fast ions that accumulate in traps in which neutral atoms are injected [12]. In connection with the latter, attention must be called to the fact that a numerical experiment on the quasilinear relaxation, in a plasma, of a group of ions with large transverse energy in two-dimensional velocity space ("random" distribution over the phase shifts of the Larmor rotation) has revealed that the resultant deformation of ion distribution function is similar to that observed in the present study.

[1] B.B. Kadomtsev, in: Fizika plazmy i problema upravlyaemykh termoyadernykh reaktsii (Phasma Physics and the Problem of Controlled Thermonuclear Reactions), AN SSSR, 1958, p. 364.
[2] A.A. Vedenov, E.P. Velikhov, and R.Z. Sagdeev, Usp. Fiz. Nauk 73, 701 (1961) [Sov. Phys.-Usp. 4, 332 (1961)].
[3] A.G. Borisenko and G.S. Kirichenko, Zh. Eksp. Teor. Fiz. 60, 384 (1971) [Sov. Phys.-JETP 33, 207 (1971)].
[4] A.G. Borisenko, G.S. Kirichenko, and V.G. Khmaruk, Plasma Phys. and Contr. Nucl. Fusion Res. Proc. 4th Int. Conf. Madison, USA, 1971, Vol. 2, Vienna, 1971, p. 141.
[5] B.D. Fried, C.F. Kennel, K. Machenzie, F.V. Coroniti, I.M. Kindel, R. Stenzel, R.J. Taylor, R. White, A.Y. Wong, W. Bernstein, J.M. Sellen, Jr., D. Forslund, and R.L. Sagdeev, Plasma Phys. and Contr. Nucl. Fusion Res. Proc. 4th Int. Conf. Madison, USA, 1971, Vol. 2, Vienna, 1971, p. 55.
[6] G.S. Kirichenko and V.G. Khmaruk, Zh. Eksp. Teor. Fiz. 63, 107 (1972) [Sov. Phys.-JETP 36, No. 1 (1973)].
[7] V.L. Sizonenko and K.N. Stepanov, ZhETF Pis.Red. 8, 592 (1968) [JETP Lett. 8, 363 (1968)].
[8] K. Papadopoulos, R.C. Davidson, J.M. Dawson, I. Haber, D.A. Hammer, N.A. Krall, and R. Shanny, Phys. Fluids 14, 849 (1971).
[9] C.E. Wagner, K. Papadopoulos, and I. Haber, Phys. Lett. 35A, 440 (1971).
[10] P.J. Barrett and R.J. Taylor, Proc. X Int. Conf. on Phenomen. in Ionized Gases, Rep. 4.3.12.1, Oxford, 1971, p. 353.
[11] R.Z. Sagdeev, in: Voprosy teorii plazmy (Problems in Plasma Theory), Atomizdat, 1964, No. 4, p. 20.
[12] V.M. Kulygin, A.B. Mikhailovskii, and E.S. Tsapelkin, Plasma Phys. 13, 1111 (1971).

LEVEL SHIFTS AND WIDTHS OF $p\bar{p}$-ATOM

O.D. Dal'karov and V.M. Samoilov
Institute of Theoretical and Experimental Physics

Submitted 12 July 1972
ZhETF Pis. Red. 16, No. 6, 353 - 354 (20 September 1972)

It was shown in [1] that an experimental determination of the shifts of the S levels of the $p\bar{p}$-atom makes it possible, in principle, to determine the sign of the real part of the $p\bar{p}$ scattering length.

The values obtained in [1] for the level shifts ΔE for the states 1S and 2S turned out to be 0.9 and 0.1 keV, respectively. However, these estimates of ΔE are qualitative in character (the $p\bar{p}$ scattering length was assumed equal to 1 F regardless of the spin and isospin of the $p\bar{p}$ system).

In this paper we calculate the shifts and widths of the S levels (principal quantum number n = 1 and 2) of the $p\bar{p}$ atom in different spin-isospin states, by using the Bryan-Phillips (BF) potential [2] for the nucleon-antinucleon interaction at low energies.

To calculate the level shifts, we use the real part of the BF potential. Allowance for the imaginary part, which corresponds to annihilation effects, leads to an additional level shift, which can be estimated by using considerations analogous to the estimates of the binding-energy shifts of nonrelativistic bound states in a nucleon-antinucleon system as a result of an annihilation interaction [3]. Such estimates show that the magnitude of this shift does not exceed 15 - 20% of the value of ΔE due to the real part of the potential. The small parameter in these estimates is the ratio of the radii of the imaginary and real parts of the potential, which is a quantity of the order of μ/m, where μ is the pion mass and m the nucleon mass. A numerical solution of the Schrodinger equations with a potential $V = V_C + V_N$ (V_C and V_N are respectively the Coulomb and nuclear potentials) leads to the results listed in the table.

Level shifts and widths of $p\bar{p}$-atom levels. $^{2s+1}X_i$ is the spectroscopic symbol of the state

	I	ΔE, keV	Γ, keV
1^1S_0	0	0.2	0.43
	1	0.85	0.17
1^3S_1	0	0.5	0.25
	1	0.7	0.33
2^1S_0	0	0.025	0.07
	1	0.105	0.13
2^3S_1	0	0.065	0.04
	1	0.095	0.05

As seen from the table, the level shifts turn out to depend strongly on the isotopic spin I of the $p\bar{p}$ system (the ratio of the shifts in states with I = 1 and I = 0 is equal to 4 for singlet S-levels and to 1.5 for triplet levels).

The table lists also the level widths. They were estimated by means of the formula

$$\Gamma = (v\sigma_a)_0 \overline{|\Psi(0)|^2}, \tag{1}$$

where σ_a is the annihilation cross section, V is the relative velocity of p and $\bar{p}$, $(v\sigma_a)_0 = \lim(v\sigma_a)$ as $v \to 0$, and $\overline{\Psi(0)^2}$ is the particle density averaged over the effective annihilation region. The quantity $(v\sigma_a)_0$ for each state with given spin and isospin was assumed to be 45 mb (see [3]).

We note that the widths listed in the table should be regarded as upper bounds, since the experimentally obtained quantity $(v\sigma_a)_0$ includes the annililation cross section not in the S states alone. We indicate for comparison that the level widths calculated with a pure Coulomb wave function (i.e., without allowance for the distortion due to the potential nuclear interaction) are equal to 1.5 and 0.19 keV, respectively.

Our results show that the shift and widths of the $p\bar{p}$-atom S levels are very sensitive to the spin-isospin structure of the strong interaction at low energies.

The authors are sincerely grateful to I.S. Shapiro for useful discussions.

[1] S. Caser and R. Omnes, Phys. Lett. 39B, 369 (1972)

[2] R.A. Bryan and R.F. Phillips, Nucl. Phys. B5, 201 (1968).
[3] O.D. Dalkarov, V.B. Mandelzweig, and I.S. Shapiro, Nucl. Phys. 21B, 88 (1970).

CRITICAL CHARGE IN THE TWO-CENTER PROBLEM

V.S. Popov
Institute of Theoretical and Experimental Physics
Submitted 21 July 1972
ZhETF Pis. Red. 16, No. 6, 355 - 358 (20 September 1972)

The energy of an electron in the field of a point Coulomb center Ze is equal to (for the 1s level):

$$\epsilon_0 = \sqrt{1-(Z\alpha)^2}, \tag{1}$$

where $\hbar = c = m_e = 1$ and $\alpha = 1/137$. This expression has a singularity at Z = 137. As noted by Pomeranchuk and Smorodinskii, allowance for the finite dimensions of the nucleus eliminates the Coulomb singularity, and formula (1) continues into Z > 137. The value $Z = Z_c$ at which the 1s level joins the lower continuum is called the critical charge of the nucleus. Quantum electrodynamics leads to a number of characteristic predictions in the region $Z > Z_c$. The main effect is the emission of positron by a "bare" nucleus, i.e., a nucleus with unfilled K-shell (for details see [2 - 4]). For a spherical nucleus with radius R ∿ 10 F we have numerically $Z_c \approx 170$ (see [2, 5]), which is far from the region of presently known heavy elements. For this reason, it is necessary to resort to another method of obtaining supercritical fields, namely, in a collision between two heavy nuclei with charges Z_1 and Z_2, such that $Z_1 + Z_c > Z_c$ (such a possibility was first discussed in [6]; see also [4, 7]). When considering this effect, it is necessary to find first the "critical" distance $R_c = R_c(Z_1, Z_2)$ in the relativistic problem of two centers, i.e., that distance R between charges, for which the ground-state level of the quasimolecule (Z_1, Z_2, e) drops to the limit $\varepsilon = -1$. We present here the results of such calculations. We confine ourselves to the simplest case $Z_1 = Z_2 = Z$.

At Z < 137, the radius of the nucleus is immaterial, for there is no "falling to the center" in a Coulomb field with Z < 137. In other words, the breakup of the total charge 2Z into two parts separated by a finite distance R is in itself sufficient for a regularization of the problem. The curve of the level $\varepsilon_0 = \varepsilon_0(Z)$ in the two-center problem reaches $\varepsilon = -1$ without having on its path singularities of the type (1). For this reason, we shall regard the nuclei as point-like (the radii of heavy nuclei are $r_0 \sim 8$ F, which is much less than the K-orbit radius $r_K = (1 + 2\sqrt{1-\zeta^2})/2\zeta$ = 700 F for uranium).

The actual excess of 2Z over Z_c is small (for uranium nuclei, $\delta = (2Z - Z_c)/Z_c = 0.08$, and for Cf + Cf we have $\delta = 0.15$), and therefore $R < \hbar/m_e c = 1$. In the region $\delta \ll 1$ we can obtain for R_c a simple formula by using the method of matching the asymptotic expansions. We shall explain the main idea with spinless particles as an example.

The form of the wave function ψ_0 at small and large distances is determined from the Klein-Gordon equation [7]. Near the nuclei we have

$$\psi_0(\xi, \eta) = (\xi^2 - \eta^2)^{-\sigma/2}, \quad \sigma = 1 - \sqrt{1-\zeta^2}, \tag{2}$$