π-π scattering cross section can be determined only by the extrapolation procedures recently suggested by Goebel and Chew and Low.[7]

The angular- and energy-correlations in the π-π c.m. system should also be sensitive to the S/P ratio: a fore-aft asymmetry should appear within this energy range, and higher c.m. energies should be favored as the P-wave interaction becomes dominant. An observation of both final pions is required to determine the relevant angle and energy. As discussed in the previous paragraph, it is difficult to make a reliable estimate of these effects using the present phenomenological approach.

According to the model proposed here, the P-wave, $T=1$, π-π interaction should dominate for $E_{\text{inc}} > 400$ Mev. It follows that the charged-to-neutral production ratio $(\pi^- + p \to \pi^- + \pi^+ + n)/(\pi^- + p \to \pi^- + \pi^0 + p)$ is predicted to be 2, the square of the ratio of the pion-nucleon coupling constants for charged and neutral meson emission. This interaction also yields no production of $2\pi^0$. For $\pi^+ + p$, only the reaction $\pi^+ + p \to \pi^+ + \pi^0 + p$ is permitted by the $T=1$ interaction. As a result, the inelastic cross section for $\pi^+ + p$ should be 1/3 that for $\pi^- + p$; experimentally,[8,9] for $E_{\text{inc}} \approx 500$ Mev, this ratio is about 1/4. Since the probability of finding two pions in the nucleon cloud is small, this model also predicts that double-pion production should be unlikely compared to single-pion production.

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[2]L. S. Rodberg, Phys. Rev. 106, 1090 (1957); E. Kazes, Phys. Rev. 107, 1131 (1957).

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[4]W. R. Frazer and J. R. Fulco, Phys. Rev. Letters 2, 365 (1959). The π-π energies involved in our problem are too small to obtain any indication of the resonance which they require. At higher energies there is some indication of a peak in the inelastic cross section at the expected energy (reference 8). See also G. Takeda, Phys. Rev. 100, 440 (1955).

[5]G. F. Chew and R. E. Low, Phys. Rev. 101, 1579 (1956).

[6]V. Perez-Mendez (private communication).

[7]C. Goebel, Phys. Rev. Letters 1, 337 (1958); G. F. Chew and F. E. Low, Phys. Rev. 113, 1640 (1959). As these authors point out, the sharp diffraction peak observed in elastic pion-nucleon scattering provides another indication of a strong π-π interaction.

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[9]R. R. Crittenden et al., Phys. Rev. Letters 2, 121 (1959).

CONSEQUENCES OF ATOMIC CONVERSION FOR THE INTERPRETATION OF EXPERIMENTS ON THE SPIN-DEPENDENCE OF MUON ABSORPTION*

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The ground state of a μ-mesonic atom of nonzero nuclear spin I is split by the hyperfine interaction into two states, of total angular momenta $F = I \pm \frac{1}{2}$. It was pointed out by Bernstein, Lee, Yang, and Primakoff[1] (hereinafter referred to as BLYP) that (a) the lifetimes of the members of this doublet may, as a consequence of the incoherence of the two states, be distinct, and that (b) these lifetimes will actually differ if the muon absorption rate depends on F, i.e., if the relevant weak interaction is at least partly spin-dependent. The total muon disappearance rate is the sum of the absorption and the decay rates, and the latter is indeed to an excellent approximation independent of F. BLYP estimated the fractional difference δ between the two lifetimes on the basis of a simple nuclear model,[2] and suggested an experimental test for the spin-dependence of muon absorption: Demonstrate that the rate of appearance of decay electrons (originating from μ^- bound in a monoisotopic target with $I \neq 0$) does not, as a function of time, follow a simple exponential. The logarithm of the decay curve should indeed exhibit (in the sense defined below) a positive curvature proportional to δ^2. This quadratic dependence would of course prevent one, as BLYP emphasized, from establishing which member of the doublet absorbs faster, i.e., from settling a question of particular theoretical significance.

In the discussion of BLYP it was assumed implicitly that atomic processes do not contribute to the lifetime of either state, and in particular that the energetically higher member of the doublet cannot be converted into the lower one at an appreciable rate. Such a conversion could take place in principle by the ejection of Auger electrons and, to a lesser extent, by $M1$ radiation. It is the purpose of this note to explore the experimental consequences of such atomic conversion processes which, in our opinion, may not be negligible in situations of actual physical interest.

We refer to the higher state of the doublet by 1, to the lower one by 2, and indicate the muon disappearance rates by λ_1 and λ_2, respectively; let R stand for the conversion rate from 1 to 2. The populations n_1 and n_2 of 1 and 2 are governed by

$$dn_1/dt = -(\lambda_1+R)n_1,$$
$$dn_2/dt = -\lambda_2 n_2 + Rn_1, \tag{1}$$

as a function of time, t. The rate of appearance of decay electrons is for all t proportional to $\lambda_0(n_1+n_2)$, indicating with λ_0 the muon decay rate (by hypothesis the same for 1 and 2). In the experiment proposed by BLYP, one measures the curvature K of $f(t)=\log(n_1+n_2)$. We adopt the standard definition

$$K=f''(1+f'^2)^{-3/2}, \tag{2}$$

where the primes indicate differentiation with respect to t. The sign of K is determined by the sign of f''. From (1) one has directly

$$f''=[(\lambda_1-\lambda_2)^2 n_1 n_2+(\lambda_1-\lambda_2)Rn_1(n_1+n_2)]/(n_1+n_2)^2, \tag{3}$$

which shows that $K \geqslant 0$ when $R=0$, i.e., in the case considered by BLYP. The curvature will, however, necessarily be negative ($K<0$) when the inequalities

$$\lambda_1-\lambda_2<0, \tag{4a}$$

$$R>|\lambda_1-\lambda_2|/(1+n_1/n_2), \tag{4b}$$

obtain under the conditions of the experiment. (4b) is of course a function of time; as K goes monotonically to zero with increasing t,

$$R>|\lambda_1-\lambda_2|/[1+n_1(0)/n_2(0)], \tag{4b$'$}$$

is sufficient to ensure, with (4a), $K<0$ for all t.

Odd Z - odd A nuclei, the most suitable targets for the BLYP experiment, have in general magnetic moments μ_N in agreement with the picture of an $I_{L\pm\frac{1}{2}}$ unpaired proton. The sign of μ_N determines which of the states $F=I\pm\frac{1}{2}$ lies lowest, so that (4a) can be written as

$$\lambda_- > \lambda_+ \quad \text{when} \quad \mu_N>0, \quad (I=L+\tfrac{1}{2}) \tag{5a}$$

$$\lambda_+ > \lambda_- \quad \text{when} \quad \mu_N<0, \quad (I=L-\tfrac{1}{2}) \tag{5b}$$

indicating with $\lambda_{+(-)}$ the disappearance rate in the $F=I+(-)\frac{1}{2}$ state. [Note that N^{15} is the sole relevant nuclide for which (5b) applies.] The extreme case of a nucleus with $\mu_N>0$ is the proton; condition (5a) requires hence that muon absorption proceed faster from the singlet than from the triplet state in the basic absorption act. This will be the case when the ratio of the Gamow-Teller and of the Fermi coupling constants is negative,[3] e.g., for the V-A interaction now well established in many weak reactions. Condition (5b) may also be fulfilled by the <u>same</u> type of coupling, because here the muon and the proton are in a relative singlet state when $F=I+\frac{1}{2}$.

Assuming that the members of the doublet are statistically populated at $t=0$, condition (4b$'$) becomes

$$R/|\lambda_+ - \lambda_-| > I/(2I+1) \qquad \text{when} \quad \mu_N>0, \tag{6a}$$

$$R/|\lambda_+ - \lambda_-| > (I+1)/(2I+1) \quad \text{when} \quad \mu_N<0. \tag{6b}$$

For Al ($Z=13$, $I=\frac{5}{2}$) a detailed calculation,[2] based on a $V-xA$ type interaction and the measured[4] muon absorption rate, gives $\lambda_- - \lambda_+ = 1.2\times10^5$ sec^{-1}. According to a recent estimate,[5] the conversion by Auger effect on the conduction electrons in metallic Al should occur at a rate $R \approx I(2I+1)^{-1}\times1.5\times10^6$ sec^{-1}. Thus, even if this estimate were too high by a factor two, (6a) should be amply fulfilled for Al. As $|\lambda_+ - \lambda_-| \sim 1/Z$, while $R\sim Z^a$ (with $a>1$), elements with $Z>13$ should <u>a fortiori</u> yield $K<0$.

We conclude that in the BLYP experiment

(a) a negative <u>curvature</u> can arise only if the basic muon absorption process is faster for antiparallel muon and proton spins, e.g. for a V-A type interaction;

(b) a zero curvature does not necessarily imply the absence of spin dependence;

(c) the conversion rates from the higher to the lower member of the μ-mesonic hyperfine doublet are for $Z \geqslant 13$ sufficiently large to lead to a negative curvature once the condition (a) holds.

These conclusions, in particular (c), have an obvious bearing on the neutron asymmetry effects in μ-capture recently discussed by Überall.[6]

The author was prompted to the considerations presented here some time ago by preliminary experimental results[7] which suggest that $K<0$ for Al; he is grateful to R. Winston for assistance with the analytic formulation of the curvature problem. He takes pleasure in thanking H. Primakoff and J. Bernstein, who had independently drawn similar conclusions, for much friendly advice.

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[1]Bernstein, Lee, Yang, and Primakoff, Phys. Rev. 111, 313 (1958).

[2]For more detailed and model-independent calculations, see H. Primakoff, Revs. Modern Phys. (to be published).

[3]T. D. Lee gave a particularly simple argument for this at the 1958 Midwest Theoretical Physics Conference at St. Louis (p. 189 of the mimeographed proceedings).

[4]J. C. Sens, Phys. Rev. 113, 679 (1959).

[5]This estimate was made by H. Primakoff and the author, and supersedes the one in footnote 16a of reference 2. R depends primarily on the probabilities for finding the 3s conduction electrons and the Auger emitted electrons near $r=0$. In this estimate $|\psi_{3S}(0)|^2 = y/\pi a_0^3$, and $|\psi_v(0)|^2 = 2\pi Z^* \alpha c/v$ were assumed, and $y=2.2$ was inferred from Knight shift and optical hfs data. One finds, for an $F=I+\frac{1}{2}\rightarrow F=I-\frac{1}{2}$ transition,

$$R=I(2I+1)^{-1}(64\pi/9)Z^*\alpha^6 y(m_e/m_\mu)^3 m_\mu c^2/\hbar,$$

and $10\leq Z^*<12$ for Al.

[6]H. Überall (to be published).

[7]Lathrop, Lundy, Swanson, Telegdi, Yovanovitch, and Winston (unpublished).

SUPPRESSION OF P-STATE CAPTURE IN (K^-,p) ATOMS*

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It is of obvious importance, in studying the reactions of K^- mesons at rest in liquid hydrogen or deuterium, to have some idea of the atomic orbit from which the K mesons are captured. Since the low-energy scattering data[1] seem to indicate a large S-wave interaction, it is simplest to ignore P-wave contributions and assume that the reactions take place from the 1S orbit. (In the case of deuterium, even the neglect of P-wave interactions does not prevent an appreciable capture from the 2P orbit.[2])

However, this neglect, in the case of hydrogen, of the 2P orbit contributions has been very hard to justify. Since transition rates due to K^--p interactions are so very much greater than those of radiative transitions, even a very small P-wave interaction can compete favorably with the radiative 2$P\rightarrow$1S transition rate, as long as the 2P state is occupied at all. Moreover, it is usually argued that the cascading mesons will predominantly pass through the 2P state (except for loss due to the direct capture from higher nS orbits) since the nature of the selection rules for dipole radiation favors populating the circular orbits.

We would like to point out in this note that successive Stark effect collisions of a highly excited (K^-,p) atom with nearby protons in the liquid hydrogen will drastically reduce the probability that the K^- meson ever reaches the 2P orbit.

Consider the following picture. The (K^-,p) atom is moving with some velocity $v(\sim 10^5$ cm/sec from considerations of thermal motion, recoil from previous radiative transitions, and possible pickup of the K^- in flight) through the liquid hydrogen. The average radius of a unit sphere (hereinafter called a unit cell) in liquid hydrogen (density 0.07 g/cc)[3] is ~1.8 A. Hence, on the average about one in ten traversals of a unit cell will result in the mesonic atom's passing within a distance of one electron Bohr radius from a proton, and thus being subjected to the intense electric field of the proton.[4] To estimate the transition rates due to this Stark effect, let us compute it in the $n=6$ level, between the 6P and 6S states.

A measure of this rate is given by

$$\gamma_S(6P\rightarrow 6S)=|\langle 6S|\vec{E}\cdot\vec{r}|6P\rangle| \simeq E_{\rm Av}(a_0)\langle 6S|r\cos\theta|6P\rangle, \quad (1)$$

where $E_{\rm Av}(a_0)$ is some average electric field due to the proton at one Bohr radius, and $r\cos\theta$ refers to the K^- meson's coordinate. One ob-