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V.A.Belyakov, V.N.Strel´tsov

THE RELATIVISTIC NUCLEON

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1. INTRODUCTION

According to modern ideas, the basic features of strong interactions are described by quantum chromodynamics. In this case, in particular, the gluon field is a definite analogue of the electromagnetic field. At the same time this theory certainly includes the previous results explaining, for example, short-active nuclear forces. As is known, the Yukawa's idea [1] played an important role in due course. According to this idea, nucleons interact between themselves with the help of pion exchange. The potential of the Yukawa's interaction (stationary meson field) takes the form

$$\phi_\pi = -g_\pi \frac{\exp(-\mu R)}{R}. \qquad (1)$$

Here g_π denotes the interaction constant similar to electron charge in electrodynamics, μ is the pion mass and $\hbar = c = 1$.

Further on exchange by heavier (vector) mesons ρ, ω and so on has been taken into account to explain the strong interaction behaviour with increasing energy.

Just Yukawa's exponent in the function ϕ_π leads to that the "action radius" of nuclear forces, $\sim\mu^{-1}$ ($\sim$1 fm), is smaller than the one of electrostatic forces described by the Coulomb potential. In other words, we can say that simply $\mu_{ph} = \mu_g = 0$ for photons and gluons.

2. RELATIVISTIC YUKAWA'S POTENTIAL

According to the solution of the wave equation for retarding electrostatic potential, we have for relativistic Yukawa's potential [2]

$$\phi_\pi = -g_\pi \frac{\exp(-\mu \cdot u^i \cdot R_i)}{u^i \cdot R_i}. \qquad (2)$$

Here u^i is the nucleon 4-velocity and R_i is the 4-distance from the observation point (P) to "charge" (c.m.s. of nucleon).

In the simplest case, when both point P and the nucleon are along the X-axis, formula (2) is transformed to

$$\phi_\pi = -g_\pi \frac{\exp[-\mu \cdot R_\parallel \cdot (1-\beta)\cdot\gamma]}{R_\parallel \cdot (1-\beta)\cdot\gamma}. \qquad (2')$$

Here $R_\parallel$ denotes the retarding distance, β is the nucleon velocity and $\gamma = (1-\beta^2)^{-1/2}$. For simplicity one supposes that the virtual pion velocity is very close to the light one ($\beta_\pi \approx 1$)*. As is shown earlier [3], the electric field in front of the moving charge increases with increasing its velocity according to the formula

$$\phi_e = \frac{e}{R_\parallel \cdot (1-\beta)}. \qquad (3)$$

From here it follows that the field potential in front of the moving charge is $\sim 2\gamma^2$ times larger than in front of the charge at rest at the same distance. One can say that "relativistic remote action" exists.

Let us now discuss the pion potential (2´). Due to the factor γ in a denominator, the noted growth in this case is much weaker. If $\phi_e \sim \gamma^2$, then $\phi_\pi \sim \gamma$. In the case of vector ρ- and ω-mesons the expression corresponding to eq.(2) for the potential takes the form

$$\phi_v = -\sum_{v=\rho,\omega} g_v \frac{\exp[-\mu_v R(1-\beta\cos\theta)\gamma]}{R(1-\beta\cos\theta)}. \qquad (4)$$

Since for the relativistic velocities of our interest $\beta\gamma \approx \gamma$, the x-component of the potential behaves in the same way as the t-component ϕ_v. As the masses of ρ- and ω-mesons are very close, one can in a good approximation move off the exponent from under the summation mark. Then for the vector field we have $g_v = g_\rho + g_\omega$ assuming $g_v/g_\pi = 0.77$ [4] in further calculations.

*The case $\beta_\pi < 1$ directly concerns an important problem of strong interaction propagation velocity. It will be studied separately. Our estimates yield negligible differences at $\beta_\pi \approx 1$.

3. RESULTS OF CALCULATION DISCUSSION

The goal of this work was to determine the equipotential curves describing the behaviour of the nuclear field radius of the relativistic nucleon. We used the value of Yukawa´s potential at the point corresponding to the Compton pion wave length $\phi_\pi(\mu^{-1}) = [\phi]$. This obviously corresponds to the usual definition for the radius of nuclear forces.

Based on this condition, the solutions of eqs.(2) and (4) relative to the value of R were searched for. Namely, the value of R was taken so that ϕ_v might be equal to $[\phi]$ with good accuracy.

The pion potential is a scalar one relative to the Lorentz transformations. In this case our task is in fact to find the surface shape for the light wave front. We suppose that in the c.m.s. (S*) this wave propagating from a moving source is spherical in form. But such a problem has been already considered previously in the frame of the conception of relativistic length (see, e.g., [5]). It has been found that the surface is in the shape of a rotating ellipsoid. This ellipsoid is stretched in the direction of notion with half-axes $a = \gamma R^*_\pi$ and $b = R^*_\pi$; the focusing distance is $c = \gamma\beta R^*_\pi$ with R^*_π - the sphere radius in the S*-system. Hence the action radius forward of the pion field is $R^\parallel_f = (a + c)$; and backward, $R^\parallel_b = (a - c)$.

The calculated results are given in three figures and in the table. Figure 1 shows a relatively "slow" nucleon although the velocity $\beta_{1b} = 0.98$. The corresponding equipotential curves (circle) are shown for the nucleon at rest. From comparison of fig.1 and fig.2 it follows that the nuclear field of the nucleon stretches more and more forward and acts at larger distances as γ increases. This reason made us change the scale of X in fig.2. The action radius of the vector field grows faster and explicitly exceeds the pion field action radius at $\gamma = 200$. The transverse size of the field begins to increase. This effect is particularly significant. As the observable fields represent the nucleon; this effect simply means the growth of the nucleon size, especially longitudinal ones. One can say that the nucleon "swells" [6]. A larger and larger stretching of the nuclear field potential with increasing γ is due to the "retardation factor" $\kappa = 1 - \beta\cos\theta$. As noted above, just this reason forms the basis of a similar phenomenon for the Lienard-Wiechert equipotentials of the electromagnetic field for a moving charge. So, in both cases we, in fact, deal with the manifestation of field "relativistic remote action".

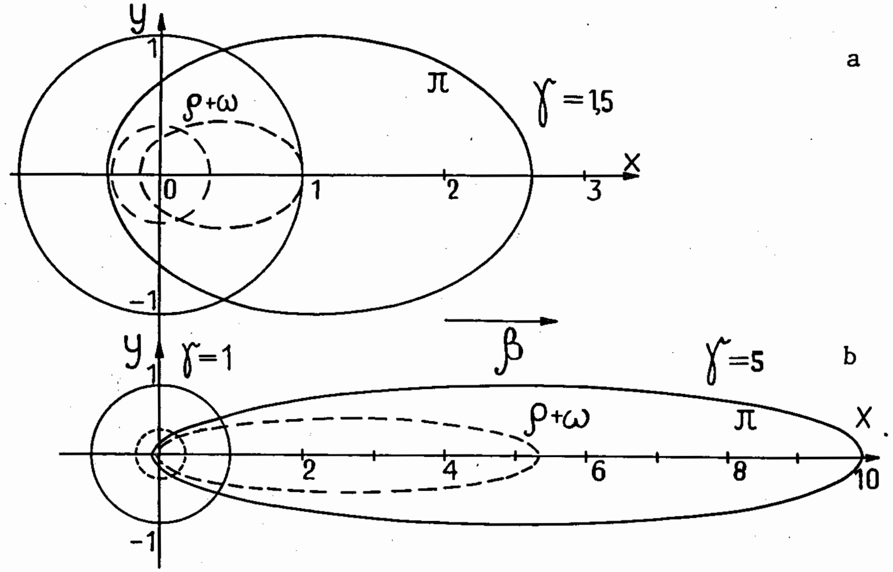

Fig.1. Equipotential curves of the pion and ρ-, ω-meson fields (corresponding to the action radius of nuclear forces) for β = = 0.745 (a) and β = 0.980 (b). The circles are for usual Yukawa's potential (β = 0).

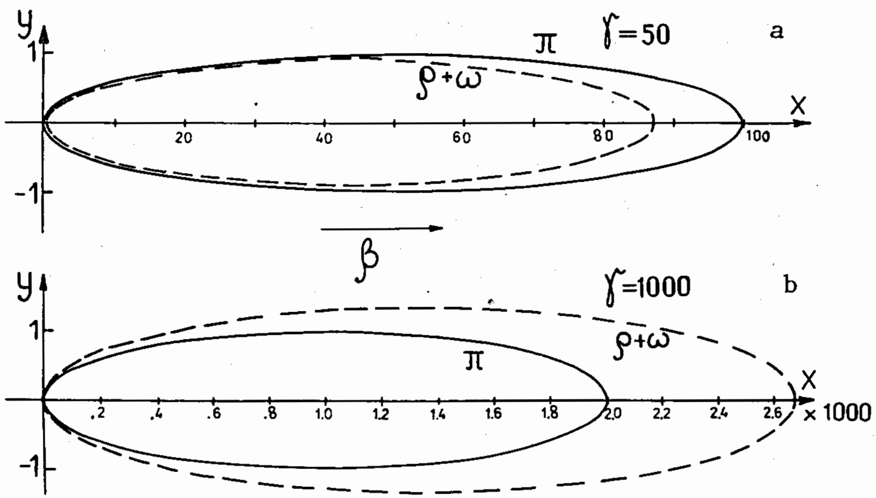

Fig.2. Similar equipotential curves of the pion meson and ρ-, ω-meson fields for β = 0.99979 (a) and β = 0.9999995 (b).

Table

γ	π-field			ρ-, ω-field		
	$R_f^{\parallel}$, μ^{-1}	$R^{\perp}$, μ^{-1}	$R_b^{\parallel}$, μ^{-1}	$R_f^{\parallel}$, μ^{-1}	$R^{\perp}$, μ^{-1}	$R_b^{\parallel}$, μ^{-1}
1	1	1	1	0.33	0.33	0.33
1.5	2.6	1	0.38	1.0	0.38	0.15
5	9.9	1	0.10	5.3	0.54	0.05
10	19.9	1	0.05	12.7	0.64	0.03
50	$1\cdot10^{2}$	1	0.01	87.1	0.87	$8.7\cdot10^{-3}$
117	$2.3\cdot10^{2}$	1	$4.3\cdot10^{-3}$	$2.3\cdot10^{2}$	1.0	$4.3\cdot10^{-3}$
10^3	$2\cdot10^{3}$	1	$5\cdot10^{-4}$	$2.7\cdot10^{3}$	1.34	$6.7\cdot10^{-4}$
10^4	$2\cdot10^{4}$	1	$5\cdot10^{-5}$	$3.4\cdot10^{4}$	1.71	$8.6\cdot10^{-5}$
10^5	$2\cdot10^{5}$	1	$5\cdot10^{-6}$	$4.2\cdot10^{5}$	2.09	$1.0\cdot10^{-5}$

The details of the calculations are given in the table. As is seen, the growth of vector field action primarily manifests itself along the axis of the nucleon moving forward ($R_f^{\parallel}$). The transverse component $R_v^{\perp}$ grows much weaker. For the pion field the value of $R_\pi^{\perp}$ does not change with increasing γ. At $\gamma \approx$ $\approx 1.2\cdot10^{2}$ the nucleon field character changes significantly: the action radius of the vector field is compared with the value of R_π. The contribution of the vector field becomes dominating with increasing γ. As is seen from the table, at γ = = 10^3 the longitudinal size of the nucleon is $2.7\cdot10^{3}$ μ^{-1} and its transverse size 1.34 μ^{-1}. Moreover it is not difficult to conclude that the angular size of the nuclear field decreases with increasing the nucleon energy $\approx\gamma^{-1}$. Then in multiparticle processes at high energy the emission angles of secondary particles* should be with necessity included in a narrow cone with apex angle $\theta \sim \gamma^{-1}$. Hadronic jets can serve as an example.

In our opinion the fact that the vector field of the nucleon plays a dominating role at $\gamma \gtrsim 1.2\cdot10^{2}$ deserves particular attention. This means that the contribution of vector meson interactions increases with increasing energy. Thus, peripheral collisions are determined just by vector exchange at

*This can be interpreted as the transformation of virtual quanta of the field to real particles.

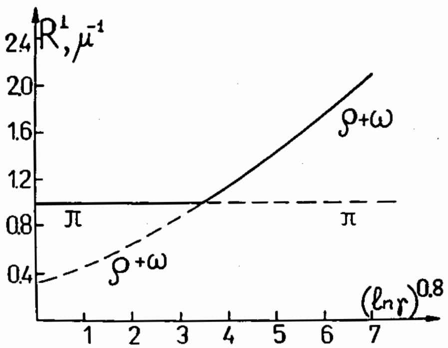

Fig.3. Change of the transverse nucleon size versus the Lorentz factor.

high energy. On the other hand, it will obviously have to lead to the corresponding increase of ρ - and ω -meson production cross sections. This result is in fact observable experimentally (see, e.g., /7/). A substantial influence of spin effects could be expected with increasing energy as ρ - and ω-mesons possess spin in distinction to pion.

But of prime importance is the increase of the transverse size of the nucleon due to the vector field (see fig.3). This fact with necessity should give rise to the cross sections. This result is found experimentally (see, e.g., /8/)*. In addition, the growth of formation length increases by $(\ln\gamma)^{0.8}$.

4. CONCLUSIONS

So, based on Yukawa's relativistic potential, we have concluded that the relativistic nucleon is a rotating ellipsoid in shape stretched in the direction of motion**. The pseudoscalar (pionic) and the vector ρ-, ω-meson fields behave in different ways. The contribution of the vector field increases and becomes dominating at $\gamma \gtrsim 1.2\cdot10^2$ with increasing nucleon energy. Just this fact can be used as an explanation of the corresponding growth for the production cross sections of vector mesons at high energies.

Of great significance is the growth of interaction cross section due to increasing the transverse nucleon size $(\sim\ln\gamma)^{0.8}$. The character of central and peripheral collisions changes.

*The values of g_ρ and g_ω are characterized by a low accuracy used in our calculations. The change in the behaviour of the total cross section of nucleons can serve as the basis for obtaining the ratio g_v/g_π more precisely. So, if σ_{tot} (pp) begins to grow at $\gamma = 90$, one gets $g_v/g_\pi = 1$ instead of a previous value of 0.77.

**According to the traditional opinion, it is a sqeezed disc. One can find an obvious illustration, for example, in/9/.

Now peripheral collisions are defined by heavier vector particles instead of pion exchange. The production cross section of ρ- and ω-meson increases. A significant contribution is expected for spin effects.

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Беляков В.А., Стрельцов В.Н. E2-90-309

Релятивистский нуклон

Отмечается, что пионное поле и поле векторных мезонов релятивистского нуклона ведут себя по разному. С ростом энергии вклад векторного поля увеличивается, а при $\gamma \gtrsim 10^2$ /γ - лоренц-фактор/ становится доминирующим. Это приводит к росту поперечных размеров нуклона. В результате меняется характер периферических и центральных соударений /последние характеризует именно пионный обмен/. Растут сечения ρ-и ω-мезонов, ожидается существенный вклад от спиновых эффектов. Высказывается мнение, что определенный вклад в рост сечений взаимодействия при высоких энергиях обусловлен как раз указанным увеличением поперечных размеров нуклона.

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Belyakov V.A., Strel'tsov V.N. E2-90-309

The Relativistic Nucleon

It is noted that the pion and vector meson fields of the relativistic nucleon behave in different ways. The contribution of the vector meson field increases with increasing energy and becomes dominating at $\gamma \gtrsim 10^2$ (γ is the Lorentz factor). This leads to the growth of the transverse size for the nucleon. As a result, the character of peripheral and central collision changes (the former is determined by vector exchange). The cross section of ρ and ω production increases. A significant contribution to the spin effect is expected. The opinion is expressed that the indicated growth of the transverse size of the nucleon leads to increasing the total cross section of nucleon interaction at high energy.

The investigation has been performed at the Laboratory of High Energies, JINR.

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