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POSSIBILITIES FOR EXPERIMENTS WITH DEUTERON AND LIGHT-ION BEAMS AT $4<E_{Beam}/A<10$ GeV

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POSSIBILITIES FOR EXPERIMENTS WITH DEUTERON AND LIGHT-ION BEAMS AT $4 < E_{\mathrm{Beam}}/A < 10$ GeV

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1. INTRODUCTION

In this note I would like to describe possibilities for experiments with deuterons and light ions at beam energies greater than a few GeV per nucleon. Currently the accelerators that supply high energy light ions with $E_{\mathrm{Beam}}/A \leq$ a few GeV are available in Berkeley, Saclay, and Dubna. However, we have no accelerators that can cover beam energies higher than a few GeV per nucleon. It is highly desirable to have in the future an accelerator which can provide these high energy nuclear beams.

In the low energy region (below a few GeV per nucleon) dominant secondaries created in nuclear collisions are Δ's and pions. Therefore, pion spectroscopy has so far played a major role in this energy domain. On the other hand, in the high energy region ($4 < E_{\mathrm{Beam}}/A < 10$ GeV), other types of secondary particles are created. The production of strange particles is especially important there, since the threshold energies for the production of K, Λ, Σ, and Ξ in nucleon-nucleon (hereafter called NN) collisions are clustered at 2 - 4 GeV. The first interesting possibility at higher beam energies is therefore the study of **strange particle spectroscopy**.

The second possibility is related to the creation of high density. In the low energy region the creation of a high density phase is expected through a massive compression of nuclear matter. However, a completely different mechanism might play a role in the creation of high density at higher beam energies. Here I will describe how high density is created at higher beam energies and suggest several experimental possibilities for both **high energy density** and **high particle density**.

The third possibility is the study of **multi baryonic excited states** using nuclear beams. So far, this subject has not been studied seriously even with low energy nuclear beams. However, I believe that in the future the study of multi-baryonic excited states will be one of the most interesting and important aspects of both low and higher beam energies. The simplest limit of multi-baryonic excited states is **dibaryon**. The search for dibaryon with nuclear beams is discussed separately as the fourth possibility.

As an extension of the study of multi-baryonic excited states, the importance of studying **unusual nuclei** which includes double hypernucleus, negatively charged nucleus, etc. will be discussed as the fifth possibility.

The organization of this note is as follows: Before discussion of the main subject, very general features that characterize the nucleus beams and nuclear collisions at high energies are briefly described in Sec. 2. In Sec. 3 a few pieces of data that have been obtained in Berkeley are introduced. In Sec. 4 our main topic, possible new experiments, is discussed. The present proposal is then briefly summarized in Sec. 5.

2. WHAT CHARACTERIZES HIGH ENERGY NUCLEAR BEAMS AND HIGH ENERGY NUCLEAR COLLISIONS?

As an introduction the de Broglie wave length of incident nucleons inside the projectile nucleus (in the NN c.m. frame) is plotted in Fig. 1 as a function of the beam energy per nucleon (in the laboratory frame). At about 1 GeV per nucleon the de

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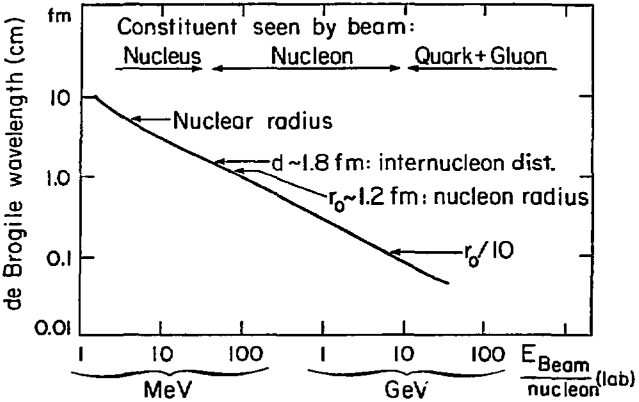

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Fig. 1

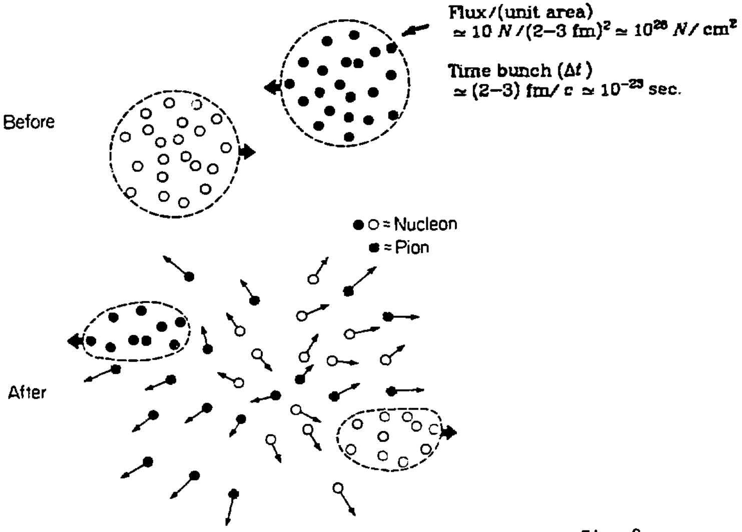

Fig. 2

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Broglie wave length is about 0.3 fm which is much shorter than the typical internucleon distance ($d \simeq 1.8$ fm). This fact implies that incident nucleons inside the projectile can recognize the individuality of target nucleons. Therefore, it is likely that individual *NN* collisions determine the basic dynamics of nucleus-nucleus collisions at high energies. Nuclear collisions at beam energies above a few 100 MeV per nucleon are thus very different from very low energy nuclear collisions (E_{Beam}/A) for which the de Broglie wave length is comparable to the whole nuclear radius. There the mean field approximation is more or less justified.

At beam energies above 10 GeV per nucleon the de Broglie wavelength is less than 1/10 of the nucleon size. Therefore, at these energies the internal structure of the nucleon might show up, and perhaps the role of quark-quark or quark-gluon interactions becomes more important there. However, in the beam energy region of $4 < E_{\mathrm{Beam}}/A < 10$ GeV, which is the main focus of the present workshop, the nucleus-nucleus collision is, to a first order approximation, regarded as an ensemble of *NN* collisions.

Then, what is the difference between the *NN* collision and the nucleus-nucleus collision at high energies? One obvious feature of the nucleus beam is, as seen in Fig. 2 (upper), that nucleons are packed closely within a small radius of a few fm. Consequently, the local nucleon flux density is about 10^{49} nucleons/cm^2/sec, which of course cannot be obtained by any proton accelerator. This "packing" feature of nucleons introduces, in fact, a great advantage of using nucleus beams instead of nucleon beams, as we will see later.

If *NN* collisions determine the basic dynamics, then what do we expect after the collision? As shown in Fig. 2 (lower), some nucleon groups which are located in the non-overlapped regions between the projectile and target will just pass through, keeping their initial velocities. These nucleon groups are called spectator. On the other hand, in the overlap region, nucleons interact violently with each other and scattered over a wide range of angles and momenta. These nucleons are called participant, and such a picture is called the participant-spectator model.[1]

Let us look at the data. Shown in Fig. 3 are the proton momentum spectra measured at 0° (Ref. 2) and 180° (Ref. 3) in 1.05 GeV per nucleon C + C collisions. Two peaks are clearly observed, one at $p_p = p_C/12$, namely at the beam velocity, and the other at $p_p = 0$ (at the target velocity). They are most likely from spectator nucleons.

How about the data at large angles? Shown in Fig. 4 are the proton spectra in 800 MeV per nucleon Ar + KCl collisions measured at angles from 10° to 145° (Ref. 4). The spectra are very smooth as a function of the proton momentum and extend up to fairly high momenta. If these cross sections are integrated over angles and momenta, then the total cross section is about 15 barns which is very close to the expected total cross section[4,5] (18 barns) of participant protons from the simple participant-spectator model.

Two macroscopic quantities, the mean free path (λ) and the collision radius (R), play an important role in collision dynamics. At $E_{\mathrm{Beam}}/A \simeq 1$ GeV, these two values have recently been determined to be $\lambda \simeq 2.4$ fm[8] and $R \simeq 2$-4 fm[7-10,4]. If $\lambda \gg R$, then the nucleus is almost transparent and each nucleon experiences at most one *NN* collision, and consequently the nuclear collision is described as a simple superposition of single *NN* collisions without any rescattering. This is called the *direct* limit. The hard-collision model[11] is applicable in this limit. On the other hand, if $\lambda \ll R$, then each nucleon experiences successive multiple collisions, and the available kinetic energy tends to be shared among all participating nucleons. This is called the *thermal* limit. Most of the macroscopic models, such as the thermal[12] or the hydrodynamical[13] models, are based on this assumption. The actual situation is, however, between these two limits, since $\lambda \simeq R$. This is one of the complexities of the reaction mechanism of high energy nuclear collisions.

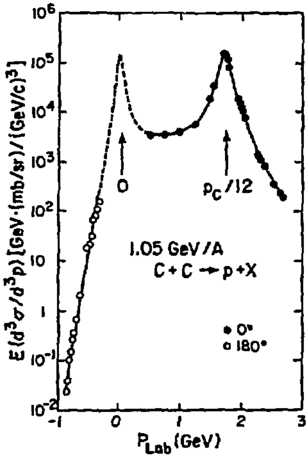

Fig. 3

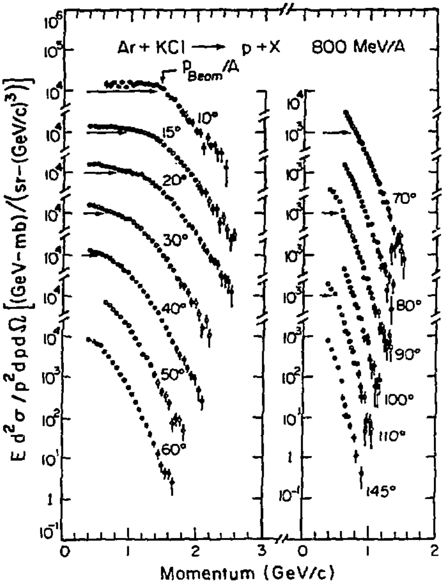

Fig. 4

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Now, we have the following general observations. Individual *NN* collisions seem to determine the basic dynamics of the nucleus-nucleus collision. Geometrically, the high energy nucleus beam is characterized by a high local nucleon flux density. Kinematically, data at large angles tend to reflect more features of the participant region, whereas the data at around the projectile and target velocities reflect more features of the spectator region. With regard to the collision dynamics, the fact of $\lambda \simeq R$ tells us that both direct and thermal limits are unrealistic. Keeping these general features in mind, we will look over the data in the next section.

3. TYPICAL SPECTRA OF LIGHT PARTICLES

3.1. Spectra of Protons, Composite Fragments and Pions

We first quickly review the spectra of protons, composite fragments and pions obtained at the Berkeley Bevalac. In Fig. 5 (upper) the proton spectra measured at c.m. 90° from almost equal-mass collisions, C + C, Ne + NaF, and Ar + KCl, at E_{Beam}/A = 800 MeV are plotted. The spectra are not purely exponential, but resemble each other. This implies that the beam energy per nucleon determines the major dynamics, rather than the total beam energy. We also observe copious production of high energy protons in the region far beyond the free *NN* kinematical limit (in this case 182 MeV). Even if a proper Fermi motion is included, the production of these high energy protons cannot be explained as a superposition of single *NN* collisions (the broken solid curve in Fig. 5 (upper)). How are these protons created? In order to study it we parameterize the same data as a power of the projectile (or target) mass number, A, as $E(d^3\sigma/d^3p) \propto A^\alpha$, and plot this α in Fig. 5 (lower). For low energy protons the value of α is very close to the geometrical limit of 5/3; in this limit the cross section is proportional to the product of the participating nucleon number ($\propto A$) times the geometrical cross section ($\propto A^{2/3}$).[4,5] However, in the high energy region $\alpha > 5/3$ and reaches the value of 2.6 or 2.7 at the highest energy. Such a large value of α suggests that multiple *NN* collision processes are important for the creation of high energy (in this case high p_T) protons.

In the presence of multiple collisions, there is a certain chance that these nucleons stick together to form a composite fragment. According to simple phase space considerations, we expect that the probability of forming a deuteron at a velocity $\vec{v}_d$ is proportional to the product of the probabilities of finding a proton and a neutron at the same velocity:

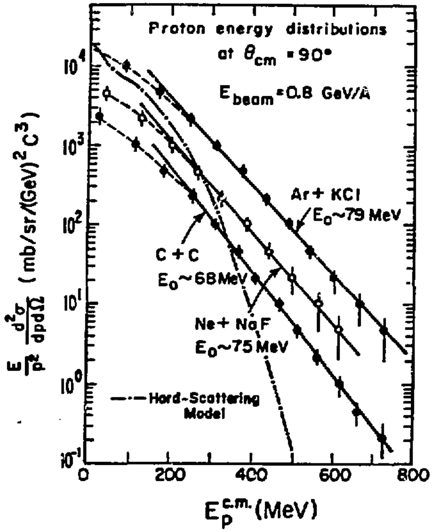
$$P_d(\vec{v} = \vec{v}_d) \propto P_p(\vec{v} = \vec{v}_d)\cdot P_n(\vec{v} = \vec{v}_d). \tag{1}$$

If the neutron spectra can be replaced by the proton spectra,[14] we have

$$E_A(d^3\sigma_A/d^3p_A) = C_A\cdot[E_p(d^3\sigma_p/d^3p_p)]^A \quad \text{for } p_A = A\cdot p_p. \tag{2}$$

The above power law is called the coalescence model[15] and is tested in Fig. 6 with the data.[4] With one normalization constant, C_A, this power law holds extremely well.

How about pion production? I examine only two examples here. The first is the energy spectra. As shown in Fig. 7, the spectra at c.m. 90° are almost exponential at any bombarding energy. This exponential behavior is a feature generally observed for pions with any projectile and target (with $A > 4$) and at any c.m. angle. We notice, however, that the inverse slope, E_0, for the exponential fall-off is consistently smaller for pions than for protons, as seen in Fig. 8. Several theoretical explanations exist to explain this. One suggestion by Siemens and Rasmussen[17] is a radially expanding flow model. At a fixed kinetic energy the velocity of a proton is much smaller than that of a pion. Therefore, if there is an explosive flow, there will be a greater enhancement of kinetic energy for protons than for pions. Consequently, the proton spectra become broader than the pion spectra. This idea explained reasonably well the difference in E_0 as well as the spectrum shapes of both pions and protons.[17]



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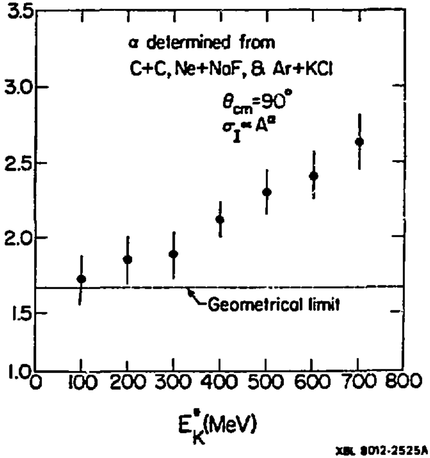

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Fig. 5

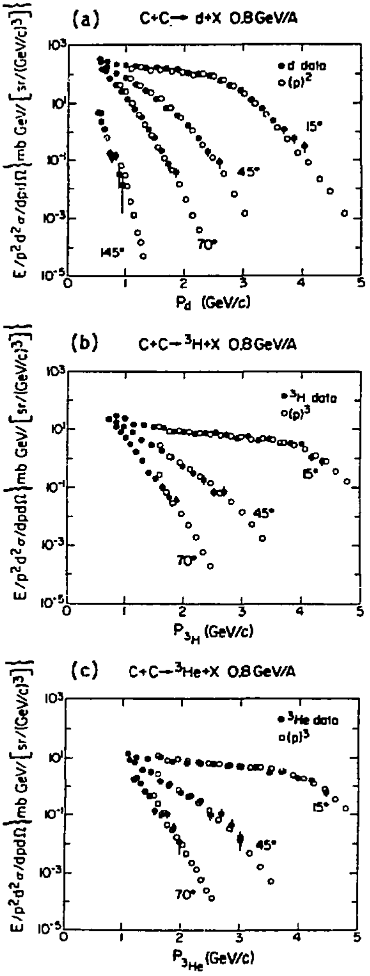
(a) C+C→d+X 0.8GeV/A
● d data
○ (p)²
15°
45°
70°
145°
P_d (GeV/c)
(b) C+C→³H+X 0.8GeV/A
● ³H data
○ (p)³
15°
45°
70°
$P_{^3H}$ (GeV/c)
(c) C+C→³He+X 0.8GeV/A
● ³He data
○ (p)³
15°
45°
70°
$P_{^3He}$ (GeV/c)
$E/p^2 d^2\sigma/dp d\Omega$ {mb GeV/[sr/(GeV/c)³]}
10³
10¹
10⁻¹
10⁻³
10⁻⁵
0
1
2
3
4
5

Fig. 6

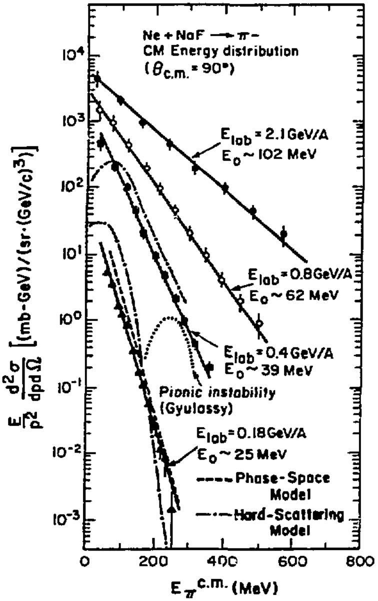

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Fig. 7

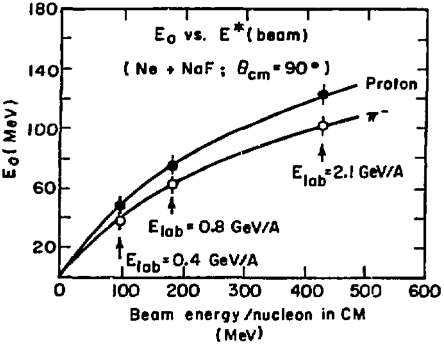

Fig. 8

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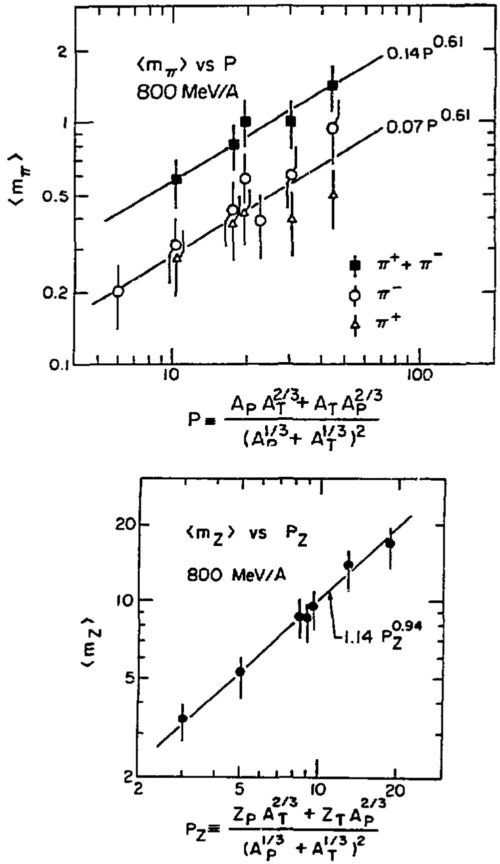

Fig. 9

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The second example is the A dependence of the total cross section. In Fig. 9 observed multiplicities for pions and nuclear fragments are plotted as a function of the participant nucleon number, P (or participant proton number, P_Z). The data of nuclear fragments (lower figure) contain mostly the contribution from the participant region, since the data at large angles are used to obtain the multiplicities. We observe $<m_\pi> \propto A^{2/3}$ while $<m_Z> \propto P_Z$. This $A^{2/3}$ dependence for pions suggests that pions are strongly absorbed before they are emitted. In other words, pions are emitted after several rescatterings with surrounding nucleons, and thereby display features of the equilibrated stage of the system.

3.2. Multiplicity, Particle Correlations, etc.

Other than these spectra, a large number of particle correlation data have been collected in Berkeley. These data have revealed several interesting phenomena of nuclear collisions, but since investigating the details of nuclear collisions is not the aim of this workshop, I will not discuss them here. If you are interested in these current data, see Ref. 18.

3.3. Spectra of Strange Particles

Recent strange particle production data are described in rather great detail here, because they are related to one of the new experimental possibilities at higher beam energies described in the next section. In Fig. 10 various threshold energies for particle production in NN collisions are displayed. As the beam energy increases (above 2 GeV) the production of strange particles becomes more important.

Schnetzer *et al.*[19] have measured K^+ spectra with a magnetic spectrometer. The motivation of this experiment is as follows: Since the cross section of $K^+ + N$ ($\simeq 10$ mb) is much smaller than that of $N+N$ ($\simeq 40$ mb) or $\pi+N$ ($\simeq 100$ mb), once K^+ is created, it is less likely to be rescattered by surrounding nucleons. In other words, K^+ may be a more reliable messenger than π or proton of the violent initial, and perhaps, very compressed and hotter stage of the nuclear collision. In Fig. 11 an example of energy spectra in the c.m. frame is plotted for 2.1 GeV per nucleon Ne + NaF collisions. The spectrum shape is almost exponential with inverse exponential slope, $E_0 \simeq 142$ MeV. This value of E_0 is larger than E_0 for protons or pions (see Fig. 8), implying that K^+'s seem to be created at a much more violent stage than pions or protons. The exponential behavior of the spectrum is a general feature for any projectile (even p or d) on nuclear targets. In addition, the angular distribution of K^+ is almost isotropic in the NN c.m. frame.

Then, how do we explain the data? So far, no satisfactory explanation has been available. Recently a linear cascade calculation based on row-on-row straight-line geometry succeeded in reproducing the shape of the energy spectrum, by including a slight rescattering of K^+ by surrounding nucleons.[20] However, this calculation fails to reproduce the angular distribution, especially for the case of proton + nucleus collisions. Therefore, this point remains an open question.

An interesting aspect of K^+ data is seen in the A dependence. If the cross section is parameterized as a power of A_T ($\propto A_T^\alpha$), then the value of α is consistently larger for Ne projectiles than for d projectiles, as seen in Fig. 12. From a simple geometrical consideration we expect the opposite trend, since with a heavier-mass projectile the increase of target size must have less effect on the yield (in fact, we expect $\propto A_T^{2/3}$ for heavy-mass projectiles and $\propto A_T$ for light-mass projectiles). Perhaps this experiment indicates that, with heavier-mass projectiles the compressed and hot region is created more copiously than with lighter-mass projectiles. Such a feature is not (or is only slightly) observed for pion production, as seen in Fig. 12.

The Λ production has been studied recently by Harris *et al.*[21] with a streamer chamber in 1.8 GeV per nucleon Ar + KCl collisions. In this measurement the decay of

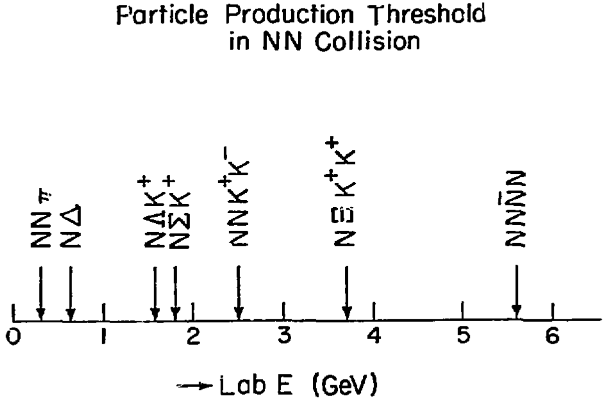

Fig. 10

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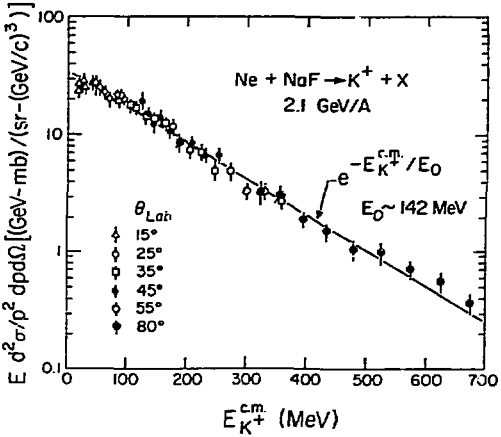

Fig. 11

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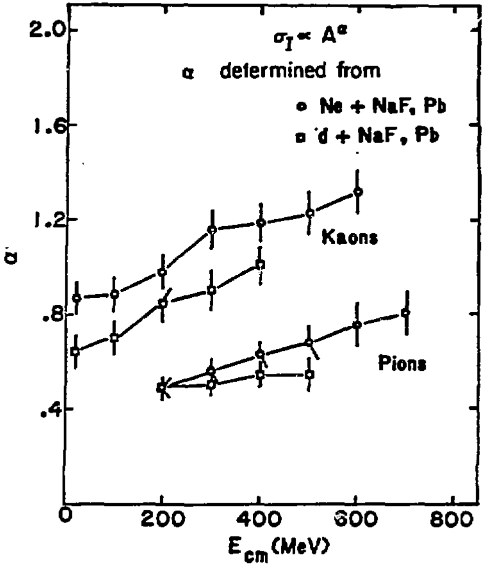

Fig. 12

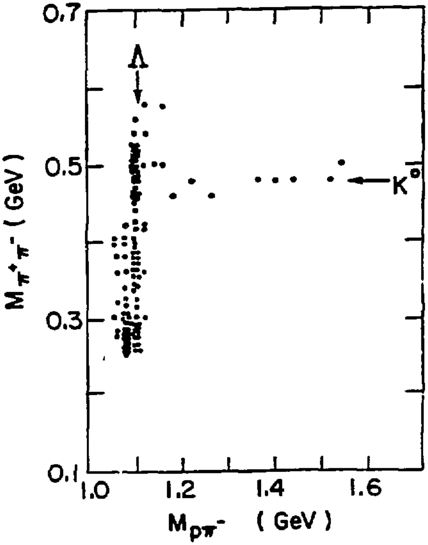

Fig. 13

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Λ,

$$\Lambda \rightarrow p + \pi^- \quad (64\ \%\ \text{branching}), \tag{3}$$

was used for the identification of Λ, as shown in Fig. 13. Clearly, Λ is observed. Although statistics of the data are low, a large number of Λ's which have momenta larger than expected from free NN collisions are observed. This is consistent with the previous data of K^+.

It is well known that the decay of Λ shown in Eq. (3) is through weak interactions. Therefore, if Λ has a polarization, P, the angular distribution of the decay products have angular anisotropy expressed as

$$W(\vartheta) = 1 + \alpha P \cos\vartheta, \tag{4}$$

where ϑ is the emission angle of p with respect to the polarization axis and $\alpha = -0.64$ in this case. By defining the reaction plane such that the beam and the emitted Λ form this plane, the value of P has been determined to $P = -0.10 \pm 0.05$. In terms of the quark model, Λ is described as (uds) in which spins of u and d are coupled to zero. Therefore, the polarization of Λ readily measures the polarization of s-quark. Measurements of Λ polarization are thus interesting and perhaps useful for studying the role of quarks in high energy nuclear collisions.

K^- has recently been measured with a magnetic spectrometer.[22] In this case, the yield is extremely low, since the Bevalac maximum energy is 2.1 GeV per nucleon while the threshold energy of K^- in NN collision is 2.6 GeV. Therefore, the data only tell us the integrated yield of K^-. Although these data were compared with various model calculations, I would say that meaningful physics can be extracted only when we have more data at higher statistics.

4. POSSIBLE EXPERIMENTS

From now on I would like to discuss possible experiments with light ions at beam energies from 4 to 10 GeV per nucleon, keeping in mind the general features which have been described in the previous two sections.

4.1. Comparison between K⁺ and K⁻ Spectra

First, I continue the discussion of the K^+ and K^- spectra described in Sec. 3.3. Since $\sigma(K^-N) \simeq 40\text{-}50$ mb is about 4 times larger than $\sigma(K^+N)$, the mean free path of the K^- inside nuclear matter ($\lambda \simeq 1.4$ fm) is much shorter than that of K^+ ($\lambda \simeq 6$ fm). The size of the interaction region, R, is typically about 3 fm. Thus we have

$$\lambda(K^-) < R < \lambda(K^+). \tag{5}$$

This relation implies that the K^+ spectrum tends to display features of the initial "hot" stage while the K^- spectrum tends to display that of the final "cold" stage. Therefore, measurements of both K^+ and K^- are important to study and compare typical features of these two stages.

At beam energies below 2 GeV per nucleons, an attempt to separate the initial stage from the final stage has been carried out by comparing K^+ with pions and protons. However, several ambiguities remain here, because masses and spins of these particles are different from each other. The spectrum of fermions can be different from that of bosons because of different statistics. In addition, as mentioned in Sec. 3.1., if a radially expanding flow exists, then this flow can distort the heavier-particle spectrum more than the lighter-particle one. With measurements of K^+ and K^- such difficulties can be avoided. The present Berkeley machine does not allow us to study both K^+ and K^- because the yield of K^- is too small. Higher beam energies are thus very desirable.

4.2. High Density?

Next, we ask if a high density phase can be created. On this subject I will introduce an idea by Goldhaber[23]. Although this idea was proposed to encourage heavy ion studies at much higher beam energies with U beams, it is still worthwhile to mention it here. My interpretation of his idea is shown in Fig. 14. At low energies the angular distribution of *NN* collisions is almost isotropic in the c.m. frame. Therefore, in the first *NN* collision the scattered nucleon tends to be emitted at a large angle and thus easily escapes out of the interaction region. However, at high energies the angular distribution is sharply forward peaked. Therefore, the scattered nucleon is forced to dive into the opponent nucleus, and will experience succeeding *NN* collisions. Through these successive *NN* collisions the energy carried by each nucleon might be accumulated in a small region, and consequently a local hot spot may be created. This local hot spot carries a high energy density. Therefore, high energy density might be more easily created at higher beam energies.

How about high particle density? At high beam energies both the projectile and target nuclei are Lorentz contracted in the c.m. frame (in our present case $\gamma_{c.m.}$ goes up to 2.5 at $E_{Beam}/A = 10$ GeV). Therefore, even temporarily the density might reach $2 \times 2.5 = 5\rho_0$. At beam energies below 1 GeV per nucleon, for which $\gamma_{c.m.} \simeq 1$, a high particle density can be reached through a macroscopic compression of nuclear matter. The mechanism discussed here is a microscopic one and is completely different from this macroscopic compression. Perhaps, the physics of high density may thus be studied more easily at higher beam energies, if macroscopic compression does not take place.

Obviously experiments involving high energy and particle densities are interesting. With regard to the high energy density, $q\bar{q}$ pairs might be created in the local hot spot, where q indicates quark. These pairs will then decay by emitting γ's or lepton pairs. Or they may form $q-\bar{q}$ jets which eventually introduce a strong 180° correlation between high-p_T pions. Or perhaps they create an abundance of strange particles, e.g. K^+, as suggested by T. D. Lee.[24] Such measurements are interesting. With regard to high particle density, no straightforward experimental methods have yet been thought out. However, I will point out a few possibilities. With high energy proton beams a broad sideward peaking of heavy composite fragments is reported[25,26] as shown in Fig. 15. Authors in Refs. 25 and 26 claimed that such a peaking may perhaps be due to nuclear shockwaves. It is certainly interesting to measure angular distribution of heavy fragments with nuclear beams. A search for the Lee-Wick type nucleus[27] has been carried out at beam energies of about 2 GeV per nucleon. In this case, a search was done for a fragment with mass number larger than the target mass. Of course, even if such a fragment was discovered, additional measurements are required to prove that this fragment actually carries higher density than ρ_0, e.g., the measurements of radius and mass. Nevertheless, a hunt of super-heavy fragments with mass number larger than the target mass is interesting.

4.3. Multi Baryonic Excited States

As mentioned in Sec. 2, the nucleus-nucleus collision at high energies is, to a first order approximation, a superposition of *NN* collisions. In each *NN* collision a baryonic excited state, such as Δ, N^*, Λ, etc., will be created. For example, Δ will be created at a probability greater than 50 %. In each nucleus-nucleus collision, therefore, several baryonic excited states might be created at the same time. The nucleus beam is also characterized by its "packing" of nucleons (see Sec. 2). Therefore, these Δ, Λ, etc. are again closely packed in a small region within a radius of a few fm. It means that there is a great chance that these excited baryons interact with each other to form an excited baryon soup (such as the Δ-soup[28]) before each excited baryon decays into a nucleon and pions, as shown in Fig. 16. In the nucleon soup a composite fragment is created out of a few nucleons, as we have studied in Sec. 3.1. Similarly, in the excited

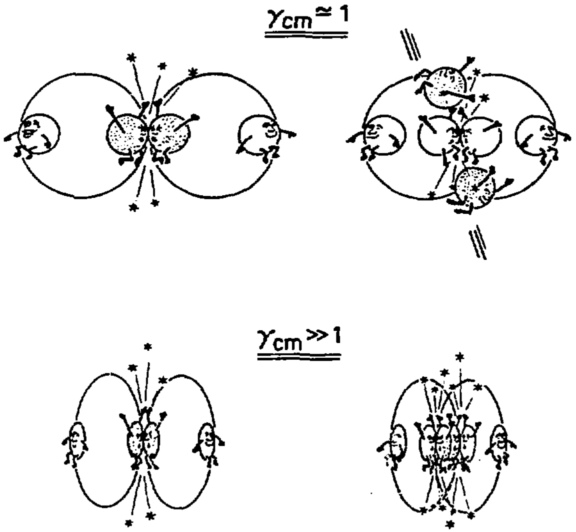

Fig. 14

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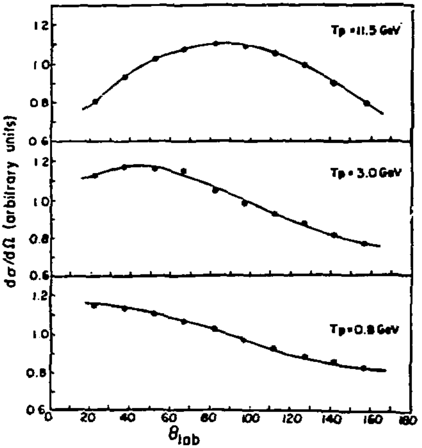

Fig. 15

Angular distribution of ^{48}Sc isotopes produced in $p + U$ collisions.

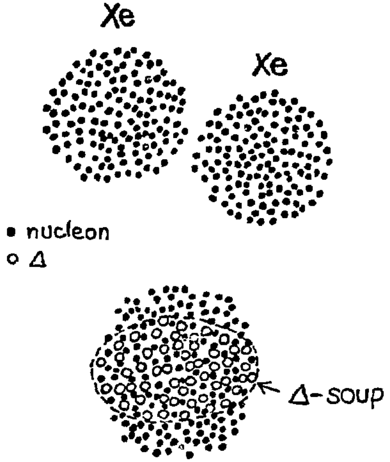

Fig. 16

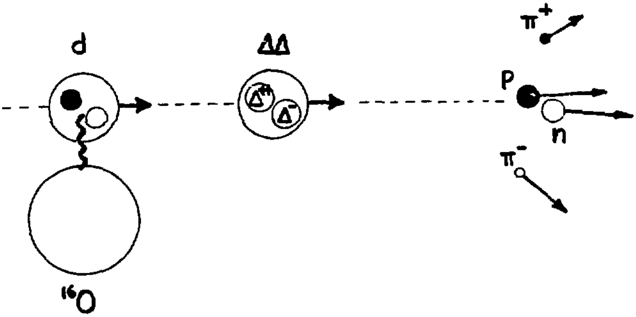

Fig. 17

Calculated cross section for $d + {}^{16}O \rightarrow D_{SC} + {}^{16}O$.

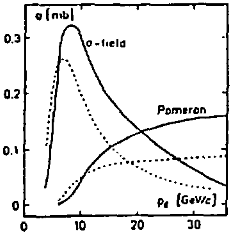

Fig. 18

baryon soup, a new type of composite fragment such as the $^4\Delta$ nucleus might be formed.

Currently I am very much interested in the possible creation of a $^{16}\Delta$-nucleus by the Bevalac, since about 30-40 Δ's are created at once in each U + U collision at $E_{\mathrm{Beam}}/A \simeq 700$ MeV. Since Δ carries spin (S) and isospin (T) quantum numbers of $S = T = 3/2$, $4 \times 4 = 16$ sublevels exist in the $1s$ orbit. These sublevels are occupied if 16 Δ are available. In the nucleon soup the α particle is much more stable than the deuteron. Therefore, $^{16}\Delta$ could be much more stable than 2Δ (which is one of the possible dibaryon candidates, as we will discuss later).

The possibility of studying the excited baryon soup will grow as the beam energy increases, since a larger number of baryonic excited states can be created. Strange baryons are especially interesting at $E_{\mathrm{Beam}}/A = 4$ - 10 GeV. We can ask if ΛΛ is metastable.[29] Or, we can ask if 3Σ forms a metastable particle.

Possible experiments will be as follows: The rapidity of such an excited baryon soup will be centered at $y \simeq (y_P+y_T)/2$, but broadly distributed over a region between y_P and y_T, where y_P and y_T are the projectile and target rapidities, respectively. If a metastable charged fragment was created in this soup with lifetime ≥ 10 ns, then the experiment would be relatively easy; a mass spectrometer could be prepared to detect such a fragment in the mid-rapidity region. If the lifetime is less than 1 ns, then a more complicated detector system would have to be prepared. Of course, it is more realistic to start with a simpler experiment.

4.4. Dibaryon Search

The simplest system of the multi-baryonic excited state is the dibaryon. So far, the dibaryon search has been done mostly with elementary beams such as γ, π, K^+, and p.[32] But, nuclear beams may offer a unique opportunity to study it.

There are two possibilities for creating dibaryons in nuclear collisions. The first one is through the coalescence between two excited baryons that are created in the excited baryon soup, as we have described it in the preceding subsection. There it is necessary to detect all final states in order to construct the invariant mass of the dibaryon of interest. Since relatively few (up to 4 or 5) final particles are involved here, the measurement is not very complex. The second possibility is to excite coherently two projectile nucleons into their excited states in a peripheral collision; for example, the excitation of a deuteron projectile into a $^2\Delta$ state in a $d + A$ collision, as illustrated in Fig. 17. This process includes relatively simpler kinematics than the first one. Since the $S = 3$, $T = 0$ $^2\Delta$ state (hereafter called D_{30}) is interesting, because it may be bound with a large binding energy up to 100 MeV,[33-36] we discuss this D_{30} in what follows.

The D_{30} state most likely decays into p, n, π^+ and π^-. In the first case of the above two possibilities this D_{30} is created out of the Δ-soup in the participant region, and thus carries a certain momentum in this soup. Therefore, we must detect all four particles to measure the mass of D_{30}. On the other hand, in the second case, the total energy of D_{30} (mass + kinetic energy) must be equal to the total energy of the projectile deuteron (here, the recoil energy of the target in a $d + A$ collision is negligibly small if $A > 4$). Therefore, if we detect three particles out of p, n, π^+ and π^-, then we can evaluate the mass of D_{30}. Since the development of high resolution neutron detector is not feasible, the second method has greater merit than the first. Rosina and Pirner[37] recently calculated the cross section of this second process, as shown in Fig. 18.

It is of course possible to excite a target deuteron into D_{30} via the second process. In fact, such a possibility has been investigated with γ beams[38] or π and K beams[39]. However, an experimental difficulty exists in identifying a two-Δ state out of the background N^*N state because of the existence of the low energy cut of the detector, as pointed out in Ref. 39. If a projectile deuteron is used to detect a 2-Δ state, a much wider kinematic domain can be covered, since we can practically measure energies and momenta down to zero values in the projectile rest frame. In other words, the identification of a 2-Δ state is much easier for projectile excitation than for target excitation. Another merit of using projectile excitation at high beam energies is seen in the simplicity of the experimental device. As the beam energy increases, most of the particles emitted from the excited projectile are sharply bunched at forward angles. Therefore, a relatively small solid angle device can detect these particles.

In addition to the 2-Δ excitation of a projectile deuteron, it is of course worthwhile to consider the possibility of exciting the projectile to a ΛΛ state.

4.5. Production of Double Hypernucleus, Negatively Charged Nucleus, etc.

Two other subjects will be discussed here in connection with projectile excitation. The first one is the creation of a double hypernucleus. For example, the following processes would be possible:

$$^{6}\mathrm{Li} + A \rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + A',$$

$$^{14}\mathrm{N} + A \rightarrow {}^{12}_{\Lambda\Lambda}\mathrm{C} + A'. \qquad (6)$$

These processes, although no calculations for cross sections are available, would be interesting, since so far very little evidence of double hypernuclei has been reported. Lifetimes of these states might be short, but they could be long because ΛΛ may carry a much longer lifetime than single Λ inside the nucleus because of the strangeness constraint. The creation of a double-Σ hypernucleus is interesting as well.

The second possibility is the creation of a negatively charged nucleus. From systematic studies of projectile fragments at the Bevalac we have learned that several neutron-rich isotopes are created. For example, from C beams the ^{8}He fragments were created with a production cross section of about 35 μbarns. In this case four protons were scraped out by the target. If three neutrons formed a projectile spectator, and if one π^- was absorbed in this spectator, then we would have a negatively charged nucleus. Such a nucleus could also be created via a single excitation of a projectile nucleon into Δ^- followed by its decay to $n + \pi^-$. There is a suggestion that the $3n + \pi^-$ system might be bound.[40] If a bound negative nucleus is discovered, it is certainly striking.

These measurements require a magnetic spectrometer at forward angles, especially at 0°. Although these ideas are still highly speculative, it is worthwhile to pursue these possibilities.

5. CONCLUSION

In this note I have presented five possible experiments with light ions with beam energies of 4 - 10 GeV per nucleon. Of course, these ideas came from my very limited knowledge of nuclear collisions at lower beam energies available at the Bevalac. Obviously other ideas must exist. For example, the study of nucleus-nucleus elastic and inelastic scatterings is a very interesting subject. Also, high-p_T physics has to be investigated in more detail. Nevertheless, the main issue that I hoped to stress in this note is that this new energy domain contains fairly rich possibilities that are not accessible with the current Berkeley Bevalac.

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