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THE POSSIBILITY OF QUARK PRODUCTION BY MULTISTAGE EXCITATION IN COLLISIONS BETWEEN HEAVY NUCLEI

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ABSTRACT

It is suggested that the possibility should be studied of producing high mass particle states by multiple interactions within two colliding heavy nuclei. In particular a nucleon or meson might be excited, in two or more stages, into its component quarks. Some rough estimates based on an empirical extrapolation of existing cross-section data appear sufficiently encouraging to justify further work based on more realistic models.

(This preliminary report contains only a brief outline of the ideas involved, prepared for informal presentation at a joint RHEL/DNPL meeting on accelerator applications.)

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1. BASIC IDEAS

In discussing possible future particle accelerator facilities, it is of interest to enquire whether collisions between heavy nuclei might be used to produce high energy events with a centre of mass energy greater than the maximum available in a normal two nucleon collision.

Perhaps the simplest possibility of this type is that a given nucleon in the target nucleus might be hit in rapid succession by two or more nucleons in the incident nucleus. There would then appear to be a finite probability of some of the nucleons being excited, in two or more stages, to very high mass states. In particular a nucleon might in this way be split into its component quarks.

As an example of the kind of energy gain which might be achieved, consider the case of particle beams produced by a 300 GeV synchrotron. The normal proton beam incident on a stationary target would give a maximum centre of mass energy of about 24 GeV. In the same accelerator, fully stripped heavy nuclei could be accelerated to about 120 GeV per nucleon, corresponding to a centre of mass energy of about 15 GeV. Consider now a target nucleon (in, for example, a uranium target nucleus) which experiences two successive inelastic collisions: suppose the first collision forms an excited state of mass, say, 12 GeV which lives long enough to be slowed down by transferring its momentum to neighbouring nucleons; it then presents a target of mass $\sim$ 12 GeV, so that the available centre of mass energy for the second collision is over 50 GeV.

Thus in this example, even assuming only two successive excitations, the maximum effective energy is twice as great as that available with 300 GeV protons.

Thus in searching for new high energy phenomenon such as quark production, heavy nucleus collisions might be an alternative to the ISR technique for increasing centre of mass energy, particularly since a suitable heavy ion injector might be provided at a substantially lower cost than a corresponding storage ring facility.

2. ASSUMPTIONS

In order to make preliminary attempts at numerical estimates we fix our attention on the specific process of quark production. Although the various quark models themselves make no specific prediction of the quark mass, there is at least some, admittedly speculative, theoretical indication that new types of particle phenomena could exist at a mass level of order $m_\mu^2/m_e \sim 22$ GeV; if we suppose this to be the quark mass we would then expect that an excitation energy of 45-50 GeV would be required to split nucleons or mesons into quarks. This figure will be used for illustration purposes in subsequent calculations, although the principles involved do not in fact depend in any way on the particular mass assumed.

We now wish to compare the possible quark production rate in heavy nucleus collisions, with the corresponding rate in a normal two-nucleon collision, (assuming sufficient energy available in each case). We can proceed in two distinct ways:

(a) Ignore the internal quark structure of the nucleons, assume they interact as a whole, and use existing data on production cross sections for 1-2 GeV mass states to extrapolate to higher energies.

(b) Recognise the internal quark structure, and treat inelastic nucleon-nucleon collisions as elastic collisions between their component quarks.

The latter is probably the only realistic way to proceed, as discussed in section 7, and this will be the direction for subsequent work. It is of interest, however, to see what indications are given by approach (a), and these will now be discussed.

3. CROSS SECTION ESTIMATES

The number of excited states increases rapidly with energy, the mass spectrum becoming effectively a smooth continuum above a few GeV. We can therefore consider the particle production cross section to be a continuous function of mass. Suppose the cross section for the production of a state between mass m and m + δm is $\frac{d\sigma(m)}{dm}\,\delta m$ then the cross section for the production of state with mass greater than some value m is $\sigma(m)$. Since the total cross section is approximately independent of energy ($\sim$ 40 mb), we may write $\sigma(m)$ as $\sim$ 40 mb x $P_e(m)$ where $0 < P_e(m) < 1$.

For heavy nucleus collisions we assume a nucleon density $\sim (2.10^{-13}\ \mathrm{cm})^{-3}$ within the nucleus, with all nucleons assumed to act independently and incoherently. At this density every nucleon has a probability of order unity of experiencing two or more inelastic collisions of some kind. The approximate production rate for creating a state of mass m_f in two stages is thus the product NA (number of accelerated nuclei per second x atomic number), for which we can assume 10^{11} - 10^{12}/sec to be technically feasible, multiplied by the separate probabilities for excitation to intermediate mass m_i, slowing down in distance x without decaying, and further excitation to mass m_f; and finally integrating over the intermediate variables m_i and x :–

$$R \simeq (10^{11} \text{ to } 10^{12}) \int_x \int_{m_i} \frac{dP_e(m_i)}{dm_i} P_e(m_f - m_i) \frac{dP_s(x)}{dx} P_d(x)\, dm_i\, dx \qquad (1)$$

where $\frac{dP_s(x)}{dx}$ is the probability of 'slowing down' (i.e. losing more than say 70-80% of its momentum) in a distance x.

$P_d(x)$ is the probability of the intermediate state surviving a distance x without decaying. Thus, for a resonance of width w(MeV):-

$$P_d(x) \simeq \exp\left[-(w/100\,\mathrm{MeV})(x/2.10^{-13}\,\mathrm{cm})\right] \qquad (2)$$

and we have also assumed the same function $P_e(m)$ to be valid for the further excitation of an excited state, provided m represents the mass <u>increase</u>.

For rough estimates it will be sufficient to use the following approximation to expression (1):

$$R \sim [10^{11} \text{ to } 10^{12}]\,[P_e(m_f/2)\, P_e(m_f/2)]\,[P_s(x)\, P_d(x)]_{AV.} \qquad (3)$$

We now wish to know the form of $P_e(m)$. Using the CERN data compilations (CERN/HERA 70-2 to 70-7) for the processes pp → excited nucleon states, also πp, Kp → excited meson states, we sum the various partial cross sections for which the final state contains a particle of given mass m, assisted by the

further assumption that (above threshold) the cross section for the production of a given particle is approximately independent of energy. Most of the data is for the production of particles up to mass 2 GeV, and at this level the discrete nature of the spectrum, together with the incompleteness of the data, makes it difficult to plot a continuous function. However, by grouping together the states in mass intervals of 500 MeV we arrive at the trend shown in fig. 1; from this it is seen that if the differential cross section is plotted against the difference Δm between the excited and ground state masses, then the trend is roughly the same for pp, πp and Kp processes.

Allowing for the increasing sparseness of the data with increasing mass, which may misleadingly steepen the downward slope of the curve, the trend is not inconsistent with a power law decrease, of perhaps $(\Delta M)^{-3}$ - although it must also be admitted that an exponential decrease is not ruled out. We can thus provisionally adopt the expression

$$P(m) \equiv P(\Delta m) \sim 1/(\Delta m)^2 \qquad (4)$$

(which correctly becomes ~ 1 for the lowest possible mass increment ~ 0.3 GeV)

Note that this probability includes all events for which the increase in mass <u>exceeds</u> Δm.

We have also studied the estimates made by Hagedorn (e.g. Nuovo Cimento LVIA, 1968, 1027-1056; CERN Th/851, 1967; Nuovo Cimento Supplement Vol VI, 1968, p 311-354, etc.) These assume that all possible particles are formed statistically from the ball of hadronic matter produced by a high energy collision; the number of available states is then predicted to grow as $(m^{-5/2})\exp(+\, m/0.16\ \text{GeV})$ with the production probability for a given state decreasing as $\exp(-\, m/0.16\ \text{GeV})$. Thus the cross section for producing any state in a given mass range is apparently predicted to decrease as $m^{-5/2}$ - approximately similar to the above empirical conclusion. However the assumptions of this model appear quite different from the single particle excitation process which we have assumed; moreover, the simple three quark model itself, together with the shape of the observed excitation spectrum up to 3 GeV, gives a maximum allowable number of states per MeV which increases much more slowly with energy (see fig. 2) than predicted by Hagedorn's formula (unless, perhaps, the multitude of possible deuteron, etc., states can be regarded as independent single particles - which seems unlikely at very high energies).

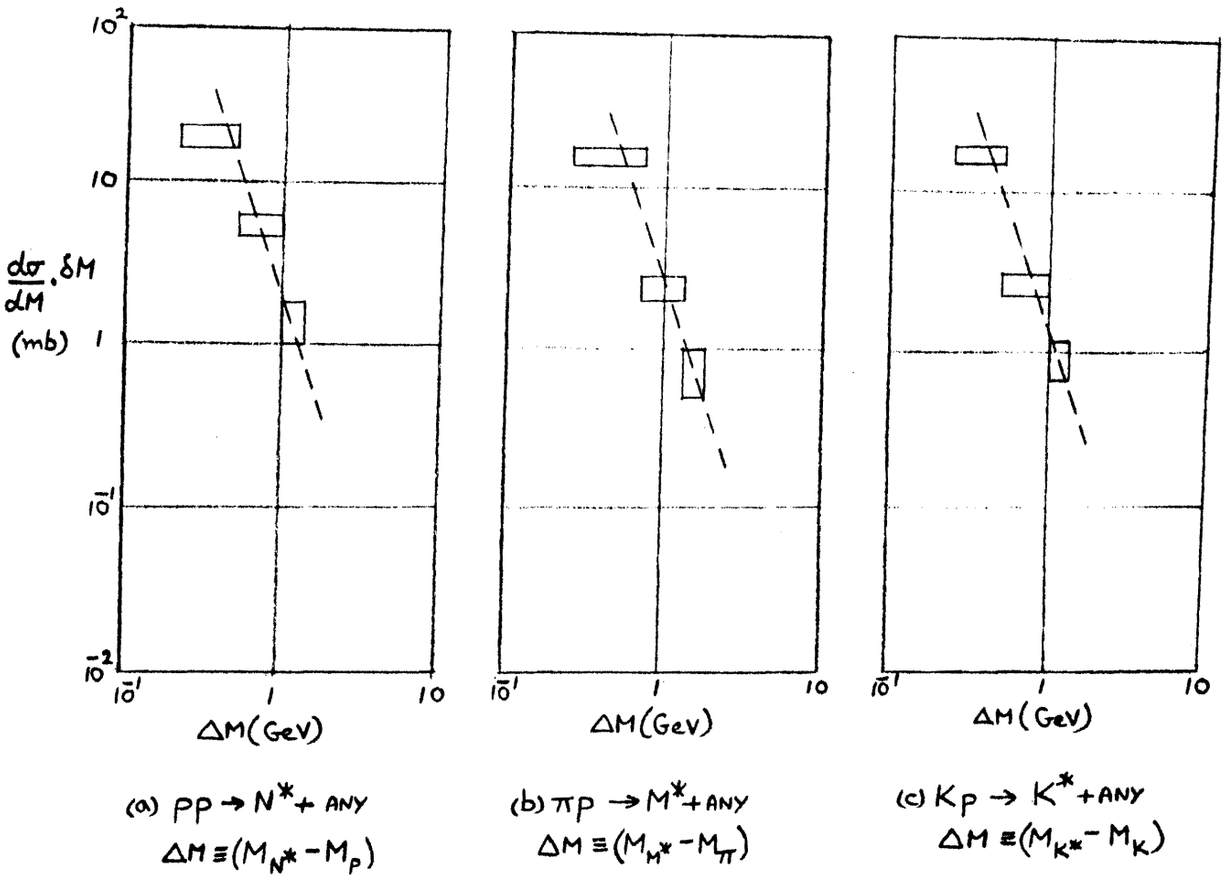

FIG. 1. General trend of cross section data for the production of (a) excited nucleon states, (b) excited meson states, and (c) excited strange meson states, estimated by grouping states into intervals δM = 500 MeV.

Only those reactions are included which can be reasonably interpreted as a simple excitation of the particle in collision with the nucleon. Thus formation processes such as $\pi p \to N^*$, are not included in (b) and (c), which represent excitation of the meson ground state by the nucleon.

The dashed lines show a slope $1/(\Delta M)^3$.

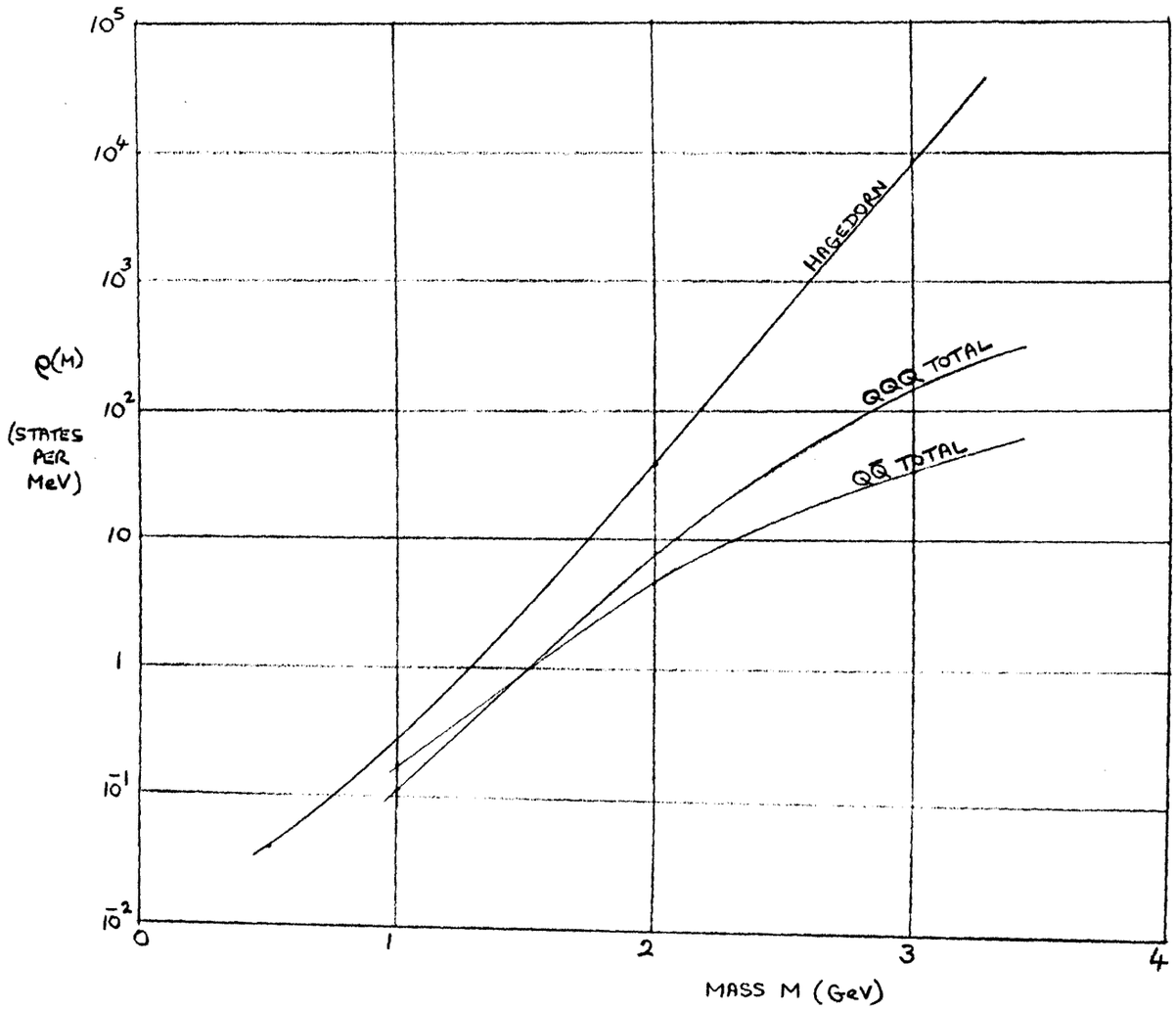

FIG. 2: Comparison of density of particle states/MeV as suggested by Hagedorn's exponential formula, with the number allowed by a simple three quark and quark-antiquark model of baryons and mesons, assuming proportionality between total quantum number and $(\text{mass})^2$, as observed, up to 3-4 GeV. The two estimates agree with one another (and with experiment) at $\sim$ 1 GeV but diverge at larger mass.

Note that estimates of a production cross section which decreases exponentially with quark mass result from the view that the Hagedorn curve continues to indefinitely large masses. The alternative, and more optimistic, viewpoint is that above a certain mass all states become ionised into free quarks (see fig. 3).

In view of this, it seems more appropriate to proceed independently of the statistical predictions for the present.

4. OTHER EXCITATION CHAINS

Before proceeding to estimates of the possible quark production rate, it is necessary to note that quarks could also be produced by a number of other processes analogous to the multi-stage nucleon excitation already discussed. In fig. 3 these are shown as routes on a simple map of the baryon and meson spectra. All particle states are contained within the area bounded by the x-axis (zero internal angular momentum) the upper curve (maximum angular momentum) and the vertical line at $2m_q$. (Note that the shapes of the m-L curves are in fact very similar for mesons and baryons in the observed range up to $\sim$ 3 GeV). The extra dimensions associated with strangeness and intrinsic quark spin are not shown explicitly - any point would in fact represent a 56 or 70 multiplet in the case of the baryons, or a 36 multiplet in the case of the mesons. (There is also a second internal degree of freedom of the three quark system which further increases the density of available states.)

The routes shown are as follows:

(a) Direct single-stage excitation into quarks, e.g. by a simple nucleon-nucleon collision.

(b) Two stage excitation, as previously discussed.

(c) Production of a 'stable' strange baryon, such as a Σ, followed by two stage excitation. (Since the strange particles tend to have smaller widths, the intermediate mass states may have a longer lifetime; this gain however, may be offset by the relatively small number of strange baryons produced).

(d) Production of a heavy meson, followed by single-stage excitation into quarks.

(e) Production of 'stable' K or π mesons, followed by two stage excitation into quarks. Meson states are observed to have smaller average widths than baryon excitations, and, in contrast to (c), the longer lifetime factor is not offset by the initial π or K production probability, since at high

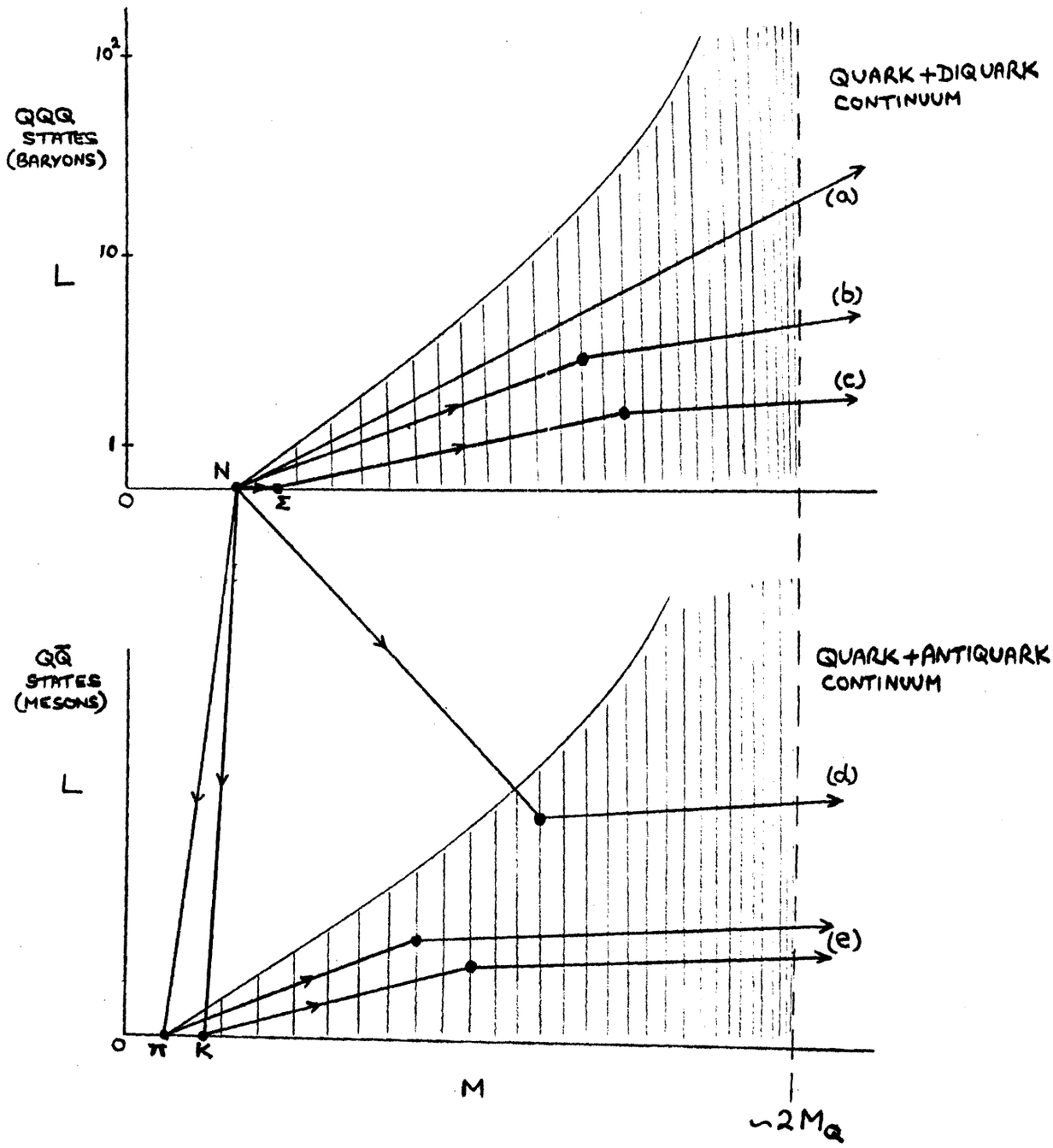

FIG. 3: Typical routes for single-stage and multi-stage excitation into free quarks

Note that in general we are picturing the processes in terms of quarks with instantaneous integral charges, the apparent fractional charge arising from a rapid internal charge sharing process. Thus we also envisage the free quark states to have charge 1 or zero, although the principles under discussion would probably be similar for fractionally charged models.

energies the number of π or K mesons produced per incident nucleon is known to be of order unity or greater. One disadvantage of this route is that a meson target has a lower mass than the nucleon so that the maximum centre of mass energy in the first stage will be less. Thus the K meson route should be more useful than the π meson route.

The total production rate is, of course, the sum of the rates for each of these routes.

5. QUARK PRODUCTION RATES

A major uncertainty which remains is the process of slowing down the intermediate state within the target nucleus. This is, of course, essential to the idea, otherwise it cannot absorb a significant amount of energy from the second incident nucleon.

The relativistic kinematics of this has been examined in some detail, from which it is concluded that even a single subsequent collision (in which the excited state could lose up to half its forward momentum) would allow a reasonable mass increment to be achieved in the second excitation.

In practice, of course, the slowing down will occur primarily via inelastic collisions, so that the excited state will in general become either de-excited or further excited. For the sake of making some kind of estimate we will assume

(a) that the mass is unchanged, on average, by the slowing down collision(s)

(b) that the slowing down collision(s) occur within a distance 2.10^{-13} cm, giving a decay factor $\sim$ exp(- width/100 MeV)

(c) that the slowing down probability, (since mainly inelastic energy transfer processes are involved) is given roughly by a function similar to the excitation probability. For example we can put $P_s(x) = P_e(m_1)$, which should be an underestimate, since it ignores processes in which the momentum is carried away by low mass particles.

On this basis, and assuming $P_e(m)$ given by equation (4), the order of magnitude for the production of a 45 GeV final state, by the various routes listed in the preceding section, would be as follows (assuming average widths of 500-1000 MeV for high mass baryon resonances, and 100-300 MeV for high mass meson resonances):

(a) Single stage (i.e. at ISR, assuming luminosity $\sim 3.10^{30}$)

$$R_a \sim 10^5 (m_f^{-2}) \sim 10^1 \text{ sec}^{-1}$$

(b) Two stage:

$$R_b \sim 10^{12} (m_f/2)^{-2} (m_f/2)^{-2} (m_f/2)^{-2} (e^{-5} \text{ to } e^{-10}) \sim 10^0 \text{ to } 10^2 \text{ sec}^{-1}$$

(c) Two stage excitation of Σ, etc.

$R_c \sim$ depends on strange particle multiplicities and widths but probably similar to (b) $\sim 10^0$ to 10^2 sec^{-1}

(d) Excitation of heavy meson state

This involves an initial production process (e.g. pair production) not covered by the above discussion. Empirically such processes appear to decrease much more rapidly with mass than the excitation processes. Thus

$R_d \sim$ (not calculated but probably negligible)

(e) Excitation of K mesons

$$R_e \sim 10^{12} (\text{multiplicity} \sim 1)(m_f/2)^{-2} (m_f/2)^{-2} (m_f/2)^{-2} (e^{-1} \text{ to } e^{-2}) \sim 10^2 \text{ to } 10^3 \text{ sec}^{-1}$$

(however, in comparison with (b), about 50% more incident energy per nucleon is required in this case, to compensate for the lower initial mass of the K meson targets).

If one is content simply with a comparison of production rates for heavy ion collisions, and for p-p collisions in an ISR, then the possible validity of these rough estimates improves somewhat, since the uncertainty in cross section behaviour occurs in each. Thus if quarks were to be observed in 25 GeV ISR proton collisions (as apparently suggested by the above estimate - but see section 7, final paragraph, for a contrary viewpoint) then it is also possible that quark beams of significant intensity might be obtainable by means of 100-200 GeV heavy ion beams (even though 100-200 GeV proton beams would have insufficient centre of mass energy).

6. COLLIDING BEAMS OF HEAVY NUCLEI

It is also of interest to note that if one considers the multistage excitation process in colliding heavy ion beams, the problem of estimating the effectiveness of slowing down the intermediate state is no longer encountered; any excited state formed within the colliding nuclei is immediately bombarded from both sides by further nucleons, so that any motion it has in the original centre of mass system will, in one direction, increase the available energy for the second collision, so that no slowing down process is necessary.

However, for the same total beam currents, the effective luminosity x cross section for collisions between nuclei is a factor $\sim A^{4/3}$ ($\sim 10^2$ to 10^3) lower than for the usual p-p collisions. This in turn means that the factor multiplying the two-stage probability factors in equation (3) is only about 10^4 - 10^5 compared with the technically possible $\sim 10^{12}$ for a heavy ion beam fully interacting in a solid target. One recovers a factor $\sim 10^4$ from the $P_s P_d$ term, so that we are left with predicted two-stage quark production rates 10^3 - 10^4 lower than the figures given in section 5.

Thus although the estimate for colliding heavy nucleus beams is substantially lower, it is nevertheless still significant, and free from one of the main uncertainties (the slowing down process) of the beam + target estimate. Moreover, the predicted two-stage events would occur in <u>addition</u> to the normal two-nucleon interactions - for which the effective luminosity would be essentially unchanged. It seems worthwhile, therefore, considering further the possible implications of colliding heavy nuclei.

7. A MORE REALISTIC APPROACH - THE INDIVIDUAL QUARK COLLISION PICTURE

The preceding rough estimates, although apparently encouraging, cannot of course be regarded as predictions at this stage. They simply show that, using the simplest (and not necessarily realistic) description of a heavy nucleus collision, and making some moderately optimistic extrapolations of existing data, appreciable rates can be obtained for two stage excitation to particle states of a few tens of GeV.

In fact, as indicated in section 2, the above calculations are almost certainly based on a rather unrealistic picture. On the basis of the simplest quark models - which account fairly convincingly for the quantum numbers and the ordering of states in the observed multiplets of baryons and mesons - we can make the following observations:-

(a) it is possible to infer from the shape of the mass spectrum that the corresponding shape of the inter-quark potential appears rather open, i.e. apparently varying as a rather low power of the quark separation. The system is thus not very rigid, and in fact from the observed approximate proportionality between $(\text{mass})^2$ and angular momentum, one can estimate that the mean quark separation increases roughly linearly with energy. Thus for excited states of mass $\sim$ 10 to 20 GeV the internal quark wavefunction

extends over a distance $\sim 10^{12}$ cm - larger than the colliding nuclei! Thus it is not consistent to treat the excited state as a single entity formed within, and moving amongst, the nucleons of the target nucleus.

(b) By similar reasoning we can estimate the characteristic periodicity associated with the oscillatory or rotational internal motion of the excited state. For states of mass $\sim$ 10 to 20 GeV we find the to be $\sim 10^{-22}$ sec, which is to be compared with the assumed 'slowing down' time $\sim 10^{-23}$ sec and the decay time constant of $\sim 2.10^{-24}$ sec. This further illustrates the point that the quark system, although acquiring some additional internal energy, does not settle into a well defined excited state before being subject to further collisions.

(c) Perhaps the most obvious point of all is that at sufficiently high energies we should describe a collision between two nucleons in terms of collisions between the individual quarks of each nucleon. Thus, just as it is the energy per nucleon which is relevant in the case of a high energy heavy nucleus (rather than the total energy of the assembly), then also we would expect that in a nucleon of sufficiently high energy the quantity of importance in an interaction will become the energy per quark. In general, this situation will always arise in a compound system when the energies involved become comparable with the binding energy, or when the collision time becomes short compared with the internal response time (i.e. the characteristic bound state period) and, as we have seen, both of these criteria are easily satisfied in the nucleon-splitting reactions under discussion.

One could, of course, imagine the possibility of types of interaction in which more than one component of a compound system participates coherently; this remark applies not only to the collision of a pair of three-quark systems, but also to our original discussion of heavy ion collisions (where only a series of independent incoherent single nucleon collisions was assumed). However, it seems likely that such coherent many-particle interactions would be of relatively low probability.

It should be noted that a description of nucleon collisions as the sum of individual quark collisions is believed to be appropriate even at energies of only a few GeV, since, it provides a natural explanation of, among other things, the approximate ratio 2/3 for πp and pp total cross sections.

The preceding remarks indicate that, for further studies of the phenomena which might occur in high energy heavy nucleus collisions, it should be reasonably realistic to adopt a model in which the nucleons transfer or absorb energy by collisions initially between single quark components, subsequently shared with the spectator quarks via the binding potential. (The model should if possible take into account the presence of virtual quark-antiquark pairs, continually interacting with the permanent quark components). The elementary collisions can, of course, be regarded as purely elastic following the usual procedure throughout physics of eventually describing any inelastic process in terms of purely elastic processes at a more macroscopic level; although the nature of this elastic interaction is at present unknown, it should nevertheless be possible to reduce considerably the uncertainties and empirical assumptions, and therefore to predict the various processes with greater confidence. *

Such calculations would also be of relevance to present attempts to produce quarks by normal proton collisions, either on stationary targets or with colliding beams. If, as suggested by the above preliminary discussion, the maximum available energy becomes dependent on the energy per quark rather than the full proton energy, then extension of the experimentally available energy range becomes even more difficult. For production of new particles on the CERN ISR, for example, the maximum effective centre of mass energy might be only $\sim$ (9 + 9) GeV rather than $\sim$ (27 + 27) GeV.

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*One prediction of immediate interest from this picture is that the decay widths of high mass states should perhaps have an upper limit, corresponding to the mean distance travelled by the component quark which has absorbed momentum in a collision, before it encounters an antiquark from the $Q\bar{Q}$ cloud.

From general considerations of the π-meson cloud, or from the 'zitterbewegung' (i.e. position fluctuation, resulting in the effective magnetic moment) of the bound quarks, we might expect this mean free path to be $\sim 4.10^{-14}$ cm for baryons, corresponding to a width $\lesssim$ 500 MeV.