fects 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.

* Research supported by a joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[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[7]Lathrop, Lundy, Swanson, Telegdi, Yovanovitch, and Winston (unpublished).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 $2P\rightarrow 1S$ 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

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

where $E_{\mathrm{Av}}(a_0)$ 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 obtains[5]

$$\langle 6S\,|\,r\cos\theta\,|\,6P\rangle = 30.8\ a_{K^-}, \qquad (2)$$

where a_{K^-} is the K-meson Bohr radius, and

$$E_{\text{Av}}(a_0) \sim e^2/a_0^2. \qquad (3)$$

Then, we find

$$\gamma_S(6P\to 6S) \simeq 2.0\times 10^{15}\ \text{sec}^{-1}. \qquad (4)$$

This is comparable to the direct capture transition rate from the $6S$ level,[6] given by

$$\gamma_c(nS) = (4.7\times 10^{17})/n^3\ \text{sec}^{-1}, \qquad (5)$$

$$\gamma_c(6S) = 2.2\times 10^{15}\ \text{sec}^{-1}. \qquad (6)$$

The radiative $6P\to 1S$ transition rate (obtained from Table XV of reference 5 upon multiplication by the K^--p reduced mass $= 648m_e$) is

$$\gamma_R = 1.26\times 10^{10}\ \text{sec}^{-1}. \qquad (7)$$

Stark transition rates for other possible $(n, l \to n, l\text{-}1)$ transitions will be comparable in magnitude to that of Eq. (4), and decrease as n decreases, so that at $n=2$,

$$\gamma_S(2P\to 2S) \simeq 0.2\times 10^{15}\ \text{sec}^{-1}. \qquad (8)$$

Note that γ_S is much larger than the reciprocal of the transit time ($\sim 10^{13}$ sec^{-1}), which, in turn, is much larger than γ_R. Hence, during the time that a highly excited mesonic atom is within a Bohr radius of a hydrogen atom,[7] radiative transitions can be ignored, while many Stark transitions can take place, so that some steady-state distribution is approached. Ignoring, for the moment, the capture from the nS state, we approximate the equilibrium distribution due to the Stark transitions with a simple $(2l+1)$ distribution.[8] Now, when the capture from the nS state is included, the nP (and, of course, the nS) states are immediately depopulated.[9] Hence, we expect that in each close collision, an appreciable fraction of the K^- mesons in the n level are lost due to capture from the nS state.

We are now in a position to make a quantitative estimate of the total effect. Since the Bethe and Salpeter tables only go up to $n=6$, we use that level as an example of a starting level and proceed as follows. Take 3600 K mesons distributed in the $6S$ to $6H$ level with a $(2l+1)$ weighting at time equal to zero. Let the mesonic atoms move and decay via radiative transitions for the time necessary to cross 10 unit cells.[10] After that time consider the atoms as passing within a Bohr radius of a neighboring proton. This has the effect, as noted above, of completely depopulating the $6P$ level and reshuffling the remaining particles into a $(2l+1)$ distribution again. Then start again with the new $(2l+1)$ distribution on another 10-cell journey, etc.

A lower limit for the total loss in the first 10-cell journey is[11] 300 particles from $6P$ plus 16.9 from $6D$, $6F$, $6G$, and $6H$ combined. When the 3600 K^- mesons are gone, the loss due to $6P\to 6S$ $\to$capture will be $(3/3.169)\times 3600$ $(=3408)$. The remaining K^- mesons are lost by direct radiative transitions and are distributed as in Table I. Thus, Table I shows that only ~ 45 K^- mesons of the original 3600 get to the $2P$ level by direct $6D\to 2P$ radiative transitions. On following the cascading mesons through the lower levels, which are also subject to the Stark effect, one finds that the population of the $2P$ level is raised to ~ 52 out of the original 3600.

So $\lesssim 1.4\,\%$ of the K^- mesons starting in the $n=6$ level distributed according to a $(2l+1)$ distribution reach the $2P$ level. Furthermore, similar considerations apply at even higher n levels. To estimate the percentage of those starting in a higher level which reach the $2P$ level, we use the fact obtained from the $n=6$ level calculation, that most of the particles reaching $2P$ came via direct $6D\to 2P$ radiative transitions. This percentage was directly proportional to the radiative transition rate for $6D\to 2P$. For a given initial l, the radiative transition rate goes as n^{-3} (see reference 4).

For example, at $n=15$, the S-state nuclear capture rate is still much faster than all radiative rates and the inverse of the transit time. Hence, our conditions are still fulfilled, and

Table I. Distribution by radiation from $n=6$ levels, starting with 3600 particles distributed in the $6S$ to $6H$ states with a $(2l+1)$ weighting. (All levels shown are taken as stable for purposes of the diagram.)

$5P/3.71$	$5D/8.9$	$5F/17.5$	$5G/31$
$4P/7.98$	$4D/16.0$	$4F/21.5$	
$3P/17.36$	$3D/26.1$		
$2P/44.59$			

now, of those mesons which start in an $n=15$ level, the percentage that reaches the $2P$ state becomes $\sim 0.1\%$. Thus, our calculations indicate that of the K^- mesons captured by protons in liquid hydrogen in highly excited states, $\lesssim 1\%$ will ever reach the $2P$ level.[12]

The above result implies that when a K^- meson comes to rest in liquid hydrogen, the nuclear capture reaction essentially always occurs with the relative orbital angular momentum of the (K^-, p) system equal to zero. This has many important consequences:

1. The isotropic angular distributions of the decays of Σ^+, Σ^-, and Λ^0 hyperons[13] produced from (K^-, p) captures at rest shows, according to the arguments of Treiman,[14] that the spins of these three hyperons are each equal to one-half.

2. The relation between the data for (K^-, p) reactions in flight and those for (K^-, p) captures at rest, assumed by many authors,[15] is now justified. In addition, the $(\Lambda^0, 2\pi)$ production data from (K^-, p) atoms can be used to determine the parity of the K^- meson relative to the (Λ^0, p) system.[16]

3. The predictions of Amati and Vitale[17] concerning the branching ratios from (K^-, p) capture reactions at rest, based on the assumption of global symmetry, may now more significantly be compared with existing data. Subject to the reservations pointed out by Dalitz,[18] the data violate the predicted inequality.

4. It is expected that the Stark effect transitions will also dominate in the capture at rest of $\bar{p}$, Σ^-, and Ξ^- hyperons in hydrogen, so that it is justified to assume that the capture reactions take place from S states.

5. Similar considerations are expected to hold for captures at rest of K^-, Σ^-, and Ξ^- particles in deuterium.

The results of this calculation indicate that essentially no mesonic x-rays should be produced when a K^- meson comes to rest in liquid hydrogen. This result can be checked experimentally with a search for such x-rays.

We are indebted to Professor L. Madansky for suggesting the possible importance of the Stark effect in (K^-, p) mesonic atoms, and to Dr. R. G. Glasser for directing our attention to the higher n levels.

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* This research was supported in part by the U. S. Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command and in part by the U. S. Atomic Energy Commission.

[1] Norden, Rosenfeld, Solmitz, Tripp, and Watson, Bull. Am. Phys. Soc. 4, 24 (1959); A. H. Rosenfeld, Bull. Am. Phys. Soc. 3, 363 (1958); M. F. Kaplon, 1958 Annual International Conference on High-Energy Physics at CERN, edited by B. Ferretti (CERN, Geneva, 1958), p. 171. R. S. White (private communication); R. D. Hill (private communication).

[2] T. B. Day and G. A. Snow, Phys. Rev. Letters 2, 59 (1959).

[3] For experiments in a hydrogen bubble chamber, a density of 0.059 g/cc should be used. This has the effect of increasing the population of the $2P$ state slightly over the estimates given in this paper.

[4] We assume that the electron shields the proton's field completely beyond one Bohr radius, and that there is no shielding within a Bohr radius.

[5] H. A. Bethe and E. E. Salpeter, Quantum Mechanics of One- and Two-Electron Atoms (Springer-Verlag, Berlin, 1957), p. 253.

[6] G. Frye, Phys. Rev. 113, 688 (1959).

[7] For distances of approach to the proton, R, smaller than a_0, $\gamma_S(R) = \gamma_S(a_0)(a_0/R)^2$.

[8] We have looked at the simple problem of three degenerate levels coupled by Stark transitions (radiative and capture transitions are ignored) and find that in the Stark reshuffling very good mixing is achieved.

[9] If we consider only the nP and nS levels as being coupled by Stark transitions, but include the capture from the nS state, the population of the nP level decays exponentially with a decay constant Γ given by

$$\Gamma \sim \tfrac{1}{2}\gamma_C(nS), \quad 4\gamma_S \gtrsim \gamma_C, \qquad \text{(a)}$$

$$\Gamma \sim \tfrac{1}{4}\gamma_C(nS)\,|4\gamma_S/\gamma_C|^2, \quad 4\gamma_S \ll \gamma_C. \qquad \text{(b)}$$

For $n \gtrsim 4$, Γ is much larger than the reciprocal of the transit time. However, for $n=2$, $\Gamma \sim 2\times10^{12}\ \mathrm{sec}^{-1}$ compared with $\gamma_R(2P\to1S) = 4\times10^{11}\ \mathrm{sec}^{-1}$. Thus, in integrating over the path of the (K^-, p) system in a $2P$ state, the Stark effect is rather small, especially when the $2S$ level shift due to nuclear capture is included [not done in Eq. (b) above].

[10] This average time for crossing one unit sphere is $\frac{2}{3}(2R_0/v)$ where R_0 is the radius of the unit sphere ~ 1.8 A, and v is the velocity. The same factor $\frac{2}{3}$ applies in crossing, on the average, a sphere of radius equal to one Bohr radius.

[11] This estimate of the loss underestimates the true effect since successive repopulation and depletion of the nP level many times within one collision is ignored.

[12] Clearly the results depend on the exact value chosen for the velocity. The loss due to radiation, and hence the percentage reaching the $2P$ state, is inversely proportional to this velocity. However, the velocity would have to be changed by a large factor to change the absolute percentages appreciably.

[13] L. Alvarez et al., Nuovo cimento 5, 1026 (1957).

[14] S. B. Treiman, Phys. Rev. 101, 1216 (1956).

[15] R. H. Dalitz and S. F. Tuan, Ann. Phys. (to be

published); Jackson, Ravenhall, and Wyld, Nuovo cimento 9, 834 (1958).

[16] L. B. Okun' and I. Ia. Pomeranchuk, J. Exptl. Theoret. Phys. (U.S.S.R.) 34, 997 (1958) [translation: Soviet Phys. JETP 34, 688 (1958)].

[17] D. Amati and B. Vitale, Nuovo cimento 9, 895 (1958).

[18] R. H. Dalitz, 1958 Annual International Conference on High-Energy Physics at CERN, edited by B. Ferretti (CERN, Geneva, 1958), p. 197.

S-MATRIX POLES IN THE DETERMINATION OF PARITIES*

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(Received May 18, 1959)

Recently it has been conjectured[1] that there exist dispersion relations in momentum transfer variables. A number of authors[2,3] have suggested using an approximation to these relations in order to determine such physical quantities as parities, coupling constants, etc. This approximation consists of extracting the contribution of certain single-particle intermediate states ("the pole terms") to S-matrix elements, and analyzing the experimental data on the assumption that these contributions predominate. In this note we wish to point out some potential difficulties inherent in such an analysis.

One of the processes which has been examined in reference 2 is the production of Λ's in π-proton collisions, that is

$$\pi^- + p \to \Lambda + K^0. \tag{1}$$

If we assume that the Mandelstam conjecture[1] is justified, there is a term in the matrix element of process (1) from the K-meson intermediate state illustrated in Fig. 1(a). This term will contribute provided the vertex parts

$$\langle K^0 | j_{\pi^+} | K^+ \rangle, \quad \langle \Lambda | j_{K^+} | p \rangle \tag{2}$$

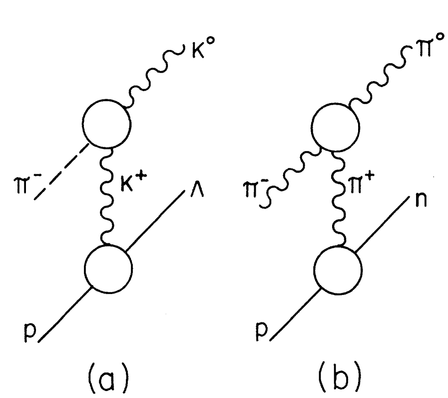

FIG. 1. Possible pole contributions for the processes $\pi^- + p \to \Lambda + K^0$ and $\pi^- + p \to n + \pi^0$.

do not vanish. In this case the matrix element will have a pole in $\cos\theta$ (θ being the angle between the incoming π meson and outgoing K in the center-of-mass system) at a point α_0. This point is in the nonphysical region, but can be near $\cos\theta = 1$. There are, of course, contributions to the matrix element arising from other intermediate states, for example the ones in which there is both a K and a π meson. These terms lead to a branch point in $\cos\theta$ at the point α_1. Specifically, for a π-meson lab energy of 1.9 Bev, $\alpha_0 = 1.24$ and $\alpha_1 = 1.40$.

If one plots $F(\cos\theta)$ using the experimental data, where

$$F(\cos\theta) = (\alpha_0 - \cos\theta)^2 d\sigma/d\Omega, \tag{3}$$

it is claimed that one can obtain direct evidence for or against the presence of the pole term. The single experiment, namely the angular distribution for process (1) at a fixed energy, could be used to prove that the vertex parts (2) do not vanish. Hence it would follow that the relative K^+-K^0 parity is odd.

We wish to examine reactions analogous to process (1). Our aim is to show that use of the type of analysis discussed above may lead to ambiguous, and possibly incorrect, conclusions. Accordingly, we shall first consider the experimental angular distribution[4] for the process

$$\pi^- + p \to \pi^0 + n \tag{4}$$

at a fixed π-meson kinetic energy of 220 Mev in the laboratory system. In strict analogy to the method outlined for process (1), we consider whether the experimental information sheds any light on the existence of the π^+-meson intermediate state illustrated in Fig. 1(b). The matrix element $M(\cos\theta)$ (θ is the center-of-mass scattering angle) for process (4) is, apart from kinema-