Anomalous P wave in $\bar{p}N$ scattering at low energies; the $\bar{p}p$ atom

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Calculations are carried out in a quasinuclear coupled-channel model on the behavior of the ratio of real and imaginary parts of the amplitude for forward $\bar{p}N$ scattering and on the nuclear shifts of the $1S$ and $2P$ levels of the $\bar{p}p$ atom. The results of the calculations indicate an anomalously large P-wave contribution resulting from quasinuclear $N\bar{N}$ resonances.

Experiments being carried out at CERN (on the LEAR antiproton storage ring) at momenta of the incident antiproton which have previously been unattainable ($K_{\bar{p}} \lesssim 300$ MeV/c in the laboratory frame) have revealed an unusually large P-wave contribution to the $\bar{p}p$ interaction at low energies.[1] This effect had been predicted comparatively recently in the first studies on the theory of quasinuclear baryon-antibaryon resonances (see the review by Bogdanova *et al.*[2]). Calculations carried out recently on the basis of the quasinuclear coupled-channel model[3] reproduce the LEAR data quantitatively. In particular, they demonstrate an unusually large P-wave contribution. In this letter we wish to discuss the predictions of the quasinuclear coupled-channel model regarding the behavior of the parameter ρ, which is the ratio of the real and imaginary parts of the amplitude for forward $\bar{p}N$ scattering, and also the nuclear shifts of the $1S$ and $2P$ levels of the $\bar{p}p$ atom. The experimental data obtained at the LEAR collider[4] demonstrate a very rapid increase in the ratio ρ with increasing momentum of the $\bar{p}$, from $K_{\bar{p}} = 0$ to ~ 300 MeV/c (Fig. 1). As was first pointed out in Ref. 5, the rapid increase in ρ with increasing momentum in the narrow interval from 0 to 300 MeV/c can be explained under the assumption of a large P-wave contribution in this region. The results of the calculations based on the quasinuclear coupled-channel model, shown in Fig. 1, confirm this observation. Qualitatively, the rapid increase in ρ occurs because the signs of the real parts of the S- and P-wave amplitudes for forward $\bar{p}p$ scattering are opposite, so the comparatively large contribution and rapid increase of the P-wave amplitude lead to a cancellation of the contributions of the S and P amplitudes and to the vanishing of ρ at momenta ~ 300 MeV/c. In the calculations of ρ we ignored Coulomb effects, which could increase ρ by about 5% in absolute value in the case $K_{\bar{p}} = 0$ (at $K_{\bar{p}} \sim 300$ MeV/c, the Coulomb corrections are small). We should also point out that in extracting the value of the parameter of ρ from data on $\bar{p}p$ scattering in the region of the Coulomb-nuclear interference one should use formulas which correctly reflect the interference of the Coulomb and nuclear interactions.[6] The effect might be to reduce the experimental values of ρ in the region $K_{\bar{p}} \approx 200$ MeV/c by an amount on the order of $\Delta\rho \approx 0.05$; the effect would be to improve the agreement between the experimental results and the theoretical curve in Fig. 1.

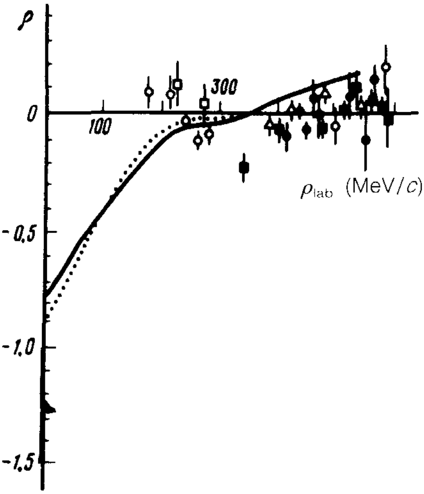

FIG. 1. Ratio of the real part to the imaginary part of the amplitude for forward $\bar{p}p$ scattering. The experimental data are from Ref. 4. Solid line—Theoretical calculation based on the quasinuclear coupled-channel model; dotted line—incorporating the $\bar{n}n$ threshold.

The sharp increase in the P-wave contribution is seen even more clearly in the behavior of ρ for the $\overline{N}N$ amplitude in the $I = 1$ isospin state, i.e., for $\bar{p}n$ (or $\bar{n}p$) scattering (Fig. 2). At present, the only way to extract the value of ρ in the $I = 1$ state is to work from data on $\bar{p}$-nucleus scattering.[7,8] The value found in Ref. 8 for $\rho_{\bar{p}n}$, at an antiproton momentum $K_{\bar{p}} \approx 600$ MeV/c, is consistent with our calculations, as can be seen from Fig. 2.

While generating a description of $\bar{p}p$ scattering on the basis of the quasinuclear coupled-channel model, we simultaneously calculated the low-energy parameters of the $\bar{p}N$ scattering for S and P waves. Table I shows the S-wave scattering lengths a and

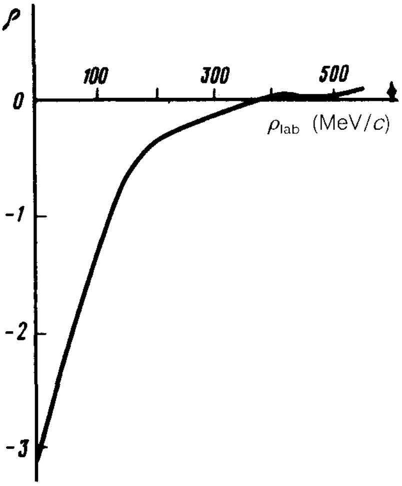

FIG. 2. Ratio of the real part to the imaginary part of the amplitude for forward $\bar{p}n$ scattering. The experimental point is from Ref. 8.

TABLE I.

$^{2I+1\;2S+1}L_J$	Re a, fm	Im a, fm	ρ
$^{11}S_0$	-1.92	6.10	–
	-2.45^*	4.27^*	
$^{31}S_0$	-1.28	0.24	–
$^{13}S_1$	-0.34	0.34	–
$^{33}S_1$	-0.71	0.29	–
S-wave $\bar{p}p$	-0.79	1.03	-0.77
	-0.86^*	0.8^*	-1.08^*
$\bar{p}n\ (I=1)$	-0.85	0.28	-3.07

the value of ρ for the amplitude for forward $\bar{p}N$ scattering at a zero energy. The value $\rho_{\bar{p}p} = 1.08$ corresponds to a change in the dimensionless annihilation parameter in the quasinuclear coupled-channel model (from $\lambda = 3.9$ to $\lambda = 4.0$) in the $^1S_0$ wave. This change does not lead to any significant change in the results at $K_{\bar{p}} \gtrsim 300$ MeV/c. We should point out that incorporating the $\bar{n}n$ threshold in $\bar{p}p$ scattering by the procedure of Ref. 5 (see also Fig. 1) leads to a change of about 10% in ρ. Furthermore, the Coulomb corrections to $\rho_{\bar{p}p}(0)$ also increase $\rho_{\bar{p}p}(0)$, by about 5% in absolute value. When these corrections are made, we find that $\rho_{\bar{p}p}(0)$ takes on the values $\rho_{\bar{p}p}(0) \approx 0.88$ and $\rho^*_{\bar{p}p}(0) \approx 1.24$.

No measurements of $\rho_{\bar{p}n}$ have been reported. However, the estimate Im$a_{\bar{p}n} = 0.235 \pm 0.121$, based on data on the annihilation of stopped $\bar{p}$ in ^{4}He (Ref. 9), agrees with value Im$a_{\bar{p}n} = 0.28$ shown in Table I.

The corresponding shifts and widths of the $1S$ level of the $\bar{p}p$ atom calculated with the help of the S-wave scattering lengths in Table I are Re$(\Delta E_{1S}) = 0.68(0.74^*)$ keV and $\Gamma_{1S} = 1.79(1.39^*)$ keV. These values are consistent with the data available on the shifts and widths of the $1S$ level of the $\bar{p}p$ atom.[10]

Table II shows the P-wave scattering lengths for $\bar{p}p$ scattering. The calculated

TABLE II.

$^{2S+1}L_J$	ReA_p, (GeV/c)$^{-3}$	ImA_p, (GeV/c)$^{-3}$
$^1P_1$	84	64
$^3P_0$	71	105
$^3P_1$	-4	96
$^3P_2$	53	130
P-wave	48	104

values of the shift and width of the $2P$ level of the $\bar{p}p$ atom in this case are $\mathrm{Re}(\Delta E_{2P}) = -18$ meV and $\Gamma_{2P} = 39$ meV. The value found for Γ_{2P} agrees fairly well with the large width found experimentally for the $2P$ level of the $\bar{p}p$ atom: $\Gamma_{2P}^{\mathrm{expt}} = 39.8 \pm 10.7$ meV (Ref. 10).

A comparison with corresponding calculations based on optical models[11] indicates that the P-wave scattering length found in our calculations is substantially greater (for example, $\mathrm{Re}A_p$ is more than three times the corresponding quantity in Ref. 11). As has been emphasized in several places already, the increase in the P wave in our calculations results from the existence of a spectrum of near-threshold P resonances of a quasinuclear nature.

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