Production of Pions in a Coherent State in Heavy-Ion Collisions

G. N. Fowler[(a)] and R. M. Weiner
Physics Department, University of Marburg, D-3550 Marburg, Federal Republic of Germany
(Received 23 January 1985)

The coherence recently observed in heavy-ion collisions is attributed to the decay of a collective state of $\Delta + N$ baryons. A simple model for this phenomenon is formulated and several new experimental implications are discussed.

PACS numbers: 25.70.–z, 21.60.Ev

Recent observations by Zajc *et al.*[1] appear to confirm that the pions produced in heavy-ion collisions at $1.8A$ GeV are partially coherent, notwithstanding the uncertainties inherent in the measurement; this suggests that the coherence is due to a collective nuclear effect.[2] Indeed, even if meson production in nucleon-nucleon collisions is totally coherent, it is to be expected, as shown by Gyulassy, Kaufman, and Wilson,[3] that unless nuclear collective effects are present the interference of the many sources present in a heavy-ion collision would eliminate the coherence. In addition, according to the pion interferometric measurements reported by Crowe,[4] the radiating fireball is not spherical but elongated at right angles to the beam direction, and we shall see that this has implications for the directionality of the coherence. The purpose of this paper is to propose a model for this collective-coherent effect and to discuss some of its implications which can be subjected to experimental tests.

Cascade calculations by Cugnon, Kinet, and Vandermeulen[5] indicate that at $1.8A$ GeV most of the pions originate from Δ resonances and so it is natural to look for some collective effects in which Δ resonances play a leading part. A model involving coherent decay of Δ's based on an analogy with the laser has been proposed by Wakamatsu.[6] This requires that the collisional transformation of longitudinal kinetic energy into Δ resonances acts as the "laser pumping" mechanism and continues to operate until the nuclear fireball disintegrates. Aside from the fact, recognized also in Ref. 6, that this assumption might be too strong, there appears to be no experimental evidence for the degree of monochromaticity expected with this mechanism.[6] On account of the short Δ lifetime, other collective quantum optical mechanisms might also be difficult to sustain, unless one assumes the existence of, e.g., a Δ matter state.[7] This possibility, however, appears rather speculative too, and will not be discussed in the present paper.

Given the importance of the experimental observation of coherence it appears necessary to investigate the problem from other points of view. In particular, we consider the possibility that the collective behavior of the system originates in the Δ-Δ and N-Δ interactions. We shall discuss this further with the help of the two-state operators used by Wakamatsu, in a model inspired by the work of Lipkin, Meshkov, and Glick.[8] This model contains the essential features of nuclear matter at high densities which we are interested in, namely, the two states N and Δ and their interactions, treated schematically.

In more detail, we write for the Hamiltonian of the N fermion system

$$H=\tfrac{1}{2}\epsilon\sum_{p,\sigma}a^{\dagger}_{p,\sigma}a_{p,\sigma}+\tfrac{1}{2}V\sum_{p,p',\sigma}a^{\dagger}_{p,\sigma}a^{\dagger}_{p',\sigma}a_{p',-\sigma}a_{p,-\sigma}+\tfrac{1}{2}W\sum_{p,p',\sigma}a^{\dagger}_{p,\sigma}a^{\dagger}_{p',-\sigma}a_{p',\sigma}a_{p,-\sigma},$$

where $a^{\dagger}_{p,\sigma}$ creates a baryon in state p of the upper (Δ) level when $\sigma=+1$ or of the lower (N) level when $\sigma=-1$. The $p=1,2,\ldots,N$ label the degenerate states of each level; $\epsilon/2$ is the energy of the upper level and $-\epsilon/2$ the energy of the lower one, by appropriate choice of energy zero. As follows from the definition of H, V is a measure of the strength of the coupling in which a pair of baryons is scattered from the same state to the other, and W of the coupling in which one baryon is scattered from one state to the other while another baryon makes the inverse transition. The quantities ϵ, V, and W are parameters of the model. [It is perhaps of interest that the Lipkin-Meshkov-Glick model predicts[8] a phase transition for $(|V|-W)>\epsilon$ which, in our case, presumably corresponds to a baryonic state in which Δ's are a substantial component.]

We now introduce the quasispin operators

$$J_+=\sum_p a^{\dagger}_{p,+1}a_{p,-1},\quad J_-=\sum_p a^{\dagger}_{p,-1}a_{p,+1},$$
$$J_z=\tfrac{1}{2}\sum_{p,\sigma}a^{\dagger}_{p,\sigma}a_{p,\sigma},$$

which satisfy the usual angular momentum commutation relations, and write H as

$$H=\epsilon J_z+\tfrac{1}{2}V[J_+^2+J_-^2]+\tfrac{1}{2}W[J_+J_-+J_-J_+]. \tag{1}$$

It should be realized that the absence of the range of forces, characterized by the treatment of V and W as independent of space coordinates, is less important in the case of highly compressed nuclear matter, which we assume is produced in the heavy-ion collisions that we are concerned with. The absence[9] of saturation which is a characteristic of the Hamiltonian of Eq. (1) is therefore also not an important problem for us.

To simplify even further we take $V=0$, $W<0$ to illustrate the possibilities of the model. This corresponds to an attractive N-Δ exchange interaction as found by Arenhövel.[10] Then J^2 and J_z are diagonal with eigenvalues $J(J+1)$ and M and the eigenenergies are given by

$$E_{J,M}=\epsilon MJ-|W|[J(J+1)-M^2]. \tag{2}$$

At sufficiently high compressions (J large enough to satisfy $WJ/\epsilon >> 1$, $J\sim N/2$) states exist with $M << J$ which are the lowest-lying states and which one may therefore expect to be preferentially occupied. Such states correspond to coherent admixtures of N's and Δ's, in contrast to the state of normal nuclear matter which has $M=-J=-N/2$. The transition to such states in circumstances of high compression is analogous to the shape transition in the original Lipkin-Meshkov-Glick model except that in our case the model is more closely related to a real physical situation.

We now introduce the usual meson-baryon interaction term which in our variables may be written

$$H_{\text{int}}=g\phi_\pi^\dagger J^- +\text{H.c.}, \tag{3}$$

where ϕ_π is the (π) meson field, and consider more realistically the implications of the fact that the system will actually be unstable and decay through pion emission. In particular, the system resembles a many-particle resonance which decays via the interaction (3), and which we may describe as a "giant Δ resonance." (This is not quite analogous to the "giant monopole" also described by the Lipkin-Meshkov-Glick model when applied to low-energy nuclear physics. This is actually an excited state of the Lipkin-Meshkov-Glick Hamiltonian.)

Now we are in a position to discuss the first important experimental consequence of this model, namely, the coherence of the emitted (pion) radiation. Indeed, we observe that the decay matrix element is

$$\langle JM|J_-|J,M+1\rangle$$
$$=[(J-M)(J+M+1)]^{1/2}\sim N/2, \tag{4}$$

as in the original treatment of superradiance given by Dicke.[11] The source of pionic radiation is now a coherent state of N's and Δ's with sufficiently many Δ's for the system to behave as a classical "macroscopic dipole" source exactly as in the corresponding superradiant optical system,[12] and so we may expect the pionic emission to be coherent.

A second important experimental consequence of the above theoretical treatment is that the coherence should depend on the emission angle of the case that the emitting source is not spherically symmetric. This may be seen in the following way. In the first place, the decay of the corresponding states, if we ignore for the moment the W term in the Hamiltonian, may be expected to proceed exactly as in the corresponding optical case for which the intensity is given[13] (at least in lowest-order perturbation theory) by

$$I(\mathbf{k}')=I_0(\mathbf{k}')(N/4)\{1+N\langle\exp[i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{x}]\rangle^2\}, \tag{5}$$

where I_0 is the spontaneous intensity, the average is taken over the coordinates of the participating baryons, and $\mathbf{k}$ is in a fixed direction in the radiating system which defines the directionality of the radiation. This directionality arises through the effect of stimulated emission, which can be expected to be most effective along the direction in which most Δ's are encountered. Actually (5) represents an idealization of the experimental situation in that a single direction is selected which would be appropriate to a needlelike system, whereas we probably have to consider an oblate spheroid.[4] This means that the directionality will be significantly less pronounced than that given by (5).

Another effect which washes out directionality (and coherence) is the spontaneous decay of the Δ's which, however, we expect to be inhibited by the collective nature of the state.

Possible evidence for this enhancement of coherence along the long axis of the fireball has been reported in Ref. 4. The evidence is exhibited in Fig. 3 of that reference in which the "degree of incoherence" λ at 45° is smaller than that at 0°, although the fact that $\lambda_{0°}>1$ suggests that the experimental result must be treated with caution.

If the origin of coherence is indeed a $\Delta+N$ collective state, there should be no coherence below the Δ threshold. Interestingly enough, the measurements by Beavis *et al.*[14] at 1.2A GeV show that the pion source is completely incoherent.

The enhancement of coherence at right angles to the beam direction should be seen both in the Bose-Einstein correlations and in the multiplicity distribution of pions, which would be more of Poisson type than the events as a whole.

Finally, since the coherence arises from a collective effect we should expect it to be relatively greater for larger N normal to the beam direction.

This work was supported in part by the Deutsche Forschungsgemeinschaft and Bundesministerium für Forschung und Technologie.

[a]On leave from the University of Exeter, Exeter, United Kingdom.

[1]W. A. Zajc *et al.*, Phys. Rev. C **29**, 2173 (1984).

[2]G. N. Fowler and R. M. Weiner, in *Proceedings of the Seventh High-Energy Heavy-Ion Study, Darmstadt, West Germany, 1984,* edited by R. Bock, H. H. Gutbrod, and R. Stock (Gesellschaft für Schwerionenforschung, Darmstadt, 1985).

[3]M. Gyulassy, S. K. Kaufman, and L. W. Wilson, Phys. Rev. C **20**, 2267 (1979).

[4]K. Crowe, in Ref. 2.

[5]T. Cugnon, D. Kinet, and T. Vandermeulen, Nucl. Phys. **A379**, 553 (1982).

[6]M. Wakamatsu, Nuovo Cimento Soc. Ital. Fis. **56A**, 336 (1980).

[7]J. Boguta, Phys. Lett. **109B**, 251 (1982).

[8]H. J. Lipkin, N. Meshkov, and A. T. Glick, Nucl. Phys. **62**, 188 (1965).

[9]D. H. Feng and R. Gilmore, Nucl. Phys. **A301**, 189 (1978).

[10]H. Arenhövel, Nucl. Phys. **A247**, 473 (1975).

[11]R. Dicke, Phys. Rev. **93**, 99 (1954).

[12]R. Bonifacio, P. Schwendimann, and F. Haake, Phys. Rev. A **4**, 302, 854 (1971).

[13]F. T. Arecchi and E. Courtens, Phys. Rev. A **2**, 1730 (1970).

[14]D. Beavis *et al.*, in Ref. 2.