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The contribution of weak three-quark forces involving meson exchanges to the longitudinal analyzing power A_L in the low-energy *pp*-scattering is calculated. The nonrelativistic potential model is used for the description of strong quark interactions, while their weak coupling is described by the Weinberg-Salam lagrangian. The contributions to A_L coming from two-particle (factorization ansatz) and three-particle quark forces involving meson exchanges are shown to cancel each other to large extent. This result implies that the vector-meson exchanges do not govern the weak interactions of nucleons. The dominant mechanism of parity violation in the NN system (provided the one-pion exchange is forbidden by selection rules) is the contact interaction of quarks.

Fig. - 3, ref. - 17

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1. Introduction

Now for the description of P-odd nucleon coupling practically only one model is applied, i.e. the model of weak one-boson exchanges. This model is based on a number of essential assumptions. According to one of them the weak interaction of nucleons is mediated by π-, ρ- and ω-exchanges only. According to the other assumption of no less importance the weak NN interaction proceeds in two stages: emission (absorption) of the meson by the nucleon [illegible] strong interaction and [illegible] (emission) of [illegible] by other nucleon [illegible] strong interaction. The [illegible] of strong [illegible] coupling being established rather firmly, the main problem in calculating such two-stage process consists in determination of weak meson-nucleon coupling constants g_M. A number of approaches [illegible] for calculation of the latter (see e.g. reviews [1,2]) which yielded only rather broad ranges of g_M coupling constants. Within these ranges one can describe (unfortunately rather meagre) experimental data on P-odd effects in nucleon systems. One should note, however, that in the model of weak one-boson exchanges the finite dimensions of nucleons are taken into account only when calculating g_M coupling constants. At the same time the nucleons at the stage of constructing the weak NN potential are either considered as point-like particles or their dimensions are accounted for indirectly by introducing formfactors in the meson-nucleon vertices [3]. This assumptions reveal themselves in the most evident way in the calculations of those P-odd effects in the NN system where due to selection rules the one-pion exchange is forbidden (longitudinal analyzing power in the pp-scattering and the circular polarization of γ-quanta in the $np \to d\gamma$ capture). Indeed, the specific features of the weak one-boson exchange model which are of interest for the present discussion are as follows.

1. The weak NN interaction due to W- and Z-boson exchanges is neglected since the wave function of NN system at distances $\sim m^{-1}_{W,Z}$ is practically equal to zero.

2. Vector-meson exchanges play the dominant role. The value of P-odd effects is governed by the wave functions of the NN system at distances $\sim m^{-1}_{V}$. Then the weak NN interaction occurrs in the region of core and consequently drastically depends upon the choice of the NN potential [4,5].

However, the nucleon's dimensions noticeably exceed the value of m^{-1}_{V} and besides the quarks constituting nucleons can couple with each other in a contact way. Account of these two factors as we show in this paper and preceeding ones [6,7] changes drastically the picture of weak NN interactions.

In the present paper we treat the weak interaction of nucleons generated by meson exchanges between quarks.

According to the approach developed intensively in papers [8,9] the QCD coupling constant α_S is small even at low energies, confinement of quarks being provided by their interaction with stochastic vacuum fields. The indication on the small value of α_S follows also from the expansion of this coupling constant in the powers of $1/N_c$. The small value of $\alpha_S \simeq 0.25 \div 0.35$ follows from the mass difference of the Δ-isobar and the nucleon provided pion-exchange contribution is taken into account [illegible] references cited therein. Since the parity violating [illegible] meson requires production of [illegible] weak [illegible] antiquark with quark [illegible] lowest order in α_s [illegible] intermediate [illegible] All [illegible] diagrams are shown in fig. [illegible] and [illegible]. In our preceding paper [7] [illegible] which hereafter [illegible] the contribution of [illegible] exchange between quark [illegible] A_L. The sign of [illegible] observed at the experiment [illegible] besides the two-quark [illegible] fig.1 there [illegible] involved three quark forces generated by the interaction of quark and antiquark in the initial state (fig.2a) and the final one (fig.2b). The present paper is devoted to the calculation of contribution coming from these forces to the value of the longitudinal analyzing power A_L.

In sect.2 we discuss briefly the choice of the model of strong NN interaction. In sect.3 the lagrangian of weak three-quark interaction is constructed. In sect.4 we calculate the contribution of three-particle weak quark forces to A_L. In the concluding sect.5 we consider the resulting value of the effect generated by weak one-meson exchanges and the general structure of weak NN interaction.

2. Constituent quarks and the model of strong NN interaction

According to the developed recently models of strong interactions of nucleons at low energies the quark degrees of freedom are materialized as constituent quarks with the mass $m_q \simeq 1/3\, m_N$. Confinement of quarks is described usually by means of some confining potential and for our purposes it is convenient to take it in the oscillator-potential form. Then the well-known repulsion at small distances is the result of quark exchanges between nucleons. As to the attraction at intermediate distances there are different points of view. According to one of them the attraction is due to the existence of 6q-states (see e.g. [11,12]). Unfortunately only S-states of the NN system are considered in these papers while the calculation of P-odd effects requires the characteristics of wave functions in both S- and P waves. So we address to the paper [13] where six-quark states are not introduced for the description of nucleons interactions and the attraction in the NN system is provided by meson exchanges. The six-quark wave function describing two nucleons is used in the quoted paper in the following form

$$\Psi = \mathcal{A}\, \{\Phi_A\, \Phi_B\, \eta(\vec{R})\},\qquad (1)$$

where $\mathcal{A}$ is the operator interchanging quarks belonging to different nucleons, $\Phi_{A,B}$ are the antisymmetrized three-quark wave functions with the quantum numbers of the nucleon (S = T = 1/2), η is the wave function of the relative motion of nucleons and $\vec{R}$ [illegible] connecting their centers of mass.

The radial wave function of three-quark clusters A and B are [illegible] of three [illegible]-quark wave functions. The latter reads

$$[illegible]$$

Taking into account [illegible] radius-vectors of quarks are not independent [illegible] that the parameter [illegible] in [illegible] equals the r.m.s. radius of the nucleon [11]. So the value of b is taken $\simeq 0.5 \div 0.6$ fm.

Using the wave function (1) Oka and Yazaki [13] succeeded in describing the phase shifts of NN scattering in the states with orbital momenta $L \leqslant 3$ in the energy range $0 \leqslant T_{c.m.s.} \leqslant 200$ MeV. The estimates show that the upper bound of this range corresponds to the distances R between the nucleons' centers of mass $\simeq 0.5$ fm corresponding to almost complete overlapping of three-quark clusters.

In the paper I we have considered the contribution to the value of the longitudinal analyzing power which is due to antisymmetrization effects. These effects were shown to depend weakly both on the range of weak interaction between quarks and on its isotopic structure. So one can assume that the value of these effects is governed by the wave function of cluster relative motion $\eta(\vec{R})$ only. The antisymmetrization of the (3 + 3)-quark wave function results in the corrections $\leqslant 30\%$ to the calculated value of the longitudinal analyzing power A_L (see the Table). The experimental data [14,15] which we compare our results to have approximately the same accuracy. So hereafter when calculating the contribution to A_L coming from three-quark weak forces we shall neglect antisymmetrization effects in the two-nucleon wave function, i.e. omit operator $\mathcal{A}$ in (1).

3. Weak three-quark forces

One of the important questions arising in the calculation of P-odd effects in a quark system is the structure of the lagrangian describing the weak interaction of constituent quarks. The celebrated Weinberg-Salam lagrangian describes the weak interaction of current quarks. Account of hard gluonic exchanges results in the renormalization of the terms of this lagrangian possessing different isotopic structure. Besides new terms appear which were absent in the initial lagrangian. The point of great importance is that newly appearing terms enter in the lagrangian with small factors $\leqslant 0.2$ (compared to 1 in the dominant isoscalar component) without any additional enhancement factors (see [1]). So taking into account the accuracy of calculations with the antisymmetrization effects being neglected (~ 30%) and the accuracy of experimental data we can neglect terms appearing as a result of the renormalization. The remaining terms of the lagrangian are responsible for the transitions without changing of the isospin of quark pair and for the transitions with this isospin changing by the value $\Delta I = 1$ and $\Delta I = 2$. The coefficients of the lagrangian terms of the last two types contain $\sin^2 \theta_W \approx 0.2$. Treating this value as a small factor we disregard the abovementioned terms of the lagrangian retaining only the dominant one corresponding to $\Delta I = 0$. The renormalization of this term due to hard gluonic exchanges results in ≈ 7% corrections [1] and with the accuracy of our calculations it can be neglected.

Account of soft gluonic exchanges which results in the non-zero quark mass can result also in the appearance of the new terms in the lagrangian proportional to the quark momentum. The latter, however, enters in combination with the $1/m_q$ factor. Such terms in the nonrelativistic quark model should be neglected. So the most noticeable result of the weak lagrangian renormalization can be the value of the axial coupling constant of quark g_A differing from unity. The corresponding modifications of the weak interaction lagrangian and of the final results are quite obvious and we shall not dwell on them taking for brevity $g_A = 1$.

The arguments mentioned above enable us to conclude that the dominant isoscalar component of the lagrangian describing weak interactions of constituent quarks coincides with the sufficient accuracy (~ 30%) with the corresponding component of the Weinberg-Salam lagrangian. Thus the lagrangian of weak interactions of quarks i and j reads

$$\mathcal{L}^{ij} = G/\sqrt{2}\,(\vec{\tau}_i\vec{\tau}_j)\,(V^i_\mu V^{j+}_\mu + A^i_\mu A^{j+}_\mu + V^i_\mu A^{j+}_\mu + A^i_\mu V^{j+}_\mu), \qquad (3)$$

where $\vec{\tau}_i$ is the Pauli isospin matrix of the i-th quark.

In (3) we have introduced the following notations

$$V_\mu = \bar{u}\,\gamma_\mu\,u \qquad (4a)$$

and

$$A_\mu = \bar{u}\,\gamma_\mu\gamma_5\,u. \qquad (4b)$$

In (4) u is the bispinor describing the quark whose orbital wave function is given by (2). Utilizing the explicit expression for the ϕ function we get that the wave function of the initial quark reads

$$u = \begin{bmatrix} 1 \\ \dfrac{i\vec{\sigma}\vec{r}}{2m_q b^2} \end{bmatrix} \phi(\vec{r})\,\chi\,, \qquad (5)$$

where $\vec{\sigma}$ is the Pauli spin matrix and χ is the spin-isospin wave function of the quark.

Lagrangian (3) describes also the weak production of a quark-antiquark pair since the bispinor u entering in expression

[illegible]

in Fig. [illegible] the matrix [illegible] expression [illegible]

for nucleonic states in the form

[illegible]

Here u_i^2 denotes the wave function of the [illegible]

[illegible]

$$\langle \rho N|\mathcal{L}|N\rangle = G/\sqrt{2}\, f_\rho\, m_\rho^2\, (\vec{\tau}_1, \vec{\tau}_2)\, (\bar{u}_3\, \bar{u}_1, \langle \bar{u}_2\, \gamma_\mu \gamma_5\, u_2 \rangle u_3 u_1)\, \rho_\mu \, . \quad (10)$$

Analogous expression can be obtained for the vertex of P-odd ω-meson production; to this end one should separate the isoscalar combination of the quark 1 and the antiquark 1'.

The vertex of the P-odd meson-quark coupling needs some comments. The approximation made refers to the orbital part of the wave function only: the spatially separated $q\tilde{q}$ pair is replaced by the point-like meson. As to the spin and isospin properties of the meson they are expressed in terms of the spin-isospin wave functions of quarks 1', 1, 2 and 3. The latter are subject to the [illegible] and [illegible] spin operators entering [illegible]. Besides in the [illegible] description of the [illegible] of the vector [illegible] it is natural to assume that it is produced in the point [illegible] with the [illegible] of mass of the quark [illegible] and the [illegible] quark [illegible] in a [illegible] way [illegible] being produced in the [illegible].

Although the amplitude (10) corresponds to the vertex of [illegible] it immediately [illegible] NN coupling constant in the [illegible]. The reason is that the latter [illegible] involves the gradients of the nucleon wave function while [illegible] (10) involves the gradients of the quarks' wave functions which cannot be reduced to the nucleon wave function gradients.

[illegible] the second term in the r.h.s. of the Lagrangian (2) [illegible] production of the vector meson by the axial-vector current of the quark. As it was stated above we neglect the antisymmetrization effects. Thus the meson interacts strongly with the vector current of the quark belonging to the other nucleon. Using the nonrelativistic expressions for currents (6) and (7) we obtain the potential of weak interactions of three quarks which is depicted in a symbolic way in fig.3 in the form

$$V_{i,j:k} = g_{Vqq} \frac{4\, m_V^2 f_V}{\sqrt{2}} \frac{(\vec{\sigma}_i \vec{\sigma}_k)}{m_q\, b^2} \vec{R}_k\, D(|\vec{r}|) , \qquad (11)$$

where g_{Vqq} is the constant of strong coupling of meson with the vector quark current, $\vec{R}_i$ is the radius-vector of the i-th quark measured from the center of mass of the corresponding three-quark cluster and, finally, D is the nonrelativistic propagator of the meson. It reads

$$D(r) = e^{-m_V r}/(4\pi r), \qquad (12)$$

where m_V is the meson's mass and its argument is the absolute value of the radius-vector $\vec{r}$ connecting the points where the meson is emitted and absorbed

$$\vec{r} = (\vec{r}_i + \vec{r}_j)/2 - \vec{r}_k .$$

Here i and j are the numbers of quarks belonging to the one nucleon A and k to the other nucleon B.

Although the potential $V_{i(j)k}$ formally contains the spin operators of two quarks only which belong to different nucleons ($i \in A$ and $k \in B$) it involves implicitely also the operator acting on the spin variable of one more quark (j) constituting nucleon A. Indeed, the $\vec{\sigma}_k$ operator governs the change of the spin projection of the quark $k \in B$. Since two other quarks in the vertex of strong VNN coupling are spectators, this operator governs simultaneously the change of the spin projection of the whole nucleon and consequently the value of the total momentum z-projection of the vector meson. The latter is the S-wave state of the $\bar{q}q$ pair and hence the z-projection of the total momentum coincides with the z-projection of the summary spin of the quark and the antiquark. Since the quark constituting the meson does not change its spin projection (see fig.2a) it determines the spin projection of the antiquark involved in the weak interaction with the quark $i \in A$. The same arguments refer also to the isospin structure of the potential (11) which follows from the isoscalar property of the lagrangian component describing weak production of the [illegible] by the quark [illegible] (cf. the fact [illegible] One should take also into considera[illegible] [illegible] effects being neglected [illegible] [illegible] only.

[illegible] the $V_\mu T_\mu$ term [illegible] [illegible] this term describ[illegible] [illegible] the vector current [illegible] the [illegible] the axial-vec[illegible] [illegible] in [illegible] [illegible] the [illegible] by the intermediate vector [illegible], the quantu[illegible] corresponding to those of the meson. The axial [illegible] P-wave formation in the $q\bar{q}$ system and since [illegible] antiquark are emitted in the factorization [illegible] in the one and the same point the vertex of W,Z-boson coupling with A_1 meson vanishes. In the considered mechanism of meson production owing to initial or final state interaction quark and anti[illegible] forming the A_1- meson are at distances ~ b. The wave function of their relative motion in the A_1-meson is characterized by the scale ~ b [15] and for this reason no suppression of the A_1-meson production amplitude occurrs.

We construct the amplitude of the axial-vector meson production by the vector current of the quark applying the same procedure as in the case of the vector meson. The expression (9) is replaced in this case by the similar one [16]

$$\langle 0|a_\mu|A_1\rangle = f_A\, m_A^2 \text{ , where } f_A = 0.15 \; . \tag{13}$$

For sake of strictness it should be noted that lateron when [illegible] as a [illegible] when [illegible]

[illegible]

[illegible] the [illegible] and [illegible] two [illegible] strong interaction vertex only [illegible] final result depends on the vertex (strong or weak), where the quark whose radius vector enters in the potential belongs to (see below).

4. The contribution of three-quark weak forces to the longitudinal analyzing power A_L

In this section we calculate the contribution of potentials constructed above to the value of A_L comparing it to the contribution coming from the factorization ansatz. The longitudinal analyzing power in the low-energy pp-scattering is controlled by the P-odd transition in the state with the total momentum $J = 0$ ($^1S_0 \to {}^3P_0$). The amplitude of this transition f_W is proportional to the matrix element of the parity-violating NN potential V

$$f_W = -2\pi^2 m_N \int \Psi_P^{(-)*}\, V(\vec{R})\, \Psi_S^{(+)} d^3R \,, \qquad (15)$$

where $\Psi^{(\pm)}$ is the wave function of the NN system with the asymptotics at $R \to \infty$ being the sum of the plain and the outgoing (incoming) spherical wave. The subscripts S and P indicate that these wave functions refer to the states $^1S_0$ and $^3P_0$ respectively. The potential V in (15) is obtained as a result of averaging of the three-quark P-odd potential (11) (or (14)) over the spin-isospin functions of two-nucleon system and integrating over the radius-vectors of all six quarks, the distance $\vec{R}$ between centers of mass of three-quarks clusters being fixed. It is convenient to present the results of calculations as a dimensionless combination kf_W where k is the momentum of colliding protons in the c.m.s.

$$e^{-i(\delta_0 + \delta_1)}\, kf_W = g_{Mqq}\, G\, m_M^2\, f_M \frac{m_N}{m_q} \frac{1}{k\, b}\, C_M\, (Q_0 - Q_1), \qquad (16)$$

where δ_0 and δ_1 are the phase shifts of the NN scattering in the states $^1S_0$ and $^3P_0$ respectively, subscript M indicates the type of the meson mediating weak interaction ($M = V, A$ for the vector and the axial-vector mesons respectively), g_{Mqq} is the constant of strong meson-quark coupling, m_M is the mass of the meson, f_M is the constant defined by the relation (9) or (13) and C_M is a numerical factor obtained by the averaging over spin-isospin variables and integrating over the quark coordinates. For the vector meson the latter reads

$$C_V = \frac{14}{(59)^{5/2}} \frac{47 \cdot 6^4}{9\sqrt{6\pi}} . \qquad (17)$$

In (16) Q_0 and Q_1 are the radial integrals reading

$$Q_l = \int_0^{\infty} dy\, y^2\, \eta_S(y)\, \eta_P(y)\, y^{1-l} e^{-\gamma y^2} \int_0^{\infty} dy' (y')^{l+1} e^{-\alpha y'^2} f_l(\beta y y') e^{-m_M b y'};$$

$$l = 0,1 . \qquad (18)$$

The functions f_l are expressed in terms of regular spherical Bessel functions

$$f_l(y) = i^l j_l(iy), \quad l = 0,1 .$$

The wave functions η_S and η_P in (18) are the solutions of the radial Schrodinger equation with the asymptotics at the infinity reading

$$\eta_l(y) \to (kb)\{j_l(kby) \cos\delta_l - y_l(kby) \sin\delta_l\}; \; l = 0,1 ,$$

where y_l is the irregular spherical Bessel function. Parameters α, β and γ entering in (18) equal

$$\alpha = \gamma = \beta/2 = 141/118 . \qquad (19)$$

The integrals Q_0 and Q_1 in the case of the axial-vector meson exchange make approximately one half of the corresponding integrals for the vector meson exchange (due to the propagator $\exp(-m_M by')$). However their decrease is compensated almost completely by the factor m_M^2 in (16). As a result the product $m_M^2(Q_0 - Q_1)_M$ in the case of the axial-vector meson ($M = A_1$) diminishes by 8% compared to the case of vector mesons ($M = \rho, \omega$). Neglecting for simplicity this small difference we can present the relative value of the contributions coming from A_1 and ρ,ω-mesons in the form

$$\frac{(f_W)_A}{(f_W)_V} = \frac{g_{Aqq}}{g_{Vqq}} \frac{C_A}{C_V} \frac{f_A}{f_V} . \qquad (20)$$

Let us give now the ratio C_A / C_V , it is equal to

$$\frac{C_A}{C_V} = \frac{11}{14} \frac{9}{47} . \qquad (21)$$

The first factor in (21) is due to the isospin structure of weak three-quark forces: in the case of the axial-vector meson the weak interaction is mediated by the isovector A_1-meson only while in the case of vector-meson exchanges it is mediated by the isovector (ρ) and isoscalar (ω) mesons. The second factor is due to the fact that potential (11) includes the radius-vector of the quark belonging to the nucleon which is involved in strong meson-nucleon interaction while in (14) the radius-vector corresponding to weak meson-nucleon vertex is present. Accounting also the values of f_V from (?) and f_A from (13) we get

$$(f_W)_A / (f_W)_V \simeq 0.1\ g_{Aqq} / g_{Vqq} . \qquad (22)$$

This result implies that with the comparable values of coupling constants of the quark with the vector- and axial-vector mesons the contribution of the axial-vector A_1-meson to A_L is suppressed by a factor of ten.

We proceed now to the calculation of the contribution of three-quark weak forces to the value of A_L. Using the vector dominance model we get the expressions relating the coupling constants of vector meson interaction with quarks to the ones of the meson-nucleon coupling

$$g_{\rho qq} = g_{\rho NN} \quad \text{and} \quad g_{\omega qq} = 1/3\, g_{\omega NN} .$$

Utilizing the known values of ρNN and ωNN coupling constants from [17] we get

$$g_{\rho qq} = g_{\omega qq} = 1/(2f_{\rho}) .$$

We have calculated integrals Q_1 (18) with radial wave functions corresponding to the Reid soft core potential. So we have all required for the calculation of A_L. Applying the well-known expression relating the P-odd amplitude f_W with the longitudinal analyzing power A_L we get for b = 0.5 fm the values presented in the Table. There we display also the values of A_L obtained for other mechanisms of weak nucleon-nucleon interactions, i.e. factorization ansatz (fig.1) and the contact *qq*-interaction. These values are taken from our papers [6,7]. For comparison we quote also experimental data for A_L obtained for T_{lab} = 15 MeV [14] and T_{lab} = 45 MeV [15]. The values of A_L presented in the Table correspond to the omission of antisymmetrization effects in the (3 + 3)q-system, in the parentheses the corrections due to these effects are given.

Concluding this section we note that three-quark forces involving the axial-vector A_1-meson exchange make contribution to A_L at the level $(0.1 \div 0.2)\cdot 10^{-7}$ and for the existing accuracy of calculations and experimental data this contribution can be safely neglected.

5. Conclusion

We have considered the mechanism of P-odd quark interactions [illegible] by the weak production of the pair of quark and antiquark and interaction of the latter in the [illegible] or final state. The quark-antiquark pair being [illegible], such mechanism induces three-quark forces depicted in [illegible]. We have calculated the contribution of these [illegible] to the longitudinal analyzing power A_L [illegible] pp scattering. Taking into account that the [illegible] A_L [illegible] the second and third rows of the Table have the [illegible] % [illegible] we can state that the obtained value cancels almost [illegible] contribution to A_L coming from two-particle [illegible] (factorization approximation shown in fig.1). As a [illegible] cancellation the weak interaction mediated by mesons [illegible] insignificant. The dominant mechanism is the [illegible] of quarks and the contribution of this mechanism to A_L [illegible] close to the experimental values. This conclusion differs drastically from the usual picture of weak [illegible] where weak interaction is mediated by mesons only. It should be emphasized in conclusion that in our approach the nonvanishing dimensions of nucleon can be consistently taken into account.

The Table

The value of $A_L * 10^7$

Interaction mechanism	T_{lab} = 15 MeV	T_{lab} = 45 MeV
Contact qq-interaction [6]	- 0.80 (-0.22)	- 1.58 (-0.41)
Two-particle qq-forces - meson exchange (factorization ansatz) [7]	+ 1.24 (+0.48)	+ 2.32 (+0.95)
Three-particle forces meson exchange (present paper)	- 1.02	- 2.09
Experiment	- 1.7 ± 0.8 [14]	- 1.5 ± 0.22 [15]

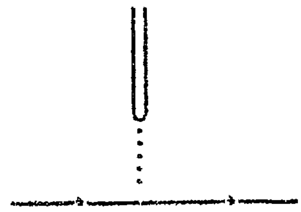

Fig.1. Diagram of the factorization approximation. Solid lines denote quarks and antiquarks, dotted line denotes W- and Z-boson exchanges

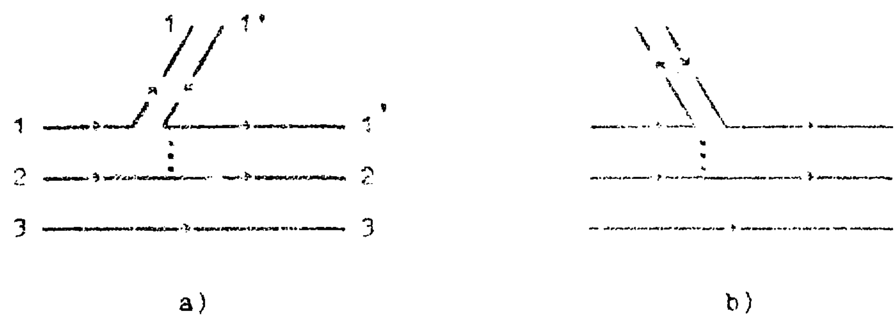

Fig.2. Diagrams describing initial (a) and final (b) state interactions. The same notations as in fig.1

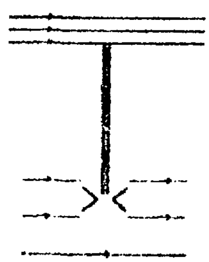

Fig.3. Weak three-quark forces. Double line denotes meson exchange

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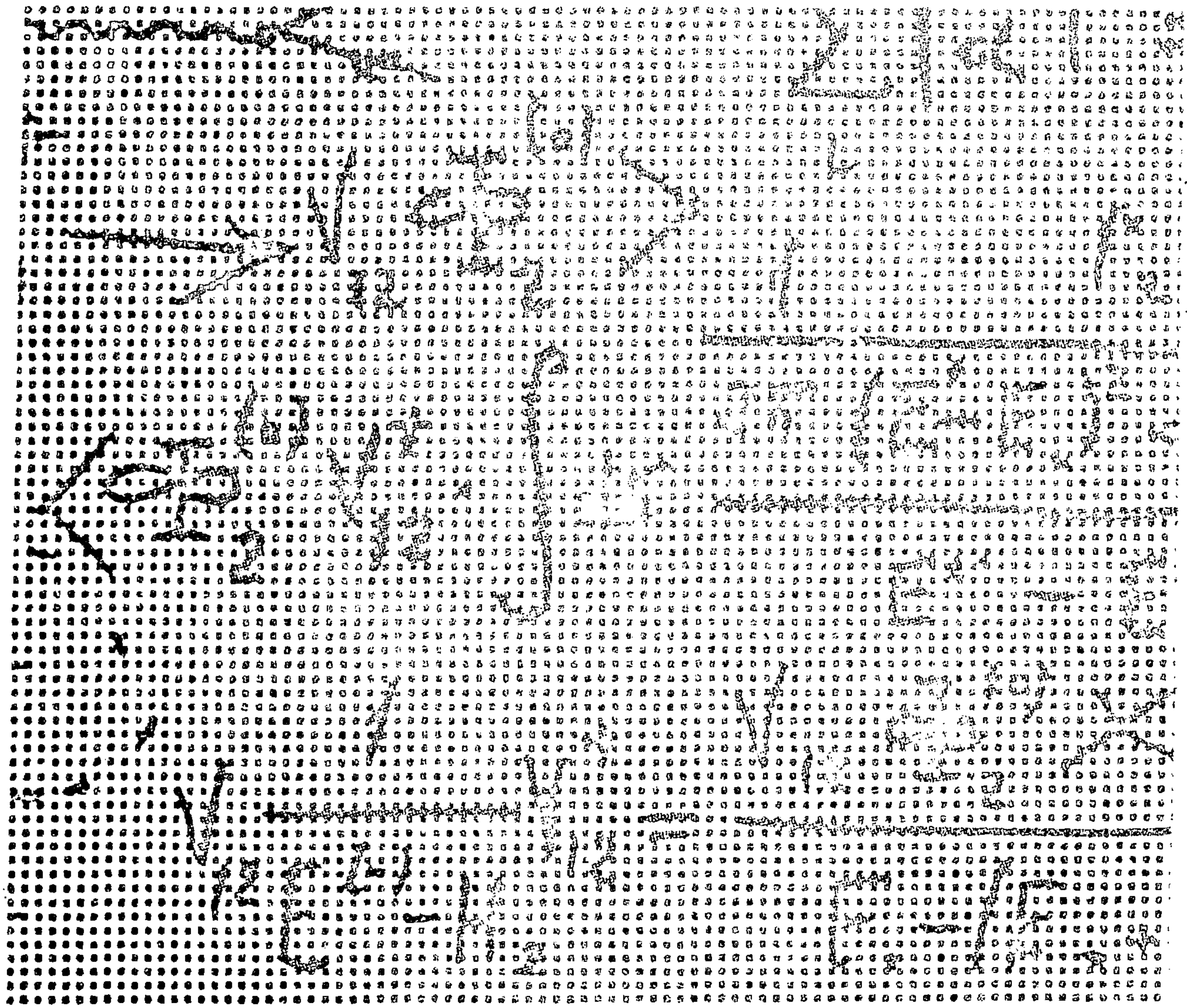

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