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METASTABLE STATES OF $\alpha\pi^-e^-$, αK^-e^-, AND $\alpha\bar{p}e^-$ ATOMS

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It is suggested that antiprotons could be used to test Condo's conjecture that the large mean cascade time for K^- mesons in atomic orbits in liquid helium is due to metastable states.

Several years ago Condo[1] suggested that negative mesons which are stopped in helium may, in a relatively small number of instances, become bound in a metastable state of a neutral mesonic atom, thereby accounting for the large values of the measured mean cascade times for π^- and K^- mesons in atomic orbits in liquid helium.[2,3] No attempt has yet been made to test this explanation experimentally, possibly in part because no calculations were presented in its support, and because there was no compelling argument given for believing that such metastable states, if they are formed, are not depopulated by Stark transitions[4] when the mesonic atom collides with helium atoms. The purpose of the present paper is to point out that under suitable circumstances it might be possible to obtain a partial experimental check on Condo's conjecture by ascertaining whether or not antiprotons sometimes have extraordinarily long cascade times in liquid helium. This suggestion is prompted by the results of some detailed calculations[5] of Auger and Stark transition rates which indicate that Condo's theory may explain, or at least partially explain, the mean cascade time in the case of K^- mesons, though probably not in the case of π^- mesons.

In order to facilitate the discussion, it is convenient to restate Condo's argument, citing some numerical results obtained in Ref. 5 and using a more detailed line of reasoning. When a negative meson or an antiproton is stopped in helium, it ejects an electron from a helium atom and becomes bound in a neutral atomic system. For the sake of brevity an antiproton is frequently referred to loosely as a meson in the present paper. Insofar as the meson and the electron may each be thought of as having a well-defined orbital angular momentum, the electron is in a 1s orbit, and the meson is in an orbit with a large principal quantum number n and an orbital angular momentum $l \leq n-1$. If $l = n-1$, the meson is in a so-called circular orbit. A state in which the meson is in a circular orbit is sometimes referred to in the present paper simply as a circular orbit. It is generally supposed that the neutral mesonic atom is formed in a state with a binding energy E_b which is not very different from the 5.81-Ry binding energy of a helium atom. The de-excitation of this atom can proceed initially by Auger ejection of the electron, by radiation, or, for the $\alpha\pi^-e^-$ and αK^-e^- atoms, by meson decay. Unless there are special circumstances, Auger ejection is the dominant process.

There are special circumstances which inhibit the Auger process for circular or very nearly circular orbits with large n.[6] Since initially the electron is in an s state, the orbital angular mo-

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mentum l_A of the Auger electron and the change Δl in the meson orbital angular momentum must be such that $l_A \geqslant |\Delta l|$. Energy conservation and the large mass of the meson require the magnitude of the change Δn in the meson principal quantum number to be greater than or equal to a certain minimum possible value $|\Delta n|_{\min}$. The relative amounts of overlap of the initial meson radial wave function with the possible final meson radial wave functions are such that Auger transitions usually occur with $|\Delta n| = |\Delta n|_{\min}$, the ejected electron in such an instance having an energy E_A which is rather small. Although this discussion is concerned with circular or very nearly circular orbits, the remarks made thus far concerning $|\Delta n|$, $|\Delta l|$, l_A, and E_A also hold for orbits which may be quite elliptical. What distinguishes the circular orbits is the requirement that $|\Delta l| \geqslant |\Delta n|$. Since, therefore, $l_A \geqslant |\Delta n|_{\min}$, the centrifugal barrier which is experienced by the outgoing electron causes the Auger rate P_A to be exceedingly sensitive to the value of $|\Delta n|_{\min}$. Table I gives values of E_b, $|\Delta n|_{\min}$, E_A, P_A, and the radiative rate P_R for several circular orbits of $\alpha\pi^-e^-$, αK^-e^-, and $\alpha\bar{p}e^-$ atoms. Although the Auger rates for the elliptical orbits of a neutral mesonic atom also decrease as $|\Delta n|_{\min}$ becomes larger, this dependence on $|\Delta n|_{\min}$ is probably not sufficiently pronounced, except for a few very nearly circular orbits, to account for the measured cascade times, since the ejected electron is not constrained to have a relatively high orbital angular momentum.

Although the Auger rate for circular orbits of the αK^-e^- atom with $n = 28$ is low enough to permit the K^- mean cascade time $T_K \approx 2\times10^{-10}$ sec to be accounted for by assuming that a relatively small number of stopping K^- mesons are trapped in these states and then decay, the circumstances are rather different for pions. The relatively high Auger rate for the circular orbits of the $\alpha\pi^-e^-$ atom with $n = 16$ would make it necessary to assume that an unreasonably large proportion of stopping π^- mesons are somehow captured into these states if the pion mean cascade time $T_\pi \approx 3\times10^{-10}$ sec is to be explained by Condo's theory.

Table I. Some properties of circular orbits of $\alpha\pi^-e^-$, αK^-e^-, and $\alpha\bar{p}e^-$ atoms. The unit of energy is the rydberg.

atom	n	E_b (Ry)	$\lvert\Delta n\rvert_{\min}$	E_A (Ry)	P_A (sec^{-1})	P_R (sec^{-1})
$\alpha\pi^-e^-$	16	−5.56	3	0.67	4×10^9	2.8×10^7
	15	−6.01	2	0.22	2×10^{12}	4.8×10^7
αK^-e^-	29	−5.50	5	0.43	6×10^2	4.4×10^6
	28	−5.73	4	0.20	4×10^5	6.0×10^6
	27	−6.00	4	0.45	1×10^6	8.1×10^6
$\alpha\bar{p}e^-$	38	−5.50	6	0.23		2.0×10^6
	37	−5.67	5	0.06		2.5×10^6
	36	−5.86	5	0.25		3.1×10^6
	35	−6.09	4	0.02	$\lesssim10^4$	3.9×10^6

The Auger rates in Table I are probably accurate to within a factor of 2 or 3. The rate for the $\alpha\pi^-e^-$ atom with $n = 16$ would make a direct experimental detection of pions trapped in these circular orbits exceedingly difficult. The difficulties would not be quite so great for the circular orbits of the αK^-e^- atom with $n = 28$, which have a lifetime equal to that of the K^- meson if Stark mixing is unimportant. A much different set of circumstances holds for the metastable states of the $\alpha\bar{p}e^-$ atom, since the cascade times for antiprotons trapped in these orbits are determined by the radiative rates. If antiprotons sufficiently free of pion contamination were available, trapping in these states might be detected by searching for fast coincidences between pions produced in an annihilation occurring about a microsecond after the antiproton is stopped. A demonstration that an $\alpha\bar{p}e^-$ atom is able to survive roughly 10^5 collisions with He atoms would be a strong indication that an αK^-e^- atom in a metastable state of comparable energy is not likely to undergo a Stark transition during the ~10^3 collisions which it must make before the meson decays.

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[1] G. T. Condo, Phys. Letters 9, 65 (1964).

[2] J. G. Fetkovich and E. G. Pewitt, Phys. Rev. Letters 11, 290 (1963); M. M. Block, T. Kikuchi, D. Koetke, J. Kopelman, C. R. Sun, R. Walker, G. Culligan, V. L. Telegdi, and R. Winston, Phys. Rev. Letters 11, 301 (1963).

[3] M. M. Block, J. B. Kopelman, and C. R. Sun, Phys. Rev. 140, B143 (1965).

[4] T. B. Day, G. A. Snow, and J. Sucher, Phys. Rev. Letters 3, 61 (1959).

[5] J. E. Russell, to be published.

[6] The mechanism described in this paragraph is essentially the same as one which was first discussed by A. S. Wightman [thesis, Princeton University, 1949 (unpublished)], in connection with the stopping of negative mesons in liquid hydrogen. It was argued that long-lived states of the $p\mu^-$ and $p\pi^-$ atoms, which Wightman called the "doldrums," would be easily depopulated by Stark transitions since hydrogenic states with the same value of n are degenerate.