

# Physics with Large Cyclotrons

A. W. MERRISON \*

Daresbury Nuclear Physics Laboratory, England

(Z. Naturforsch. 21 a, 1748—1750 [1966] ; received 21 March 1966)

*Dedicated to Professor Dr. W. GENTNER on the occasion of his 60th birthday*

The physics done with large cyclotrons in the last 10 years is outlined, with particular reference to experiments done with the 600 MeV cyclotron at CERN.

One of the many contributions which W. GENTNER has made to European physics was the bringing into operation of the CERN 600 MeV synchro-cyclotron and the successful launching of the experimental programme on it. The CERN cyclotron was the last of the big synchro-cyclotrons to be built and it seems appropriate in honouring GENTNER to say something of the contribution that these accelerators have made to physics and in particular to discuss some of the beautiful experiments which have been carried out with the CERN cyclotron. As one who was closely associated with GENTNER in his years at CERN it is a particular privilege and pleasure for me to record some of this work.

The CERN cyclotron started work in August 1957 at a particularly critical time for such machines. LEE and YANG had made their suggestion<sup>1</sup> that parity was not conserved in the weak interactions just about a year previously. Since pions and muons, beams of which are readily available from large cyclotrons, both decay through a weak interaction, it was clear that parity violating effects should be quite apparent in such decays. The first experimental confirmation of this was the experiment at Columbia of GARWIN, LEDERMAN, and WEINRICH<sup>2</sup> which showed not only that parity was not conserved in either the pion or muon decays, but that the violation seemed to be complete. It is interesting also that in this first paper GARWIN et. al showed that because the muon was polarised it was possible to make a very precise measurement of the anomalous magnetic moment of the muon (the “ $g-2$ ” experiment) which later both GARWIN and LEDERMAN were to help carry out on the CERN cyclotron.

The publication of the Columbia experiment in January 1957 led to a feverish burst of activity on the decay of the pion and muon with cyclotrons all over the world, and many theoretical and experimental questions were settled rather quickly, to the uneasiness of the experimenters in CERN who were waiting for the cyclotron to start work!

However, I think it is no exaggeration to say that the programme on the CERN cyclotron has been outstanding among the world's cyclotrons and this is certainly due in large measure to the guidance it was given in its initial stages by GENTNER and his colleague BERNARDINI.

The whole question of conservation laws in elementary particle physics has played a dominant role since the work of LEE and YANG. The surprise of parity violation was quickly replaced by a deeper understanding of nature based on the CPT theorem<sup>3</sup> which guarantees that any theory which is invariant under proper LORENTZ transformations is invariant under the combined operation of charge conjugation (C), space inversion (P) and time reversal (T) though it need not be invariant under any one of them. The theorem has as a consequence, for example, that the lifetimes for particle and anti-particle decay through a weak interaction must be the same, and the best experimental confirmation of this is that the ratio of positive and negative muon lifetimes is indeed unity to an accuracy of about 0.1%.

The elementary observation that the muon from pion decay and the electron from muon decay are always polarised along the direction of motion shows immediately that parity is violated in both processes. Similarly since the  $\mu^-$  is emitted with

\* Daresbury Nuclear Physics Laboratory, England.

<sup>1</sup> T. D. LEE and C. N. YANG, Phys. Rev. **104**, 254 [1956].

<sup>2</sup> R. L. GARWIN, L. M. LEDERMAN, and M. WEINRICH, Phys. Rev. **105**, 1415 [1957].

<sup>3</sup> W. PAULI, Niels Bohr and the Development of Physics, Pergamon Press, London 1955.



its spin always parallel to its direction of motion while that of the  $\mu^+$  is antiparallel it follows that charge conjugation is violated in pion decay. These questions, and many others, were settled during 1957, and early in 1958 FEYNMAN and GELL-MANN<sup>4</sup> proposed their conserved vector current theory of weak interactions which not only settled the nature of the coupling in the weak interaction but put forward a mechanism which eliminated the need for renormalisation of the coupling constant. This was to receive confirmation in two experiments later carried out on the CERN cyclotron.

The first, completed in the summer of 1958, was concerned with the branching ratio of the decays  $\pi^+ \rightarrow e^+ + \nu$  and  $\pi^+ \rightarrow \mu^+ + \nu$ . FEYNMAN and GELL-MANN had shown that there should be no large corrections to a simple calculation of this ratio based on the assumption that the electron and muon were coupled symmetrically to the nucleon. This calculation, with a small radiative correction, leads to a predicted branching ratio of  $1.23 \cdot 10^{-4}$ , and this the CERN experiment<sup>5</sup> confirmed to the experimental accuracy of 25%. The best measurement to date of this ratio is  $(1.21 \pm 0.07) \cdot 10^{-4}$  by the Chicago group<sup>6</sup>.

The second experiment, most beautifully carried out at CERN and also at DUBNA and BERKELEY, is on the FEYNMAN-GELL-MANN prediction for the branching ratio  $(\pi^+ \rightarrow \pi^0 + e^+ + \nu) / (\pi^+ \rightarrow \mu^+ + \nu) = 1.07 \cdot 10^{-8}$ . The experimental value for this ratio is  $(1.12 \pm 0.08) \cdot 10^{-8}$ . It is a measure of the extraordinarily careful way that this experiment has been done that its accuracy is about the same as that for the  $(\pi \rightarrow e + \nu) / (\pi \rightarrow \mu + \nu)$  branching ratio despite the fact that the decay is rarer by a factor of  $10^4$ .

The experiments I have described so far have all been directed towards the fundamental conservation laws of nature. But there has been one substantial contribution which the large cyclotrons have made to quantum electrodynamics and that is in the so-called " $g-2$ " experiment on the muon.

From the point of view of elegance of experimental technique and measurement, perhaps the outstanding experiment carried out with the CERN cyclo-

tron is this on the anomalous part of the  $g$ -factor of the muon. This experiment was based on the principle, used by Crane in his measurement of the  $g$ -factor of the electron, namely that for any particle with  $g=2$  (a DIRAC particle) the LARMOR precession frequency is equal to the cyclotron resonance frequency. So in a uniform magnetic field the spin of the particle precesses at the same rate with which the particle performs a circular orbit. Hence the spin vector maintains always the same orientation with respect to the direction of motion. Correspondingly, the rate at which the spin vector rotates around the direction of motion is a measure of the deviation of  $g$  from the value 2. And it is for this reason that the experiment is named the " $g-2$ " experiment.

This experiment carried out at CERN<sup>7</sup> during the years 1959–63 has led to the value for the muon  $(g-2)/2 = 1.001162 \pm 0.000005$  to be compared with the theoretical prediction of 1.001165. The experiment was done in a long (6 m.) magnet along which the muon "walked" while it rotated. In this way the spin rotation after many hundreds of revolutions could be measured. Again an interesting measure of the care with which this experiment has been carried out is to compare it with the latest measurement for the electron with

$$g-2 = 1.001159622 \pm 0.000000027.$$

The accuracy of the electron experiment has been increased substantially in this latest result of Wilkinson and Crane. An improvement of the muon experiment of this kind will not be possible because of its finite life-time.

The attention of experimenters on the large cyclotrons is turning away from elementary particles to some extent to the area of nuclear structure which can be illuminated by experiments with large bombarding energies.

In such experiments higher momentum states of nuclei are excited and with modern analysis techniques they are already making substantial contributions to our understanding of nuclear structure.

But the interest in fundamental experiments on the elementary particles with large cyclotrons is

<sup>4</sup> R. P. FEYNMAN and M. GELL-MANN, Phys. Rev. **109**, 193 [1958].

<sup>5</sup> J. ASHKIN, T. FAZZINI, G. FIDECARO, A. W. MERRISON, H. PAUL, and A. V. TOLLESTRUP, Nuovo Cim. **13**, 1240 [1959].

<sup>6</sup> H. L. ANDERSON, T. A. FUJII, R. H. MILLER, and L. TAU, Phys. Rev. **119**, 2050 [1960].

<sup>7</sup> G. CHARPAK, F. J. M. FARLEY, R. L. GARWIN, T. MULLER, J. C. SENS, and A. ZICHICI, Nuovo Cim. **37**, 1241 [1965].

by no means dead and I can best illustrate this by some considerations of BERNSTEIN, FEINBERG and LEE<sup>8</sup> on the discovery that the long-lived neutral K-meson can decay into  $\pi^+ + \pi^-$ , implying that CP is not conserved in this decay<sup>9</sup>.

The proposal of BERNSTEIN et al. is that the breakdown is not in the weak interaction but that there is a large violation of both C and T in the electromagnetic interaction. One would expect this to "leak" through into the weak decay of the  $K_2^0$  with an amplitude of  $\sim \alpha/\pi (=2.3 \cdot 10^{-3})$  and this compares with the observed amplitude of  $K_2^0 \rightarrow \pi^+ + \pi^-$  (relative to  $K_0' \rightarrow \pi^+ + \pi^-$ ) of  $2.2 \cdot 10^{-3}$ . Thus it becomes important to examine experiments which test the conservation of C and T in the electromagnetic interaction.

<sup>8</sup> J. BERNSTEIN, G. FEINBERG, and T. D. LEE, Phys. Rev. **139**, 1650 [1965].

One such experiment which is being carried out at Columbia by LEDERMAN and SCHWARTZ<sup>10</sup> is to look for the polarisation of the neutron with respect to the plane of the DALITZ pair in the reaction  $\pi^- + p \rightarrow n + \pi^0 \rightarrow \gamma + e^+ + e^-$ . Such a polarisation would immediately indicate the breakdown of time reversal invariance in this process.

In this very partial selection of experiments I have tried to show something of the contribution that the large cyclotrons have made to physics over the last two decades. This contribution is certainly not at an end, and although the work which GENTNER and his colleagues started at CERN in 1957 has been most fruitful it is quite certain we can still look forward to novel and interesting developments in this field in the future.

<sup>9</sup> J. H. CHRISTENSON, J. W. CRONIN, V. L. FITCH, and R. TUSLAY, Phys. Rev. Letters **13**, 138 [1964].

<sup>10</sup> L. M. LEDERMAN and M. SCHWARTZ (private communication).