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Coherence and self-induced transparency in high energy hadronic collisions*

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Abstract

Two consequences of coherence of mesonic fields have been tested in proton-nucleus collisions. Multiplicity fluctuations measured in finite rapidity intervals are found to obey a Poisson distribution at large rapidities where nuclear transparency occurs. In close analogy to quantum optics we present a quark-parton model in which this link between coherence and transparency is realized via the phenomenon of self-induced transparency.

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It has been known for thirty years that in hadron collisions with nuclei at high cosmic ray energies a suppression of cascading takes place. The ratio between the number of secondaries N_{pA} produced, e.g. in a collision of a proton p with a nucleus of atomic number A and the number of secondaries N_{pp} produced in p-p collision $R = N_{pA}/N_{pp}$ is a slow function of A not exceeding the value of 2. This effect was interpreted by Landau and Belenkii[1] within a hydrodynamical model as a consequence of the formation of a tube in nuclear matter. Although the idea of a "coherent" tube has been considered by many workers[2] up to the present, no explanation or direct experimental confirmation for this "coherent" property was given. With the advent of high energy accelerator beams the suppression of cascading was confirmed[2] in the energy range 50 GeV-400 GeV. Moreover, it was found that the increase of multiplicity with target size is localized in the backward hemisphere and the name "transparency" was coined[3] for this effect.

In this paper:

1. We introduce a different (quantum-optical) concept of coherence in the physics of proton-nucleus scattering.
2. We show how this leads to self-induced transparency (SIT) in nuclear matter in close analogy to the same effect discovered in optics in 1967 by McCall and Hahn[4].
3. We present the first direct experimental evidence for the coherence of meson (pion) fields.
4. We show that in the forward cone a coherent part of the mesonic field is filtered out.

I. Theory

We start with the observation that in a hadron-hadron collision a partially coherent mesonic field is created. By coherent field we understand a field the state of which is an eigenstate of the annihilation operator[5]. So far the existence of this coherent field was "derived"[6] from theoretical arguments (spontaneous breakdown of symmetries, classical solutions in field theory, etc.) and from experimental indications in the Bose-Einstein correlations.

Additional indications to the same effect come from the observation[7] that the multiplicity distribution in p-p collisions (50-400 GeV) is well described by a mixture of two types of events, each of which obeys a Poisson distribution (a Poisson distribution is a consequence[5] of coherence). Although the importance of this effect was realized immediately[8], an independent confirmation has been lacking until now. We believe that we possess now this confirmation in experimental form (cf. Part II--Experiment).

In a proton-nucleus collision such a partially coherent field is created in the first encounter of the projectile with a constituent of the target.

The following conditions are sufficient for SIT:

(i) The coherent pulse is broad enough in the direction of propagation to overlap many scattering centers which remain to be identified.

(ii) There exist (at least two) energy levels of the scattering centers in the medium such that the excited levels have lifetimes comparable to or longer than that of the coherent pulse.

(iii) The intensity of the pulse is high.

Condition (i) can be met if there exists a long-range component in the quark-parton interaction. Condition (ii) is expected to be satisfied since the coherent pulse is emitted through de-excitation of a system similar in nature with the system to be excited when the pulse propagates. Condition (iii) is essentially a requirement that nonlinear effects should be important. However, in optics it has been shown that provided the width of the pulse in time is no greater than the lifetime of the resonance significant transparency is observed even for weak pulses[9] (cf. below).

If conditions (i)-(iii) are met, the front of the coherent pulse produced in the first collision will excite the scattering centers as it encounters them, and the rear of the (same) pulse will then de-excite them by stimulated emission. This process will continue so that the pulse will eventually leave the medium without cascading.

There is a rather vast literature on this subject in quantum optics and we shall discuss in the following only some relevant points emphasizing the differences between the atomic and nuclear case. In nuclear matter one can treat the problem in terms of meson fields and nucleons or in terms of their constituents. A treatment in the former term has been given in reference (10) but, for reasons which will emerge, it seems more appropriate to discuss the problem in terms of hadronic constituents. A natural basis for this would seem to be the gluons and quarks of QCD. Unfortunately QCD is not yet developed enough to be used in the low momentum transfer regime which is relevant for SIT. We shall consider therefore an effective microscopic hamiltonian for field sources or scattering centers (fermions) and fields (bosons) without specifying their concrete nature except the statistics they satisfy.

We describe the struck nucleon as a collection of sources which are energized by a boson of energy ω in the incident field. The important nucleon states produced in this way will be the resonant states of lifetime τ assumed to be larger than the pulse time. Many resonant states produced by energizing different nucleon sources by boson quanta of the same energy ω may be involved in the propagation of a particular field mode.

Our model hamiltonian is the following[11]

$$H = \omega \left[a^{\dagger} a + \frac{1}{2} \sum_{i=1}^{n} (b_i^{\dagger} b_i - c_i c_i) \right. - ga \sum_{i=1}^{n} b_i^{\dagger} c_i + h.c. \tag{1}$$

The operators $a^{\dagger}$, a create and annihilate boson quanta of the field with energy ω, the operators $b_i^{\dagger}, b_i$ create and annihilate fermion i in the nucleon with excitation energy ω and $c_i^{\dagger}, c_i$ create and annihilate the ith nucleon fermion constituent in the ground state; n is the number of fermions of type i in unit volume and g is a coupling constant. The energy zero is chosen to be $\frac{\omega}{2}$. Since we shall take the fermions to be noninteracting, we need only consider a single excited state and a single boson energy; for the present we neglect recoil effects (see below).

We shall use the coherent state representation to describe the states of the boson and of the fermion fields

We introduce quantities

$$\sum_i b_i^{\dagger} c_i \equiv \sigma^{+} \quad , \quad \sum_i c_i^{\dagger} b_i \equiv \sigma^{-}$$
$$\sum_i b_i^{\dagger} b_i - \sum_i c_i^{\dagger} c_i \equiv \sigma_z \tag{2a}$$

and

$$p \equiv g\langle a^{\dagger} + a \rangle \ , \ \sigma_1 \equiv \langle \sigma^{+} + \sigma^{-} \rangle \ , \ \sigma_3 \equiv \sigma_x$$
$$q \equiv ig\langle a^{\dagger} - a \rangle \ , \ \sigma_2 \equiv i\langle \sigma^{+} - \sigma^{-} \rangle \tag{2b}$$

where the brackets refer to coherent states; the σ's are polarization operators possibly connected with color degrees of freedom.

The matter coherent states are linear superpositions of nucleon states with different numbers of fermions excited and so they refer to coherent linear superpositions of resonances of different energies (but the same quantum numbers). This presupposes sequences of baryon resonance levels which differ from one another by multiples of the same energy, a simplified resonance model which has been used in other studies (cf. ref. 12). Implicit in the model is the assumption that the resonances are highly degenerate at high energy, a characteristic of some thermodynamic models in which an exponential increase in level density is called for.

We now assume [condition (i)] that all quantities are expressible in terms of slowly varying amplitudes in one space dimension, functions of $\xi \equiv t - x/v$, multiplied by a rapidly varying plane wave factor and take the pulse velocity v to be sufficiently larger than recoil velocities for recoil effects to be small (cf. references 13 and 14). x is the cartesian coordinate in the direction of propagation. We use Maxwell type equations for the boson field and in the present phenomenological application omit boson-boson interactions. For the slowly varying parts the equations become

$$\left(1 - \frac{1}{v}\right) \frac{d\tilde{p}}{d\xi} = \frac{g^2}{2} \tilde{\sigma}_2 \quad (3a) \qquad \left(1 - \frac{1}{v}\right) \frac{d\tilde{q}}{d\xi} = - \frac{g^2}{2} \tilde{\sigma}_1 \quad (3b)$$

$$\frac{d\tilde{\sigma}_1}{d\xi} = -\tilde{q}\tilde{\sigma}_3 \quad (3c) \qquad \frac{d\tilde{\sigma}_2}{d\xi} = \tilde{p}\tilde{\sigma}_3 \quad (3d)$$

$$\frac{d\tilde{\sigma}_3}{d\xi} = \tilde{q}\tilde{\sigma}_1 - \tilde{p}\tilde{\sigma}_2 \quad (3e)$$

One integral of the motion is readily found

$$\tilde{\sigma}_3 + \frac{1 - 1/v}{2g^2}(\tilde{p}^2 + \tilde{q}^2) = \text{Const} =$$

$$= \tilde{\sigma}_3(0) + \left(1 - \frac{1}{v}\right)\frac{\tilde{p}^2(0) + \tilde{q}^2(0)}{2g^2} \equiv R(0) \tag{4}$$

which corresponds to the conservation of energy.

In addition we have

$$\left(1 - \frac{1}{v}\right)\frac{d^2\tilde{p}}{d\xi^2} = \frac{g^2}{2}\tilde{p}\tilde{\sigma}_3 \tag{5}$$

$$\left(1 - \frac{1}{v}\right)\frac{d^2\tilde{q}}{d\xi^2} = \frac{g^2}{2}\tilde{q}\tilde{\sigma}_3 \tag{6}$$

so that if we define

$$\tilde{p} + i\tilde{q} = 2gA \tag{7}$$

we have

$$\frac{d^2A}{d\xi^2} = -\frac{g^2AR(0)}{2(\frac{1}{v} - 1)} - g^2|A|^2A \tag{8}$$

For small amplitudes A, the pulse is strongly attenuated.

The general solution of equation (8) is discussed in, for example, reference (15) in which it is shown that a wide variety of pulse shapes is possible, including a soliton pulse which would travel through the medium undistorted.

If in equations (3) we take $\tilde{\sigma}_1 = \tilde{q} = 0$ (a characteristic of strongly nonlinear resonant processes) then eqs. (3d) and (3e) and (3a) can be rewritten in the form

$$\frac{\partial^2\theta}{\partial\xi^2} = \frac{g^2n}{2(1 - \frac{1}{v})}\sin\theta \tag{9}$$

where $\theta \equiv g\int_0^t \tilde{p}\,dt$

This equation admits soliton solutions

$$\tilde{p} = a \sec h\left(\frac{a}{2}\xi\right) \tag{10}$$

with a an arbitrary constant and one has the "area" theorem

$$\frac{d\theta}{dx} \sim -\sin\theta \tag{11}$$

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 phenomenon is the self-induced transparency of optical fame and it requires that the pulse is intense, i.e. θ large [condition (iii)]. On the contrary in the $\theta \to 0$ limit, eq. (11) yields an exponentially attenuated pulse (Lambert's law). The above sketched model essentially outlines the main physical phenomena in close analogy to optical SIT. While it does not, however, explain the origin of coherence in p-p collisions it leads to the reintroduction of a coherent tube in a new guise.

So far we have ignored nonlinear interactions between fields and nonlinear interactions between sources. A treatment which includes the interaction between the sources considered as nucleons is possible and has been given in reference (10). It leads among other things to the possible existence of metastable nuclear states, a subject of high interest in itself. Eventually one would have to combine the nonlinear treatment of sources with the nonlinear treatment of fields, a topic which is under investigation.

Finally, one should emphasize that an essential element of our description of nuclear transparency is the existence of coherently excited states of nucleons and of nuclear matter. Conceivably they indicate the existence of rearrangements of the nucleon (nuclear) constituents which might also be involved in the anomalous mean free path effect observed in heavy ion collisions.[16]

There are a series of physical consequences which follow from SIT and which clearly distinguish this interpretation of nuclear transparency from others. One of these consequences has been tested experimentally and will be described here. It consists in the expectation that the mesonic (pionic) field traversing nuclear matter will show more coherence in the forward hemisphere since according to SIT only for the coherent part of the pulse the medium is (partially) transparent.

II. Experiment

In order to check this prediction one has to apply the known criteria for coherence in particle physics. These have been discussed in ref. 6 and consist essentially in the particular forms of the multiplicity distributions, rapidity gap distributions and intensity (second order) correlations e.g. Hanbury Brown - Twiss (HBT) effect. Possible evidence for coherence was reported[6] so far only through the HBT effect, and there the situation is complicated mainly because the second order correlations are rather insensitive to even large admixtures of coherence. There exists, however, another way to look for coherence, i.e., through the shape of the multiplicity distributions; when the fields are completely coherent the multiplicity distributions have Poisson form.

We now present experimental evidence for "Poissonicity" of the particles emitted into the forward cone of high-energy proton-nucleus collisions. The data come from nuclear emulsion exposures to high-energy proton beams, viz. 69 GeV (IHEP-Serpukhov) and 200 and 300 GeV (FNAL-Batavia). Scanning and measuring procedures were described in refs. (3,17). Events were classified according to the number of (target related) heavy prongs N_h which is a very good measure of target size and/or involvement[2]. Actually N_h is practically proportional to the number of nucleons lying along the projectile's path through the nucleus.

It is well known from the integral two-particle correlation function that in proton-nucleus collisions the total multiplicity distribution deviates strongly from the Poisson form.[17,18] For the purpose of this analysis each event* was divided into several pseudo-rapidity ($\eta = -\ln \mathrm{tg}\frac{\theta}{2}$) bins. Each such bin was treated as a "ministar" of multiplicity n_i, where i denotes the η-bin. Obviously, the total multiplicity n of the event is

$$n = \sum_i n_i \tag{12}$$

The multiplicity distribution of these ministars was recorded for each primary energy and N_h combination.

Figure 1a shows an example of the dependence of the mean multiplicity $\bar{n}_i$** in four η-intervals on N_h. Nuclear transparency is seen at the largest rapidities through the constancy of $\langle n_4 \rangle$.

In fig. 1b we present the observed multiplicity distributions in the same η-bins. The full curves are the Poisson distributions

$$P(n_i) = e^{-\langle n_i \rangle} \frac{\langle n_i \rangle^{n_i}}{n_i!} \tag{13}$$

corresponding to the estimated mean multiplicities $\bar{n}_i$.

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*Visual detectors are obviously an ideal tool for such an event by event analysis.

**Hereafter barred quantities denote sample means while brackets denote expectation values.

The straight lines represent chaotic distributions

$$P_{ch}(n_i) = \frac{1}{1 + \langle n_i \rangle} \left(\frac{\langle n_i \rangle}{\langle n_i \rangle + 1} \right)^{n_i} \qquad (14)$$

with the same mean values.

It can be seen that whereas at low η (backward in c.m.s.) the distribution is close to chaotic, in the forward direction it becomes purely Poisson. To illustrate this behavior we define the following measure for the deviation of each local multiplicity distribution from the Poisson law. Since from eq. (13)

$$P_i(0) = \exp(-\langle n_i \rangle) \qquad (15)$$

the quantity

$$\Delta_i \equiv \left| |(\ln P_i(0)| - \langle n_i \rangle \right| \qquad (16)$$

should vanish for a Poisson distribution.

In fig. 2 we plot estimates for the Δ_i (i = 1-12) against pseudorapidity. It is obvious that in the "forward" η-bins the Δ-values are well compatible with zero, while highly significant deviations occur in the low-η bins; this effect increases strongly with N_h, i.e. with nuclear size.

The level of significance of the deviation from a Poisson distribution on all our data can be judged from Table I which displays for all available combinations of E and N_h the χ^2 values and the numbers of degrees of freedom for the Poisson fits. Only the most forward η-bin shows good consistency (1.4 standard deviations), whereas everywhere else the discrepancy exceeds five standard deviations.

We have checked that in this rapidity region the experimental multiplicity distribution can be described in a satisfactory way by a superposition of coherent and chaotic fields* as defined by Mollow and Glauber[19]. Details of this analysis will be published elsewhere.

Discussion

One might be tempted to attribute the Poisson character of the "forward" cone multiplicity distribution to other causes than coherence, inherent to the primordial p-nucleon encounter in the nucleus. This, however, cannot explain the transparency of nuclear matter for that cone and the associated survival of poissonicity. This puzzle is resolved in a natural way by SIT. Thus nature provides us apparently with a filter which selects out in the forward hemisphere a pure coherent pulse. The fact that the multiplicity distribution is Poisson only in the forward direction combined with the observed transparency is strong evidence for coherence. In order to prove that this transparency is really self-induced as implied by the formalism derived in the first part of this paper, further tests are necessary. Thus e.g. at present we cannot rule out the possibility that the link between transparency and coherence is due to another type of cooperative phenomenon, namely superfluidity of hadronic matter[20]. This alternative could be naturally incorporated in Landau's hydrodynamical model and is at present under investigation.

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*Obviously, a superposition of a variable number of "Poisson-emitting" clusters could also lead to the observed non-Poisson shape in this rapidity region. But then, again, the transparency effect remains unexplained.

An implication of SIT is that, if fully developed, the transparency should be a periodic function of the field intensity reflecting the production of more than one soliton. High multiplicity events are expected to correspond to higher intensities and thus the transparency should change both with the increase of multiplicity at a given energy or with the increase of the beam energy, since the total multiplicity is an increasing function of energy. In optics this periodicity has been experimentally observed, although it is a small effect. Whether the analogous effect in high energy physics is observable is a challenging problem.

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Figure captions

Fig. 1 Proton-nucleus data at 200 GeV.

a) dependence of local mean multiplicity $\bar{n}_i$ on N_h.

b) local multiplicity distributions

for the case N_h = 2-8. Curves: Poisson distributions; straight lines: chaotic distributions.

Fig. 2 Plot of Δ (eq. 16) versus η for three ranges of N_h: a) N_h = 0 or 1, i.e. mostly p-p collisions; b) N_h = 2-8, i.e. mainly collisions with light (C, N, O) nuclei; c) $N_h \geqslant 9$, i.e. collisions with heavy (Ag, Br) nuclei.

Table caption

Values of χ^2 and number of degrees of freedom for various beam energies and N_h ranges. The maximum available rapidity Y_m at a given beam energy was divided into six equal bins. The rightmost three columns give for each bin the summed χ^2 values, degrees of freedom (DOF) and equivalent standard deviations (E.S.D.)

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Table 1

η \ N_h	69: 2-8	69: $\geqslant 9$	200: 0-1	200: 2-8	200: $\geqslant 9$	300: 2-8	300: $\geqslant 9$	$\Sigma\chi^2$	DOF	S.D.
$< \frac{Y_m}{6}$	20.4 5	36.8 8	46.6 5	33.3 6	108.6 10	12.6 6	74.9 10	333	50	13
$\frac{Y_m}{6} \ldots \frac{2Y_m}{6}$	42.3 7	119.2 10	86.8 7	127.3 8	153.0 12	73.4 8	114.3 12	716	64	>20
$\frac{2Y_m}{6} \ldots \frac{Y_m}{2}$	37.4 7	55.9 10	120.8 8	305.9 10	147.8 12	49.8 9	101.8 12	819	68	>20
$\frac{Y_m}{2} \ldots \frac{4Y_m}{6}$	17.3 7	23.3 8	104.7 9	187.6 9	91.4 11	27.8 8	74.7 11	234	45	10.5
$\frac{4Y_m}{6} \ldots \frac{5Y_m}{6}$	8.9 6	2.5 6	29.8 8	30.5 7	20.5 7	26.6 7	7.9 8	127	49	5.6
$> \frac{5Y_m}{6}$	5.4 5	4.0 4	6.6 6	15.3 6	12.7 5	1.9 5	1.1 4	47	35	1.38

Beam Energy (GeV)

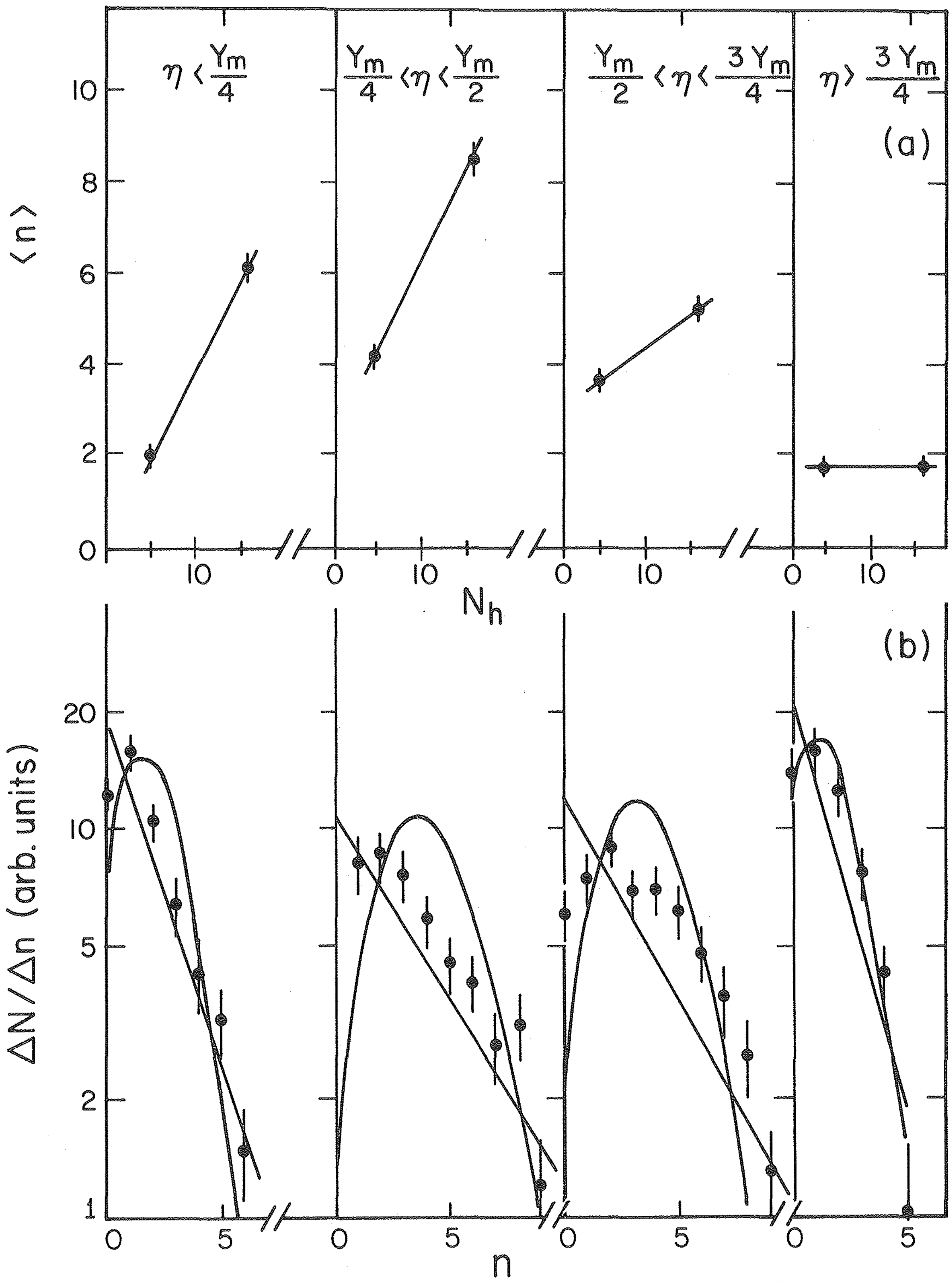

Fig. 1

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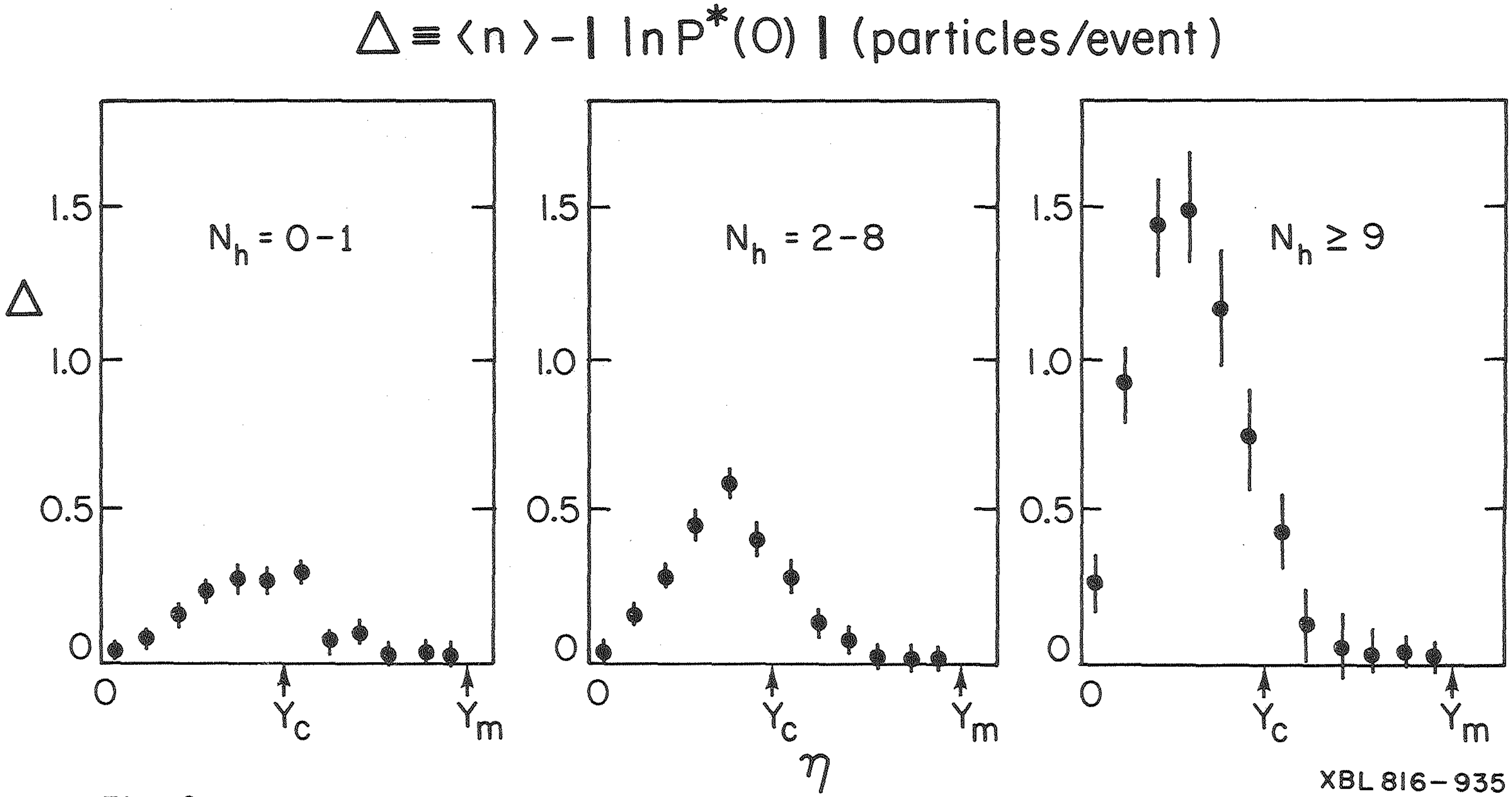
Δ ≡ ⟨n⟩ − | ln P*(0) | (particles/event)
Δ
N_h = 0-1
N_h = 2-8
N_h ≥ 9
1.5
1.0
0.5
0
Y_c
Y_m
η
XBL 816-935

Fig. 2