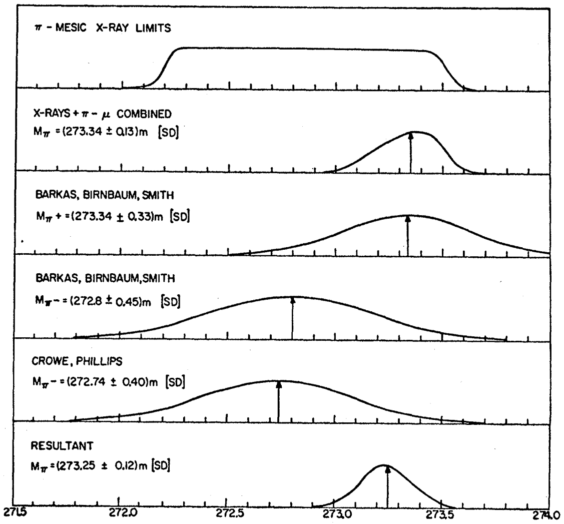


FIG. 1. Graphical summary of the data on the pion and muon mass values.

knowledge, the $\pi-\mu$ mass difference is the only appreciable source of error in the derivation of masses from the x-ray limits. However, even if the error of the $\pi-\mu$ difference were doubled, the final error would be raised only to $\pm 0.15\ m_e$. Errors in the $K$ edges, and uncertainties in and corrections to the mesonic x-ray levels due to vacuum polarization, finite nuclear size, pion-nucleon interactions, etc., contribute a negligible error.

* A more detailed discussion will appear in Cohen, Crowe, and DuMond, *The Fundamental Constants of Physics* (Interscience Publishers, Inc., New York, to be published).

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## Mass Difference of $\Sigma^\pm$ and Their Anomalous Magnetic Moments*

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THE idea that the various hyperons constitute definite isotopic multiplets is finding increasing use in the explanation of the interactions of strange particles. One would then expect that the relatively small mass difference between components of the same multiplet is due to interactions which are electromagnetic in origin. In another connection Feynman and Speisman[1] and Peterman[2] have shown that the mass difference between neutron and proton can be understood in terms of electromagnetic self-energies, if their anomalous moments are taken into account. Unlike the proton-neutron case, it will turn out that, since $\Sigma^\pm$ are both charged, a much larger mass difference is possible for comparable values of the anomalous moments.

The mass measurements on the $\Sigma$ hyperon[3] indicate that

$$m(\Sigma^-)-m(\Sigma^+)=(16.2\pm 5.5) \text{ electron masses.}$$

If we assume that the $\Sigma$ is a Dirac particle, we find that the observed mass difference requires that the sum of the magnetic moments of the $\Sigma^+$ and $\Sigma^-$ is positive and of the order of 3 to 4 nucleon magnetons.

The self-energy contribution to the mass of a fermion of charge $e$ and anomalous moment $\mu$ is given by (for notation see reference 1)

$$\Delta m=\frac{e^2}{(2\pi)^4 i}\frac{m}{E(p)}\bar{u}(p)\int d^4k \times\left\{\gamma_\nu-\frac{\mu}{4m}(\gamma_\nu k-k\gamma_\nu)G(k)\right\} \times\{p-k-m\}^{-1}\left\{\gamma_\nu+\frac{\mu}{4m} \times(\gamma_\nu k-k\gamma_\nu)G(k)\right\}\frac{C(k)}{k^2}u(p), \quad (1)$$

where $G(k)$ and $C(k)$ are invariant cut-off factors for the divergent integrals. Performing the indicated integration leads to an expression of the form

$$\Delta m/m=(\alpha/4\pi)\{2I_0\mp 3\mu I_1+\tfrac{3}{4}\mu^2 I_2\}, \quad (2)$$

where $I_0$, $I_1$, and $I_2$ are positive functions of the mass of the particle and of the cutoffs; the $\mp$ signs correspond to positively or negatively charged particles, respectively. We have chosen two typical forms of cutoff:

| Type | $C(k)$ | $G(k)$ |
|---|---|---|
| $(A)$ | $\Lambda^2/(\Lambda^2-k^2)$ | $\lambda^2/(\lambda^2-k^2)$ |
| $(B)$ | $\Lambda^4/(\Lambda^2-k^2)^2$ | $\lambda^2/(\lambda^2-k^2)$. |

From (2), the mass difference of the charged $\Sigma$ hyperons, can be written in the form

$$m(\Sigma^-)-m(\Sigma^+) =(\alpha m/4\pi)\{3I_1-\tfrac{3}{4}I_2(\mu^+-\mu^-)\}(\mu^++\mu^-). \quad (3)$$

We note that the sum of the anomalous moments has to be positive in order to explain the observed mass difference. Typical numerical values are given in Table I; the cut-off parameters $\Lambda^2$, $\lambda^2$ were chosen so as to reproduce the observed neutron-proton mass difference.

The anomalous moments in Table I indicate a significant contribution from the virtual emission and reabsorption of mesons. To judge the qualitative implications of these anomalous moments, we have performed a second-order calculation of the anomalous moments due to the virtual intermediate states in which the hyperon dissociates into a baryon and a meson (and still conserves the strangeness quantum number).[4] Thus, the anomalous moments may be due to the following virtual interaction schemes:

(1) $\Sigma^+ \to p + \bar{K}^0$, $\quad \Sigma^- \to n + \bar{K}^-$,

(2) $\Sigma^+ \to \Xi^0 + K^+$, $\quad \Sigma^- \to \Xi^- + K^0$,

(3) $\Sigma^\pm \to \Sigma^0 + \pi^\pm$, $\quad \Sigma^\pm \to \Sigma^\pm + \pi^0$.

(4) $\Sigma^\pm \to \Lambda^0 + \pi^\pm$,

Nonvanishing contributions come from two different types of processes, which may be called the baryon current term (denoted by $B_1$ below) and the meson current term (denoted by $B_2$ below). An examination of the symmetry properties of the hyperon and pion multiplets shows that, in all orders, the contributions of the reactions (3) and (4) to the anomalous moments of $\Sigma^+$ and $\Sigma^-$ are equal and opposite. There are two further contributions to the moments, from a fermion (boson) current from reaction (1) and from a boson (fermion) current from reaction (2) for the anomalous moment of $\Sigma^+(\Sigma^-)$. The evaluation of the various terms is straightforward[5] if we assume that the $K$ meson is a spin-zero particle; we find

TABLE I. Electromagnetic self-energy differences of the charged hyperons.

| Cut-off type | $\Lambda^2$ | $\lambda^2$ | $\mu^+$ | $\mu^-$ | $\mu^+ + \mu^-$ | $m^- - m^+$ |
|---|---|---|---|---|---|---|
| (A) | $2m^2$ | $2m^2$ | 1.5 | 1.5 | 3.0 | 16.9 |
| (A) | $2m^2$ | $2m^2$ | 3.0 | 1.0 | 4.0 | 17.5 |
| (A) | $m^2$ | $4m^2$ | 1.5 | 1.5 | 3.0 | 15.1 |
| (A) | $m^2$ | $4m^2$ | 3.0 | 1.0 | 4.0 | 15.1 |
| (B) | $4m^2$ | $4m^2$ | 1.5 | 1.5 | 3.0 | 16.3 |
| (B) | $4m^2$ | $4m^2$ | 3.0 | 1.0 | 4.0 | 15.0 |
| (B) | $1.5m^2$ | $\infty$ | 1.5 | 1.5 | 3.0 | 12.0 |
| (B) | $1.5m^2$ | $\infty$ | 3.0 | 1.0 | 4.0 | 7.0 |

$$\mu^+ = g^2(\Sigma N\bar{K})B_1(\Sigma N\bar{K}) - \tfrac{1}{2}g^2(\Sigma\Xi K)B_2(\Sigma\Xi K) + g^2(\Sigma\Sigma\pi)\{B_1(\Sigma\Sigma\pi) - \tfrac{1}{2}B_2(\Sigma\Sigma\pi)\} - \tfrac{1}{2}g^2(\Sigma\Lambda\pi)B_2(\Sigma\Lambda\pi),$$

$$\mu^- = \tfrac{1}{2}g^2(\Sigma N\bar{K})B_2(\Sigma N\bar{K}) - g^2(\Sigma\Xi K)B_1(\Sigma\Xi K) - g^2(\Sigma\Sigma\pi)\{B_1(\Sigma\Sigma\pi) - \tfrac{1}{2}B_2(\Sigma\Sigma\pi)\} + \tfrac{1}{2}g^2(\Sigma\Lambda\pi)B_2(\Sigma\Lambda\pi),$$

where $g^2 = (G^2/4\pi\hbar c)$ and the functions $B_1$ and $B_2$ of the masses have the numerical values given in Table II; the $\pm$ signs are to be taken consistently according as the coupling chosen is scalar or pseudoscalar, i.e., the $K$ meson is scalar (pseudoscalar) or pseudoscalar (scalar), respectively, assuming the parity of the $\Sigma$ hyperon to be the same as (opposite to) the parity of the nucleon.

Apart from the coupling constants which are still arbitrary, we notice that the scalar and pseudoscalar coupling give similar results, except for a scale factor and a change of sign. This change of sign was already noted by Case[5] in his calculations of the nucleon anomalous moments and is connected with the parity difference of the virtual bosons.

The sum of the anomalous moments of the charged hyperons is given by

$$\mu^+ + \mu^- = g^2(\Sigma NK)\{0.76 \pm 1.39\} - g^2(\Sigma\Xi K)\{0.23 \pm 0.71\}.$$

Combining this with the earlier quoted results of the value of the same quantity estimated from the mass difference, we obtain an estimate of the coupling constant,

$$g^2 \sim 2.4 \text{ to } 3.2,$$

for scalar coupling, assuming that

$$g(\Sigma N\bar{K}) \simeq g(\Sigma\Xi K).$$

TABLE II. Baryon and boson current contributions to the anomalous moments.

| Interaction | $B_1$ | $B_2$ |
|---|---|---|
| $\Sigma N\bar{K}$ | $0.45 \pm 0.97$ | $0.31 \pm 0.42$ |
| $\Sigma\Xi K$ | $0.16 \pm 0.54$ | $0.07 \pm 0.16$ |
| $\Sigma\Sigma\pi$ | $0.38 \pm 0.81$ | $0.52 \pm 0.71$ |
| $\Sigma\Lambda\pi$ | $0.43 \pm 1.24$ | $0.90 \pm 1.04$ |

Pseudoscalar coupling gives the wrong sign of the anomalous moments so that $\Sigma^+$ would be heavier than $\Sigma^-$. It is obvious that the value of the estimated coupling constant is too large for a second-order perturbation calculation to be reliable. However, calculations in the analogous case of the strongly coupled pion-nucleon system reproduce the correct signs of the proton and neutron anomalous moments. We would like to believe that the signs of the anomalous moments are significant in the present case also.

It is clear from experiment that, if the $K$ meson possesses spin 0, both parities are present. If this is so, both types of coupling (scalar and pseudoscalar) must occur for the $K$ meson. From the foregoing calculations, we would conclude that the observed sign of the mass difference of $\Sigma^\pm$ is an argument for the presence of strong scalar coupling of the $K$ meson to the baryons.

Similar calculations have been done for the anomalous moments and the mass spectrum of the other hyperons and the contribution of the virtual emission of $K$

mesons to the nucleon anomalous moments. These results will be published in a separate note.

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## Suggestion Concerning the Nature of the Cosmic-Ray Cutoff at Sunspot Minimum

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UNDER quiet solar conditions near sunspot minimum, no cosmic rays with magnetic rigidity less than ~1.5 Bev appear to reach the earth.[1,2] An attempt to explain this cutoff as arising from a solar magnetic field of dipolar form was made many years ago by Janossy.[3] The solar magnetic moment demanded by this explanation is too high, however, by a factor ~10 to be in accord with the modern solar magnetic measurements of Babcock and Babcock.[4] The present note offers a suggestion for explaining the cutoff, not in terms of a solar field, but of an interstellar magnetic field, the possible importance of which has been noted by Davis.[5]

Two main steps are concerned in the following argument, one a consideration of the magnetic field of the earth and the other a consideration of the interstellar field. Both these issues are concerned with the diffuse gas that probably exists in interplanetary space.[6] The density of the gas in the neighborhood of the earth is usually set[7] at $\sim 10^{-21}$ g/cm$^3$. With the gas mainly composed of hydrogen atoms, this density corresponds to $\sim 10^3$ atoms/cm$^3$. Since a considerable fraction of the atoms appears to be ionized, there must be a strong interaction between the gas and the terrestrial magnetic field. The interaction must produce a gross modification of the earth's field at distances away from the earth where the magnetic energy density is less than $\frac{1}{2}\rho v^2$, $\rho$ being the gas density and $v$ the streaming velocity relative to the earth. That is to say, there must be a gross modification of the earth's field at and beyond a distance where the magnetic intensity is of order $(4\pi\rho v^2)^{\frac{1}{2}}$. With $\rho \simeq 10^{-21}$ g/cm$^3$ and $v \simeq 30$ km/sec, this gives an intensity $\sim 3\times 10^{-4}$ gauss, and the terrestrial field falls to such an intensity at a distance of about 10 earth radii. Beyond this distance gross modification from a dipolar form of field must occur. It is emphasized that the general orders of magnitude appearing in this result are quite insensitive to the particular values chosen for $\rho$ and $v$—the distance in question being proportional to $\rho^{\frac{1}{6}}$ and to $v^{\frac{1}{3}}$.

The question now arises as to what form the modification will take. Two possibilities seem to exist. If the lines of force of the terrestrial field extend outwards into the gas beyond about 10 earth radii, they will be twisted and contorted by the motion of the gas, the nature of the deformation depending on the detailed flow of the gas. The other possibility is that the lines of the earth's field close up within a distance of ~10 earth radii and that they do not penetrate outwards beyond this distance and are then not subject to violent deformation. In this case, any gas that is present within a distance of order 10 earth radii will have its motion controlled by the terrestrial field; it will move along with the earth around the sun and it will rotate with the earth. Of these two possibilities the second seems the more likely, although a strict proof appears difficult. In what follows, the second possibility will be assumed.

Turning now to the interstellar gas, it is at once apparent that cosmic rays within the interstellar gas cannot reach the neighborhood of the earth unless the interstellar gas itself approaches close to the earth—at any rate this is so if the magnetic field within the gas has an intensity comparable with the average value of order $10^{-5}$ gauss that is currently supposed. Thus, for example, a proton of energy 10 Bev moves around the lines of force of a field of intensity $10^{-5}$ gauss in a circle with radius close to $3\times 10^{12}$ cm. Unless the interstellar gas approaches within this distance of the earth, or unless the interstellar magnetic field happens to be much less than $10^{-5}$ gauss in the vicinity of the solar system, such a particle cannot reach the earth; it remains "attached" to the interstellar magnetic field which it cannot leave. Since a distance of $3\times 10^{12}$ cm is small compared with the dimensions of the solar system and since an exceptionally weak field in the vicinity of the solar system seems implausible, it is reasonable to conclude that the interstellar gas penetrates the solar system. Accordingly the interplanetary gas apparently cannot be derived wholly from the sun as some authors have supposed, unless the cosmic rays are wholly of solar origin which again seems unlikely.

One point remains before the main conclusion is reached. The value of $10^{-5}$ gauss usually quoted for the interstellar magnetic field refers to the average situation within the interstellar medium. In particular, it refers to a gas density of order $10^{-24}$ g/cm$^3$. Any compression of the interstellar gas by the gravitational field of the sun must increase the magnetic intensity, an isotropic compression causing an increase by the two-thirds power of the gas density. Thus if we regard the interstellar gas as supplying a major contribution to an