MICROSCOPIC TESTS OF SYMMETRY PRINCIPLES

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In the analysis of the phenomena involved in the interaction of elementary particles, use is often made of the implications of "absolute" conservation laws, such as the conservation of charge, the conservation of baryons, and the conservation of leptons. It is known from the general principles of quantum mechanics that the existence of such conservation laws is connected with certain symmetries which are believed to be possessed by the equations describing the behavior of the elementary particles. Some of the conservation laws are familiar from classical physics, because the conserved quantity which appears in them can be directly measured by macroscopic experiments (e.g., the charge). In other cases, a conservation law appears only indirectly in classical experiments, and the evidence for it derives from experiments involving elementary particles.

While no apparent contradictions have arisen from the application of the absolute conservation laws, and the symmetries with which they are connected may appear quite reasonable on theoretical grounds, we should remember that in the history of physics it has been demonstrated many times, most recently in the discovery of the non-conservation of parity in weak interactions, that the basic principles of theoretical physics cannot be accepted *a priori*, no matter how convincing they may seem, but rather must be justified on the basis of relevant experiments. The acceptance of this empiricist view of symmetry principles has an obvious consequence. One would like to know what the specific experimental evidence for a particular symmetry is, both in the qualitative sense of knowing which experiments bear on it, and in the quantitative sense of knowing what the limits are of possible violations of the particular symmetry. It is often the case that we believe in certain conservation laws, not so much because they have been explicitly tested to a considerable degree, but because they are implicitly used in many experiments without leading to difficulties. It is therefore desirable to replace, wherever possible, implicit and qualitative statements concerning the validity of conservation laws by explicit tests leading to quantitative limits.

Of course, it has been recognized for a long time that the final justification of symmetry principles, as of all other physical laws, is the experimental evidence for them. Some of the experiments we shall cite in this paper were done some time ago, and it is possible that still others, unknown to us, have been done which have an important bearing on this question. Nevertheless, it appears worth while to collect in this preliminary form some samples of the experiments which put rather stringent limits on possible violations of conservation laws and related symmetry principles. We shall concentrate on some of those symmetries which are believed to be universally valid, rather than restricted to a particular class of interactions. We do this because the evidence about other types of symmetry such as parity, charge conjugation, charge independence, etc., has been the subject of much recent analysis[1] and we have nothing new to add to it. In the second section we shall discuss the evidence for the absolute conservation laws connected with gauge transformations, i.e., the conservation of charge, of baryons and leptons. In the third section we shall discuss the evidence for the equality of the charges of the various charged elementary particles, a symmetry which corresponds to no known conservation law, but which is nevertheless rather striking, since, as we shall see, the assumption of charge conservation and the existence of the known reactions among the elementary particles do not by themselves imply all of the charge equalities which appear to exist. In the fourth section we discuss some of the evidence for the conservation of angular momentum, which is associated with symmetry under space rotations. It may be useful to state here that we do not know of any evidence against any of the symmetries which we discuss. However, the rather extreme experimental limits which can be placed on violations of the conservation of charge and of baryons indicate that any attempt to give up these laws, even in a restricted class of interactions, must be made with great care.

The Absolute Conservation Laws for Additive Quantum Numbers.—By an additive quantum number one means a quantity which can be assigned to each particle, such that its value for a system of particles is the algebraic sum of its values for the separate particles and is independent of the state of the system. There are examples of additive quantum numbers, such as "strangeness" which are conserved in some classes of reactions but not in others. When such a quantity is conserved in all reactions, one speaks of an "absolute conservation law" for the quantity. It can be shown that the existence of absolute conservation laws is associated in a field theory with the invariance of the total Lagrangian under a gauge transformation in which the field operators for all of the particles are multiplied by phase factors of the form

$$\psi_N \rightarrow e^{iN\lambda}\psi_N \qquad (1)$$

where ψ_N is the field operator for a particle with the value N for the quantum number in question and λ is an arbitrary number which is the same for all the particles. There are three conservation laws which are believed to be absolute in the present theory of elementary particles. These are the conservation of electric charge, the conservation of baryons, and the conservation of leptons. We shall now discuss some experiments which give limits on possible violations of these conservation laws.

Conservation of electric charge: For the known elementary particles, the charges take on only a small number of values which appear to be integral multiples of the electron charge. It is therefore not possible to have transitions among these particles in which the charge changes by some fraction of this unit. If there were interactions which do not conserve charge, these would produce transitions from an initial state containing particles whose total charge is some integral multiple of the unit charge to a final state containing particles with a total charge which is a different multiple of the unit charge. A measure of charge nonconservation will then be the branching ratio for such transitions compared to other transitions from the same state, in which the total charge is unchanged. The question of why charge is quantized is a separate question with an as yet unknown answer, which we return to, but do not solve, in the next section. The situation here may be compared with that for angular momentum, where it follows from the quantum conditions on angular momenta, that even if angular momentum were not conserved, it could only change by multiples of $\hbar/2$.

In discussing conservation laws, it is useful to consider, whenever possible, experimental effects which depend only on the violation of the conservation law in question, leaving the specific mode of violation as arbitrary as possible. Since we are looking for effects which are much smaller than those with which we are familiar, it would not be wise to assume that the principles governing known interactions, such as the assumption that only a small number of particles are involved in each elementary process, are valid. One may even consider the possibility that several of the conservation laws may be violated simultaneously. Some of the experiments we consider are more or less independent of the mode of violation of the conservation laws, while others are not. In the discussion of the significance of some of the experiments we shall consider particular modes of possible violations of the conservation laws. These are only used for illustration.

For some possible violations of conservation laws, limits have been deduced from macroscopic considerations, such as the apparent "electric neutrality" of macroscopic bodies. However, to make these arguments precise involves in some cases a detailed analysis of compensating phenomena. It is therefore desirable to set limits for possible violations in elementary processes, though they are sometimes not so stringent as those suggested by macroscopic arguments.

A failure of charge conservation would allow processes to occur which are otherwise forbidden. Clearly, a particularly good place to look for such violations is to examine systems which cannot make any transitions at all if the conservation laws are satisfied, but could if charge were not conserved. An example of such a system is an electron, either free, or bound in an atom which is in its ground state. The electron is the state of lowest rest mass with an electronic charge. However, there are states of lower rest mass into which the electron could decay if charge were not conserved, such as a state with one neutrino and one photon, or two neutrinos and an antineutrino. Therefore, the "lifetime" of a free electron, or an electron in the ground state of an atom, is a test of charge conservation. Strictly speaking, electron decay might occur into unknown charged particles with mass smaller than the electron mass, without violating the conservation of charge. The existence of such particles is presumably ruled out by the fact that they have not been produced in pairs by photons.[2]

The possibility of electron decay was recently investigated at this Laboratory.[3] One of the consequences of the decay of atomic electrons would be the formation of K-electron "holes," which could be well detected in a NaI scintillation counter by the subsequent emission of an X ray. A search for the iodine K X rays leads to a lower limit for the electron "life-time" $\tau_e > 10^{17}$ years.

It should be noted that this experiment is sensitive to the decay of electrons by any mode since all that is involved is the disappearance of an inner electron. The lower limit for the partial lifetime for some specific modes of decay can be made larger; e.g., for the process $e \rightarrow \nu + \gamma$, which would lead to energetic γ-rays, more easily distinguished from background, it is found to be $>10^{19}$ years.

Another test of charge-conservation comes from the stability of certain nuclei. Consider two nuclei whose atomic number and mass number are given by (Z, A) and $(Z + 1, A)$. Let us distinguish between nuclear masses (m) and atomic masses

(M). Suppose that the nuclear masses of the two nuclei are such that $m_{Z+1} < m_Z < m_{Z+1} + m_e$, where m_e is an electron mass. In this case, the nucleus (Z, A) cannot decay by beta emission into ($Z + 1$, A) because there is not enough energy available to create an electron. However, if charge-nonconserving decays were allowed, the decay could occur via processes which have zero energy threshold, such as neutrino pair emission or photon emission. The latter process might be directly detected by conventional methods. Alternatively, one may make use of the fact that the nucleus ($Z + 1$, A) is itself unstable against K capture, since the masses of the atoms are related by $M_Z < M_{Z+1}$. It is therefore possible to search for the decay of (Z, A) by detecting the radioactive product nucleus, though, to our knowledge, this has not yet been done. (An example of a nuclear pair which fulfills these energy conditions is ${}_{19}K^{41}$ and its isobar ${}_{20}Ca^{41}$.)†

It is of some interest to estimate the maximum strength of interactions consistent with the limits given above for the electron decay. Such estimates must necessarily depend on the models assumed for the violation of charge conservation. However, we believe that they will give some indication of the orders of magnitude involved.

Suppose that there is an interaction producing the decay $e \rightarrow \nu + \gamma$. This could, for example, be represented by an effective matrix element

$$M = \frac{\lambda_c}{m} \bar{\psi}_\nu \sigma_{\alpha\beta} \psi_e F_{\alpha\beta}, \tag{2}$$

where ψ_e is the electron wave function, ψ_ν the neutrino wave function, $F_{\alpha\beta}$ is the electromagnetic field tensor and $\sigma_{\alpha\beta}$ is the spin tensor. Here λ_c is a dimensionless number measuring the interaction strength, while m is a mass which we shall take to be the mass of the electron. The lifetime for the free electron calculated with this matrix element is

$$\tau_e = \frac{2\pi}{\lambda_c^2} \frac{\hbar}{m_e c^2} = \frac{7 \times 10^{-21}}{\lambda_c^2} \text{ sec.} \tag{3}$$

Using $\tau_e > 10^{19}$ years $= 3 \times 10^{26}$ sec., we find

$$\lambda_c^2 < 2 \times 10^{-47}. \tag{4}$$

This number may be taken as an indication of the weakness of any possible decay interactions involving electrons and not conserving charge. The number may be compared with the dimensionless Fermi coupling constant g which we here define in terms of the conventional Fermi coupling constant G_F, by

$$G_F = \frac{g}{m_e^2},$$

again using m_e as the standard mass for comparison purposes, giving

$$g^2 = 10^{-23}.$$

It may be seen that any charge-nonconserving interactions of the type discussed are, if they exist, many orders of magnitude weaker than the "weak interactions." The limit on the dimensionless coupling constant for decays like $e \rightarrow 2\nu + \bar{\nu}$, which follows from the above experiments is similar. One can conclude from a corresponding calculation that $g_c^2 < 10^{-42}$, where the interaction leading to $e \rightarrow 2\nu + \bar{\nu}$ is taken to be:

$$\frac{g_c}{m_e^2} \bar{\psi}_\nu \psi_e \bar{\psi}_\nu \psi_\nu. \tag{5}$$

It is also desirable to investigate possible interactions which violate charge conservation by several units at once, i.e., "modulo n." By this is meant that, while processes which change the charge by 1, 2, ... $n - 1$ units at once are forbidden, these interactions permit processes which change it by n, $2n$, $3n$, etc. units. Selection rules of this kind occur when one deals with multiplicative quantum numbers rather than additive ones. Such theories are proposed from time to time. Evidence against some interactions of this type is provided by the stability of many-electron atoms, as in the experiment quoted above. For instance, if it were possible for several electrons to annihilate at a point, with the emission of neutral particles, one would expect this to happen in elements such as iodine, where the overlap of the electron wave functions is substantial. This would again lead to the "disappearance" of electrons in the inner shells and the subsequent emission of X radiation. A comparison of the rate of this type of annihilation with the lower limit on the lifetime of these atoms gives upper limits for the coupling strengths for interactions like $4e \rightarrow 4\nu$ which are comparable to the limit quoted for g_c above.

Conservation of Baryon number: We next consider the conservation of baryons, a law first suggested by Wigner[4,5] in view of the apparent stability of the proton, and later found to be useful in discussing the decays of hyperons, which end up in a proton or a bound neutron. This law states that in all elementary particle processes there exists a conserved additive quantum number which is chosen as +1 for nucleons and hyperons, −1 for their antiparticles and 0 for all other known particles. Since the proton is the lightest known particle with the value +1 for this quantum number, the conservation of baryons guarantees the stability of the free proton against decay into known particles. It would appear that the "lifetime" of the proton, either free, or bound in nuclei which are stable against the ordinary decays, is a sensitive test of the existence of interactions which do not conserve baryons.[6]

An experiment which places a limit on the proton lifetime for certain decay modes has been done by Reines, Cowan, and Goldhaber,[7] who looked for possible proton decays in a large hydrogeneous scintillation counter (C_7H_8). The limit obtained for the free proton lifetime is $\tau_p > 10^{21}$ years and for bound protons $>4 \times 10^{23}$ years.[8]

Again, an experiment which is independent of the method of decay is useful because it involves the fewest extensions of present ideas into realms where they may not apply. An experiment of this kind is provided by the stability of certain heavy nuclei against spontaneous fission.[7]

From the absence of spontaneous fission in Th^{232}, Flerov *et al.*[9] find a limit $> 2 \times 10^{23}$ years for bound nucleons decaying by any mode.

An analysis of the upper limit of the strength of baryon nonconserving interactions, based on a hypothetical process such as $P \rightarrow e^+ + \pi^0$, can be done, similar to the one carried out for charge nonconservation. If we take the matrix element for this process as

$$M = \lambda_\beta \bar{\psi}_e \psi_p \phi_{\pi^0}, \tag{6}$$

where ψ_p is the proton wave function, ϕ_{π^0} is the π^0 wave function and λ_β is a dimensionless constant. We find that

$$\tau_p \simeq \frac{\hbar}{m_p c^2} \frac{1}{\lambda_\beta^2} < 10^{29} \text{ sec.}$$

or

$$\lambda_\beta^2 < 10^{-53}. \tag{7}$$

Similar values are obtained for the dimensionless coupling constants for processes[10] like

$$P \rightarrow 2e^+ + e^-,$$

provided that all quantities with the dimension of a mass are taken to be about m_p.

The results for nucleons bound in nuclei also restrict the possibility of interactions in which nucleon number is changed "modulo n." In heavy nuclei it is to be expected that the overlap of the wave functions for n nucleons is appreciable $\left[\sim \left(\frac{r_{nuc.}}{r_0}\right)^{3(n-1)}\right]$. Here $r_{nuc.}$ is the "mean extension" of the nucleon, while r_0 is the "average separation of nucleons" in a nucleus, or 1.2×10^{-13} cm. One sees that interactions involving several nucleons at a point will not be reduced by many orders of magnitude, unless the matrix elements have some special space or spin dependence. Like the processes discussed for single nucleon decay, processes where many nucleons are destroyed simultaneously would in general give charged decay products, or lead to a product nucleus unstable against fission. We therefore find, for example, that the square of the dimensionless coupling constant for interactions which are "baryon nonconserving modulo 2" must be $<10^{-49}$.

Conservation of leptons: The third absolute conservation law which is generally believed is the conservation of leptons. The evidence for this law in the usual weak interactions has been the subject of much analysis since the discovery that neutrinos and antineutrinos differ in their helicity. We will not review these discussions, except to note that the conclusion is that any lepton nonconserving terms in processes such as β decay, π-μ decay and K-μ decay are probably <10 per cent of the lepton conserving terms.[11]

As far as we know now, the leptons do not possess any interactions other than minimal electromagnetic interactions,[12] or weak interactions involving neutrinos. However, the experimental limits on the strength of other lepton-involving interactions are not very severe. For instance, from the fact that the decay $\pi^0 \rightarrow e^+ + e^-$ is no more than 10^{-4} of all π^0 decays,[13] it can be concluded that an interaction

$$\lambda_\pi \bar{\psi}_e \psi_e \phi_{\pi^0} \tag{8}$$

must satisy $\lambda_\pi^2 < 10^{-10}$.

From the lack of existence of the decay $\mu \rightarrow e + \gamma$($10^{-6}$ of ordinary μ decays[14]) it follows that the dimensionless coupling constant g_μ for an interaction which could produce this decay,

$$\frac{g_\mu}{m_e} \bar{\psi}_e \sigma_{\alpha\beta} \psi_\mu F_{\alpha\beta}, \tag{9}$$

where ψ_μ is the μ meson wave function, satisfies $g_\mu^2 < 10^{-27}$.

It is also possible to obtain severe limits on some conceivable leptonic interactions which do not involve neutrinos and which do not conserve the number of leptons. As a hypothetical interaction of this kind, consider a coupling which changes $2\pi^-$ into $2\ e^-$,

$$M = g_L/m_e(\phi_{\pi^-})^2 \bar{\psi}_e{}^c \psi_e. \tag{10}$$

Here $\psi_e{}^c$ is the charge conjugate of the electron wave function. This interaction, when combined with the strong π-nucleon interaction, would lead to processes such as

$$(Z,A) \rightarrow (Z + 2, A) + 2e^-,$$

a double β decay process. Note that this process would now occur in the first order of this assumed lepton nonconserving interaction, whereas double beta decay via the often discussed lepton nonconserving interactions involving neutrinos is a second order process. An order-of-magnitude estimate of the rate for double β decay via the new interaction is given by the rate of single β decay via the Fermi coupling, multiplied by $(g_L/g)^2$. In the well investigated case of Ca^{48} one finds a limit for the lifetime for double β decay $> 7 \times 10^{18}$ years,[15] whereas, for a corresponding energy release, the lifetime for single β decay via the Fermi interaction would be $\sim$1 sec. From this it may be concluded that the coupling strength for interactions like the above which change the lepton number by 2, must be 10^{18} times weaker than the Fermi coupling, or

$$g_L^2 \lesssim 10^{-49}. \tag{11}$$

It is also of some interest to consider a more general case of possible interactions in which leptons are not conserved modulo n (>2, even). If such interactions exist, it is expected that decays of the type

$$(Z, A) \rightarrow (Z + n, A) + ne^- \quad \text{or}$$

$$(Z, A) \rightarrow (Z + n - m, A) + (n - m)e^- + m\nu$$

could occur when they are energetically possible. We are not aware of any search for such decay modes.

Charge Equalities of the Elementary Particles.—We have seen in the last section that the evidence for the three absolute conservation laws is quite strong. To start with, we will therefore assume in this section that these laws are satisfied rigorously. The existence of these three conservation laws, rather than just the conservation of charge, is relevant to the problem which has often been raised of why the charges of all the elementary particles are $\pm Q_e$ or zero. To demonstrate the connection between the conservation laws and the charge equalities, we note that the conservation laws state that there are three independent sets of numbers Q_i, B_i, L_i, the charges, baryon numbers, and lepton numbers of the particles, which satisfy

$$\sum_i Q_i = \text{constant in time},$$
$$\sum_i B_i = \text{constant in time}, \qquad (12)$$
$$\sum_i L_i = \text{constant in time}.$$

It is clear, however, that if this is the case, then also any independent set of linear combinations of these numbers, such as

$$\begin{aligned} Q_i' &= a_1Q_i + b_1B_i + c_1L_i \\ B_i' &= a_2Q_i + b_2B_i + c_2L_i \\ C_i' &= a_3Q_i + b_3B_i + c_3L_i \end{aligned} \qquad (13)$$

will also satisfy the relations (12). Furthermore, since the a, b, c are arbitrary, except that the determinant formed by them must be nonzero, it follows that if the ratio of the Q_i are integers, the ratio of the Q_i' will not necessarily be so. Thus, because of the conservation of baryons and leptons, the application of conservation of charge to the known reactions involving elementary particles does not, of itself, determine the ratio of the charges of all the elementary particles. Instead, there will be two ratios which are left arbitrary by all reactions. For instance, the apparent absence of $p \rightarrow e^+ + \pi^0$ and of similar processes leaves the relative charge of p and e undetermined. Even if one assignment of charges, Q_i, leads to a conservation law with all charges integral, another conserved assignment would be obtained by adding to the charge of each particle a fixed multiple of its baryon number or lepton number. The same holds for the assignments of baryon or lepton number, i.e., one could for each particle add a fixed multiple of the other two additive quantum numbers and obtain a new assignment of baryon or lepton number which is conserved. This would leave unchanged the quantum numbers only of those particles for which all conserved additive quantum numbers have the value zero (e.g., the π^0).

These results are summarized, for the case of charge, in Table 1, which lists in four columns those particles whose charges are required to be equal because of existing reactions. Also listed, in brackets, is a reaction implying this result.

TABLE 1

$Q = 0$	$Q = Q_p$	$Q = Q_n$	$Q = Q_{e^-}$
$\gamma(p + p \rightarrow p + p + \gamma)$	p	n	e^-
$\pi^0(p + p \rightarrow p + p + \pi^0)$	$\Sigma^+(\Sigma^+ \rightarrow p + \pi^0)$	$\Lambda^0(\Lambda^0 \rightarrow n + \pi^0)$	$\mu^-(\mu^- \rightarrow e^- + \nu + \bar{\nu})$
$\theta_1^0(\theta_1^0 \rightarrow 2\pi^0)$		$\Sigma^0(\Sigma^0 \rightarrow \Lambda^0 + \gamma)$	
$\theta_2^0(\theta_2^0 \rightarrow \pi^+ + \pi^- + \pi^0)$		$\Xi^0(\Xi^0 \rightarrow \Lambda^0 + \pi^0)$	

We also have the following relations:

$$Q_{\text{particle}} = -Q_{\text{antiparticle}} \text{ (particle + antiparticle} \rightarrow 2\gamma)$$

$$\begin{aligned} Q_{\pi^+} &= Q_p - Q_n \; (p \rightarrow n + \pi^+) \\ Q_{K^+} &= Q_{\pi^+} \; (K^+ \rightarrow \pi^+ + \pi^0) \\ Q_{\Sigma^-} &= 2Q_n - Q_p \; (\Sigma^- + d \rightarrow \Lambda^0 + 2n) \\ Q_{\Xi^-} &= 2Q_n - Q_p \; (\Xi^- \rightarrow \Lambda^0 + \pi^-) \\ Q_\nu &= Q_p + Q_{e^-} - Q_n \; (n \rightarrow p + e^- + \nu^-) \end{aligned}$$

These equations exhaust the relations among the charges of elementary particles implied by the conservation of charge in the known reactions.[16] It can be seen that after fixing the scale of charge by measuring in terms of Q_{e^-}, there are still two charges left undetermined by these relations, which we can choose as Q_n and Q_p.

It is important to realize that the charges of particles are in fact measured, not by an appeal to conservation laws, but by placing the particles in external electromagnetic fields and observing their behavior. For the baryon number and lepton number, however, there is no evidence that fields which interact specifically with the "baryonic charge" or "leptonic charge" actually exist,[11] and so it is doubtful that any physical significance can be attributed to any one of the possible conserved assignments of these quantities in preference to others, at least at present. Thus, only for the electric charge is it possible to decide experimentally which of all the possible conserved assignments of Q_i is correct. The results of various experiments are that the possible freedom in the relative electric charges of the particles is practically removed. Consider first the charge of the neutron. A possible small charge for the neutron could be detected by the deflection of a neutron beam by a homogeneous electric field. Such an experiment has been carried out by Shapiro and Estulin,[18] who find an upper limit for the charge of the neutron $\leq 6 \times 10^{-12}|Q_{e^-}|$. A similar experiment has been done by Hughes,[19] on the CsI molecule, who finds

$$|Q_{CsI}| < 4 \times 10^{-13} |Q_e| \tag{14}$$

Using

$$Q_{CsI} = 108 (Q_p + Q_e) + 152 Q_n,$$

and assuming that there is no accidental cancellation between the two terms, one can conclude that

$$\begin{aligned} |Q_p + Q_{e^-}| &< 4 \times 10^{-15} |Q_{e^-}| \\ |Q_n| &< 3 \times 10^{-15} |Q_{e^-}|. \end{aligned} \tag{15}$$

Alternatively, one can combine this result with the previous result on the neutron charge and conclude that

$$|Q_p + Q_{e^-}| < 9 \times 10^{-12} |Q_{e^-}|, \tag{16}$$

whether or not there is cancellation. The assumption of charge conservation then implies that the charges of all the other elementary particles are equal to the values usually assigned, within limits which are comparable to equations (15) and (16).

These results make it seem reasonable that all the known particles have charge $\pm Q_{e^-}$ or 0. This would follow on the basis of our previous discussion, if the conservation of baryons and leptons were only approximate, and the conservation of charge were the only absolute conservation law, since there would then be only one possible assignment of charges. As mentioned above, if processes like $p \rightarrow e^+ + \pi^0$ were observed, then charge conservation would require $Q_p = Q_{e^+}$. Conversely, if it were found that the electric charges of the baryons were all slightly displaced from their usually accepted values, say by the common value ϵ, the conservation of baryons would follow from the conservation of charge, instead of being an independent physical principle.[20] Similar remarks hold for leptons. However, the results of the previous section give little encouragement to these "explanations." It therefore seems that the apparent equality of the charges of the elementary particles involves some new physical principle.

Conservation of Angular Momentum.—It is well known that the invariance of particle interactions under rotation of the coordinate system implies the existence of a conserved axial vector, the angular momentum of the system of particles. The consequences of this conservation law have been very useful in many fields of physics, such as atomic and nuclear spectra, angular correlations, etc. It is useful to enquire about a possible violation of this conservation law, which violation would presumably imply some lack of isotropy of space.

One consequence of the conservation of angular momentum is that the stationary states of every system are also eigenstates of the square of the angular momentum operator and one of its components, in the absence of accidental degeneracy. This allows the usual classification of nuclear or atomic states in terms of the eigenvalues of J^2, J_z, etc. A violation of the conservation of angular momentum in the interactions which bind nuclei and atoms would, among other things, lead to admixtures of several different total angular momenta into a given stationary state. If this occurs there will be, in transitions between these states, violations of the selection rules which are based on the usual assignments of angular momentum. This will occur whether or not angular momentum is conserved in the interactions which produce the transitions between the states. As an example, consider two states of a nucleus, or an atom, which have angular momentum zero. Then a transition between these two states with the emission of one photon is forbidden by the conservation of angular momentum, since the photon has spin 1. If, however, the nuclear force has a part which does not conserve angular momentum, then one would expect that these states could have some admixture of angular momentum one. In that case the emission of a photon can proceed either by electric or magnetic dipole radiation, even if no change is made in the electromagnetic interaction.[21]

An experiment to detect γ transitions between two nuclear states of "spin O^+" has been performed by Sunyar.[22] He searched for γ-rays in competition with the 700 Kev $O^+ \rightarrow O^+$ internal conversion electron transition in Ge^{22}. He found $\gamma/e^- < 1/1000$. Since the γ rate for a $1^{\pm} \rightarrow O^+$ transition would be of the order of 10^6 faster than the e^- rate for the $O^+ \rightarrow O^+$ transition, we can conclude that the amplitude for admixture of a spin 1 state is $< \sqrt{10^{-9}}$ (assuming normal matrix elements).

Other evidence for the nonmixing of angular momenta in stationary states comes from the approximate validity of the forbiddenness rules for estimating lifetimes of nuclear states against β or γ decay (or of atomic states against radiative transitions). The decay rate for "forbidden" transitions is generally reduced by a factor like $(ka)^{2n}$ where k is the energy release in natural units, a is some length characterizing the nucleus, and n is the order of forbiddenness. From an analysis of lifetimes, therefore, one can place limits on the admixture of states with angular momentum $J \pm \Delta J$, into a state whole "main" angular momentum is J, of the order

$$f \sim (ka)^{\Delta J}, \tag{17}$$

where f is the amplitude for admixture. Any appreciably greater admixture would make the lifetime much shorter than the forbiddenness rule would allow. In this way, one may conclude that, for a given state, limits on the admixing amplitudes for angular momenta differing by several units must be small since ka may typically be $\sim 10^{-3}$. Clearly, this discussion is oversimplified in that the effects of other approximate selection rules are omitted. Some improvement in these estimates might be obtained by an analysis of angular correlations, or spectrum shapes, which are sometimes more sensitively dependent on spin changes than are lifetimes.

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† *Note added in proof:* A pair of nuclei which are more amenable to an experimental test, and which differ by $\sim 0.8m_e$ in their nuclear masses are Rb^{87} and Sr^{87m}. An attempt was made to detect the 390 kev γ-rays from Sr^{87m} (2.7 hours), extracted from a Rb sample. This yields a lower limit for the partial lifetime of Rb^{87} decaying by a charge-non-conserving process to Sr^{87m} of $\tau > 10^{16}$ years. (A. W. Sunyar and M. Goldhaber, unpublished).

[1] See Lee, T. D., and C. N. Yang, "Elementary Particles and Weak Interactions," BNL 443.

[2] Electrons bound in atoms, or free, could also "disappear" if instead other conservation laws, such as the conservation of energy, were violated. If one detects all electron "decays," as in the experiment described below, this places an upper limit on the number of electrons decaying by transitions which do not conserve charge.

[3] derMateosian, E., and M. Goldhaber (unpublished).

[4] Wigner, E. P., *Proc. Am. Phil. Soc.*, **93**, 521 (1949).

[5] Wigner, E. P., these PROCEEDINGS, **38**, 449 (1952).

[6] It should be recognized that decays of a proton involving a hitherto unknown particle would not necessarily violate the conservation of baryons, even if this particle had a quite small mass, provided that the new particle were itself stable, since in this case one would simply assign baryon number +1 to the new particle. On the other hand, the occurrence of processes like $n + n \rightarrow \gamma + \gamma$ would automatically involve violation of the conservation of baryons, since the photon cannot have a nonzero baryon number because it may be produced singly, as in $p + p \rightarrow p + p + \gamma$.

[7] Reines, F., C. L. Cowan, Jr., and M. Goldhaber, *Phys. Rev.*, **96**, 1157 (1954).

[8] Reines, F., C. L. Cowan, Jr., and H. W. Kruse, *Phys. Rev.*, **109**, 609 (1957).

[9] Flerov, G. N., D. S. Klochov, V. S. Skobkin, and V. V. Terentiev., *Soviet Physics, Doklady* **3**, 78 (1958).

[10] Y. Yamaguchi (private communication) recently has considered the possibility of the decay $p \rightarrow 2e^+ + e^-$, $2p \rightarrow 2\pi^+$ and other baryon nonconserving interactions and obtained similar limits on the coupling constants. We would like to thank Dr. Yamaguchi for sending us his preprint.

[11] See Goldhaber, M., "1958 Annual International Conference on High Energy Physics." (Geneva: CERN), p. 234.

[12] Minimal electromagnetic interactions are interactions of the electromagnetic field with the current of charged particles. See Pais, A., *Phys. Rev.*, **86**, 663 (1952); Gellmann, M., *Proc. Sixth Ann. High Energy Conference* (1956).

[13] Samios, N., and J. Steinberger, private communication.

[14] Davis, H. P., A. Roberts, and T. F. Zipf, *Phys. Rev. Lett.*, **2**, 211 (1959); D. Berley, J. Lee, and M. Bardon, *Phys. Rev. Lett.*, **2**, 357 (1959).

[15] Dobrokhotov, E. I., Ya Lazarenko, and S. Yu. Luk'yanov, private communication (see ref. 11).

[16] Since the K^0 and $\bar{K}^0$ mesons are linear combinations of θ_1^0 and θ_2^0 they must also be electrically neutral. This also follows from the production process $\pi^- + p \rightarrow \Lambda^0 + K^0$ and the above relations

[17] The possible existence of a "baryon gauge field" has been discussed by Lee, T. D., and C. N. Yang, *Phys. Rev.*, **98**, 1501 (1955), who point out that if it exists, it must interact extremely weakly. The existence of a "lepton gauge field" has also been considered by many physicists.

[18] Shapiro, I. S., and I. V. Estulin, *Soviet Physics. JETP*, **3**, 626 (1957).

[19] Hughes, V., *Phys. Rev.*, **105**, 170 (1957). This paper also discusses several macroscopic experiments which give considerably smaller limits for the charges of molecules.

[20] If the charge of the proton were $(1 + \epsilon)\,|Q_{e^-}|$ then, e.g., the decay $p^+ \rightarrow e^+ + \pi^0$ would be forbidden. However the stability of an arbitrarily large number of protons would not be guaranteed by this alone, unless ϵ is irrational. Formally, this follows from the fact that then a subgroup of the charge gauge transformations (1) forms a dense subgroup of the baryon gauge transformations, and this implies baryon conservation.

[21] Of course, if angular momentum were not conserved, there might be additional electromagnetic interactions which would produce $O^+ \rightarrow O^+$ γ-transitions. However, the effect of such new interactions will depend critically on the type of interaction assumed and so we do not discuss them here.

[22] Sunyar, A. W., private communication.

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*MINIATURIZATION OF THE ELECTROMAGNETIC BLOOD FLOW METER AND ITS USE FOR THE RECORDING OF CIRCULATORY RESPONSES OF CONSCIOUS ANIMALS TO SENSORY STIMULI**

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Introduction.—The original electromagnetic flow meters[1–5] utilized large magnets. An artery (A in Fig. 1a) was inserted into the gap between the pole pieces of the magnet. As the blood traversed the magnetic field at right angles, an emf was induced in the blood stream. This emf served as the measure of the rate of blood flow. The flow signal was picked up by means of two electrodes E_1 and E_2 touching the outer wall of the artery at the end points of a diameter perpendicular to the magnetic field, as shown in Figure 1*a*. The use of a constant magnetic field necessitated the use of nonpolarizable electrodes. The size of the magnet and the complication of using nonpolarizable electrodes restricted the application of this method to exteriorized arteries of anesthetized animals. The introduction of the alterating magnetic field[3, 6] simplified the design of the amplifying system and made the use of ordinary metal electrodes possible. This paved the way for the development of a small flow meter which could be implanted into animals to study blood flow in the conscious state in chronic experiments.[7] Chronic implantations up to 4 weeks' duration have been thus obtained. But the implanted units of the original design whose iron and copper skeleton weighed 5.5 gm and whose weight when encased in a plastic body was somewhat over 10 gm were still too large in comparison with the artery diameter for successful permanent implantations (Fig. 2*b*). The present paper describes simple designs of flow meter implants which, for a given artery diameter, are greatly reduced in size as compared to units built according to the original pattern.[7] Reductions in weight by a factor of twenty and, in some instances, more have been achieved. Such flow meters can be easily constructed to accommodate arteries of diameters in the neighborhood of 1 mm. The same objective of design can, of course, be used also for larger blood vessels. A special design for arteries over 1 cm in diameter is described below. Figure 2 shows a comparison between the original "miniature" flow meter implant[7] for an artery diameter of