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GSI 80-8
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30 SEP. 1980

GSI-PREPRINT 80 - 8
FEBRUAR 1980

NON LINEAR EFFECTS IN NUCLEAR MATTER AND SELF-INDUCED TRANSPARENCY*

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CM-P00067710

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Abstract

We suggest that in high energy hadron-nucleus and nucleus-nucleus reactions a partially coherent intense mesonic field is created. Two non-linear models for the propagation of this mesonic field in nuclear matter are considered which both admit soliton solutions. The effect of this could be a self-induced transparency of nuclear matter. This might explain various experimental observations in hadron-nucleus reactions and leads possibly also to the existence of new metastable states. Experimental consequences of this are discussed.

* Work supported in part by NATO and GSI, Darmstadt.

January 1980

GSI-PREPRINT 80 - 8

GESELLSCHAFT FÜR SCHWERIONENFORSCHUNG, DARMSTADT

To be published in Proceedings of "Orbis Scientiae" 1980.

INTRODUCTION

In hadron collisions with nuclei at high energies the suppression of cascading ¹⁾ (transparency effect) which is observed is commonly interpreted in terms of a coherent interaction between the projectile and the nuclear matter traversed. In the first encounter of the projectile within the nucleus an intense coherent mesonic field is expected to be created. It thus seems plausible that the response of the nuclear medium will be non-linear in the mesonic field.

Furthermore and particularly in the case of heavy ion collisions at high energy one has the added complication that quite apart from possible high meson field intensities the nuclear density is also expected to undergo large fluctuations implying a significant interaction in the meson field source.

Of course to treat these problems in anything like full generality is out of the question quite apart from the fact that much of the basic interaction required for a solution is unknown.

Nevertheless on the basis of models drawn from optics and solid state physics it is possible to make certain qualitative suggestions.

In particular in this paper we apply the formalism used in the description of self-induced transparency (SIT) to high energy nuclear reactions and discuss some possible tests of this approach.

NON-LINEAR EFFECTS IN THE MESONIC FIELDS

The conditions for SIT to develop as discussed by McCall and Hahn ²⁾ are:

- i) An intense, coherent (classical) field which interacts with the medium.
- ii) The existence of at least two energy levels in the medium - such that the excited level has a lifetime larger than that of the coherent pulse.

If one assumes as indicated by recent experiments (cf. below) that in the collision of a highly energetic hadron with a nucleon in the nucleus an intense coherent pion field is created, conditions (i) and (ii) could be met in nuclear matter. Among other things, the condition that the pulse should be broad enough in the direction of propagation to overlap more than one nucleon is very similar to that postulated by the hydrodynamical and coherent tube model. At laboratory energies of 200-400 G.e.V. the levels to be excited in the nuclear medium would be in the 5-10 G.e.V. region where a continuum of resonances might exist. The resonance lifetime in the nucleus (laboratory frame) is enhanced by Lorentz effect. The pion field satisfies the Klein Gordon equation.

$$(m^2 + \square) \phi = j \quad (1)$$

where j is the current induced by ϕ and m the pion mass; we neglect meson-meson interactions in this first overview. Within the SIT mechanism the width Γ of the pulse is given by

$$\Gamma = g^2/2 \quad (2)$$

where g is the pion nucleon coupling constant (we write the pseudoscalar pion-nucleon isoscalar interaction $g \bar{\psi} \gamma_5 \psi$).

Consider for Φ and j a plane wave approximation

$$\Phi = \tilde{\Phi}(z-vt) e^{i(kz-\omega t)}; \quad j = \tilde{j}(z-vt) e^{i(kz-\omega t)} \quad (3)$$

where $\tilde{\Phi}$ and $\tilde{j}$ are slowly varying functions.

z denotes the propagation direction (we treat the problem in one dimension only which should be satisfactory at high enough energies where the average P_n of secondaries is limited) ω and k are the energy and wave number of the pulse in the medium which are to be determined.

Substitution of (3) into (1) yields

$$-(\omega^2 - k_0^2) \tilde{\Phi} + 2ik \frac{\partial \tilde{\Phi}}{\partial z} + 2i\omega \frac{\partial \tilde{\Phi}}{\partial t} = \tilde{j}; \quad k_0 = \sqrt{k^2 + m^2} \quad (4)$$

Choosing $\tilde{\Phi}$ real one has

$$-(\omega^2 - k_0^2) \tilde{\Phi} = k_0 \tilde{j} \quad (5)$$

$$-2k \frac{\partial \tilde{\Phi}}{\partial z} - 2\omega \frac{\partial \tilde{\Phi}}{\partial t} = \tilde{j} \quad (6)$$

The nucleon wave function of a two level systems reads

$$|\psi(t)\rangle = a(t)|\psi_0\rangle + b(t)|\psi_1\rangle \quad (7)$$

where ψ_0 and ψ_1 denote the ground and excited level respectively. The current j is given in terms of a , b and $\dot{Q}$ by the Bloch equations

$$\begin{aligned} \frac{\partial W}{\partial t} &= -g \tilde{g} W \\ \frac{\partial V}{\partial t} &= g \tilde{g} W \\ \frac{\partial U}{\partial t} &= 0 \end{aligned} \quad (8)$$

with

$$\begin{aligned} g(ab^* + a^*b) &= n^{-1} R_{ij} = gU \\ ig(ab^* - a^*b) &= -n^{-1} I_{ij} = gV \\ bb^* - aa^* &\equiv W; \quad aa^* + bb^* = 1 \end{aligned} \quad (9)$$

W is the inversion which is the essential factor in the saturation effect necessary for SIT, and n is the number of nucleons per unit volume. For simplicity only one resonance level has been assumed and the resonance condition $\omega = \bar{\omega}$ has been postulated, where $\bar{\omega}$ is the pion energy corresponding to the excited level $\bar{\omega}$. This means that only resonant collisions are considered, which are expected to be the main contributors to nuclear opacity.⁴⁾

It is known from the theory of SIT that these simplifications do not alter the main characteristics of the effect⁴⁾. In particular transparency is also present when the slowly varying approximation is inadequate, which may be a characteristic of the hadron case⁵⁾.

The soliton³⁾ solution of Eq. (5) reads

$$W = \cos \theta$$

$$V = \sin \theta \quad (10)$$

$$u = 0$$

$$\text{with } \theta = g \int_{-\infty}^t \tilde{\varphi} \, dt \quad (11)$$

which can be inverted to

$$\frac{\partial \theta}{\partial t} = g \tilde{\varphi} \quad (12)$$

Substitution of (12) into (6) yields the sine-Gordon equation

$$\frac{\partial^2 \theta}{\partial \xi^2} - \frac{\partial^2 \theta}{\partial \tau^2} = \frac{1}{2k} \sin \theta \quad (13)$$

$$\text{where } \xi = g(t - \lambda z), \quad \tau = g t$$

Eq. (13) admits the solution

$$\tilde{\varphi} = g \tilde{\varphi}_0 \operatorname{sech} [g \tilde{\varphi}_0 (t - \frac{z}{v})] \quad (14)$$

where φ_0 is an arbitrary constant. The system of equation (6), (10) and (11) leads to the "area" theorem

$$\frac{d\theta}{dz} \propto - \sin \theta \quad (15)$$

which implies that the intensity of the pulse is not attenuated in the medium provided θ is a multiple of π for large times. This in turn requires that the pulse is intense, i.e. θ large. On the contrary in the $\theta \rightarrow 0$ limit Eq. (15) yields an attenuated pulse (Lambert's Law). It is interesting to emphasise that the strength of the pulse is determined both by the magnitude of the coupling g and the amplitude of the field $\tilde{\varphi}$, so that when using hadronic (pion) fields one can afford to have smaller field amplitudes as compared with the optical (electromagnetic) case because of the favourable $g/\sqrt{k}$ ratio, $\propto$ being the fine structure constant.

In the derivation of the transparency effect an essential element was the coherence of the meson field. This gives a more precise form to the conjecture often made in the literature that the nuclear transparency is due to the long formation time of the secondary hadrons compared with nuclear dimensions. However, transparency can also be produced by incoherent fields ("hole-burning") and if the tests for coherence referred to below fail this may be a possible approach. In any event both procedures rely on saturation effects in the nuclear medium.

NON-LINEAR EFFECTS IN THE NUCLEAR DENSITY

If now we take the view that saturation of the nuclear medium is unlikely but that high density nuclear matter is created a different model is required. Since this has not been so extensively explored we present some details here.

We start from a Lagrangian of mesons and meson field sources in a one dimensional approximation⁶⁾

$$L = \frac{1}{2} \left(\frac{\partial \phi}{\partial t} \right)^2 - \frac{1}{2} \left(\frac{\partial \phi}{\partial z} \right)^2 - \frac{1}{2} b \phi^2 - \frac{1}{4} c \phi^4 + g \phi \mathcal{G} + L_H \quad (16)$$

where $\phi(z, t)$ is the meson field source, $\mathcal{G}(z, t)$ the meson field variable, L_H is the free meson field Lagrangian (in which we ignore meson-meson interactions), b is an effective mass of the nucleonic excitation, and c a self-coupling constant of the sources. To fix ideas one can picture the source field as creating or annihilating πN resonances which are allowed to propagate through nuclear matter with a ϕ^4 interaction term. Since ϕ and $\mathcal{G}$ are pseudo scalars no odd powers in ϕ alone appear. The one dimensionality of the problem is expected to arise from the well known limitation on the transverse momentum of pions produced in nucleon-nucleon collisions.

The equations of motion are now

$$\frac{\partial^2 \phi}{\partial t^2} - \frac{\partial^2 \phi}{\partial z^2} = -b \phi - c \phi^3 + g \mathcal{G} \quad (17)$$

$$(M^2 + \square) \mathcal{G} = g \phi \quad (18)$$

We now assume that the fields may be treated as c numbers (coherence property) and that the intensities are high enough for classical behaviour to be a reasonable approximation. Finally we write for ϕ and $\mathcal{G}$

$$\phi = \tilde{\phi}(z, t) e^{i(kz - \omega t)} \equiv (\tilde{\phi}_R(z, t) + i \tilde{\phi}_I(z, t)) e^{i(kz - \omega t)} \quad (19)$$

$$\mathcal{G} = \tilde{\mathcal{G}}(z, t) e^{i(kz - \omega t)}$$

where $\tilde{\phi}$ and $\tilde{\mathcal{G}}$ are slowly varying. Two different extreme cases may be investigated namely:

$$i) \quad \phi_R \gg \phi_I \quad \text{and}$$

$$ii) \quad \phi_I \gg \phi_R$$

(c.f. references (7), (8) and (9)).

For simplicity we shall discuss only case (i) the other can be treated on similar lines.

Thus we may take/see also references (7) and (8)/

$$\tilde{\mathcal{G}}(z, t) = \frac{\tilde{\phi}_R(z, t)}{k^2 m_\pi^2 - \omega^2} \quad (20)$$

and substitute in (17). If we write:

$$\tilde{\phi}_R(z, t) \equiv \tilde{\phi}_R\left(\frac{1}{\tau}(t - z/v)\right) \equiv \tilde{\phi}_R(z) \quad (21)$$

we find that (17) becomes:

$$\frac{1}{\tau^2} \left(1 - \frac{1}{v^2}\right) \ddot{\tilde{\phi}}_R + \left(k^2 - \omega^2 + b - \frac{g^2}{k^2 + m_\pi^2 - \omega^2}\right) \tilde{\phi}_R + c \tilde{\phi}_R^3 = 0 \quad (22)$$

The solution to (22) is the usual sech pulse soliton

$$\tilde{\rho}_0 = \tilde{\rho}_0 \operatorname{sech} \left(\frac{1}{\tau} (t - \frac{z}{v}) \right) \quad (23)$$

where

$$\tau^2 = \frac{2 \left(1 - \frac{1}{v^2} \right)}{c \rho_0^2} \quad (24)$$

with the dispersion relation

$$k^2 - \omega^2 + c - \frac{g^2}{k^2 m^2 - \omega^2} + \frac{c \rho_0^2}{2} = 0 \quad (25)$$

In this approximation v is arbitrary but an additional relation arises in a more exact treatment (references 8, 9 and 10).

A condition for this non-linear excitation is $\tau < \tau_{relax}$ where τ_{relax} is the relaxation time of the nuclear excitation, for high enough ρ_0 (nuclear density fluctuation) this should be true. The existence of a soliton solution in $\tilde{\rho}$ leads again to transparency of nuclear matter for pions.

CONCLUSIONS

We now turn to the qualitative predictions to which models of the type we are discussing give rise.

1. If a coherent meson field is indeed responsible for the transparency effect, then we should expect it to manifest itself in the Bose-Einstein correlations of secondary pions as described e.g. in references 11 and 12, particularly

for large positive pseudo-rapidity where a one dimensional approximation is expected to hold.

2. There should exist a threshold in the coherent pion field intensity above which transparency should occur.

3. The suppression of cascading, if due to SIT, should be a periodic function of the intensity of the coherent meson field.

4. Early observations in cosmic ray physics and more convincing recent work at LBL¹³⁾ with emulsions has provided evidence for the existence among the fragments arising in heavy ion collisions of "anomalous" objects with a lifetime $> 10^{-13}$ sec. and a mean free path several times smaller than that to be expected from normal nuclear interactions. It is conceivable that in heavy ion collisions the non-linear excitations produced could be metastable (soliton property) and could be carried off by an outgoing nuclear fragment. The interaction of such an excited fragment with ordinary nuclei might lead to a transverse instability¹⁴⁾ (growth) which could increase every time a collision takes place until eventually the excitation disintegrates. This would lead to a decrease of the mean free path compared with what one would expect from "normal" events.

It would be very interesting to investigate whether there is indeed a connection between these experimental findings and the theoretical speculations put forward in this note.

We are indebted to E.M. Friedlander for very useful discussions.

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