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Hadron Structure Explored in High-Energy Nuclear Reactions*

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Current data indicate that fast "excited hadrons," produced in high-energy collisions with nuclei, interact with the nuclear medium no more strongly than stable hadrons of the same internal quantum numbers. Considerations on the time development of excited hadron systems suggest that, in coherent nuclear production at *any* finite energy, the (indirectly) measured cross section of an excited hadron on a nucleon differs negligibly from its value immediately after production. Significant further information should be obtained from deep-inelastic lepton-nucleus collisions, but the results already found are most easily interpreted by supposing hadrons to be constructed from small or pointlike units, each of definite cross section, which do not have time to change in number during passage of a fast hadron through a nucleus.

I. INTRODUCTION

For a long time it has been known that a beam of rapidly moving elementary particles could be used to study nuclear structure. For almost as long, the idea of using particle-nucleus collisions to learn about some aspects of elementary-particle structure has attracted theoretical and experimental studies. Partly for practical reasons, such studies have usually exploited a static picture of the collision process. For example, a production reaction might be described by saying particle a enters the nucleus and travels some distance, while undergoing elastic collisions with one or more nucleons. Then, in a collision with a single nucleon, a is transmuted into a different particle b, which leaves the nucleus after several b-nucleon elastic interactions. The description is static in the sense that both a and b are treated as fixed entities – nothing changes except during the collision with one nucleon in which a becomes b. It is obvious that such a description cannot be entirely correct. The main interest in such experiments is to learn about the b-nucleon interaction when this cannot be studied directly because b is highly unstable. An unstable b could disintegrate even before leaving the nucleus, in which case the "b-nucleon interaction" inferred from the data would really be a composite of effects due to b and due to its decay products. If b were a resonance of known lifetime, one could apply the conventional picture in which the probability of decay is given by an exponential law in the rest frame of b. This in turn implies exponential decay as a function of distance from the production point. For typical cases of production in nuclei, the energy is sufficiently high so that b usually escapes the nucleus before decaying, and the corrections to the static picture are negligible.[1]

But what if the state b is not a resonance, or, at least, not known to be a resonance? In that case much less is known or accepted about the dependence of the structure of b on distance from the production point. In this paper we shall study available data and argue, in the case of coherent production, that the static picture is still good. Section II contains a summary of current experimental information, indicating a remarkable weakness of interaction between excited hadron systems and the nuclear medium. Section III, the main part of the paper, contains arguments about the proper interpretation of the data. The arguments are based on the assumption that the "on-mass-shell" relation, between time in the rest frame of an excited hadron and distance of travel in the laboratory, is at least approximately valid (an assumption supported by arguments in the Appendix). This assumption implies that, in coherent production reactions, the produced system does not have time to change appreciably before leaving the production region. Consequently, we learn from coherent nuclear production how the produced system interacts with the nuclear medium immediately after production has occurred. This interaction turns out to be the same as that of a stable hadron with the same internal quantum numbers – a result easily explained if the production process is merely the rearrangement of a wave function of small, hard hadronic constituents. Only much later, after leaving the nucleus, does some slower process cause the appearance of several hadrons in the final state. Finally in Sec. IV appear conclusions, along with a vigorous plea for deep-inelastic lepton-nucleus scattering experiments, which could reveal the time scale of the slower processes, unobservable in coherent production reactions.

II. EXPERIMENTAL CLUES

A remarkable pattern is beginning to emerge from the modest, but steadily growing, store of information on multi-GeV hadron-nucleus interactions. It appears that a fast hadronic system produced in a nucleus interacts with the same strength as the initial fast hadron (e.g., proton or pion) which was excited to produce this system. The evidence is the following.

(1) 3π coherent production in nuclei may be analyzed in a high-energy optical model under the assumption that the transition $\pi\to 3\pi$ occurred in a single step – that is, in interaction with a single nucleon. Then the only unknown parameters are associated with the interaction of the outgoing 3π system; specifically they are the real and imaginary parts of the 3π-nucleon forward scattering amplitude. Analysis of a 16-GeV experiment in a Freon bubble chamber[2] indicated that the 3π-nucleon total cross section was less than or about equal to the π-nucleon total cross section:

$$\sigma_{(3\pi)N} \lesssim \sigma_{\pi N}\ . \tag{1}$$

This result has been confirmed by a far more extensive and systematic study of 3π production with various nuclear targets, using counters.[3] There are similar data for the reaction $K\to K\pi\pi$ in neon,[4] which give

$$\sigma_{(K\pi\pi)N} \approx \sigma_{KN}\ . \tag{2}$$

Proton reactions at 28 GeV with a neon target, in the channel $p\to p\pi\pi$, are insufficient statistically to draw any firm conclusion. One has only[5]

$$\sigma_{pN} \lesssim \sigma_{(p\pi\pi)N} \lesssim 1.8\sigma_{pN}\ . \tag{3}$$

In Ref. 2, it was suggested that these data pose a problem from the following point of view. To take the 3π case in particular, the produced system is largely $\rho\pi$. If the ρ and π are present already at the point of production, and interact weakly with each other, one would expect the optical density of the $\rho\pi$ system, as seen by a nucleon, to be simply the sum of the corresponding densities for π and for ρ. Since pions are fairly transparent, and ρ's are presumably similar, as confirmed by data on ρ photoproduction in nuclei, addition of optical densities implies almost addition of cross sections. The estimate in Ref. 2 was

$$\sigma^{\text{est}}_{(\rho\pi)N} \gtrsim 1.7\sigma_{\pi N} \tag{4}$$

or only a fifteen percent "shadowing" correction to the first guess that the cross sections add. Clearly this $\rho+\pi$ composite assumption contradicts the results of experiment plus optical model quoted above.

(2) Because the $\rho\pi$ system (as well as its $K\pi\pi$ and $p\pi\pi$ analogs) is the most prominent inelastic "excitation" of the π at 16 GeV, it is implausible to explain the high coherent production as a result of "multistep" processes with other intermediate excited states.[6] However, such processes may help to account for data on 5π production[7] which indicate

$$\sigma_{(5\pi)N} \approx \tfrac{1}{2}\sigma_{\pi N}\ . \tag{5}$$

This indication is not yet very strong in view of the experimental uncertainties, but even if it should be confirmed by a more accurate experiment, the possibility remains of significant $\pi\to 3\pi \to 5\pi$ contributions. Nevertheless, even the present crude data make it seem unlikely that the 5π system has a nucleon interaction cross section significantly greater than a single π. Thus, two or even four extra π's (perhaps grouped in one or two resonant clusters) are produced without substantial increase in interaction cross section.

(3) Emulsion observations on 1-TeV cosmic-ray protons interacting with heavy nuclei indicate produced pion multiplicity no more than twice that with an H_2 target.[8] This is the result one would expect for a single proton interacting 1 or 2 times, assuming that the pions produced in the early collisions did not interact at all with nucleons.

The same cosmic-ray data also indicate an approximate forward-backward symmetry of produced particles in the center-of-mass frame, defined by taking the target as a single nucleon. If produced particles suffered secondary interactions, one would expect a strong asymmetry, in the direction of the target particle.

III. THEORETICAL GUESSES

The simplest way to explain the results described above (at least those on coherent production reactions) would be to say that the excited hadron system is a resonance with a cross section on nucleons similar to that of the incident hadron, and that only after leaving the nucleus does the resonance decay, revealing many extra pions. While this explanation cannot be excluded, there are well-known difficulties already for the "A_1"$\rho\pi$ system.[2,9,10] The difficulties are, if anything, greater for arbitrarily-high-multiplicity states produced in very high-energy collisions.

Let us therefore turn to a more detailed study of coherent production reactions, to see what the data imply if the resonance hypothesis does not hold. Coherent production emphasizes so-called "diffractive" processes which conserve internal quantum numbers such as isospin, and also are independent of the spin of the nucleon target. We must begin with a brief excursion into the theory of diffraction production.

To give a framework for discussing diffraction production at laboratory and cosmic-ray energies, let us consider the infinite-energy limit. We follow an analogy with the results obtained for electrodynamics by Cheng and Wu and others.[11] These authors found a simple interpretation for the dominant contribution to pair production by an infinite-energy photon colliding with an electron. The incident photon state has as its principal component a "bare" photon which does not interact appreciably with the target electron. However, there is a small (order $e=\sqrt{\alpha}$) component consisting of a virtual (zero-mass) electron-positron pair. The pair production process is seen as a "materialization" of this small component, following scattering of either member of the pair by the static field of the target electron. This picture of diffraction production is not new to theories of hadronic processes. Feinberg and Pomeranchuk and Good and Walker[12] introduced long ago a very similar notion, that a fast hadron state may be taken as a superposition of "bare" states, which are not mixed but only suffer elastic scattering, or are absorbed, on encounter with a target nucleon. The "diffractive" inelastic scattering of a physical hadron would then be due to differences in the elastic scattering amplitudes f_m for the bare states, which would change their relative coefficients in the final state,

$$|h_{\text{initial}}\rangle = \sum_m a_m |h_m^{\text{bare}}\rangle \ , \tag{6}$$

$$|h_{\text{scatt}}\rangle = \sum_m a_m f_m |h_m^{\text{bare}}\rangle \ . \tag{7}$$

Here, $|h_{\text{scatt}}\rangle$ is a multiple of $|h_{\text{initial}}\rangle$ only if all f_m are the same. An example at the border between electrodynamics and hadron physics is photoproduction of vector mesons. At high energies, this process is probably due entirely to the almost elastic scattering of a small (order e) virtual-vector-meson component of the incident photon state.[13]

In pair production, and especially in vector-meson photoproduction, the scattering cross section on a hadron target of the small virtual component is very different from that of the dominant bare-photon component. If we assume that an analogous scattering of bare-hadron components occurs in high-energy hadron-hadron collisions, we might expect that these components would differ significantly among themselves in strength of interaction with the target hadron. In this case, the produced particles in, say, pion-induced reactions would have different elastic scattering cross sections from that of the pion. In the reaction

$$\pi \to A_1 \to \rho\pi$$

one might be guided by perturbation theory to expect that the A_1 is a small virtual $\rho\pi$ component of the pion, with a cross section on hadrons equal to that of a $\rho\pi$ system, i.e., roughly twice the pion cross section. The optical model analysis of meson production in nuclei rules out such a possibility, for the A_1, and even for 5π systems. Thus, if that analysis is qualitatively correct, and if finite-energy effects do not alter the conclusion for the infinite-energy limit, we are forced to a different conclusion: Inelastic production, if described by Eq. (7), occurs by small cross section differences between several large bare componen of the incident hadron state, rather than large cross-section differences of small bare components.

We shall not explore here the question of the reliability of the high-energy optical model for coherent nuclear reactions. Both theoretical and experimental works, especially on vector-meson photoproduction, serve to confirm the model.[14] However, the subject of finite-energy corrections to the infinite-energy limit does merit discussion here. The result is remarkable: In coherent production of hadron states on nuclei, the outgoing hadron-nucleon cross section cannot change appreciably from its value at the point of production. This is true even for the largest nuclei, and holds even if the outgoing hadron is not a resonant system. Thus, coherent production at finite energies gives direct information about the bare-hadron components of the infinite-energy limit, provided the production on a single nucleon is independent of energy.

Let us examine an elementary, naive argument for this conclusion, and later (in the Appendix) see what further evidence can be marshaled in support. The incident hadron $|i\rangle$ collides with a nucleon at some point in the nucleus and is transmuted into the "final" hadron state $|f\rangle$. Passage of time τ in the rest frame of $|f\rangle$ is related to distance D from the production point by

$$\begin{aligned} D &= c\gamma_f \beta_f \tau \\ &= p_f \tau / M_f \ , \end{aligned} \tag{8}$$

where p_f is the momentum ($p_f \approx p_i$) and M_f the mass of the final system. If the interaction causing $i \to f$ is local, i.e., if the production amplitude is a superposition of amplitudes for interaction at points in particle i, then the cross section of particle f can increase from its initial value no faster than the cross section of a black sphere expanding from the interaction point at the speed of light,

$$\begin{aligned} &\Delta\sigma(\tau) \leq 2\pi c^2 \tau^2 , \\ &\Delta\sigma(D) \leq 2\pi c^2 D^2 M_f{}^2/p_f{}^2 . \end{aligned} \tag{9}$$

The fact that the production reaction is coherent implies that it will be suppressed if the region of production is longer in the beam direction than

$$L = \pi\hbar/q , \tag{10}$$

with

$$q = p_i - p_f \approx (M_f{}^2 - M_i{}^2)c^2/2p_f . \tag{11}$$

The typical value of D will be $\lesssim \frac{1}{4}L$, giving

$$\begin{aligned} &\langle\Delta\sigma\rangle_{\text{av}} \lesssim 2\pi x^2 , \\ &x = \pi\hbar M_f/2c(M_f{}^2 - M_i{}^2) . \end{aligned} \tag{12}$$

For the typical case of the A_1, we have

$$x \approx \pi\hbar/2M_f c \approx 0.3 \text{ F} \tag{13}$$

and

$$\langle\Delta\sigma\rangle_{\text{av}} \lesssim 6 \text{ mb} , \tag{14}$$

which is hardly detectable. We conclude that in coherent production the coherence restriction implies an energy-independent restriction on the amount of rest-frame time which the produced hadron can spend in the production region, and consequently, the cross section $\sigma(f\text{-nucleon})$ cannot change appreciably from its initial value before particle f leaves the nucleus. Thus, only a cross-section difference $(\sigma_{fN} - \sigma_{iN})$ already present at the production point can significantly influence the coherent production rate. The result mentioned earlier, that all infinite-energy components of the pion have similar interaction strength with nucleons, is valid even though based on finite-energy data. The only extra assumption here is that the elementary production process does not change appreciably with energy, once past the kinematic threshold for a particular final state. This is a natural assumption for diffraction production, if elastic and total cross sections approach constant values at infinite energy.

The critical assumption relating rest-frame time and laboratory distance has not been proven, but supporting arguments based on models are given in the Appendix.

So far we have been concerned with analysis of experiments in the range of tens of GeV. If we consider the less precise information from higher energies, there is no contradiction, but conclusions are less clear-cut. The bulk of particles going backwards in the c.m. frame after a nucleon-nucleon collision have fairly low energy in the laboratory. This backward cluster would usually produce few, if any, secondary particles while traveling through the nucleus, for kinematic reasons. Thus, the results mentioned before, on 1-TeV nucleon-nucleus collisions, suggest that the forward cluster remains a single unit, interacting like a nucleon, until after exit from the nucleus – a picture consistent with that from coherent production at lower energies. This is an inference very much in the spirit of "fragmentation"[15] models of hadron collisions, provided the fragmentation occurs slowly after the initial impact. Since the forward clusters have Lorentz factors $\gamma > 20$ with respect to the laboratory frame, it is not surprising if they hold together while passing through the nucleus. The cosmic-ray results follow logically from the coherent production results if one assumes that the mechanism of excitation of a projectile hadron is independent (or nearly so) of the final state (excited or not excited) of the target nucleon. In coherent production the target nucleon is not excited, while in the cosmic-ray data the target nucleon is nearly always excited (that is, a backward c.m. cluster is seen).

Even these conclusions must be treated with caution. Fishbane *et al.*[8] assert that similar results would hold for such cosmic-ray data even if the incident hadron broke up inside the nucleus, emitting several pions which interacted separately with the nuclear medium on their way out. One can be skeptical about this assertion, but it indicates the difficulty of drawing strong conclusions before abundant and precise very-high-energy data become available.

IV. PROPOSALS AND CONCLUSIONS

Having argued that a fast hadron does not have time to alter its structure during passage through a nucleus, we are naturally led to ask if there exist circumstances in which such changes could be observed. The natural place to look is deep-inelastic lepton-nucleus scattering. When very high momentum and energy are transferred by electromagnetic or weak interactions, we may assume that only one nucleon in the nucleus receives this impulse. By varying the amount of impulse and the size of the nuclear target, we may "scan" a range of rest frame time τ, and see, if this variable has the significance argued earlier, how the struck nucleon changes with τ. To understand this, let us first take the simple hypothesis that the nucleon immediately recoils as a unit whose mass is given by the kinematics. In this case, the Lorentz factor of our struck nucleon is

$$\gamma = \zeta \frac{1+\zeta^{-2}}{(2(1-\omega)+\zeta^{-2})^{1/2}} \ ,$$

$$\zeta = (\nu/M_N)^{1/2} \ , \qquad (15)$$

$$\omega = q^2/2M\nu \ ,$$

where ν and q^2 are the usual energy transfer and invariant squared 4-momentum transfer variables describing the virtual photon. Values of γ at least up to $\gamma = 3$ should be obtainable with appreciable intensity. For such cases the excited nucleon should move $1\frac{1}{2}$ to 3 F before changing size appreciably. Therefore, the multiplicity of pions produced with a small nuclear target will be the same as in hydrogen, except that some additional pions would be produced when the excited nucleon struck a nucleon in the nucleus, just as if an unexcited nucleon of the same γ had followed the trajectory of the excited nucleon. Thus we obtain the multiplicity estimate for deep-inelastic scattering

$$n_\pi^{(1)}(A) \approx n_\pi(\mathrm{H}_2 \text{ target}) + \tfrac{1}{2} n_\pi(p+A \text{ collision}) \ . \qquad (16.1)$$

The $\frac{1}{2}$ arises because, on the average, the excited nucleon will travel only half as far through the nucleus as would an incident proton, which must traverse the whole nucleus.

For an alternative guess we may suppose, as suggested in the "pulverization" picture,[16] that some fraction of the struck nucleon is immediately expelled by the virtual photon, with a slow residue following later. The pulverized part might escape the nucleus before exhibiting any appreciable interaction strength. In this case, if the slow residue had insufficient energy to create π's while passing through the nucleus, we would have

$$n_\pi^{(2)}(A) = n_\pi(\mathrm{H}_2 \text{ target}). \qquad (16.2)$$

Finally, one might suppose that the struck nucleon takes some time to absorb the photon impulse, and during this time many pions are "shaken off" before the nucleon begins to move. These pions could each produce secondary pions in the nucleus, contributing to a very large multiplicity

$$n_\pi^{(3)}(A) \gg n_\pi^{(1)}(A) \ . \qquad (16.3)$$

In both the second and third cases, one could expect a much larger number of low-energy nucleons to be expelled than in the first case.

It is obvious that we have no firm prediction about the results of such deep-inelastic nuclear excitation experiments, except that they should give significant insight into the short distance and time dependence of the response of a nucleon to a sharp impulse. This would yield a powerful constraint on speculation about hadron structure.

Experiments which would be easier to do but harder to analyze would replace the leptons discussed earlier by hadron projectiles. The trouble here is that a given experimental outcome could occur in many different ways because hadron beams can interact many times inside the nucleus. However, if the incident hadron can remain intact during nuclear passage, even after receiving a very large momentum transfer, this technique might be workable. At present, there is no clear sign whether this is so. The lepton experiments would give such information; hence they should come first.

The results on coherent production and cosmic rays do suggest the answer to one interesting question, the size of "diffractive inelastic shadowing" contributions to the elastic scattering of hadrons on nuclei. The idea here is that an incoming hadron may be excited on colliding with one nucleon and then de-excited by a second nucleon, emerging from the nucleus to contribute to the elastic scattering channel.[17] An indication that this occurs to some extent is found in the energy dependence of neutron-nucleus total cross sections between 8 and 21 GeV. For *all* targets, the cross sections decrease by (3 ± 1)% as the energy increases through this range.[18] In the approximation neglecting inelastic shadowing, one would expect the cross section of a Pb target to decrease less than that of hydrogen, because the Pb cross section is mainly determined by the geometrical area "blacked out" by the nucleus. Quantitative estimates[19] indicate the decrease should be about one-third as great for Pb as for H_2, which means the effective nucleon-nucleon cross section in Pb was decreased by (9 ± 3)%, the extra (6 ± 4)% coming presumably from inelastic shadowing.

The analysis of this paper, which suggests that "bare" diffractive eigenstates all have similar cross sections to the corresponding stable hadrons, implies that the diffractive shadowing will not increase in significance at higher energies. While it is true that more excited states become energetically accessible at higher energies, the total probability of exciting any of these states must level off if total hadron-hadron cross sections approach constant values. Experiments to test this assertion would be quite attractive possibilities at the highest-energy proton accelerators. As mentioned earlier,[20] if inelastic shadowing is sizable at high energies, this implies the existence of diffractive eigenstates with very low cross section, and the unstable states corresponding to such an eigenstate will be coherently produced with cross sections much larger than those observed to date. This seems unlikely.

Note added in proof. L. Van Hove [Nucl. Phys. B46, 75 (1972)] has proposed an elegant mathematical model for propagation of excited hadrons through nuclear matter. The excited system is labeled by a single continuous variable, its mass, and the refractive index of the nuclear medium is taken to be an operator which does not include a mass-conserving δ function. This model immediately leads to the existence of diffractive eigenstates with very low absorption in nuclear matter. From the viewpoint of the present paper, Van Hove's model is more radical than required by available data. However, it does raise a challenge which has not yet been met [J. S. Bell (unpublished); K. Gottfried, Acta Phys. Polon. (to be published)], to construct a detailed dynamical model in which states with very low absorption appear. In this connection, it is worth noting that a naive quark model could accommodate excited-pion cross sections on nucleons as low as half the pion-nucleon cross section. The assumptions required are that quarks are small dark objects, and that they are much closer together (in position) in the excited pion than in the stable pion.

We conclude with a summary of results and speculations.

(1) Coherent production reactions permit measurement of unstable hadron-nucleon cross sections immediately after production of the unstable hadron system.

(2) These cross sections are approximately the same as those of stable hadrons of the same internal quantum numbers.

(3) Cosmic-ray data at 1 TeV indicate that results (1) and (2) apply also to the hadronic system eventually observed as a collection of particles going forward in the nucleon-nucleon c.m. frame.

(4) To study the time dependence of excited hadron structure, it is necessary to use incoherent reactions. The most useful and interesting of these are deep-inelastic lepton-nucleus collisions, where attention must be paid to pion and low-energy nucleon multiplicities.

(5) Higher-energy coherent production and total hadron-nucleus cross section measurements should confirm the result (2), both directly and by placing limits on inelastic shadowing.

Data from nuclear targets help to confirm the view that, during short times, hadrons react to external impulses like assemblies of small, hard objects. New experiments with nuclei may show in detail how the hadrons "relax" on a longer time scale.

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APPENDIX

Here are some examples and arguments to confirm the applicability to coherent production of Eq. (8), relating time in the rest frame of an excited system to distance in the laboratory. Of course, argument by example is not rigorous, and relevant counterexamples may exist.

Example 1. Consider an atom traveling at relativistic velocity through a gas of atoms. Neglect the strong interactions. The atom will not ionize the gas appreciably because it is electrically neutral. Now suppose the atom passes very close by a gas atom nucleus, and a large momentum is imparted to an electron in the moving atom. If the transferred momentum has a component perpendicular to the direction of motion, the electron path will diverge from the path of the remaining ion by an angle

$$\theta \approx \Delta p_\perp/(\gamma\beta m_e) \,, \tag{A1}$$

where γ and β are the usual Lorentz factors corresponding to the transition from the laboratory frame to the moving atom frame and $\Delta p/m_e$ is assumed small. Of course, the ionizing power of the ion-electron (excited atom) system will go up as the separation increases, reaching a plateau when the two paths are separated by a few times the mean interval between gas atoms. In this approximation, the masses of the excited atom and the incident atom are the same, and the result, Eq. (A1), for θ can also be obtained by computing the transverse distance traveled by the electron in the atom rest frame as a function of rest frame time τ.

Even when these convenient smallness approximations are not made, the excited-atom rest frame is still the appropriate one in which to compute transverse separations of ion and electron, hence ionization strength, i.e., strength of interaction with the medium.

Naturally, there can also be appreciable momentum transfer to the electron along the line of atom motion, but as long as ion and electron are both traveling in the laboratory at essentially the speed of light in the same direction, there will be no longitudinal separation of charge, so that the transverse separation is the only significant effect unless θ is large enough to make $\cos\theta$ significantly different from unity. It is easily seen that the relation

$$\theta \lesssim 1/\gamma^* \tag{A2}$$

holds, where γ^* is the Lorentz factor from lab to excited atom rest frame. This means that longitudinal separation is negligible compared to transverse as long as the excited atom is also moving at highly relativistic speed.

Example 2. Still in the framework of electrodynamics, we may consider a case which looks very different from the first one, but is really quite similar. This time, the incident neutral system is a photon, which creates a pair of oppositely charged spinless particles in the field of an extended static source. We work to the lowest nontrivial order of perturbation theory in which the pair can interact with the source once more after production. We must sum all Feynman graphs involving two virtual photons emitted by the source and absorbed by one or the other scalar particle in the pair.

For fixed final pair mass, the amplitude may be expanded in inverse powers of the (high) incident photon energy. The first term in this expansion is obtained simply by "linearizing" the scalar-particle propagators

$$\frac{1}{(p+k)^2-m^2} \to \frac{1}{2p\cdot k}\ , \tag{A3}$$

where p is the final scalar-particle momentum, and k is a virtual-photon momentum. The momentum p is taken to lie along the initial photon direction. This procedure is well known, and has been applied to give high-energy limits of infinite sums of ladder and crossed ladder diagrams, for such problems as pair production in photon-electron collisions.

However, at least to the low order discussed above, the next correction in powers of $1/E_{\text{photon}}$ is easily found. If the mass M of the pair is much greater than the mass of a scalar particle, but much less than the energy E_{photon}, then the scalar particles may make (equal and opposite) angles to the incident photon direction so that the opening angle of the pair is

$$\theta_P \leq 2M/E_{\text{photon}}\ . \tag{A4}$$

Again, as in Example 1, the resulting $1/E$ correction, obtained by putting the correct p's in the linearized propagators, is an amplitude in which the second interaction of the pair is bigger, the later it occurs: The two charges separate by a distance $\theta_P D$, where D is the distance along the photon direction from the point where the pair was created to the point of the second interaction.

The amplitude for the second interaction is proportional to $V(\vec{x}_+) - V(\vec{x}_-)$, where V is the electric potential of the external source, and $\vec{x}_+$ ($\vec{x}_-$) is the position of the positive (negative) scalar particle. Clearly, the more widely they separate, the stronger the interaction.

In perfect agreement with the results for Example 1, we have found that the strength of secondary interactions of the excited neutral system depends on how much rest frame time has passed. This is no accident because the QED problem we have treated has no intrinsic length scale, except the very short photon wavelength. For macroscopic distances the result must agree with classical physics, the content of which is seen in Example 1. Since there is no length scale, the result must hold even for submacroscopic distances, and it does (the macroscopic phenomenon, of gradually increasing ionization by an initially invisible high-energy electron pair, is known as the Chudakov effect).

After these definite, but restricted examples, let us turn to a more qualitative argument. Since the nucleus receives such small momentum transfer in coherent production, it is reasonable to consider it as a static absorptive potential acting on the incident hadron. If we view this potential in the rest frame of the projectile, the "static" nucleus is seen as a spheroid moving near the speed of light, Lorentz contracted in its direction of motion. During collision, the whole flattened nucleus passes quickly through any point in the hadron in a time

$$\tau_i = (M_i/p)D_0\ , \tag{A5}$$

where D_0 is the thickness of the nucleus in the laboratory frame. In order to interact with the nucleus for a time longer than τ_i, a piece of the hadron must accelerate in the direction of the nuclear motion. The results in the text are based on the simplification that each part of the hadron is accelerated by the same amount, as it is passed by a particular nucleon in the nucleus. It is certainly more plausible to suppose, as in our electrodynamics examples, that different parts are accelerated by larger or smaller amounts – perhaps only one small constituent is accelerated.

In this case, that small constituent could be accelerated more than in the simple version. However, if it contains a finite fraction of the mass of the hadron, it will not begin moving fast enough to stay with the nucleus, but will have a finite Lorentz factor with respect to the final excited hadron rest frame. At infinite energy, the nucleus becomes infinitely thin in the initial *or* final hadron frames, or, equally, in the frame of the hypothesized accelerated constituent. Therefore there is no time in any of these frames for changes in interaction strength to occur. At finite energies, the single accelerated component could have substantially more time than estimated in the text to change its interaction strength. However, if the QED example is any guide, it is not the acceleration, but the previous virtual momentum of the component, which decides its motion after the initial collision. Only in a small fraction of cases will the virtual momentum be so nicely aligned with the nuclear direction as to make the component "stick" with the nucleus. Thus, the production mechanism would have to be very special in order to give appreciable violations of Eq. (8).

Finally, we may argue *ex post facto* that, if absorption of final and initial hadron states is the same, then the production process is plausibly interpreted as a rearrangement of definite constituents. This case is so similar to that of the atom discussed earlier that "atomomorphic" arguments are very likely right.

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