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PARTON DISTRIBUTIONS IN NUCLEI: QUAGMA OR QUAGMIRE?

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ABSTRACT

I review the emerging information on the way quark, antiquark, and gluon distributions are modified in nuclei relative to free nucleons. I place particular emphasis on Drell-Yan and ψ production on nuclei and caution against premature use of these as signals for quagma in heavy-ion collisions.

If we are to identify the formation of quark-gluon plasma in heavy-ion collisions by changes in the production rates for ψ relative to Drell-Yan lepton pairs, then it is important that we first understand the "intrinsic" changes in parton distributions in nuclei relative to free nucleons. So, I will review our emerging knowledge on how quark, antiquark, and gluon distributions are modified in nuclei relative to free nucleons, and briefly summarize the emerging theoretical concensus.

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PARTONS IN NUCLEI

The best known nuclear distortion is that of the EMC effect which reveals a modification of the valence quark distributions in nuclei relative to those in free nucleons.

All experiments now show broad agreement.[1,2] The rise in F_A/F_N at $x > 0.7$ is due to Fermi motion causing the structure function F_A to leak out to $x > 1$; dramatic as this appears, it occurs where $F_{A,N} \approx 0$, and is, in fact, a very minor contributor to the overall phenomenon. Indeed, overall, the effect is a subtle 10% affair and we don't need to rewrite the nuclear physics textbooks. As $x \to 0$, we are beginning to see evidence for shadowing, a subject on which theory is now also starting to develop.[3]

QUARKS IN NUCLEI

In the "intermediate" region $0.2 \lesssim x \lesssim 0.6$ the ratio falls below unity as (valence) quarks lose momentum due to nuclear binding. The A dependence was successfully predicted in advance of data[4] and is rather well understood. It was first <u>pre</u>dicted in the context of the rescaling analysis and subsequently verified by experiments at SLAC.[1] However, the A-dependence is more general than the rescaling model[5] and will arise in any model in which (i) the EMC effect is fitted or predicted for one A value, say iron, (ii) the physics underwriting the effect has a finite range in coordinate space, and (iii) the effect is expressible as a functional of the nuclear density operator, $\rho(r)$. If $g_k(r_1,\ldots r_k,x,Q^2)$ is an A-dependent function expressing the change in F_2^A arising from the overlap of k-nucleons, $\rho^A(r)$ is the mean nuclear density, then

$$\delta F^A_{k=2}(x,Q^2) = \frac{A-1}{2} \int d^3r_1\, d^3r_2\, \rho^A(r_1)\rho^A(r_2)[f(r_{12})-1]g_2(r_1,r_2;x,Q^2)$$

where $f(r_{12})$ was assumed to be A independent. Qualitatively, the effect is driven by the chance that there is a nearby nucleon correlated with the target nucleon. Reference 4 made a geometrical model for g_2 and predicted δF^A_2 for all A. (As the volume of a nucleon is only about 40% of the available volume, the two-nucleon contribution is ≤ 10% effect, and three-body and higher contributions can be ignored.) The fit is excellent and shows that the EMC effect is sensitive to details of nuclear structure, reflected in $\rho^A(r)$ as a result of which significant fluctuations are predicted at small A which have yet to be studied. At large A the behavior is smooth and it is safe to interpolate. Thus, one can infer the $F_A(x)$ when A = tungsten, say, and use this as input to $\pi W \to \mu\bar{\mu}$ ... analyses for example.

A common feature of models is that the degradation of the valence quarks transfers energy momentum to some other component (gluons and $q\bar{q}$ in rescaled QCD[6] or the partons in the π that are responsible for nuclear binding).[7,8] Thus, they generate an increased sea in nuclei relative to that measured in free nucleons. In turn, this implies that $F_A/F_N > 1$ as $x \to 0$. However, this predicted enhancement will probably be blacked out by shadowing (which has not been incorporated in these models so far). Mueller and Qiu[4] have begun to illuminate us about the x and Q^2 dependence of nuclear shadowing; the quantitative combination of their work with "soft π"[7,8] or rescaled QCD[4,6] remains to be completed. What impact does this have on Drell-Yan?

If $x_{1,2}$ refers to the beam and target partons, $x_F = x_1 - x_2$, and $x_1x_2 = Q^2/s$, then the ratio of cross sections for some fixed Q^2/s is

$$\frac{\sigma^{bA}}{\sigma^{bN}} \sim \frac{\bar{q}^{b}(x_1)q^{A}\ (x_2) + q^{b}(\bar{x}_1)q^{A}\ (x_2)}{\bar{q}^{b}(x_1)q^{N}\ (x_2) + q^{b}(\bar{x}_1)q^{N}\ (x_2)}$$

where sum over flavors weighted by their squared charge is understood. In the case of π^- beams, if $x_2 > 0.2$ so that $\bar{q}^A \ll q^A$, the DY process is dominantly due to $\bar{q}^\pi$ annihilating with $q^{A,N}$. Thus, in this kinematic regime

$$\frac{\sigma^{\pi\text{-}A}}{\sigma^{\pi\text{-}N}} \sim \frac{u^A(x_2)}{u^N(x_2)} \sim \frac{F^A(x_2)}{F^N(x_2)}$$

This is the same ratio as measured in inelastic lepton scattering ("EMC effect") and must be obtained here too if factorization is valid. Thus, we should not be surprised by the results from NA10[9] who study

$$\frac{\sigma(\pi^-\ W\to\mu^+\ \mu^-\ldots)}{\sigma(\pi^-\ D\to\mu^+\ \mu^-\ldots)}$$

and by varying Q^2 and x_F can separate both the pion and target structure functions. In Ref. 9 they exhibit the resulting ratio of $q^A/q^N(x_2)$ and $\bar{q}^{\pi(A)}/\bar{q}^{\pi(N)}(x_1)$.

The latter should be unity and is within errors when one combines data from two energies, 140 GeV and 286 GeV incident π beams. (However, if one restricts attention to the lower energy sample, the situation is more messy and the pion distributions do not seem to factorize. Why this should be is unclear to me, but bear it in mind as an empirical observation for later reference.)

So the message is: do not be misled by $\sigma = A^\alpha$, $\alpha \simeq 1$ for Drell-Yan pair production on nuclei. While this may be approximately true for the total rate, there can be (and are) non-trivial effects in x and p_t^2. A depletion at large x may be compensated by an enhancement as $x \to 0$ for example. The kinematic conditions of experiments may emphasize different regions of x for the beam and target. The extent to which A-dependent effects will arise depends on $\bar{q}^A(x)$ and $g^A(x)$, about which we know almost nothing. Rescaling and pion models imply that both $\bar{q}(x,Q^2)$ and $g(x,Q^2)$ have non-trivial A dependence; moreover, shadowing effects will modify them as $x \to 0$. Empirical information is only now beginning to emerge.

ANTIQUARKS IN NUCLEI

The Drell-Yan process with incident nucleons can probe q in the target if suitable kinematics are chosen, e.g., $x_1 \approx 0.7$ and $x_2 \ll x_1$. An investigation of this in various models has been made by Bickerstaffe <u>et al.</u>[10] and by Berger <u>et al.</u>[8] As an example, in Fig. 1, I show the predictions for $\bar{q}^A/\bar{q}^N(x)$ in iron in three models compared with information gleaned from CDHS.[11] The dramatic rise in the Berger-Coester model at $x > 0.3$ is due to their prediction that $\bar{q}$ leak out to moderate x values in nuclei. However, it is illusory to some degree as both $\bar{q}^A$ and $\bar{q}^N$ are vanishingly small; even so, experiment E772 may be able[16] to test this. Independent of specific models, it is an interesting question whether $\bar{q}$ leak to "large" x in nuclei as this will have a bearing on the Q^2 shape of Drell-Yan pairs in nuclei which may differ from the ψ production (produced by gluons) and potentially provide a background to the plasma signal sought in heavy-ion collisions. Indeed, there are hints of a change in the ψ/Drell-Yan ratio in comparing nucleon data with that from oxygen-uranium (NA38 collaboration at CERN,[17]) but close examination suggests that the shape of the Drell-Yan continuum has changed. This implies that "conventional" A dependence of $\bar{q}(x)$ may be significant, and that this is not a first hint of plasma formation.[18]

Recently WA25 and WA59 in cc11aboration have studied the EMC effect using ν and ν interactions in neon and deuterium. The x,y distributions allow separation of quark and antiquark distributions, and there is some indication that the sea decreases in going from deuterium to neon. Depending upon the model assumed for σ_L/σ_T, the fractions of sea in neon is 7 ± 6% or 18 ± 10% less than in deuterium. Presumably, these data are being dominated by nuclear shadowing, like the electromagnetic data for $x \leq 0.1$, again highlighting the need to see how shadowing modifies the curves in Fig. 1 at small x.

GLUONS IN NUCLEI

Insofar as inelastic $\gamma A \rightarrow \psi + \ldots$ proceeds via photon-gluon fusion and $NA \rightarrow \psi + \ldots$ involves gluon-gluon fusion, these processes probe $g^A(x)$. There have been early claims that $g^A > g^N$ ($x \sim 0.05$), this based on the EMC data[12] for $(\gamma Fe \rightarrow \psi)/(\gamma O \rightarrow \psi \ldots)$. Expressed as A^α this gave $\alpha = (1.10 \pm 0.03 \pm 0.04)$. However, it is now less clear whether coherent ψ production (for which $\alpha \simeq 4/3$) has been entirely removed from the data. Indeed E691 (Sokoloff et al.) report[13] that (at $Q^2 = 0$)

$$\alpha_{\text{coherent}} = 1.40 \pm 0.06 \pm 0.04$$

$$\alpha_{\text{incoherent}} = 0.94 \pm 0.02 \pm 0.03$$

This suggests that gluons are shadowed in nuclei.

There are also confusing signals[14] coming from E537 who probe the gluon distribution with $\pi^- W/Be \rightarrow J/\psi \ldots$ at 125 GeV, measuring the x_F distributions and thereby enabling $g^{W/Be}$ to be measured for x_{Bj} 0.2. If $x_F = x_1 - x_2$, then for J/ψ production at 125 GeV

$$x_F = \frac{1}{25x_2} - x_2$$

Thus, we can replot the data from E537 against X_2 (Fig. 2). This is equivalent to $g^W(x)/g^{Be}(x)$ only if $g^{\pi(W)} \neq g^{\pi(Be)}$ cancels out. However, we have no immediate way of knowing if this is true empirically as $Q^2(=m_\psi^2)$ is fixed. Prima facie, one may justifiably be worried. First, which is theoretical prejudice, if Fig. (2) is interpreted as $g^{W/Be}(x)$, it implies that gluons are significantly shadowed for x as large as 0.2. Our understanding of shadowing is still rather primitive, but such behavior would be against all current models.

The NA(10) data[9] on $\pi^- W/D \rightarrow \mu^+\mu^-$ ... may give hints that we are right to be wary of E537. Recall their extracted quark ratio which is in line with the EMC data from inelastic muon scattering — "EMC effect".[3] This is fine for the 140-GeV and 286-GeV data combined, but when one looks at the NA(10) data 140 GeV sample alone, things are less clear. The x_F distribution from NA(10) (which is a convolution of beam and target and thus "nearest" to the E537) for 140 GeV matches smoothly onto E537 at $x = 0.2$ — and the reason is that $q^{\pi(W)} \neq q^{\pi(Be)}$ in the 140-GeV data sample. I have no idea why this should be so, but if it is true for gluons too that $g^{\pi(W)} \neq g^{\pi(Be)}$ at 125 GeV, then it raises a question about extraction $g^W(x)/g^{Be}(x)$ from E537. If we take the NA(10) data on quarks as a guide, then it is possible that the $g^{W/Be}(x)$ is, in effect, to be renormalized upwards by 20%. (More legitimately, I don't know why there is such an energy dependence, or even if it is real, but I would be happier to see the E537 experiment with 300 GeV incident beams or comparison with Υ production so as to get some lever on the x_1x_2 separation directly.)

If one renormalizes the ratio in Fig. 2 upwards by 20%, then there is no shadowing at $x \simeq 0.2$ and, furthermore, the data then look quantitatively as expected in Mueller-Qiu theory of shadowing.[4] It is important that this problem with separation be better understood before we can conclude very much on the $g^{W/Be}(x)$ ratio. (Another reason why one might regard this renormalization as reasonable is that "infinite" shadowing leads to an $A^{2/3}$ behavior and for W/Be ratio this is 0.37. The trend of the E537 data looks set to violate this, whereas a 20% increase would bring this into line.)

Experiment E672 at Fermilab is measuring[15] $\pi^- A \to \psi$ on four nuclei at 530 GeV. I await their "high energy" extraction of $g^{A/N}(x)$. Until the conundrum of energy dependence (i.e. the non-factorization of the partons in the incident beam) is settled, I conclude that $g^{A/N}(x)$ probably falls as $x \to 0$, in qualitative agreement with the shadowing phenomenon, but the quantitative measure is unclear.

Thus, with the exception of valence quarks for $x > 0.2$, there is little or no evidence for non-trivial behavior for $\bar{q}^{A/N}$ and $g^{A/N}$. It is imperative to know these quantities much better, and to understand the anomalous energy dependence manifested by NA(10), and implicitly hinted at by E537. Until we do, then we cannot, with any confidence, use J/ψ relative to Drell-Yan production in AA collisions as a signal for quark-gluon plasma formation. Note that if the E537 experiment's dramatic suppression of nuclear glue is true, then ψ production per nucleon in heavy-ion collisions will be markedly suppressed relative to that in pp or even pA interactions. There is no reason to anticipate such drama for Drell-Yan.

SHADOWING

Early parton-inspired models of shadowing include Refs. 19 and 20. The former predicted that shadowing dies out rapidly with Q^2, and the emerging data suggest that this might not be the case. Reference 20 predicted antishadowing — an enhancement around $x \simeq 0.1$ — in order to maintain momentum conservation. It is interesting that the nuclear data exhibit such an enhancement, and that in recent years, models have described it[4,6,7,8] by invoking momentum conservation relative to the depletion at *large* x ($x > 0.2$)! In general, things are more subtle in that $F(x,Q^2)$ probes only the charged partons directly, and it may be that momentum is distributed among quarks and gluons differently in nuclei than in free nucleons.

The model of Ref. 20 predicts shadowing at smaller x in heavy nuclei and tends to disagree with what is observed. What is now needed is a combination of the surviving models of the EMC effect and a well-founded model of shadowing.

With the recent work of Mueller and Qiu[3] we have such a model. As $x \to 0$, the evolution equations imply that the number densities of gluons become very large. Gluons (and quarks) from different nucleons should interact with each other and reduce the number densities through annihilation. These annihilations are then responsible for nuclear shadowing.

(It is interesting that gluon recombination within individual nucleons becomes important at very small $x \simeq 10^{-4}$ and may indicate transition from naive evolution — with its threat to violate the Froissart found[21] — to the hadronic or Regge regime.) For our present purposes, we need only be concerned with the x dependence of the input shadowed distributions. Arguments based on the longitudinal length scales probed suggest that shadowing vanishes if $x > x_n \approx 1/2\ rm$ (*m* = *nucleon mass*, *r its radius*) and becomes total if $x < x_A \approx 1/2\ Rm$ (R = nuclear radius). Qiu then interpolates; his formula for the shadowing ratio $F^A/F^N(x)$ may be written (Fig. 3)

$$F^A/F^N(x) = R(x) = \begin{cases} 1 - K\left(\frac{x_n}{x} - 1\right) & (x_A < x < x_n) \\ 1 - K\,(A^{1/3} - 1) & (0 < x < x_A) \end{cases}$$

where K is a constant to be fitted by $x \to 0$ data. We thus see that R is a universal curve whose only A dependence is the saturation point.

We can now see the effect of shadowing combined with EMC-inspired models. For heavy nucleus B, the enhancement is generally expected to be *greater than for a light nucleus A. On shadowing these expectations with* Qiu's universal curve, one finds that the crossover from enhancement to shadow at small x will be $x(B) < x(A)$ (Fig. 4). This will be a subtle effect and more analysis is needed to see precisely what the values of the crossover should be. The empirical extraction of the crossover $x_c(A)$ will be an interesting exercise in the future.

The emerging data suggest that $x(B) > x(A)$, contrary to the above. This may imply that x_n is A-dependent. Qiu assumed, for simplicity in a first orientation, that $x_n \sim 1/R$ where R is the nucleon size — this being a measure of the distance scale for quarks from neighboring nucleons to "interfere". However, the A-dependence of the large x data ("EMC effect") suggests that quarks in neighboring nucleons have a greater chance to interfere as A increases; therefore the interference distance scale decreases and x_n increases with A. This qualitatively mimics the trend of the shadowing data but, of itself, does not seem to be sufficient. (Berger and Qiu in a recent ANL preprint have proposed a similar idea but have refrained from making a quantitative comparison.)

A Model for the EMC Effect and Rescaling?

At the quark-gluon level of reality, rescaled QCD describes the bulk of the nuclear data but does not explain it. The extra freedom of partons in nuclei relative to when in nucleons has been taken to imply that the nucleon is physically larger in a nucleus (e.g., Refs. 22). This would lead to a change in some static properties of the bound nucleon, such as magnetic moment and g_A/g_v. Whether or not this is empirically so is the topic of much debate, but in Ref. 23 we argued that the nucleon's g_A/g_v, in particular, is not nuclear dependent.

I suspect that the increased freedom of partons is due to their exchange among nucleons; "on the average", a quark can voyage more than 1 fm. A specific formulation of such a picture has been developed in Refs. 24. They consider a purely valence quark model for nucleons and consider only two-nucleon correlations.

Figure 5(a) shows the "direct" constitution, i.e. the incoherent process covered by the convolution model, while Fig. 5(b) shows an example of an exchange contribution not included in convolution models. Using Gaussian wavefunctions, the quark momentum distribution for Fig. 5(a) is essentially that of the free nucleon

$$\rho_{dir}(\vec{k}) \sim \exp\left[-\frac{3}{2}\, b^2 \vec{k}^2\right],$$

where k is the quark momentum and the scale $b = \langle \vec{k}^2 \rangle^{-1/2} \sim \langle r^2 \rangle^{1/2}$ can be interpreted as the mean radius of the quark in the nucleon. The contribution from the single quark exchange (Fig. 5(b)) and double quark exchanges are

$$\rho_{1,ex} \sim \exp\left[-\frac{12}{7} b^2k^2\right]; \qquad \rho_{2,ex} \sim \exp[-3b^2k^2].$$

Thus, the effective r^2 for two quark exchanges is $2r^2$ for the quarks in a free nucleon; the single exchange liberates to $\frac{8}{7} r^2$.

In general, for N constituents with E exchanged, the general result for partons in two nucleons is

$$r^2_{E,N} = \left(\frac{2(N-1)(N-E)}{2(N-1)(N-E)-E}\right) r_o^2$$

So, if one parton is probed by the current and <u>all</u> spectators are exchanged, E = n-1, and one has

$$r^2_{N-1,N} = 2r_o^2.$$

This is intuitively sensible; the maximum possible overlap of two nucleons at parton level has maximally convoluted the Gaussians. This model appears to underwrite many phenomena met in nuclear deep inelastic data. One can vary N to simulate Q^2 evolution (Q^2 increases and the improved resolution increases the effective N), the increased freedom of partons in coordinate space is seen, relation to nuclear density is a natural extension, quark exchange is related to nuclear binding, and so on. In Ref. 23 we showed how this can also accommodate convolution models if one includes six quark, etc. packages — as such, one makes contact with some ideas of multiquark bags and their relation to the EMC effect. Also, we showed how this model can be very well approximated by a single change of scale ($r^2 \to \beta r_0^2$) and that QCD rescaling can result from such a model.

The model can be extended and developed to provide a proto-quark model of the nucleus. To the extent that it works, it will show that the increased freedom of quarks is due to their exchange between nucleons and that this is the origin of Q^2 rescaling, and of the EMC effect. We may then extend to exchanges among many nucleons and investigate the circumstances where (if) quarks can be viewed as percolating throughout the nucleus, which is, of course, what we are all looking for.

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FIGURE CAPTIONS

Fig. 1. Data from Ref. 11 on the ratio $\bar{q}^{Fe}/\bar{q}^{D}(x)$ from neutrino scattering. Here $\bar{q} = (\bar{u}=\bar{d}=2\bar{s})$. The solid curve illustrates predictions of pion exchange model (Refs. 8 and 11), the dot-dash is the pion model of Ref. 7, and the dashed curve is the rescaling model, Ref. 6.

Fig. 2. Ratio of ψ production in π^-W/π^-Be from E537 (Ref. 14) which is indicative of $g^W/g^{Be}(x)$, plotted against x-Bjorken for the nuclear target (x_2).

Fig. 3. A dependence of shadowing in Mueller-Qiu model.

Fig. 4. Effect of Mueller-Qiu shadowing combined with enhancements in naive EMC models. Note the crossover $x_b < x_a$.

Fig. 5. Graphs contributing to leptoproduction off a nuclear target. (a) graph included in convolution model, (b) quark exchange; example of a graph not included in a convolution model.

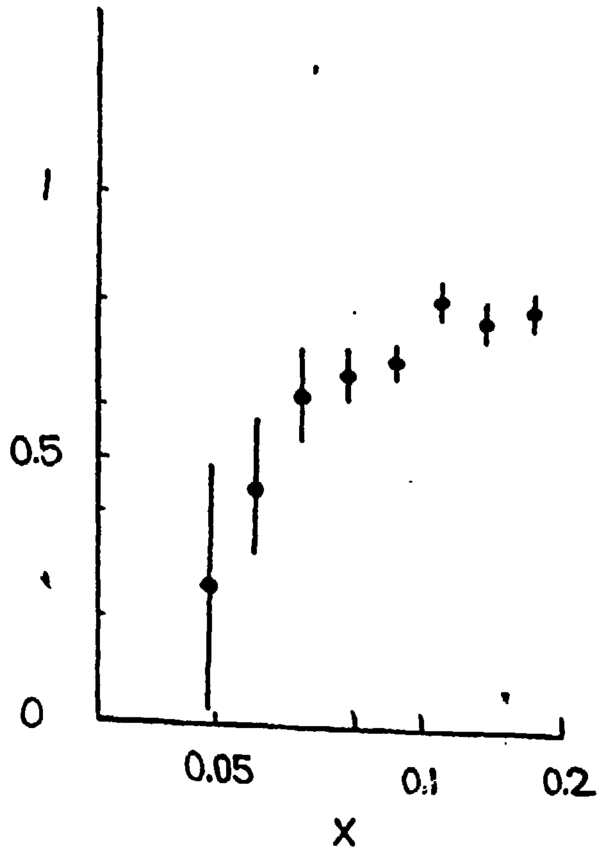

Fig.2

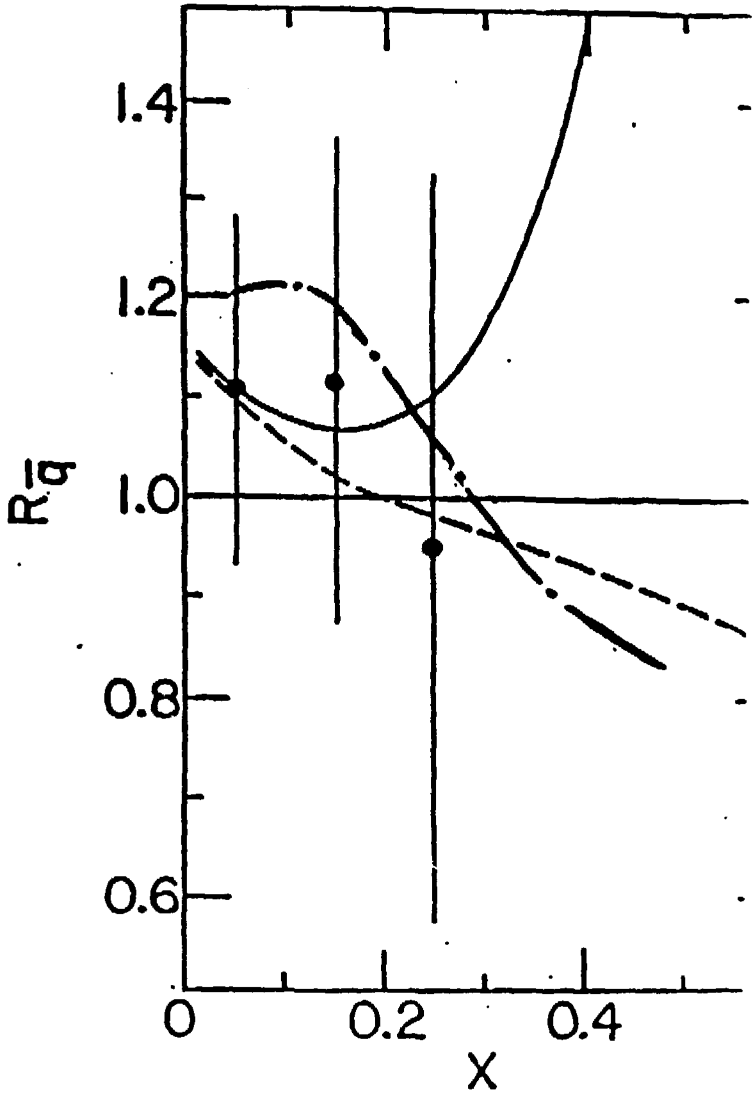

Fig. 1

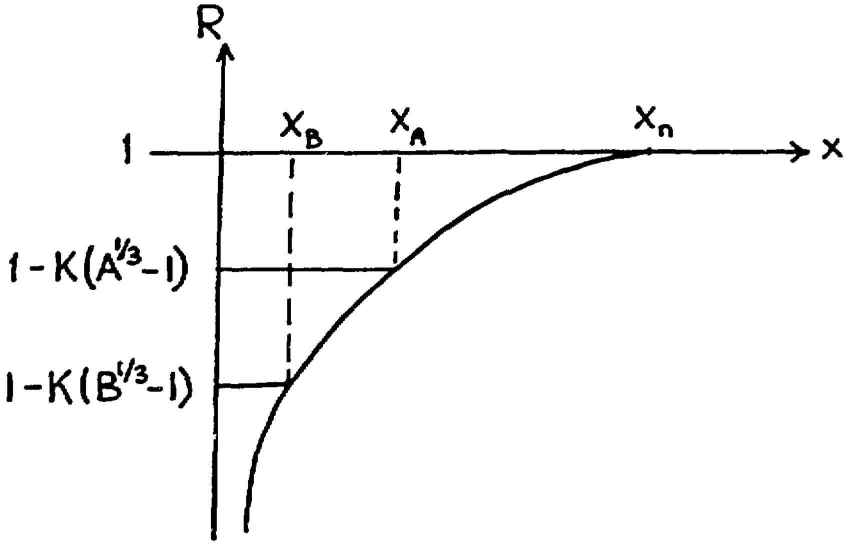

Fig 3

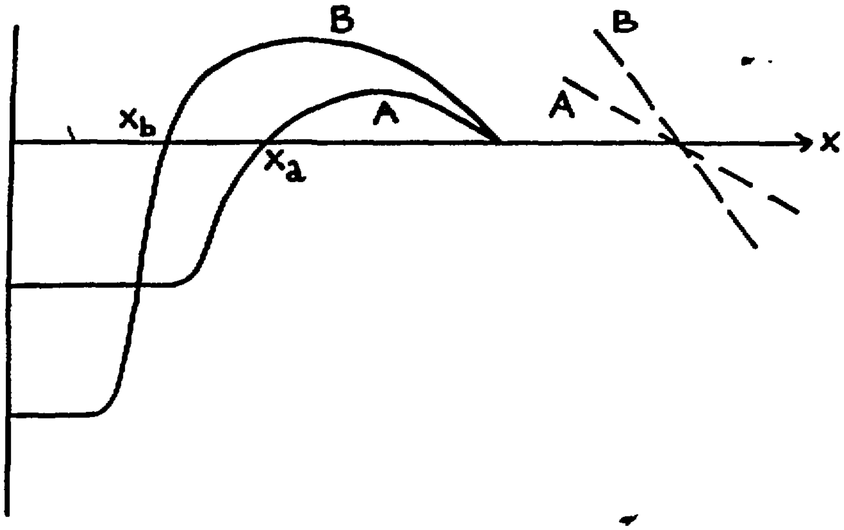

Fig 4

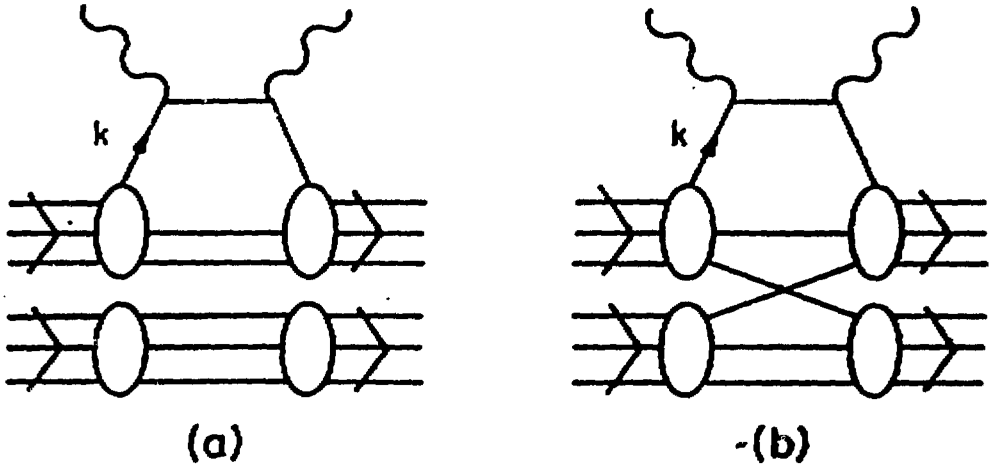

Fig. 5.