Electromagnetic form factor of the nucleon in the timelike region

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A mechanism is proposed for dynamic enhancement of the electromagnetic form factor of the nucleon in the timelike region of momentum transfers q^2 close to the threshold of the production of the NN pair. The large nucleon form factor measured in experiments on the annihilation of slow antiprotons into an e^+e^- pair [G. Bassmpierre *et al*., CERN Preprint, 1977] will be shown to be caused by the strong t-channel interaction between p and $\bar{p}$ in the initial state. By way of consequence of this proposed model, a sharp increase is predicted for the quantity $R = \sigma_{had}/\sigma_{\mu\mu}$ in e^+e^- annihilation in the region $S \approx 4m^2$ (m is the nucleon mass).

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We consider first the annihilation of slow antiprotons into an e^+e^- pair. This process corresponds (in first order in σ) to the diagrams of Fig. 1. The oval denotes the amplitude of the strong t-channel interaction of p and $\bar{p}$ in the initial state. It is known that the potential of this interaction is strongly attracting and sufficient to produce in

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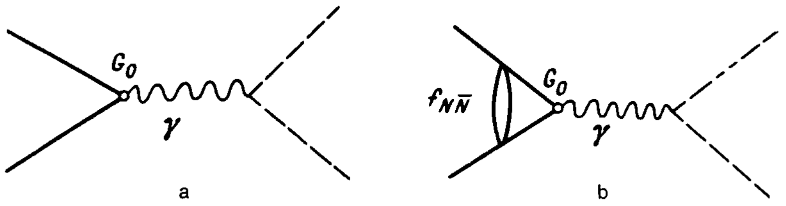

FIG. 1. Feynman diagrams for the $pp \to e^+e^-$ annihilation.

the system a rich spectrum of near-threshold bound resonant states of quasinuclear type (quasinuclear "baryonium").[2] These include, in particular, states with the photon quantum numbers $J^{PC} = 1^{--}$, corresponding to $^3S_1$ and $^3d_1$ waves in the $N\bar N$ system. The radii of these states are quite large (typical dimensions are $R \approx 1$–1.5 F). The spectrum of these states determines in fact the behavior of $f_{N\bar N}$ in the near-threshold region. Consequently the amplitude $f_{N\bar N}$ as a function of the virtual momenta in the diagram 1(b) changes noticeably over values on the order of R^{-1}. At the same time, the form factor G_0 corresponding to the change of the $N\bar N$ pair into a photon via the annihilation interaction, is determined by characteristic momenta of the order of r_a^{-1}, where $r_a \approx 1/2m$ is the annihilation radius. Thus, the small parameter $1/2mR$ turns out to be of the order of 0.1. Using this, we can take G_0 outside the integral sign in the diagram 1(b), since it varies slowly in comparison with $f_{N\bar N}$. The sum of the diagrams on Fig. 1 then leads to the following formula for the annihilation cross section:

$$\frac{k}{m}\,\sigma\,(p\bar p \to e^+e^-) = \frac{\pi a^2}{2m^2}\,|\,G_0\,|^2\,|\,\psi_k(0)\,|^2, \tag{1}$$

where k is the antiproton momentum in the c.m.s. and $|\psi_k(0)|$ is the value of the wave function of the continuous spectrum of the $p\bar p$ system in the annihilation region (This quantity is usually called the enhancement coefficient).[3]

Figure 2 shows the behavior of $|\psi_k(0)|^2$ calculated with a realistic $N\bar N$ potential of

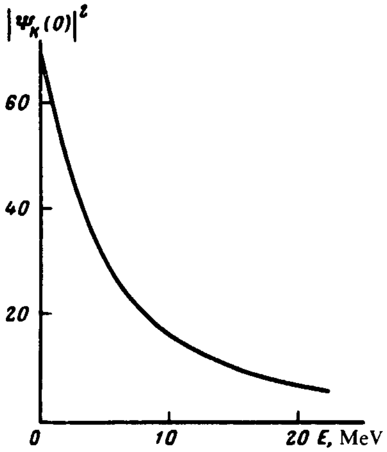

FIG. 2. Behavior of the enhancement coefficient $|\psi_k(0)|^2$. (E is the summary kinetic energy of N and $\bar N$ in the c.m.s.).

the OBEP type.[4] At short distances $r \leqslant r_c$ the potential was assumed to be $V(r) = V(r_c)$. The cutoff radius r_c was chosen such that the first radial excitation in the state $^3S_1$ with unity isospin coincided with the vector meson with mass 1820 MeV observed experimentally in e^+e^- annihilation.[5] As seen from the figure, the enhancement coefficient $|\psi_k(0)|^2$ is a rather rapidly growing function as $k \to 0$. Consequently, the experimentally observed cross section of the $p\bar{p} \to e^+e^-$ annihilation should also increase steeply in the near-threshold region considered by us; in particular, as follows from (1) a strong deviation from the $1/v$ law should be observed.

The nucleon electromagnetic form factor determined from the experimental data on the $p\bar{p} \to e^+e^-$ annihilation near threshold[1] is connected with the non-observable quantity G_0 by the formula

$$G = |G_0|\,|\psi_k(0)| \tag{2}$$

(here, as usual, $G_E = G_M = G$). This value was measured in experiment at only one value of the incident-antiproton momentum ($k \approx 150$ MeV/c) and turned out to equal $0.45^{+0.15}_{-0.09}$. At the same time the form factor G_0 corresponding to allowance for singularities far from the threshold (for example, in the VDM model, to the contribution of the ρ, ω, and ϕ mesons), usually varies in the range 10^{-1}–10^{-2}.[6] However, as follows from (2), the experimentally observed form factor is enhanced on account of the factor $|\psi_k(0)|$. Figure 3 shows the behavior of the form factor G, as calculated from formula (2). It must be noted here that the authors of the experimental paper,[1] assuming that the cross section $(k/m)\sigma(p\bar{p} \to e^+e^-)$ is constant (i.e., that the cross section σ behaves in accord with the $1/v$ law), obtained practically the same value of G in the entire momentum interval $k = 0$–150 MeV/c. The extrapolation used in[1] is shown by the dashed curve in Fig. 3. It follows from our work that the form factor G should increase as $k \to 0$ (in particular, at the point $q^2 = 4m^2$ it can reach a value 1.5–2).

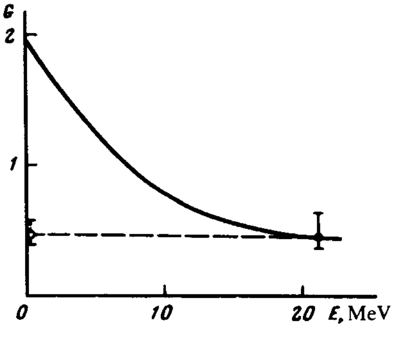

FIG. 3. Electromagnetic form factor G of the nucleon. The theoretical curve is normalized to the experimental value at $E \approx 20$ MeV.

The considered mechanism of dynamic enhancement of the nucleon form factor in the region close to the threshold of the $N\bar{N}$ pair production is equally applicable to the calculation of the contribution of the cross section of the inverse process $e^+e^- \to N\bar{N}$ to the quantity $R = \sigma_{had}/\sigma_{\mu\mu}$ in the region $S \approx 4m^2$. With the aid of the detailed balancing principle these cross sections are connected by the obvious relation

$$\sigma(e^+e^- \to N\bar{N}) = 2\left(\frac{k}{m}\right)^2 \sigma(p\bar{p} \to e^+e^-). \tag{3}$$

Figure 4 shows the behavior of the quantity $\Delta R = \sigma_{e^+e^- \to N\bar{N}}/\sigma_{\mu\mu}$ near the $N\bar{N}$ threshold, as calculated with the aid of (3). It should be noted that a similar behavior of ΔR can be expected near any new channel if there is a sufficiently strong attraction between the particles in this channel (this question was considered in[7] for the threshold of charmed-particle production). As to the contribution made to R by the $N\bar{N}$ pair production process with subsequent annihilation into pions, estimates show that this contribution is of the same order as that of the $e^+e^- \to N\bar{N}$ channel. (This question, which calls for consideration of the multichannel problem, will be discussed in a separate article.)

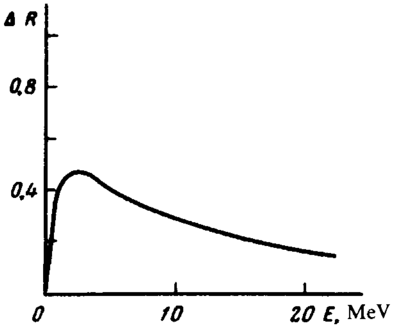

FIG. 4. Behavior of $\Delta R = \sigma_{e^+e^- \to N\bar{N}}/\sigma_{\mu\mu}$ in the near-threshold region.

The foregoing analysis can be summarized as follows: a) In view of the strong t-channel interaction between p and $\bar{p}$ in the initial state, the $p\bar{p} \to e^+e^-$ annihilation cross section turns out to be enhanced by a factor $|\psi_k(0)|^2$. The enhancement coefficient turns out to increase rapidly when the $N\bar{N}$ threshold is approached, and this should lead to a strong deviation of the $p\bar{p} \to e^+e^-$ annihilation in the near-threshold region from the $1/v$ law; the behavior of the form factor G is also determined by an enhancement factor $|\psi_k(0)|$, therefore the form factor G should increase as the $N\bar{N}$ threshold is approach and should reach a value 1.5–2 at $q^2 = 4m^2$. b) The opening of the $N\bar{N}$ channel can lead to an increase of R by a value on the order of unity. The value of ΔR depends strongly on the enhancement factor $|\psi_k(0)|^2$ considered above. c) Since the behavior and the absolute value of the enhancement coefficient are determined by the $N\bar{N}$-interaction potential, the entire aggregate of the data considered above can be effectively used to determine the true $N\bar{N}$-interaction parameters at low energies.

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