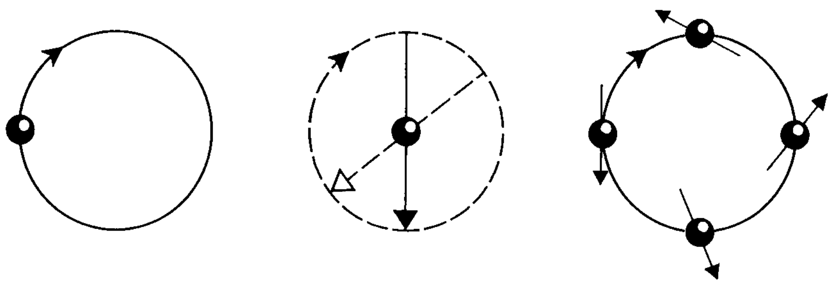


Fig. 5. The muon travels in circles in the magnetic field (a). Its spin axis also rotates in the same sense (b), but slightly faster, so that it is no longer pinting backwards along the line of flight (c) – the angle that the spin axis makes with the line of flight increases slowly with each circle made by the muon, and there are very many turns between each position shown. In the CERN experiment, each circle was slightly displaced sideways with respect to the previous one.

(a) No. of circles made by muon	(b) No. of revolutions of spin axis	(c) Difference between spin axis and line of flight
2	g	(g - 2)
2	2.0023	0.0023 = 0.83° *
200	200.23	0.23 = 82.8°
1000	1001.15	1.15 = 414°

It follows that the spin axis revolves around the direction of motion of the muon at a rate proportional to (g-2), a characteristic that has given the experiment its name. Thus, if the angle between the spin axis and the direction of motion can be measured before and after a known time in the field, it is possible to find (g-2). The longer the time, the greater the accuracy, for a fixed accuracy in measuring the angle.

THE CERN EXPERIMENT

Two major problems had to be overcome before the idea could be made to work successfully. First of all, how could one 'capture' the muons in the magnetic field and get them out again? Fundamental physics laws implied that if the muons had sufficient velocity to get into the field they would just turn round and come back, like a comet round the sun ; if they started life inside, they would not come out. The second problem was that of measuring accurately the directions of motion and spin of the incoming and outgoing muons.

Magnet

Both these problems, and many subsidiary ones, were eventually solved by the CERN (g-2) team. The pole pieces of their magnet were carefully built up with fine metal strips to give a sequence of eight distinct magnetic fields, the strength of each one varying from place to place in a carefully calculated way. Muons, arising from the decay of pions produced by the 600-MeV synchro-cyclotron, were directed with sufficient speed to enter the magnet. There they encountered a beryllium block which slowed each one down so that the magnetic field was then strong enough to curl its track into a circle wholly within the magnet (fig. 6). The successive fields were of such a form that the muon continued to move in circles, each a little to one side of the other so that it 'walked' along the centre of the magnet, with first a few big 'steps' and then many very small ones. Great accuracy was needed to make the muons travel exactly along the centre of the magnet. At the far end the 'steps' were made bigger and the muon was finally 'thrown out' into a special absorber which brought it to rest. There it decayed with the emission of a positive electron.

Spin direction

Now this electron was more likely to be emitted 'backwards', with respect to the spin direction, than in any other way. In fig. 7 the thick arrow represents the spin direction, and the length of each thin one indicates the relative chance of detecting the electron in that particular direction; for a large number of 'identical' muons, the ratio of the numbers of electrons detected at A and B would be different to the ratio for, say, A' and B'. Conversely, if the counters were fixed the ratio would change in a known way as the spin axis was rotated between them. This is how the direction of the muon spin axis was found. Each muon was 'timed' on its journey through the magnet, using scintillation counters and an accurate electronic 'clock' (times varied from about 2 to 8 millionths of a second). In this way the muon was assigned to one of 50 different groups, according to the number of revolutions it had made in the magnet. The ratio of 'forward' to 'backward' electrons was obtained separately for each group, and the systematic change of this ratio with increasing time spent by the muon in the magnet showed, in effect, how fast the spin axis turned around the instantaneous direction of motion. The spin axis revolved about 0.5° per turn faster than the muon, so that for the earliest muons (those taking 2 microseconds to go through the magnet) the spin axis was found to have made an extra half turn, while for the 'latest' ones (taking 8 microseconds) it had made about two turns extra.

In practice the method was considerably more complicated than described here, to eliminate systematic errors that could arise (for example, the simple theory given above is valid only if the decaying muon is exactly half way between the two counters), but the direction of the muon spin after any particular time was effectively determined to less than 1°. To obtain the (g-2) value from this also meant that the direction of the muon spin when it entered the magnet had to be accurately known. Again, this could not be measured for each muon separately, but the average value for the beam was found in a separate experiment, using the same method as for the emerging muons. This also was not easy. For example, the muons arriving from the cyclotron did not all have the spin axis pointing backwards. It was realized that the small proportion of the incident muons that finally got through the magnet

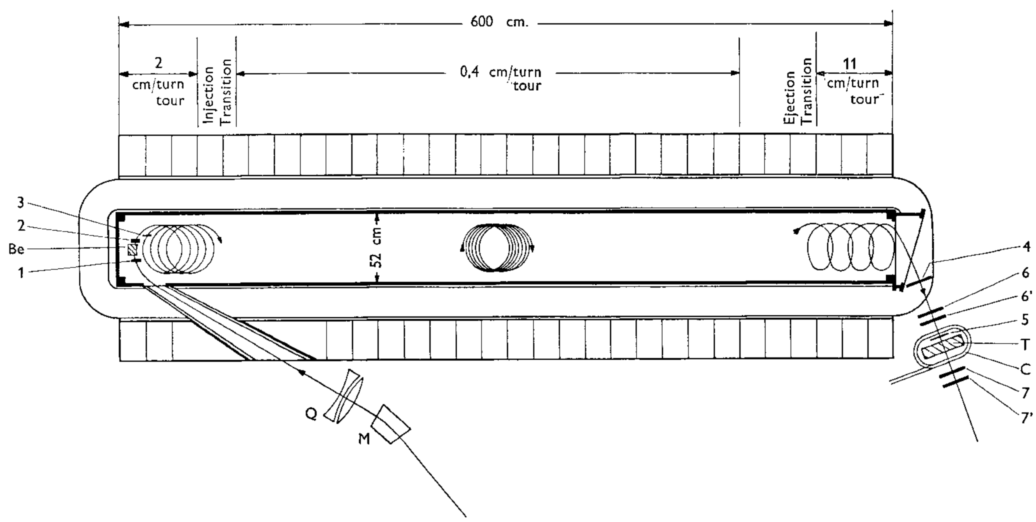


Fig. 6. Simplified plan of the 6-metre magnet used in the CERN experiment. Muons entered via the bending magnet M and the quadrupoles Q. They were slowed down by the beryllium block Be, and the passage of each one noted by the counters 1, 2, 3. A muon that had circled along the centre of the magnet and been ejected at the far end was detected by counters 4 and 5. The muons stopped and decayed in the target T, and electrons were counted by the counter 'telescopes' 6,6' and 7,7'. Because of slight differences in their initial direction, some muons took larger 'steps' and went through the magnet more quickly than others. The time spent in the magnet was measured separately for each one, and showed how many turns it had made. Many muons did not get into a stable orbit, and many decayed on the way through the magnet, so that relatively few completed the course.

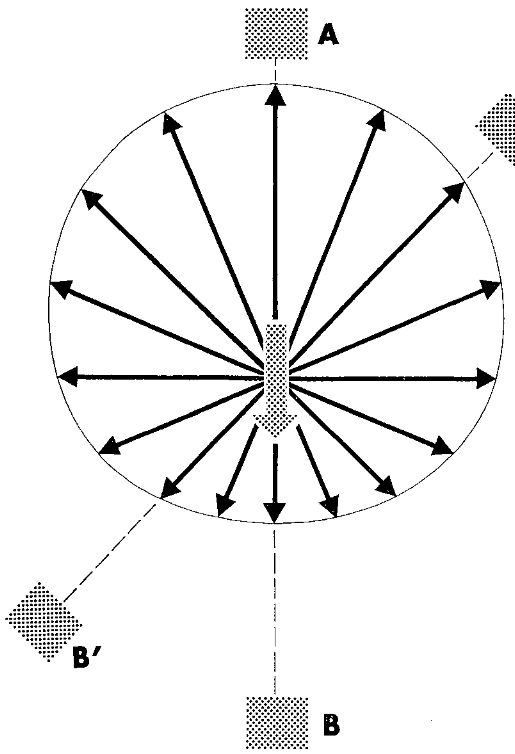


Fig. 7. When the muon decays it emits an electron. The thick arrow here represents the spin axis of the muon, and the length of each thin arrow represents the chance of detecting the electron in that particular direction. Counters placed at A and B to detect electrons from hundreds of similarly aligned muons will record different numbers to those placed at A′ and B′. A variation of this was used to find the directions of the spin axes of the muons emerging from the magnet.

might somehow be specially selected, and thus have an initial spin direction quite different from the average. This variation of spin-axis direction was much less in the vertical plane than in the horizontal one, however, and by passing the muons through a solenoid which produced a magnetic field parallel to their direction of travel, this vertical variation could be made the horizontal one. Any remaining error from this was largely eliminated by 'scrambling' the incident beam so that each part of it entering the magnet would contain muons of the same, known, average spin angle. Even then, muons taking different times to go through the magnet were found to have slightly different initial spin directions, so that separate corrections had to be applied for different groups. Similar complicated corrections had to be made to take account of various other small effects, which all had to be carefully measured. Finally, the (g-2) team could calculate their new result: **the anomalous magnetic moment is 0.001162 ± 0.000005.**

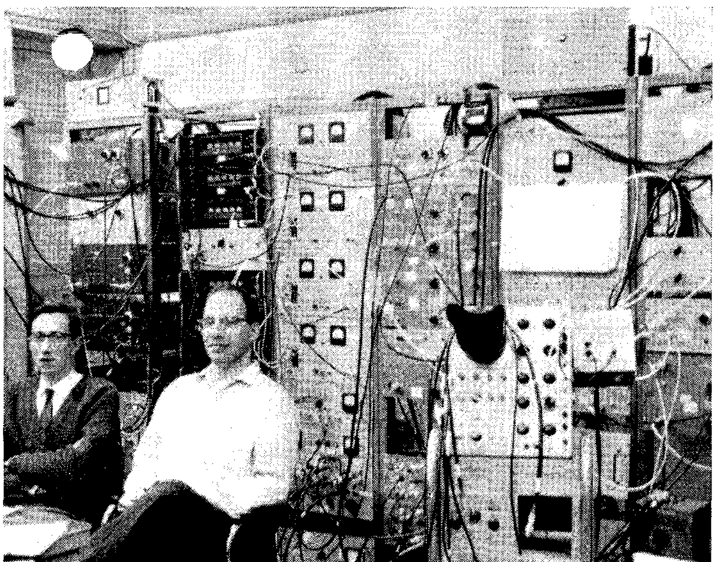


Fig. 8. J. C. Sens (left) and R. L. Garwin are seen here in front of some of the many racks of transistorized electronic counting equipment that the experiment required.

SOME IMPLICATIONS

The first part of this number is the most probable 'answer' from the experiments; from the second part it can be said that the odds are 20 to 1 *against* a true value larger than 0.001172 or smaller than 0.001152.

Thus, it has been shown that **the muon is best regarded simply as a 'heavy electron',** and not as some quite distinct particle. The closeness of the agreement with the calculated value shows in fact that, if the muon interacted with some unknown particle other than a photon, the 'strength' of this interaction would be thousands of times weaker than the strong interaction of the proton.

The result is of great importance in itself, but also has a number of other implications of a more abstruse character. For example, although the theory of quantum electrodynamics has been remarkably successful in explaining very exactly many electromagnetic phenomena, it has often been suggested that it is really only valid down to a certain small, critical distance, in much the same way as classical dynamics is quite accurate enough for material bodies but breaks down for particles of nuclear size. If this were so, the value of the anomalous magnetic moment would be changed by a certain amount, depending on the value of this critical distance. Agreement betweeen the experimental and theoretical values thus shows that **there is no breakdown of quantum electrodynamics down to about 10^{-14} cm.**

By combining the (g-2) results with the accurate value of the magnetic moment obtained by other experiments, the **muon mass** is now known with much higher precision than ever before. It is **206.768 ± 0.003** times the mass of the electron.

CONCLUSION

The successful completion of the (g-2) experiment has told us that the muon in itself has no unusual properties, and has extended the range over which the equations of quantum electrodynamics are certainly applicable. In doing so, it has highlighted the fundamental mystery of the muon. If these two particles, the electron and the muon, are not basically different, why should they both exist and what is the significance of their difference in mass? This remains a challenge for some future experiment ●

The (g-2) team

Much of this issue of *CERN COURIER* is devoted to one experiment, of which the results have just been published, because it seemed worthwhile trying to show its significance and to give an idea of the work involved in such a high-precision meausurement. It is quite common nowadays for experiments in high-energy physics to take several years from the time the idea is first put forward until the final paper is written. During this time many people become involved; there is little possibility in this field for the physicist to think up his experiment, make the necessary apparatus and find the result by himself.

At the centre of all the activity, though, there is a team of physicists who ultimately determine the success or failure of the experiment. Although a number of others were associated with it at various times, the (g-2) Group consisted essentially of six physicists, from almost as many different countries.

Georges CHARPAK comes from France, where he studied engineering at the École des Mines, Paris, and physics at the University of Paris. He then entered Prof. Joliot-Curie's Laboratory at the Collège de France and obtained his Doctorat ès sciences for the study of problems in low-energy physics. In 1957 he discovered how a spark chamber could be used to give photographs of the actual tracks of ionizing particles, but the significance of his findings was not appreciated for several years afterwards. His own development of this new detection method was interrupted when he came to CERN in 1959 to enter the field of high-energy physics with the (g-2) experiment.

Francis J. M. FARLEY is English, and obtained his M. A. and Ph. D. degrees at the University of Cambridge. From 1941 to 1946 he worked on the development of radar, particularly on equipment for locating ships at sea with very high precision, requiring the precise measurement of very short times. After a short while in Canada, where he worked on the first nuclear reactor to be built outside the U.S.A., he returned to Cambridge and began to experiment with cloud chambers, studying the condensation processes that result in particle tracks in the chambers, as well as carrying out research on the decay of muons.

For seven years from 1950, he was a University lecturer in New Zealand, at Auckland, where he supervised the construction of a Cockcroft-Walton accelerator, carried out experiments on nuclear reactions and cosmic rays, and wrote a book on 'Elements of pulse circuits'. A year's leave at Harwell was spent studying fission physics.

Coming to CERN in 1957, he spent two years working on the muon channel and the redesign of the meson beams from the synchro-cyclotron, before joining the (g-2) Group in 1959.

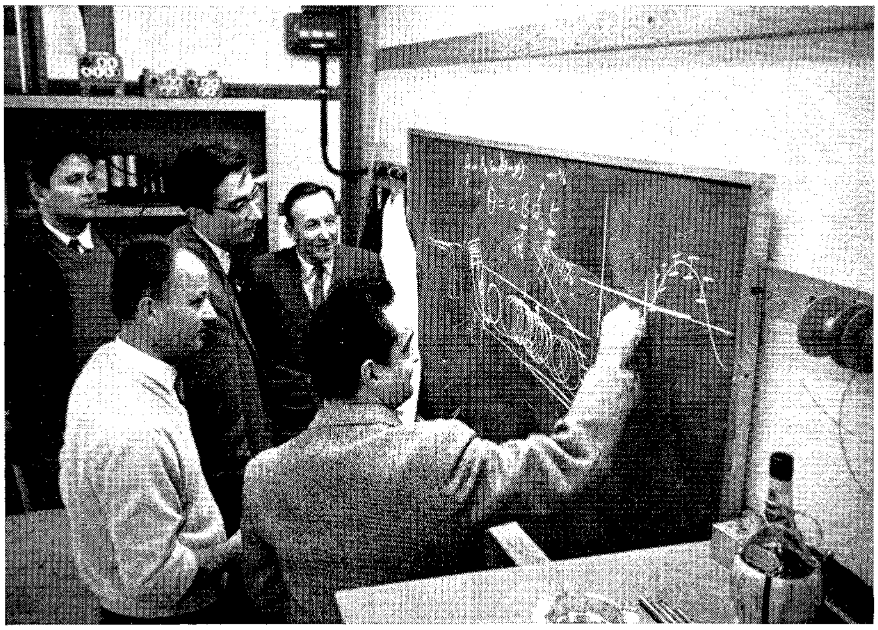
Théo MULLER was born in Strasbourg in 1923, and studied physics at the University there. His first nuclear-physics research was done at the Institut de Recherches Nucléaires of the University, and in 1956 he received his Doctorat d'État for a thesis on electromagnetic transitions in light nuclei. The experiments were carried out with the aid of a 1.5-MeV Cockcroft-Walton accelerator, using scintillation counters and electronic coincidence techniques. In 1957 he spent a year at the University of Utrecht, using an 800-keV Cockcroft-Walton accelerator for the production of positron-emitting nuclei in order to study their subsequent decay.

He is still on the staff of the University of Strasbourg, but his research is now carried out with the aid of the experimental facilities of CERN, where he has been a member of the (g-2) team since his arrival in 1959.

Johannes C. SENS comes from the Netherlands, where he obtained an engineering degree at the Technological University of Delft. The next five years were spent in the U.S.A., at the University of Chicago. After completion of an experiment on the properties of positronium (the short-lived 'atom' formed by a positron bound to an electron) he participated in a series of experiments on muons, involving studies of mesic x-rays, the non-conservation of parity, the polarization of the muon, muon decay, and muon capture. This work included the development of a new technique for measuring the magnetic moment (the g-factor) of the muon to a high degree of accuracy. He received his Ph. D. at Chicago for studies on the capture rate of muons in some 30 different nuclei.

He joined CERN in 1958, and began work on the (g-2) experiment immediately after his arrival.

Antonio (or Nino) ZICHICHI comes from Sicily, where he was born at Trapani and obtained his Dottore in Fisica degree at the University of Palermo in 1953. The following year he went to the University of Rome as a Fellow at the National Institute of Nuclear Physics. Like many others in Europe at that time he had to be content with cosmic rays as the source of particles for high-energy research, and he participated in studies of the production and decay of 'strange'



Five of the Group's physicists discuss the principles of their experiment: left to right are G. Charpak, Th. Muller, J.C. Sens, F. J. M. Farley, A. Zichichi. In the foreground is a souvenir of the day when muons first made 1000 turns within the magnet.

particles in multiplate cloud chambers at the Institute's mountain Laboratory of Testa Grigia. Among their observation was the first example of an 'unstable fragment' a kind of nucleus which contains a lambda hyperon instead of a normal neutron.

Joining CERN in 1956, before either of the machines was in operation, he became a member of the Jungfraujoch Group, which was at that time also carrying out experiments on cosmic rays, using cloud chambers. The most important of the results obtained by this Group were the first examples ever observed of the neutral tau meson and of the neutral anti-K particle.

When the synchro-cyclotron came into full operation and this work was ended, he became a member of the (g-2) Group.

Although he is no longer at CERN, one other member of the team should be mentioned. **Richard C. GARWIN** is an expert in many fields. He was born at Cleveland, Ohio, U.S.A., and studied at the Case Institute of Technology and the University of Chicago, where he received his Ph. D. in 1949. In 1952 he joined the IBM Watson Laboratory at Columbia University, and since then has combined low-temperature research with high-energy physics at the Columbia cyclotron, as well as being a consultant for thermonuclear research. In 1957 he participated in the discovery of the non-conservation of parity for muons. He was a member of the (g-2) team during a year's stay at CERN, as a Ford Foundation Fellow, in 1960, the year in which the first results were obtained. Since then he has paid a number of visits to Geneva and continued to take an active interest in the experiment.

Also playing a large part in the experiment were the technicians who often worked long hours in helping to construct the equipment.

Bruno NICOLAI comes from Italy, where he studied at the Instituto Industriale in Ferrara, and obtained his Diplom de Perito Industriale in electrical and mechanical subjects. Before coming to CERN at the end of 1958 he worked for the Istituto Nazionale di Fisica Nucleare in Milan.

Roger BOUCLIER, who is French, came to CERN early in 1960, having previously worked in Geneva for the Société des Compteurs. He is skilled in electrical and mechanical work, after training at the École nationale professionnelle d'Horlogerie at Cluses.

Julien BERBIERS, who assisted with the later experiments, joined CERN in August 1961. He comes from Belgium, where he trained as an electronics technician at the Institut pour Industrie nucléaire in Brussels. Before coming to CERN he worked at the Institut interuniversitaire de Physique nucléaire of the École Militaire in Brussels.

What are the (g-2) physicists doing now? Three of them, Farley, Muller and Zichichi, with Th. Massam, have been using the special timing apparatus for new measurements on the muon lifetime at rest. With M. Conversi and L. Di Lella they are planning an experiment at the proton synchrotron, to detect electron pairs in the decay of antiprotons. Sens is preparing an experiment, with P. J. Duke and P. G. Murphy, both from Harwell, England, on the 'peripheral' capture of muons in nuclei; later they plan to measure correlations in the beta-decay of the lambda particle. Charpak has returned to the development of spark chambers, on which he has some promising new ideas ●

BOOKS

L'Homme dans l'espace, by A. Ducrocq
(René Julliard, Paris, 15.— NF)

Founder of a new concept in the field of automation, which he named 'intellectique', the science writer Albert Ducrocq is now directing his attention firmly towards space. After two previous volumes devoted to the cosmos, this book, published last May, deals with space machines of the 'second generation' — space ships, rather than the artificial satellites that represented the first generation.

The book is a review of astronautics on the threshold of a new stage in its development. The author explains the operational research that determines the programme of human ventures into space, and studies the vehicles now being made and used.

At a time when people in all parts of the world are becoming aware of the necessity for a space policy, this book will find a place on the shelves of all those who wish to have a clear and imaginative description of the problems involved in the conquest of space. R.A.

CPS User's Handbook (CERN, private distribution)

— What are the ranges of energy and intensity of the CERN proton synchrotron (CPS)?
— How are the experimental halls laid out?
— What is the procedure for obtaining machine time?
— How many antiprotons were found in the fast separated antiproton beam?
— What are the facilities available in the Counting Rooms?
— What are the characteristics of the CERN beam-transport elements, and under what conditions may additional equipment be brought to CERN?
— How is experimental apparatus aligned?
— What kinds of shielding material are available at CERN?
— What are the main safety regulations and standards in CERN?
— How is hydrogen handled around the CPS?
— Which reports are available for ready information on these subjects?

These are just some of the many questions to which a newcomer to the CPS wants to find answers before he gets to the stage of actually starting his research work. And even after he knows his way around the accelerator, he likes to have on hand a collection of data, graphs and tables for improving the first experiment or designing a new one.

Most of this information is now available (though in English only) in the CPS User's Handbook. In about 200 pages this deals with:
(i) generalities of the CPS,
(ii) primary beam data,
(iii) information on the CPS distributed to users during operation,
(iv) secondary beams and their use,
(v) general facilities in experimental areas, and
(vi) security regulations and safety codes.

A loose-leaf binding enables the information to be kept always complete and up to date.

Besides distribution to physicists working at CERN, about thirty copies of the Handbook have been sent to the libraries of Universities and Research Institutes with whom CERN is in close contact, and more copies are about to go out. It is hoped that this will help to smooth the path of all those carrying out experiments in conjunction with the CPS, and especially of teams doing so for the first time. K.H.R. ●

A search for Dirac magnetic poles

by **L. HOFFMANN, W. O. LOCK,** and **G. VANDERHAEGHE**

Nuclear Physics Division

About 30 years ago Dirac predicted the existence of positive electrons as a natural consequence of his quantized theory of the electromagnetic field. As is well known, his prediction was experimentally verified rather quickly. At about the same time, Dirac showed that one can construct a theory which contains, as sources of the electromagnetic field, point magnetic poles (monopoles) besides point electric charges. The theory in fact is not at all complete; however, the existence of magnetic poles does not contradict any well-established law of nature. Therefore, many authors have proposed experiments in order to search for poles, either in cosmic radiation or among the secondary particles produced in high-energy collisions. For example, Bradner and Isbell, in 1958, carried out a series of such experiments at the Berkeley Bevatron. The fact that none of these experiments showed any evidence for the existence of poles may be interpreted as the consequence of either of two things:

1. Their mass was too large to allow their production (in pairs) at the energies reached with the accelerators used. (The energy of the Bevatron is enough to produce a proton-antiproton pair; the mass of the poles should then be larger than that of the proton.)

2. The cross-section for their production was so small that it was very unlikely they would be found amongst secondary cosmic rays.

The higher energies available at CERN make it possible to extend the search up to mass values for the poles nearly three times the proton mass. It was therefore suggested independently by Amaldi (November 1959) and Bradner (January 1960) that a series of experiments should be carried out at CERN to search for poles, using nuclear emulsions as detectors.

Eventually a mixed research group was set up for this work consisting of E. Amaldi, G. Baroni, H. G. de Carvalho and A. Manfredini, from the Institute of Physics of Rome, H. Bradner, from the Lawrence Radiation Laboratory at Berkeley, and L. Hoffmann and G. Vanderhaeghe, from CERN. Two types of experiment were carried out in 1961, and both gave a negative result.

It should be mentioned that similar experiments, but using counter techniques to detect the poles, were carried out in 1961 by a group at Brookhaven and by M. Fidecaro, G. Finocchiaro and G. Giacomelli at CERN; both groups also obtained negative results.

A third experiment using emulsions has been started at CERN in February of this year. It is more straightforward than the two previous ones and should give the most reliable upper limit of the cross-section for the production of poles in proton-nucleon collisions at 28 GeV. We will describe it here; the experimental apparatus used is shown in the accompanying photograph.

It is assumed that pairs of poles will be produced in a target, placed in the proton-synchrotron accelerator,

P. A. M. Dirac is an English physicist who introduced the relativistic quantum theory of the electron that is the basis of present-day quantum electrodynamics. He was a joint recipient of the Nobel Prize for Physics in 1933.

Mass and energy are interchangeable, so that if any fundamental particle is accelerated and given a sufficiently high energy the possibility exists of converting a large part of the combined mass and kinetic energy of the particle into the mass of some new, heavier particle. Conversely, before there can be any hope of producing any new particle postulated theoretically, a certain minimum energy is required, corresponding to its mass.

The gauss is the unit in which the strength of magnetic fields is measured. For example the earth's magnetic field is equivalent to about 1/5 gauss while a small horseshoe magnet gives a field of a few hundred gauss.

Nuclear emulsions are special photographic emulsions, basically similar to the coating on an ordinary film. A charged nuclear particle passing through the emulsion causes ionization along its path, and this shows up as a trail of tiny black blobs on development of the emulsion.

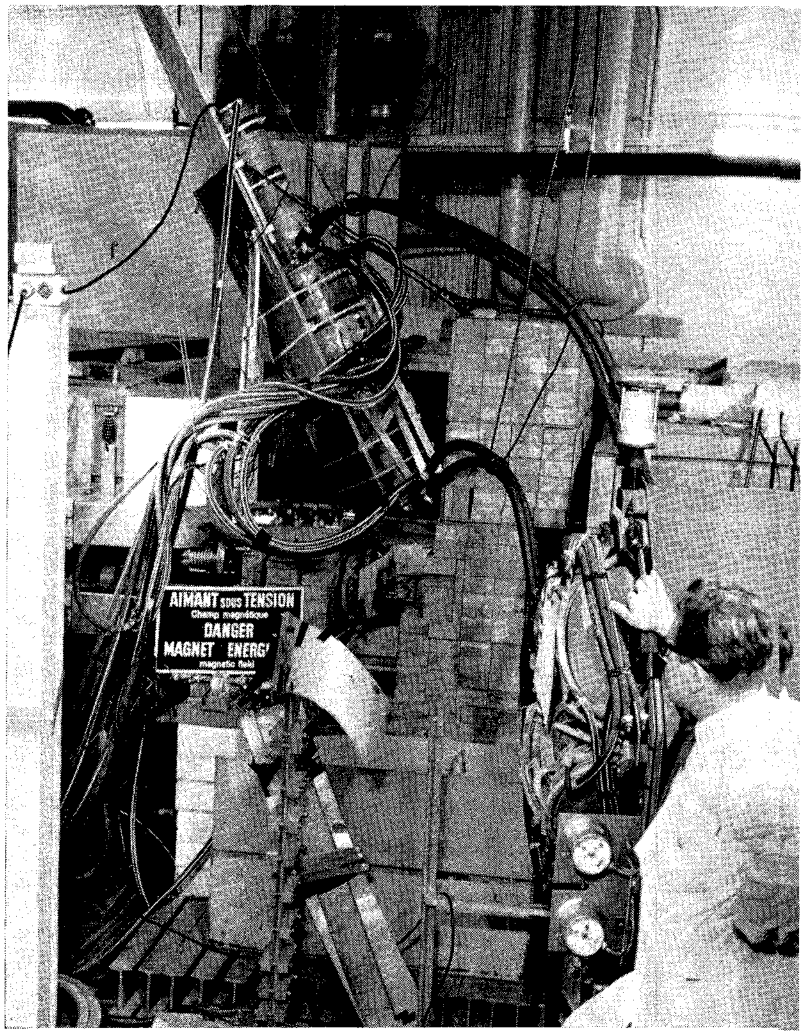
A relativistic particle is one that is moving at such a high speed that the classical laws of mechanics are no longer completely accurate. For example any further gain in energy tends to increase its mass rather than its velocity, and 'relativistic' mechanics have to be used in any calculations.

Cross-section of a nuclear reaction is a measure of its probability of occurrence. For a common nuclear reaction the cross-section is about 10^{-24} cm^2, so that a cross-section of 10^{-39} cm^2 represents a reaction some 10^{15} times less probable.

when it is bombarded by 28-GeV protons. At a short distance downstream from the target, the poles enter a high magnetic field (about 20 000 gauss) produced by a pair of pulsed coils (Krienen coils, partly visible at the bottom of the photograph to the right of the warning notice). The poles are deflected by this field in such a manner that a reasonable fraction of them are extracted from the vacuum chamber of the machine and 'sucked' through the upper coil. They are then steered by a smaller magnetic field (about 2000 gauss) inside a series of three solenoids, in which emulsion stacks are placed at different levels. (The solenoids are visible on the photograph, making an angle of 60° to the horizontal). A shielding of lead protects the emulsion against direct radiation from the target.

Now it follows from Dirac's theory that poles lose energy very rapidly by ionization when passing through matter (relativistic poles ionize at least about 4700 times more than a relativistic elementary charged particle). Thus, in nuclear emulsion, a pole should leave a very distinctive heavy track. In the experiment we are describing, relatively insensitive emulsions were used, in conjunction with a special processing technique so that the general background from the synchrotron gives only a slight fogging after two hours of irradiation. The track of a pole should still show up clearly, however.

The emulsions have already been processed and are now being examined. If no poles are found, the experiment will allow an upper limit of the order of 10^{-39} cm^2 to be assigned to the cross-section for the production of poles in proton-nucleon collisions at 28 GeV (or 7,5 GeV in the centre-of-mass system) ●



The experimental arrangement used in the search for magnetic monopoles. Immediately to the right of the warning notice can be seen the bus-bar connexions to the pulsed coil, and above these the three solenoids that contain the nuclear emulsions slope up to the left.

News from Abroad

ACCELERATOR DEVELOPMENT IN THE U.S.A.

A simultaneous announcement on 1 February from the U.S. Atomic Energy Commission and the **University of California** gave the news that the **88-inch cyclotron** at the University's Lawrence Radiation Laboratory had accelerated its first beam.

This machine, the latest in the battery of particle accelerators at the Laboratory devoted to exploring the atomic nucleus, is especially interesting, because of its **'spiral-ridge'** design. Its general appearance is similar to that of other cyclotrons, including the 600-MeV synchrocyclotron at CERN, but there is an important difference in the magnet. The two pole faces, 2235 mm (88 inches) in diameter, are not flat, but each have three spiral ridges, plateaus about 5 mm high, radiating rather like the arms of a starfish from the centre. In this way the strength of the magnetic field which acts on the accelerated particles between the pole faces varies along the path of the beam, keeping it focused and 'in step' with the accelerating frequency to a higher energy than is possible with a simple cyclotron.

Protons will be accelerated to 50 MeV, deuterons (nuclei of heavy hydrogen) to 60 MeV, and alpha particles (nuclei of helium) to 120 MeV. Later the machine will be used to accelerate heavier nuclei, such as carbon-12 or oxygen-16, to about 10 MeV. Although these energies are not high compared to those produced by many larger machines, the beam intensity is expected to be some thousand million million (10^{15}) particles per second (about 200 times higher than that of the CERN synchro-cyclotron). The energy can also be varied over a very wide range by adjusting the accelerating frequency.

The new accelerator will allow more accurate measurement of phenomena occuring in nuclear scattering experiments and will permit the production in larger quantities than before of selected isotopes of all the elements, including the man-made elements heavier than uranium. New areas are expected to be opened up in atomic-beam research, nuclear spectroscopy, and the biological effects of radiation.

Another giant accelerator went into operation in the U.S.A. in March. This was the **Cambridge Electron Accelerator,** a synchrotron for accelerating electrons to 6 GeV. Similar in principle to the CERN proton synchrotron, it is 72

(continued on p. 12)

Last month at CERN (cont.)

Prof. V. F. Weisskopf (extreme right) **is seen here in conversation with Mr. Jenö Kouti** (left) **the Hungarian Minister to Switzerland, and Mr. Istvan Bartos** (right), **Permanent Representative of Hungary to the International Organizations in Geneva. The photograph was taken on 14 March 1962, on the occasion of the presentation at CERN of the Grand Prix cup and diploma won by the CERN film 'Matter in Question' at the 2nd International Festival of Technical and Scientific Films in Budapest.**

proton synchrotron, the members of R. Bizzarri's group have returned to the **University of Rome.** Their **20-cm liquid-helium bubble chamber** has been put into store at CERN awaiting possible future experiments.

The **Health Physics Group** began operating its own blood-test service on 12 March. All those who carry film badges will be subject to a test at least once a year, depending on their measured radiation dose. Previously this service had been conducted in co-operation with a clinic in Geneva, but the number of people involved (some 800) now makes this impracticable.

Dr. P. Maurice, a specialist in radiation haematology at the Hôpital Cantonal, Geneva, is acting as Consultant for the new service, which will be operated by two specially trained medical technicians.

Among the **visitors** last month was the U.S.S.R. Ambassador to Switzerland, Mr. I. Kouzmine, who was welcomed to CERN by Prof. Weisskopf on 7 March. He was accompanied by Mr. N. Afonine, Councellor, and Mr. A. Doubrovine, Secretary at the Embassy in Berne, and during their tour they met the three members of the Dubna Laboratory who are at present at CERN.

A week later, Mr. J. Kouti, Hungarian Minister to Switzerland, and Mr. I. Bartos visited CERN to present the silver cup and diploma awarded to the CERN film last December ●

We regret to report the sudden death of **Marcel Grütter,** of Nuclear Physics Apparatus Division. Leaving CERN as usual on the previous day, he died in his sleep during the night of Saturday 24 March.

At CERN since 1954, he was the first electronics technician of the Magnet Group, and the Laboratory that grew up around him worked on instrumentation for magnetic measurements on the big PS magnet and other electronic devices. Later on Marcel Grütter was seriously involved in construction of the instrumentation and controls for the 1-m CERN propane bubble chamber.

The heartfelt sympathy of all his colleagues at CERN is extended to his wife and children.

News from Abroad (cont.)

metres in diameter and cost 12 million dollars (51 million Fr. s.) to build.

The electron energy expected to be achieved with this accelerator is about the maximum possible with a circular type of machine. This is because an electron moving in a magnetic field (necessary to keep it in a circular orbit) radiates energy, and the rate at which energy is lost in this way increases rapidly with increase in the energy itself. Thus a limit is reached when the rate of energy input to the electron is just balanced by the rate of energy loss. This limit is at about 6 GeV.

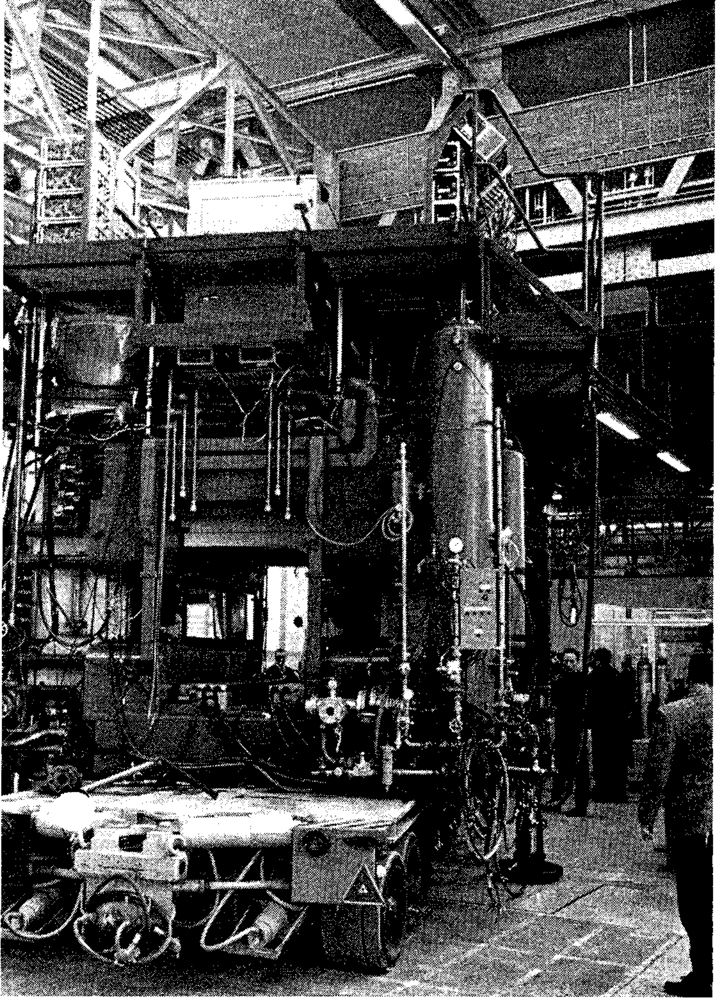
Apart from high-energy electrons which can be used to explore nuclear structure, the machine will generate intense beams of 6 GeV gamma rays (high-energy x-rays), for exploring the structure of matter and producing other nuclear particles.

Further information on U.S. accelerators has been given in the **U.S. Atomic Energy Commission's annual report** for 1961, published recently. Last August, the **Cyclotron Analogue II** went into operation at the Oak Ridge National Laboratory and achieved its design energy of 450 keV. This Analogue, on the same principles as the 88-inch cyclotron, is an electron accelerator which models the magnetic field of a fixed-frequency proton cyclotron to operate at 850 MeV. To obtain such energies with constant accelerating frequency, the average magnetic field has to increase with radius, to allow for the increase of particle mass at speeds approaching that of light. Normally, this field increase would have the effect of defocusing the beam so that the particles would be lost, and machines like the CERN SC avoided the difficulty by varying both the magnetic field and the accelerating frequency with time as the particles were accelerated. The new principle, which is also being actively studied at CERN, employs an azimuthal variation of the field as well as the steady radial increase, the overall effect being to keep the beam in focus as well as in step with the frequency. Such **isochronous cyclotrons** have the advantage of giving a continuous beam instead of a pulsed one, and that is why they are capable of producing such high beam intensities. The successful operation of the Analogue II has strengthened the belief that a proton cyclotron in the range of 800 to 1000 MeV is possible.

Another machine of this type, the **Oak Ridge Isochronous Cyclotron** will soon be completed, and is expected to give very large beam currents at energies of up to 75 MeV for protons. Focusing of the beam in the median plane between the magnet faces is achieved by the specially shaped pole pieces and a total of 21 separate magnet-coil circuits, each with its own well-regulated electric power supply.

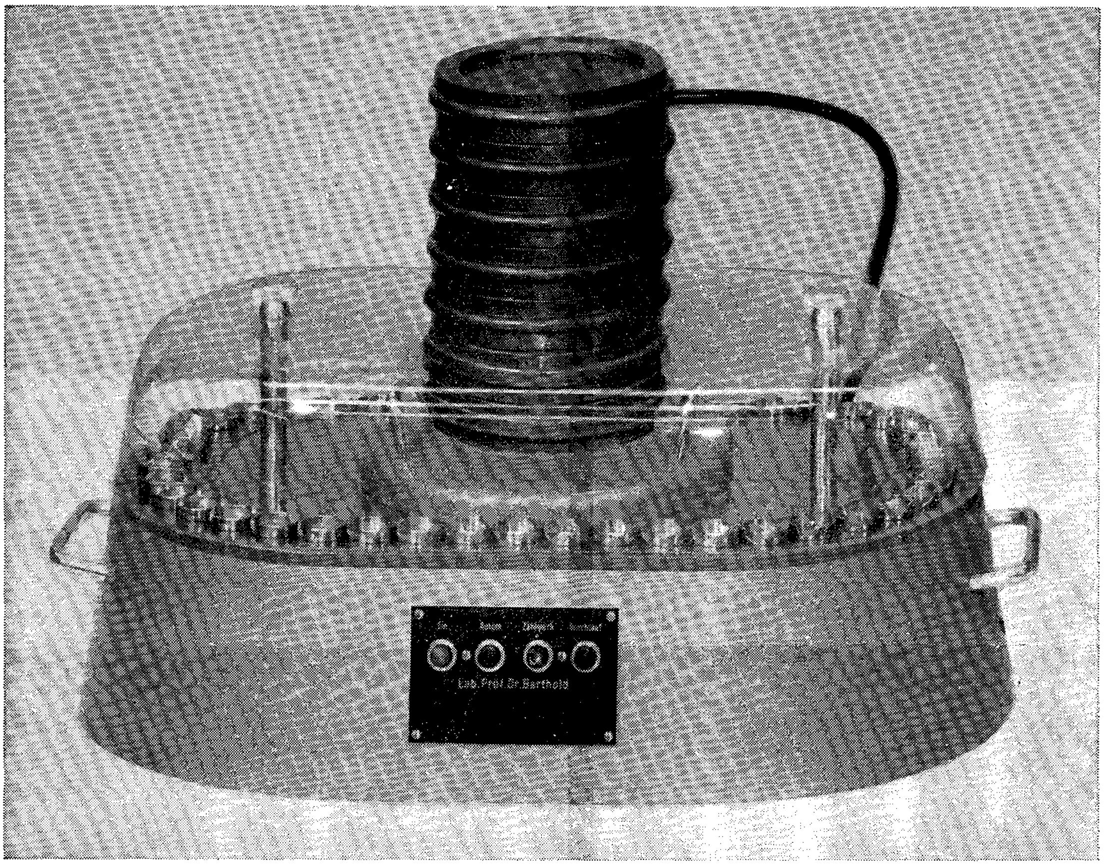
In 1961, the U.S.A.E.C. spent 48 million dollars (210 million Fr. s.) on high-energy research, out of 124 million dollars devoted to research in chemistry, metallurgy, and physics. This total amount represents a 23% increase on the expenditure for 1960.

The latest news from **Brookhaven** is that their 33-GeV Alternating Gradient Synchrotron (AGS) is now producing beams of over **4.5×10^{11}** particles per pulse ●



The 85-ton magnet structure of the CERN Wilson Cloud Chamber during its journey along the PS South experimental hall on 7 March.

for quantity assay of radio-active samples



The construction of automatic sample changers has evolved a long way. Since a solution was found for the sample-changing mechanism per se, ingenuity was aimed at obtaining optimum measuring geometry and suppression of the background, in short at the improvement of the measuring and the reproducibility.

A definite point has been reached with the new Philips/Berthold automatic sample changer, type PW 4001.

In it the 40 samples are carried along a race track which has been shaped in such a way as to obtain an almost even distribution of active matter around the radiation detector.

Moreover the detector is shielded from the waiting samples by more than 10-cm (4-in) of lead equivalent.

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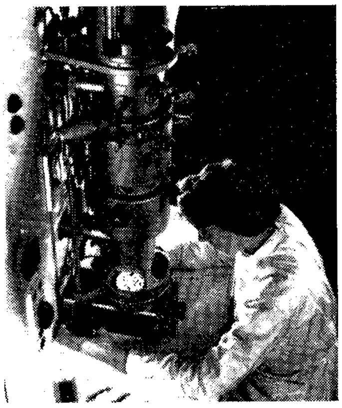

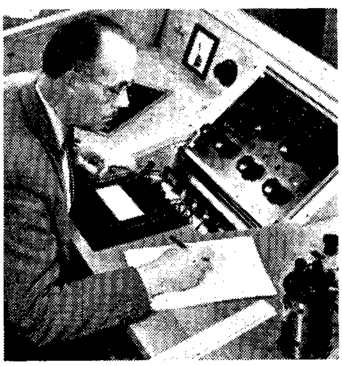

Measurement and control in thermal and processing techniques

Electrical metrology

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Measurement of mechanical quantities

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