APPLICATIONS OF CYCLOTRONS IN PARTICLE PHYSICS

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Abstract

Experiments at low and medium energy cyclotrons have made in the past, and will continue to make in the future, important contributions to Particle Physics which are often complementary to research work at high-energy accelerators. We discuss a few examples, mainly from electromagnetic and weak interactions, which illustrate this and most of which concern problems of current interest in Particle Physics.

1. Introduction

For most physicists Particle Physics is synonymous with High Energy Physics. Indeed, new particles, new phenomena in their behaviour and their interactions, new systematics in their spectroscopy, symmetries and symmetry breaking, are usually discovered at accelerators of high and ultra-high energies. Progress in the phenomenology of the particles and their interactions comes indeed mostly from the high-energy accelerators; past experience shows, on the other hand, that progress in the understanding of Particle Physics comes often from the combined experimental information at high and low energies. This is illustrated very clearly by the history of the theory of Weak Interactions, as an example. Here experimental research covers all available energies, from nuclear β-decay up to neutrino reactions at high energies. A satisfactory theory of Weak Interactions (possibly and quite likely combined with electromagnetism) will eventually be constructed on the basis of the experimental information at all energies.

Even today, at the beginning of the era of accelerators in the hundreths of GeV region and of the various storage rings, cyclotrons at low and intermediate energies can yield important contributions to Particle Physics. In many cases, results from research at moderate energies are complementary to information from high energies. While experimental research at high-energy accelerators is often rather of an exploratory nature, experiments at low and intermediate energies are competitive for Particle Physics mainly through the precision which can be reached here. The high intensities of medium-energy accelerators, in particular, allow for experiments of very high precision and make possible studies of extremely rare processes. Below, we give a few examples of both types of experiments.

In our discussion we have chosen a few examples which attack rather fundamental questions of Particle Physics and which are typical, it seems to us, for research which can be done at low and medium energies. Our choice is guided by current interest in Particle Physics (and by personal taste, of course). In particular, we do not intend a complete survey of possible experiments nor a complete review of what has been done in the past. There are many more applications upon which we touch briefly, or which we do not discuss at all, for lack of time.

2. Particle Properties, Strong Interactions

2.1 Particle Masses

While the mass of the positive muon is determined from its magnetic moment and its g-factor, the most precise determination of the pion mass comes from pionic atoms[1][2]. The Bohr radius of an atom is inversely proportional to the (reduced) mass of the trapped particle. Therefore, there are intermediate pionic orbits which are hydrogen-like to a very good approximation: they lie sufficiently far outside the nucleus, so that the nucleus can still be regarded as a point-like charge; at the same time, these orbits fall well inside the electronic shell of the host atom so that screening effects are small. The transition energies are then those of the hydrogen atom and are proportional to the reduced mass. The result for the negative pion mass is

$$m_{\pi^-} = (139.568 \pm 0.005)\,\mathrm{MeV} \qquad (1)$$

(average of the results from Ref. 1 and 2)

It is of greatest theoretical importance to establish that the masses of the two kinds of neutrinos ν_e and ν_μ are exactly zero. Indeed, it is a basic assumption of the theory of Weak Interactions that $m(\nu_e) = m(\nu_\mu) = 0$ and, therefore, that neutrinos are eigenstates of helicity. Neutrinos, i.e. the particles ν_e and ν_μ, are left-handed, i.e. their spin is always directed opposite to their momentum, while their antiparticles $\bar{\nu}_e$ and $\bar{\nu}_\mu$ are right-handed. For this to be true the masslessness is essential.

There is a fairly good upper limit for $m(\nu_e)$, from the Kurie plot for triton decay, of about 60 eV. The limits for $m(\nu_\mu)$ are much less impressive. One of them comes from the so-called $K_{\mu 3}$ decays, i.e. from the process

$$K^+ \to \mu^+ \pi^0 \nu_\mu$$

and its charge conjugate, and gives[3]

$$m(\nu_\mu) < 650\ \mathrm{keV}/c^2 \qquad (2)$$

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 488-495

Another way of determining $m^2(\nu_\mu)$ consists in measuring the momentum of the muon p_μ from the decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

for pions at rest. This momentum is given in terms of the muon mass and of an assumed neutrino mass by

$$p_\mu = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} \sqrt{1 + \frac{m_\nu^2\,(m_\nu^2 - 2m_\pi^2 - 2m_\mu^2)}{(m_\pi^2 - m_\mu^2)^2}} \qquad (3)$$

The average experimental value (references are found in Ref. 1) is

$$p_\mu = (29.794 \pm 0.010)\ \mathrm{MeV/c} \qquad (4)$$

If this is inserted into eq. (3), together with the values obtained for m_μ and m_π (eq. (1)), it is found that

$$m^2(\nu_\mu) = (-0.29 \pm 0.90)(\mathrm{MeV/c^2})^2 \qquad (5)$$

This is compatible with zero, but the negative sign is a little uncomfortable and the experimental error is still large. Clearly, this important quantity must be studied further. For this, it has been proposed to remeasure p_μ more accurately⁴⁾ and to repeat the above analysis. Another project underway at SIN proposes to measure pion decay $\pi^\pm \rightarrow \mu^\pm\nu_\mu$ in flight⁵⁾. Specifically, it aims at a precision measurement of the difference $|\vec{p}_\pi - \vec{p}_\mu|$ for muons emitted in the forward direction and as a function of the pion's momentum between 200 and 400 MeV/c. A fit of m_π^2 and $m^2(\nu_\mu)$ to the kinematics of the process should yield m_π to about 2×10^{-5} as well as an upper limit for the mass of the muon neutrino,

$$m(\nu_\mu) < 200\ \mathrm{keV/c^2} \qquad (6)$$

2.2 Magnetic Moment of Muons

The muonic (g-2) experiments, which are of utmost importance for quantum electrodynamics, were originally carried out at the CERN-cyclotron⁶⁾, but for the new high-precision measurement it was necessary to move to higher muon energies⁷⁾ (increased lifetime due to time dilation). The measurements of the magnetic moments of μ^+ and μ^-, however, still belongs to the realm of medium-energy machines. We would like to discuss briefly one interesting project here. The magnetic moment of the positive muon is known to about 2.6 ppm⁸⁾, and there is even hope to improve this to 1 ppm or better by means of a stroboscopic method⁹⁾. The magnetic moment of the negative muon, however, is known to about 100 ppm only¹⁰⁾. There is now the interesting possibility of obtaining this magnetic moment, to a similar accuracy as the one of the positive muon, from the neutral muonic Helium atom($\alpha\mu^-e^-$). The formation of this system in Helium gas with a 2% admixture of Xenon (which is the donor of the extra electron) has recently been established through the observation of its characteristic Larmor precession frequency¹¹⁾. The two spin-1/2 particles, the muon which moves close to the Helium nucleus and the electron which moves much further outside, form a system which behaves very much like muonium μ^+e^-, the main difference being that here the two fermions have equal charges whereas in muonium they have opposite charges. As the muon retains some of its initial polarization, it should be possible to perform precision measurements of the hyperfine structure interval and of the Zeeman effect in ($\alpha\mu^-e^-$), very much like for muonium¹¹⁾¹²⁾. From these one can extract the mass and the magnetic moment of the negative muon, hopefully to a precision which is comparable to the results for the positive muon. This will then allow for an accurate test of CPT-symmetry (invariance under the combined operations of charge conjugation, parity and time reversal) which says that the masses should be equal, the magnetic moments equal and opposite.

2.3 Pion-Nucleon and Nucleon-Nucleon Scattering

There is considerable interest in precision studies of pion-nucleon scattering from threshold on up to Δ(1236 MeV) resonance with spin and isospin $\frac{3}{2}$. We mention a few points of special importance. The isospin-symmetric combination of s-wave scattering lengths

$$a_+ \equiv \tfrac{1}{3}(a_{\frac{1}{2}} + 2a_{\frac{3}{2}}) \qquad (7)$$

(equal for instance to the average of π^--proton and π^--neutron scattering lengths) which is expected to be close to zero, on theoretical grounds, is still very poorly known. There is a lot of interest in the Coulomb corrections, i.e. the interference between the strong and the electromagnetic interactions, in the effects of small violations of isospin symmetry, as well as in differences between the four charge states of the Δ-resonance. First precision data, obtained at the CERN-SC, are presented and analyzed in refs. 13 and 14. Also, the determination of the small scattering phases (i.e. all s-,p- and d-waves except the resonating p-wave with spin $^3\!/_2$ and isospin $^3\!/_2$) from a complete experiment are needed for tests of dispersion relations. First impressive results from SIN have recently been published¹⁵⁾.

Nucleon-nucleon scattering data below the threshold for pion production can be analyzed fairly uniquely in terms of phase shifts of partial waves. These are important for the construction of nucleon-nucleon potentials[16] and therefore for a proper understanding of nucleon-nucleon forces at low energies. In the past, nucleon-nucleon scattering has often been invoked in justifying the need for new accelerators. It is surprising, indeed, that still today nucleon-nucleon scattering in this energy range is not too well known. While the isospin one phases are believed to be known up to about 450 MeV, the knowledge of the isospin zero phases is satisfactory only from 50 up to about 200 MeV[17]. Precision measurements of neutron-proton cross sections and of the various polarization parameters thus are of considerable interest and are in fact planned at SIN and TRIUMF[18][19][20].

3. Electromagnetic Interactions

3.1 Radiative Corrections in Heavy Muonic Atoms

Besides muonium (μ^+e^-) which has been studied extensively in the past, current interest centers on the radiative corrections in heavy muonic atoms, in muonic Helium and muonic Hydrogen. In heavy muonic atoms the situation is still somewhat confused and puzzling. Two precision experiments, measuring 5g-4f and 4f-3d muonic transitions in heavy and medium-weight atoms, were in disagreement with the calculated radiative corrections by about three standard deviations[22][23]. These corrections are dominated by vacuum polarization through virtual electron-positron pairs and have been calculated and checked very carefully by a number of authors. The apparent discrepancy has stimulated considerable theoretical activity. In particular, the contribution of virtual Delbrück scattering (light-by-light scattering diagram in muon-nucleus interaction) has been debated for some time. One rough estimate[24] gave an appreciable contribution, of the right magnitude and with the sign needed to remove the alleged discrepancy, while another estimate[25] gave a rather small number, with the opposite sign. Recent very careful and detailed calculations[26] confirm the estimate by Rinker and Wilets, finding a negligibly small correction from this diagram. Recently some of these muonic transitions have been remeasured and no discrepancy is found anymore[27]. Clearly, this puzzling situation must be cleared up by further precision experiments. Should a real discrepancy persist, then this would imply serious trouble in the theory of electromagnetic interactions of muons.

3.2 Lamb Shift in Muonic Helium and Hydrogen

In an ingenious experiment performed at the CERN-SC, E. Zavattini and collaborators have measured the level spacing $2p_{3/2} - 2s_{1/2}$ in muonic Helium 4[28]. The experimental result

$$\Delta E = (1527.4 \pm 0.9)\ \text{meV} \qquad (8)$$

($1\ \text{meV} = 10^{-3}\text{eV}$) seemed to be in agreement with earlier calculations (quoted in ref. 28). Here again, this energy shift is dominated by vacuum polarization due to virtual (e^+e^-)-pairs (about 1678 meV), and it is thus complementary to the corresponding shift in (electronic) hydrogen where vacuum polarization is a small correction only. In Helium, however, there are two sizeable corrections beyond the well-known pure radiative corrections: The finite size effect and the polarizability of the nucleus. The finite size correction is known if the electromagnetic radius of Helium is known to a sufficient accuracy. The polarizability shift which is of the order of 10 meV, depends on the nuclear excitation spectrum and is difficult to calculate. A recent rather careful reevaluation of these and the radiative corrections[29], using the experimental value for the r.m.s. radius of ^{4}He, $\langle r^2\rangle^{1/2} = 1.650 \pm 0.025$ fm, points to a discrepancy with Zavattini's result

$$\Delta E_{\text{exp.}} - \Delta E_{\text{theor.}} = -12\ \text{meV} \qquad (9)$$

with a somewhat debatable theoretical uncertainty of a few meV. Here, a new determination of the r.m.s. radius as well as further studies of muonic ^{3}He and ^{4}He are highly desirable.

Ideally, one should go to muonic hydrogen, where the finite size effect is better known and where the polarizability correction is much smaller. We know of two experiments which aim at the study of the $2s_{1/2}$ state of muonic hydrogen[30][31].

There are also many interesting and important experiments which deal with electromagnetic interactions of pions, such as radiative pion capture, (e^+e^-)-pair production in charged pion capture, π^0 decay into (e^+e^-)-pairs etc., but we do not have time to go into these.

4. Weak Interactions

As in the past, cyclotrons and other accelerators at low and intermediate energies will allow for a variety of experiments of great importance for our understanding of Weak Interactions. These range from weak interaction processes involving neutrinos, muons and pions, to parity violating effects in proton-proton scattering. In the following we discuss a few selected examples, concerning ordinary μ-decay, the mystery of the muonic lepton number and charged pion decays, which have aroused much interest recently.

4.1 Muon Decay and Muon Radiative Capture

Ordinary muon decay

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \qquad (10)$$

is the only purely leptonic process which can be studied whith sufficient accuracy, to date. It is of fundamental importance for the theory of leptonic interactions. A close look at the existing data shows that the interaction governing the process (10) is not too well determined[32] and a lot more needs to be done. The measured values of the Michel parameters are listed in Table I.

Table I: μ-decay parameters

Parameter	Experiment	"V-A" coupling
ρ	0.752±0.003	3/4
η	-0.12±0.21	0
δ	0.755±0.009	3/4
ξ	0.972±0.013	1
ξ'	1.00±0.13	1

ρ and η determine the shape of the energy spectrum of the positron from unpolarized muons; δ is a spectrum parameter in the correlation term (muon spin expectation value $\vec{\zeta}_\mu$ x positron momentum $\vec{p}_e$) and is analogous to ρ. ξ (magnitude of $\vec{\zeta}_\mu \cdot \vec{p}_e$ correlation and ξ' (longitudinal polarization of positron, essentially) are measures for the degree of parity violation.

In particular, the spectrum parameter η and the polarization parameter ξ' are poorly known. η measures admixtures of scalar and pseudoscalar interactions, ξ' depends on possible tensor and pseudotensor interactions. In addition, both are sensitive to deviations from the pure (vector-axial vector)-combination.

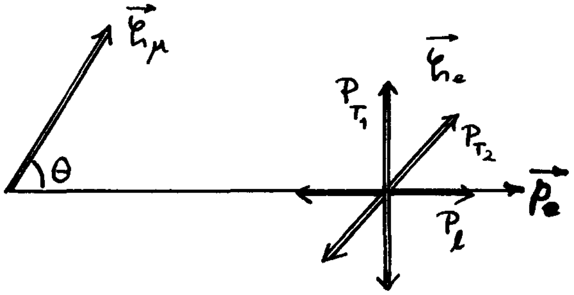

Fig. 1: Longitudinal and transverse polarizations of the positron, in the muon's rest frame.

An experiment at SIN aims at a measurement of the longitudinal polarization of the positron from the decay of polarized muons[33], i.e. the quantity P_ℓ. If $\rho = \delta = \frac{3}{4}$ is already known, then P_ℓ is given by (for $E_e >> m_e$)

$$P_\ell = \xi' - \frac{(2x-1)\cos\theta}{3-2x-\xi\cos\theta(2x-1)}\,\sigma \qquad (11)$$

where x is the ratio of the positron energy to its maximal value ($\simeq m_\mu/2$), θ is defined in Fig. 1, and σ is a new parameter which is bounded by ξ, namely[34]

$$\xi^2 - 1 \leq \sigma \leq 1 - \xi^2 \qquad (12)$$

A measurement of P_ℓ will yield the parameter ξ'; at the same time it should be possible to test the "V-A" prediction, ξ = 1, by checking whether or not P_ℓ is independent of x and θ.

It should also be possible to measure the two transverse components P_{T_1} and P_{T_2} of the positron polarization (see Fig. 1). P_{T_1}, the transverse polarization in the plane spanned by $\vec{\zeta}_\mu$ and $\vec{p}_e$, is essentially proportional to η[34], without the disturbing factor m_e/m_μ which supresses the η-dependent term in the spectrum; while P_{T_2}, perpendicular to the same plane, measures the amount to which invariance under time reversal is violated[34]. Neither of those has ever been measured.

Muonic semileptonic interactions are a field which is still wide open and of considerable interest for particle physics. We mention the possibility of detecting parity violating, neutral Weak Interaction currents through mixing of muonic atom orbits of opposite parity, which is being explored by several groups. Good candidates for such mixing transitions are shown in Fig. 2. Muon capture,

$$\mu^- + p \rightarrow n + \nu_\mu \qquad (13)$$

and muon radiative capture on the proton

$$\mu^- + p \rightarrow n + \nu_\mu + \gamma \qquad (14)$$

are still of vital interest for the study of semi-leptonic weak interactions at non-vanishing momentum transfer. In particular, the induced pseudoscalar coupling constant is still poorly known and should be obtained from the triplet capture rate in process (13) and from reaction (14).

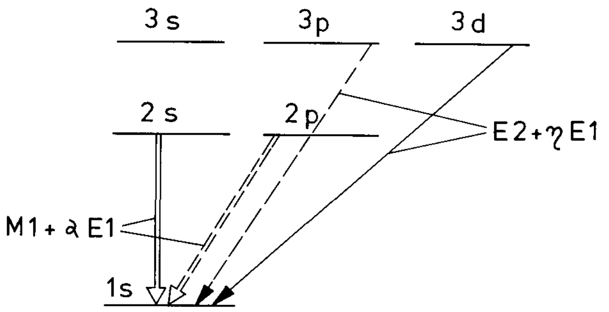

Fig. 2

4.2 The Mystery of the Muonic Lepton Number

It has been known for a long time that the electron and the muon, as well as their respective neutrinos, carry different kinds of lepton numbers. The nature of the quantum number which distinguishes the μ^- from the electron, and ν_μ from ν_e, is not understood. It is currently assumed that beyond the ordinary lepton number there exists an additional muonic lepton number which is additively conserved. The assignment is supposed to be as indicated in Table II, the conservation laws being $\sum_i L^i$ = const. and $\sum_i L^i_\mu$ = const. in any reaction.

Table II: Lepton numbers for electrons and muons

Particles		L	L_μ
e^-	ν_e	1	0
μ^-	ν_μ	1	1
e^+	$\bar\nu_e$	-1	0
μ^+	$\bar\nu_\mu$	-1	-1

With this scheme μ^+-decay proceeds with the bars on the neutrinos as indicated in eq. (10). If, on the other hand, muonic lepton numbers were connected to some kind of conserved parity, where $\prod_i (-)^{L^i_\mu}$ were conserved, rather than $\sum_i L^i_\mu$, then also the decay

$$\mu^+ \to e^+ + \bar\nu_e + \nu_\mu \qquad (15)$$

would be allowed. So far there is only a limit from bubble chamber experiments at high energies which is[35]

$$\frac{\Gamma(\mu^+ \to e^+ + \bar\nu_e + \nu_\mu)}{\Gamma(\mu^+ \to \mathrm{all})} < 0.25$$

There is the interesting possibility of testing the existence or absence of the decay mode (15) at intermediate energy accelerators by identifying the $\bar\nu_e$ through inverse β-decay

$$\bar\nu_e + p \to e^+ + n$$

This is being looked for at LAMPF at present.

What else can we do, at intermediate energies, to help to understand the nature of muonic lepton number? A classical candidate for testing the conservation of muonic lepton number is the decay process

$$\mu^+ \to e^+ + \gamma \qquad (16)$$

With additive, as well as with multiplicative conservation of L_μ this process is forbidden. The present experimental limit is 36)

$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar\nu)} < 2\cdot 10^{-8} \qquad (17)$$

On the theoretical side, not much can be said, as at least one L_μ-violating term must occur in the weak interaction Hamiltonian 37). For example, the process could proceed by the steps sketched in Fig. 2

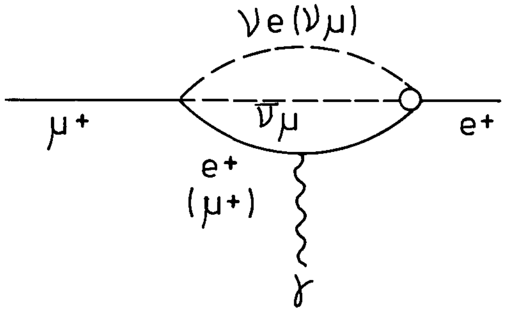

Fig. 3: Typical diagram for the process $\mu \to e + \gamma$

Since nothing is known about vertices which do not obey conservation of L_μ, theoretical estimates are bound to be uncertain. The experimental search for this decay will be taken up again at SIN and the hope is to push the limit (17) to about 10^{-10}. This in turn would limit L_μ-violating terms very strongly.

Closely related to this topic is the search for exotic μ-capture processes on nuclei such as

$$\mu^- + (Z,N) \rightarrow e^- + (Z,N)^* \qquad (18)$$

$$\mu^- + (Z,N) \rightarrow e^- + (Z-2,N+2)^* \qquad (19)$$

where Z and N are the proton and neutron numbers of the initial nucleus. Present limits for the rates of these processes as compared to ordinary μ-capture are also of the order of 10^{-8}. An experiment which is presently being prepared at SIN[39] will push these limits to about 10^{-10} or less - or find a nonzero rate! The second process, eq. (19), seems particularly interesting as it tests still another lepton number scheme which was proposed by Konopinski and Mahmoud in 1953[40]. In this scheme there is only one kind of lepton number, but with a different assignement than above, for instance μ^- and e^+ are assigned the same lepton number, as well as ν_μ and $\bar{\nu}_e$ etc. With this scheme the process (19) would be strongly suppressed only because it needs a double charge exchange in a one-step process. Since it is not possible to take two units of charge out of a nucleon while transforming it to another nucleon, the process must take place on mesonic or Δ-degrees of the nucleus[41]. Figs. 4 illustrate various possibilities.

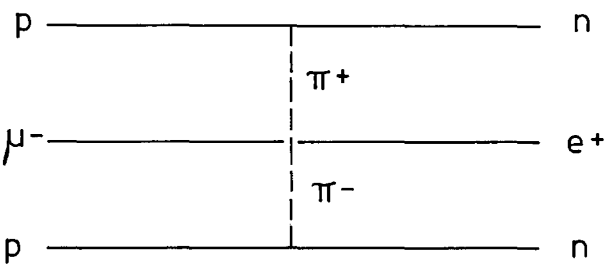

Fig. 4a: μ - e conversion on virtual pions

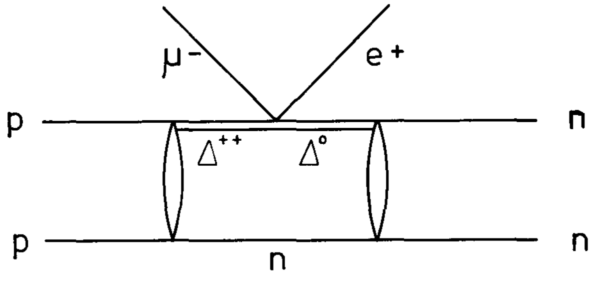

Fig. 4b: μ - e conversion on Δ-components in the nucleus

The small branching ratio for this capture process would then be due to the smallness of such virtual pion or Δ configurations in normal nuclei - a very interesting possibility indeed.

4.3 Rare Pion Decays

The predominant decay mode of the charged pions is the mode

$$\pi \rightarrow \mu\nu_\mu$$

which accounts for practically 100% of the pion lifetime. A few other decay modes of special interests are listed in Table III.

Table III: Decay modes of charged pions

Decay	Branching ratio	Ref
(a) $\pi^+ \rightarrow e^+\nu_e$	$(1.25 \pm 0.03)10^{-4}$	42
(b) $\pi^+ \rightarrow \pi^0 e^+ \nu$	$(1.00 \pm 0.08)10^{-8}$	43
(c) $\pi^+ \rightarrow e^+ \nu_e \gamma$	$(3.0 \pm 0.5)\ 10^{-8}$	44

It is an intriguing observation that the weak and electromagnetic interactions of electrons and of muons are universal - except for the extra selection rule of muonic lepton number. By this we mean that their interactions are governed by the same coupling constants and have identical structure when formulated in terms of Hamiltonians. The numerical differences in cross sections, energy levels, decay rates etc. arising only through the difference in mass of the two particles. Reaction (a) of Table III is an important test of μe-universality which predicts for this branching ratio

$$R_{\text{theor}} = \frac{\Gamma(\pi\rightarrow e\nu)}{\Gamma(\pi\rightarrow\mu\nu)} =$$

$$\frac{m_e^2}{m_\mu^2}\left(\frac{1-(^{m_e}/_{m_\pi})^2}{1-(^{m_\mu}/_{m_\pi})^2}\right)^2 = 1.228\cdot 10^{-4} \qquad (20)$$

- in good agreement with the experimental value[41]. Note, in particular, that the Fermi coupling constant G drops out of the ratio (20), provided it is indeed the same for muons and electrons. Clearly, further and more precise studies of this decay mode will be very valuable[45].

The decay mode (b) of Table III is the analogue of nuclear Fermi-type β-decay. By reason of the pion's quantum numbers, the pionic matrix element can depend only on the vector part of Weak Interactions. The hypothesis of the conserved vector current (CVC) relates this vector matrix element to the electromagnetic form factor of the pion. Thus the decay rate (b) is predicted in absolute magnitude. Except for small and well-known correction terms it is

$$\Gamma(\pi^+\to\pi^0 e^+\nu_e) \simeq \frac{1}{30\pi^3} G^2 (m_{\pi^+}-m_{\pi^0})^5 \qquad (21)$$

Taking radiative corrections into account, the branching ratio is found to be

$$R_{theor} = (1.035\pm0.005)\ 10^{-8} \qquad (22)$$

A further improvement of the experimental result would bear on a number of questions: relation of G_V from semi-leptonic decays to G_μ from μ-decay (Cabibbo angle); quality of CVC and isospin violations; role of radiative corrections.

The radiative decay (c) in Table III, finally, is of special interest at present, as all reliable theoretical models have difficulties in explaining the data[46]. Here one can measure the positron and the photon spectra[44]. From the spectra one can extract the transition matrix elements between the initial pion's and the emerging photon's states including their relative signs. These matrix elements are calculable in certain quark models, and also in the framework of current algebra and vector meson dominance[46]. A new experiment[47] should help clarifying the apparent discrepancies.

5. Conclusion

We have presented a set of selected experiments at intermediate energy accelerators whose motivation stems primarily from open problems in Particle Physics. Our list is far from complete and many more examples of current interest could be quoted. We hope, however, that the few samples discussed here illustrate and demonstrate the claim made in the Introduction: namely that experimental research at low and intermediate energy machines is often complementary to research at high and ultra-high energies, and is still competitive in trying to answer fundamental questions of Particle Physics.

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