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Interactions of 600 GeV Muons with Emulsion Nuclei

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To find small-distance structure of the nucleon and nuclei, the high energy lepton(especially the muon) has been proved to be very effective. The EMC effect is one of such kinds of investigation.[1]

We propose an emulsion experiment to study the 'diffractive excitation (DE)' mechanism by high-energy muon exposure in the nuclear emulsion.

Up to now we have studied the DE of 14.6-, 60-, and 200- GeV/nucleon ^{16}O and 14.6-GeV/nucleon ^{28}Si nuclei in nuclear emulsion.[2-4] The identification method of DE events in nuclear emulsion, such as $^{A}Z \longrightarrow {}^{A-1}(Z-1) + p$, $^{A}Z \longrightarrow {}^{A-4}(Z-2) + \alpha$, · · · of the 'incident' heavy ions ^{A}Z, consists in the angular method which was developed newly for identifying DE interactions (coherent multiple production events) of 30 - 400 GeV protons in 1980.[5]

But in interpreting the "Coulomb dissociation" of the projectile heavy ions, the prevailing view is the mechanism of gaint dipole resonance (GDR),[6] which we disagree.

The controversial point is to be clarified by observation of the present 600 GeV muon exposure in nuclear emulsion. The Coulomb field of the muon will fairly abundantly induce the DE process of one of the 'target', C, N, O, Ag, and Br nuclei, which constitute the nuclear emusion. Thus, when observed in nuclear emulsion about 80% of the 'target' DE events must be in the form of (1+1), i.e., one heavy fragments and the muon track, undeviated from the incident direction. In fact, high energy μ-emulsion interactions have been reported.[7-9] Reference 9 clearly gives the impression of abundant and enhanced production of pions with 150-GeV μ^+ jets. This phenomena may correspond to the formation of Δ by the 'target' DE process in the anti-laboratory system.

Thus, as our view is expounded in Ref. 4, 600-GeV muon will give us clear indication of *enhanced* DE production to give us the important contribution of the process in contrast to the ordinary inelastic cross sections, which might give a clue to an understanding of the EMC effect.

THE MAIN FEATURES OF THIS EXPERIMENTS

1. Multiplicity of charged hadrons as a function of 4-momentum transfer.
2. Measure the angular distribution of the shower particles.
3. Energies of slow baryons.
4. Production rate of strange particles.
5. New particles with short life-times.

FLUX REQUIREMENTS AND EMULSION DIMENSIONS

Flux : $\sim 5 \times 10^4$ (particles/cm^2)
3 stacks of 40 pellicles (size : $10 \times 10 \times 0.06$ cm^3)

BEAM CHARACTERISTICS

The density of the beam should be as constant as possible.
Energy of the muon beam be 600 GeV or higher.
Pion contamination should be less than 10^{-6}.

EXPERIMENTAL PROCEDURE

Stacks of nuclear emulsion of about 720 cm^3 are exposed to the muon beam of energy 600 GeV with the beam density of 5×10^4 particles/cm^2. The number of events induced by the incident muon is expected to be about 10^5 events.

The event required is mainly detected by the along the track method. By using this method we can find all elastic and inelastic events. The tracks with the very high momentum among the emitted particles are considered as the outgoing muon. If possible, secondary particles are identified through the measurements of their multiple Coulomb scatterings, grain and blob counting.

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Diffractive excitation of 14.6-, 60- and 200-GeV/nucleon ^{16}O and 14.6-GeV/nucleon ^{28}Si nuclei in nuclear emulsion*

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ABSTRACT

An angular method of identifying Diffractive Excitation (DE) events for interactions of a hadron beam in nuclear emulsion (Kim, Hong and Park, 1980) is applied to identifying DE events in interactions of heavy ion beams. The 'apparent' mean-free-paths (MFP) of DE processes for ^{16}O (^{28}Si) beams are 1.00 ± 0.12, $2.4^{+1.6}_{-0.7}$, and 2.2 ± 0.4 (1.5 ± 0.2) m, respectively, at 200, 60, and 14.6 GeV/nucleon, which corresponds to 20 - 10 % of the MFP for total inelastic interactions. Distinctive features of diffractively excited nuclei are discussed.

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I. Introduction

A new improved experimental method of identifying diffractive excitation (DE) of projectile *protons* of the primary beam energy E_b = 30, 200, 300, and 400 GeV in nuclear emulsion was introduced by Kim, Hong, and Park in 1980 (see Appendix I),[1] and yielded the reasonable values of mean-free-path (MFP) consistent with the conventional $\Sigma_i \sin\theta_i$ method.[2] The techniques, which are based on the same principles mainly applied to low-multiplicity events, commonly involve accurate measurement of the emission angles θ (up to 10^{-4} radians) in the laboratory system (LS), and potential DE events are those interactions showing *no visible target excitation* ($N_h = 0$),[3] when the interactions are examined in the emulsion using the optical microscopes. Besides its great advantage of studying DE interactions in a wide range of primary beam energies with identical criteria, the angular method of Ref. 1 has been proved to be powerful and easily applicable also for identifying DE events of projectile *heavy ions* of primary beam energies E_b = 14.6, 60, and 200 GeV/nucleon, which is the very subject we report in this paper.

Small-p_T multiparticle production at high energy can be categorized roughly into multiperipheral particle production and DE to higher-mass states, where, in the latter, the nucleus (or excited hadron) subsequently decays into several fragmented nuclei or final state hadrons.[4 - 7] At sufficiently high energy, valid in most of our present cases, the condition of identifying DE events becomes $q_L R \ll 1$, which is that of the "virtuality (or *coherence*)" with respect to the individual constituents of b,[6 7] where q_L is the longitudinal component of the momentum transferred to the target nucleus, and the 'interaction' nuclear radius for the projectile heavy ion of mass number A_b and target nucleus of mass number A_t is $R = (A_b^{1/3} + A_t^{1/3})/m_\pi$, m_π being the rest energy of a pion. (Here, the natural unit of $\hbar = c = 1$ is used; $1/m_\pi = 1.45$ fm.) For the projectile nucleus of ^{16}O (^{28}Si), $q_L < 0.040$ (0.035), 0.029 (0.026), and 0.020 (0.018) GeV/c, respectively, for the composite targets of the hydrogen nuclei (H), the light nuclei (C, N, and O), and the heavy nuclei (Ag, Br) in nuclear emulsion.

For the incident heavy ion with an LS primary energy $E_b = m_b \cosh y_b$ in the DE interaction of $b + A_t \rightarrow b^* + A_t$, it is straightforward to derive the good approximate expression for m_{b*} from energy-momentum conservation. As shown in the Appendix I,

$$m_{b*} \simeq m_b \left(1 - q_L^2/m_b^2 + 2q_L \sinh y_b/m_b\right)^{1/2} \qquad (1)$$

since the LS energy of b^*, $E_{b*} = m_{Tb*} \cosh y_{b*} = (m_{b*}^2 + q_T^2)^{1/2} \cosh y_{b*} \cong m_{b*} \cosh y_{b*}$ (q_T^2 is extremely small), and the energy transferred from the projectile to the target in the DE process, $\Delta E = E_b - E_{b*}$ ($\simeq q^2/2\, A_t m_N < 0.001$ GeV, m_N being the rest energy of a nucleon) is also negligible. From Eq. (1) for $q_{Lmax} = 0.029$ GeV/c, the values $m_b^*/m_b = 1.03$, 1.12, and 1.36 and $\Delta m = m_{b*} - m_b = 0.447$, 1.764, and 5.289 GeV/c^2, respectively, for 14.6-, 60-, and 200-GeV/nucleon ^{16}O. For $q_{Lmax} = 0.026$ GeV/c, $m_b^*/m_b = 1.0155$ and $\Delta m = 0.404$ GeV/c^2 for 14.6 GeV/nucleon ^{28}Si.

Because $\Delta E < 0.001$ GeV in the DE process, the *formation time* of b* should be as long as 10^{-21} sec, i.e., b^* is a sharp resonant state in the continuum above the ground state b (b^* decays long after passing through the target nucleus).[8] Also, the average of LS rapidities ,$\langle y \rangle$, of its decay particles in the decay process, $b^* \to N_1 + N_2 + \ldots + \pi + \pi + \ldots$, should be $y_{b*}(= y_b - \Delta y)$, where $\Delta y \simeq \ln (m_{b*}/m_b)$, i.e.,

$$\langle y \rangle = \langle \bar{y} + y_{b*} \rangle \simeq y_{b*}, \qquad (2)$$

where $\bar{y}$ is the rapidity in the rest frame of b^* and $\langle \bar{y} \rangle \sim 0$, which essentially comes from the requirement of energy-momentum conservation in the rest system of b^* as stated in detail in Ref. 1 and we would like to assume separately for singly-charged or α fragments in the present experiment. This crucial condition has been proved to be largely valid from our data, as shown later. For q_{Lmax} = 0.029 (0.026) GeV/c, Δy = 0.03 (0.0155), 0.113, and 0.307, for ^{16}O (^{28}Si) of E_b = 14.6, 60, and 200 GeV/nucleon, respectively.

For relativistic heavy ion projectiles with E_b up to 200 GeV/nucleon the process called "electromagnetic dissociation or spallation" has been recently reported[9] to confirm the very existence of the DE process. Furthermore, ^{16}O events of the same DE interactions as in our present experiment were reported by N. Ardito *et al.*,[10, 11]

In Sec. II, experimental materials and methods are explained. In Sec. III, experimental results are presented, and finally discussions and conclusions are described in Sec. IV.

II. Experimental Materials and Methods

Stacks of BR-2 (Fuji ET-7B) emulsion pellicles with dimensions 5 x 10 cm^2 x 600 μm were exposed horizontally at BNL to the 14.6 GeV/nucleon ^{16}O (^{28}Si) beam and at CERN to 60 and 200 GeV/nucleon ^{16}O beams. The emulsions were scanned with typical magnification of 500 x by the along-the-track scanning method. However, most of the 14.6-GeV/nucleon ^{16}O data and all of the ^{28}Si data were obtained using magnifications of 125 x and 750 x, respectively. In tracing 69.31, 72.37, and 67.24 m, for 200-, 60-, and 14.6-GeV/nucleon ^{16}O tracks, respectively, 659 (among them, 187 of $N_h = 0$), 636 (134), and 532 (62) interactions were found and yielded MFP's of 0.105 $\pm$ 0.004 m (1.19 $\pm$ 0.05 b),[13] 0.114 $\pm$ 0.005 m (1.09 $\pm$ 0.04 b), and 0.126 $\pm$ 0.005 m (0.99 $\pm$ 0.04 b), respectively. While in tracing 71.69 m for 14.6-GeV/nucleon ^{28}Si tracks, 737 (137) interactions were found and gave an MFP of 0.097 $\pm$ 0.004 m (1.28 $\pm$ 0.04 b). Main experimental results about 'central collisions' using the ^{16}O part of the present material have been already reported.[12]

Identification of DE events of *soft splitting* of nuclei, such as $^{16}O^* \rightarrow 4\alpha$, $\alpha + {}^{12}C$, $p + {}^{15}N$, $2d + {}^{12}C$, and $^{28}Si^* \rightarrow {}^{24}Mg + \alpha$, $^{27}Al + p$, etc. is routinely achieved by inspection under the microscope only, and the gross features of their decays can be well understood under the premise of Eq. (2). While the average LS rapidity $\langle y \rangle$ of the decay particles of b^* is y_{b*} ($\simeq y_b$), that of shower particles of non-DE events is nearly $y_b/2$.

Nevertheless, in the practical experimental situation, only the LS emission angles θ are readily and accurately known; β is not known. Therefore, to define an LS rapidity $y = \text{arctanh}(\beta \cos\theta)$, y must be approximated by a pseudorapidity $\eta = \text{arctanh} (\cos\theta) = -\ln\tan(\theta/2)$. Facing this difficulty, our analysis makes use of a good approximation,[14] $y \simeq \eta + \ln(p_T/m_T)$. As detailed in Appendix II, fairly large empirical correction factors, $\langle y - \eta\rangle \simeq \langle \ln(p_T/m_T)\rangle =$ 1.61 and 2.71 are deduced,[15] for proton (deuteron, or triton) fragments from the study of singly-charged shower particles,[16] and α fragments,[17, 18] respectively.

Thus, the angular method of Ref. 1 is extended for identifying DE events of *heavy ion beams* in nuclear emulsion with the following conditions. First, (i) instead of the constraint on the second moment of the pseudorapidity distribution in Ref. 1, ["standard deviation" = $\{\Sigma(\eta_i - \langle\eta\rangle)^2/(n_s - 1)\}^{1/2}$],[3] events with charged shower particles of $\sin\theta > 0.4$ are classified as non-DE ones. This is due to the constraint condition of $\Sigma_i \sin\theta_i < 0.4$ of Ref. 2. Second, (ii) the practical constraints,

$$\langle\eta_\alpha\rangle > y_b - \Delta y + 2.71 \qquad \text{for } \alpha \text{ fragments}$$

and (3)

$$\langle\eta_p\rangle > y_b - \Delta y + 1.61 \qquad \text{for p fragments}$$

are applied in place of Eq. (2) for the $N_h = 0$ subgroups of the interactions. (As has been mentioned above, derivation of the constants 2.71 and 1.61 in Eq. (3) is explained in detail in Appendix II.) According to Eq. (3), $\langle\eta_\alpha\rangle > 8.5$, 7.4, and 6.1 and $\langle\eta_p\rangle > 7.4$, 6.3, and 5.0, respectively, for DE events of ^{16}O ions with 200, 60, and 14.6 GeV/nucleon. These are equivalent to the average emission angle $\langle\theta_\alpha\rangle < 0.41$, 1.22, and 4.5 mrad., and $\langle\theta_p\rangle < 1.22$, 3.7, and 13.5

mrad. On the other hand, for non-DE events, $\langle y \rangle \sim y_b/2$ = 3.0, 2.4, and 1.7, i.e., $\langle\theta\rangle \sim$ 0.13, 0.23, and 0.35 rad.[14]

Emission angles θ of singly-charged shower particles and α fragments were measured, typically up to the accuracy of less than 0.1 mrad for 200 GeV/nucleon ^{16}O, mostly with the Koristka R-4 microscopes with a magnification of 1,000 x, with respect to a heavier fragments of Z > 2, to the centroid of the α fragments, or to a single α track in the case of single α track events. In the rest system of their mother nucleus, especially of two-body decays, heavier fragments of Z > 2 are usually emitted with little energy, compared with lighter partner of p or α fragments (Z = 2), and so fly almost in the same direction as the primary projectiles do after interactions.

III. Experimental Data

Table I (a) and (b) summarizes our identified DE events of 200-, 60-, and 14.6-GeV/nucleon ^{16}O ions and 14.6-GeV/nucleon ^{28}Si ions, respectively, by applying the criteria (i), (ii) for each individual interaction. Table I (c) presents a similar summary for 200-GeV/nucleon ^{32}S ions without $\langle\eta\rangle$.[19] In the first column, the modes of decay of b^*, deduced mostly from the charge conservation and topological feature among the decay fragments, are listed and 'nominal threshold energies' of the given decay modes are shown in the parentheses after the modes. In each energy category of 200, 60, and 14.6 GeV/nucleon, the column lists the number of DE events identified, and in Table I (a) and (c), the number of DE events of the corresponding mode in Ref. 11 is presented in parenthesis. In the computation of the thresholds in MeV, the fragments were assumed to have zero kinetic energies in the rest frame of b^* and the adopted mode was assumed to have the least threshold among the possible modes from the given topology.

The following two columns of Tables I (a) and (b) list the averages $\langle\eta_p\rangle$ of the average of pseudorapidities of singly-charged p(d, or t) fragments in an event and that of α fragments $\langle\eta_\alpha\rangle$. The charges $Z > 3$ of heavy fragments of those DE events which had *two decay pions* were especially measured with the method of δ-ray counting, while all the rest of the fragments of $Z > 3$ were not identified specifically through δ-ray counting.

As shown in the Table I, the most determinative constraint on $\langle\eta_p\rangle$ for a DE events is universally met by the data except for two events: An event of $d + \alpha + {}^{10}B$ of 60 GeV/nucleon with $\langle\eta_p\rangle$ =

5.3 (< 6.3) and an another event of 4d + α of 14.6 GeV/nucleon with $\langle\eta_p\rangle$ = 4.6 (< 5.0). We took these two events as DE ones because both of them passed the $\langle\eta_\alpha\rangle$ criterion of Eq. (3). In addition to the 68 events of 200 GeV/nucleon DE events listed in Table I (a), an extra event (2d + 3α ?) had to be included in the calculation of the MFP's of DE processes which, for ^{16}O projectiles, are 1.00 ± 0.12 m (125 ± 15 mb),[13, 20] $2.4^{+1.6}_{-0.7}$ m (52 ± 15 mb), and 2.2 ± 0.4 m (56 ± 10 mb) for 200, 60, and 14.6 GeV/nucleon, respectively.

For ^{28}Si, the only event of the mode, 3α + 9p was hard for us to identify, because all the possible decay modes of $^{28}Si^*$ violated charge and nucleon conservation. Fig. 1 displays the distribution of ($\langle\eta_\alpha\rangle - y_b$) in the upper half and that of ($\langle\eta_p\rangle - y_b$) in the lower half of 135 N_h = 0 ^{28}Si events, where open squares for the 46 DE events and filled squares show the non-DE events. The average pseudo-rapidities, $\langle\eta_\alpha\rangle$ of the DE events tend to be slightly larger than those of non-DE events, but they are all larger than the limit imposed by Eq. (3), which is shown as an arrow in the figure. As the distribution of ($\langle\eta_p\rangle - y_b$) shows in the lower half of Fig. 1, where the arrow indicates the condition of limits imposed by Eq. (3), seperation of DE and non-DE interactions of the 135 N_h = 0 events of 14.6-GeV/nucleon ^{28}Si is clearly feasible. Including the event of 3α + 9p, the MFP of ^{28}Si at 14.6 GeV/nucleon was obtained as 1.09 ± 0.13 m (114 ± 14 mb).

The 'apparent' MFP versus the primary energy E_b is plotted in Fig. 2. Since detection efficiency is not assessed and modes which include decay neutrons or neutral pions are not included, the 'apparent' MFP's should be taken as upper-limit values.

Figure 3 shows the proportion of decay modes of $^{16}O^*$ among three intervals, 0 - 30, 30 - 60, and 60 - 90 MeV of the 'nominal threshold energy' for all the DE events (excluding those with two pions) in Table I using filled circle for 14.6 GeV/nucleon, shaded ones for 60 GeV/nucleon and unfilled circles for 200 GeV/nucleon. No strong dependence of the proportion on E_b is noticed in Fig. 3. In the range of E_b = 14.6 - 200-GeV/nucleon for ^{16}O, the dependence on the nominal threshold energy seems to be approximately the same for the various breakup channels.[21] The solid line histogram is our combined result for ^{16}O ions and displays the *rough* trend of exp{a Δm + b} with a = - 0.025 $\pm$ 0.005 (χ^2/DOF = 7/1), while the broken-line histogram represents the recent combined data of DE events of Ref. 11 in Table I with a = -0.036 $\pm$ 0.003 (χ^2/DOF = 16/1). Figure 4 displays proportion of occurrence of decay modes in terms of 'nominal threshold energy' for the intervals, 0 - 30, 30 - 60, and 60 - 90 MeV by unfilled circles for the 14.6-GeV/nucleon ^{28}Si data with the *rough* trend of exp {a Δm + b} with a = -0.025 $\pm$ 0.008 (χ^2/DOF = 2/1). Included in the same plot are the proportion of decay modes for the combined data of 14.6-, 60-, and 200-GeV/nucleon ^{16}O from our data plus the massive data of Ref. 11 with a = -0.034 $\pm$ 0.003 (χ^2/DOF = 21/1) as shown by the filled circles and for the same authors, data of 200-GeV/nucleon ^{32}S for the four intervals, 0 - 30, 30 - 60, 60 - 90, and 90 - 120 MeV with a = -0.036 $\pm$ 0.003 (χ^2/DOF = 7/2) as shown by the shaded circles.

IV. Discussions and Conclusions

In the present experiment by use of a new powerful angular method for identifying DE events of projectile heavy ions in nuclear emulsion, *firstly*, preliminary trends of high-energy augmentation of DE process may be concluded. Due to the factor of sinh y_b ($\simeq \gamma_b$ for the large Lorentz factor γ_b), Eq. (1) shows that, even with a longitudinal momentum transfer of as small as ~ 0.03 GeV/c, a few excited states of high mass m_{b*} can be reached from the ground state of a projectile beam nucleus, as the primary rapidity y_b (i.e., E_b) becomes large (see Appendix I).

Secondly, as shown in Figs. 3 and 4, almost all the possible modes of decay, up to several hundreds of MeV/c^2 of Δm are found to occur independently of the kind of incident projectile heavy ion b and its incident energy E_b and with exponentially decreasing trend with almost the same exponential index a = (-0.2) - (-0.3),[22] i.e., the higher the mass of b^* is, the harder it becomes to produce. Further, the fact that the proportions of various breakup channels of b^* (except those with pion production) seem to have no dependence on E_b for the soft-breakup processes reminds us that, because of Eq. (1) as well as the above considerations, the distribution of Δm reflects that of the longitudinal momentum transfer to the target nucleus q_L ($\simeq (m_{b*}{}^2 - m_b{}^2)/2E_b \simeq (m_{b*} + m_b)\Delta m/2m_b\gamma_b \simeq \Delta m/\gamma_b$). Since the distribution of $\gamma_b q_L \simeq \Delta m$ is independent of γ_b, the DE process requires *less* q_L for *larger* γ_b.

Thirdly, as seen from Figs. 3 and 4, at least 60 - 70 % of DE events are those with the removal of a proton or an α fragment from the projectile ($\Delta Z \leq 2$), which supplements the extensive informations obtained from other experiments involving fragmentation or DE processes.[9]

In this context, there have been the past investigations of keen interest about high energy μ-emulsion interactions,[23 - 25] since the electromagnetic field of a muon will induces soft-breakup of C, N, O, Ag, Br nuclei in nuclear emulsion which must be the inverse of the projectile DE (the *'target'* DE) of the present experiment in the anti-laboratory system (ALS). And about 80% of them must be in the form[3] of (1 + 1) with emission of an α or p with $\theta \sim 90^{o}$ in the LS. Ref. 25 clearly gives the impression of abundant and enhanced production of pions with 150-GeV μ^{+} jets,[25] which may correspond to the formation of a Δ by the 'target' DE process in the ALS and coincides with our present experiment as opposed to 5 GeV/c,[23] 10.1- and 15.8-GeV μ jets.[24]

Also, many semi-classical calculations based on the Weizsacker-Williams method for virtual photons[26] have been done to obtain the cross sections of electromagnetic dissociations (see, for example, Refs. 9 and 27). But to our knowledge, no serious theoretical calculations to attack the DE processes fully have been done (see Appendix I).[28]

Fourthly, the majority of DE events of soft splitting of incident heavy ions in our data may be attributed to the Coulomb interactions as well as to 'grazing' nuclear collisions. Sixty-four events, out of a total of the 69 events of 200-GeV/nucleon ^{16}O (68 events, listed in Table I, plus one extra event), for example, belong to this catagory. On the other hand, the remaining five *high-energy* DE events of 200 GeV/nucleon (and one DE event of 60 GeV/nucleon and none in the data of 14.6 GeV/nucleon events) with two decay pion, which were not particularly investigated in Refs. 9 - 11, should be attributed to the onset of some 'new' contributions. An indication of a drastic increase of DE events with the fragmentation plus the emission of an additional two pions from E_b = 14.6 GeV/nucleon to 200 GeV/nucleon coincides with that of DE events from 30 to 400-GeV protons[1] where a Δ resonance may be involved primarily (also Δ production in the LS by muons as mentioned above, see Appendix I).

The implication of the present experiment might be summarized well by use of the uncertainty relation both in the transverse and longitudinal directions: When the interacting two nuclei are viewed as *two whole entities* having the *largest* dimensions of their hierarchy among our three points of view for looking at a nucleus —— a) as a whole entity in decay and excitation, neglecting the size of a nucleon, (b) as an aggregate of A_b and A_t nucleons individually, and (c) as an aggregate of quarks and gluons —— their 'interaction' radius must be the order of $R \simeq (A_b^{1/3} + A_t^{1/3})/m_\pi$ so that

$$q_T R \sim 1 \tag{4}$$

from the diffractive condition, and, since the distribution of $\Delta m \simeq \gamma_b q_L$ seems almost independent of the incident energy E_b and the mass of the projectile A_b,

$$\gamma_b q_L R' \sim 1, \tag{5}$$

where $R' \simeq R/\gamma_b$, the Lorentz-contracted size of the target nucleus as seen by the incident heavy ion, which quarantees $q_L R \sim 1$. This condition has been the starting point of defining DE process and has been retrieved as the concluding one from the data of Δm-distribution. The next *smaller* ladder of hierarchy, (b), of looking at A_b and A_t nucleons individually is to take them as two aggregates of $(A_b + A_t)$ nucleons, interacting individually. In these interactions between a nucleon and another nucleon,

$$q_{TN}R_N \sim 1, \tag{4'}$$

where the size of a nucleon $R_N \sim 1/m_\pi$, and

$$\gamma_b q_{LN} R'_N \sim 1, \tag{5'}$$

indicating $\Delta m_{bN} \simeq \gamma_b q_{LN}$ which is an order of magnitude larger than the values involved in two collisions of two whole nuclei in the first ladder of the hiearchy (a). The fact that the MFP (of ~ 0.1 m for 200 GeV/nucleon ^{16}O) of DE interactions with pion production is the same order as that (of ~ 0.2 m for 200 GeV proton) of (0 + 3) events in the high-energy proton-emulsion collsions[1] convinces us of this point. The excitation and decay of the baryon multiplets involve hundreds of MeV. Thus, we may have two kinds of soft processes of DE interactions, with and without pion production, which are distinctively different from the third *smallest* ladder of hierarchy (c) —— looking at an interaction of two nuclei as quark-quark interactions with 'multiple' production of medium and high p_T —— whose aspects and properties were exploited preliminarily by our group.[29]

For one direct application of the DE process, we may be able to explain the puzzle of the cosmic ray Physics: The Centrauro events observed in emulsion chambers exposed to cosmic rays[30] are very high energy events characterized by a very large multiplicity of *hadrons* and a multiplicity of electromagnetic showers that is consistent with zero.[31] Hadron parts would be observed decay fragments produced in DE interactions of heavy primary cosmic rays ($Z > 1$) without producing any *pion* components, among which π^o's give rise to electromagnatic showers from $\pi^o \longrightarrow 2\gamma$.

In view of recent advances in accelerating heavy ions at the BNL AGS, CERN SPS and in the future at the BNL RHIC, the aspect of high energy DE interactions will provide an opportunity for study of clean breakups of high-mass excited states of various beam nuclei of the 'LS' lifetimes $\simeq 10^{-21}$ seconds or longer (see Appendix I). Further, as far as kinematics are concerned and *contrary* to the common belief that "deconfinement" will occur only in central collision, the high-mass state of $m_{b*} > 10\ m_b$, especially because of its long lifetime in order to attain equilibrium state in the whole system of nucleon of the same size with the "higher" energy density, will be able to be produced copiously in the CERN SPS and BNL RHIC colliders for the investigation of the "deconfinement phase transition" of nuclei through the DE process.[5]

ACKNOWLEDGEMENT

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APPENDIX I

Derivation of Eq. (1) and the diffractive excitation(DE) process

Essentially with the same argument as in Ref. 1, Eq. (1) is derived in the following. For an incident beam particle with LS primary energy $E_b = m_b \cosh y_b$ in the quasi-two-body (DE) interaction

$$b + A_t \;\text{--->}\; b^* + A_t \qquad \text{(A1)}$$

where A_t stands for the constituent target nucleus of mass number A_t in nuclear emulsion, the LS energy of the high mass state b^* becomes $E_{b*} = (m_{b*}^2 + q_T^2)^{1/2} \cosh y_{b*} \simeq m_{b*} \cosh y_{b*}$. Because of the 'diffractive' condition (or equivalently, the uncertainty relation) of the process (A1),

$$q_T R \simeq 1, \qquad \text{(A2)}$$

where q_T is the transverse momentum transfer to the target nucleus and R, the 'interaction' nuclear radius obtained by looking at the incident and target nuclei as one entity. Thus, we may assume $R \sim (A_b^{1/3} + A_t^{1/3})/m_\pi$ ($1/m_\pi \simeq 1.41$ fm, numerically) and $q_T^2/2A_t m_N < 0.001$ GeV, which guarantees the last step of the approximation involved in E_{b*} in the above. Further, the condition[6, 7] relating the longitudinal momentum transfer q_L to the target and R,

$$q_L R \ll 1 \qquad \text{(A3)}$$

amounts to "virtuality (or coherence)" with respect to the individual constituents of b.

Thus, from the energy conservation equation for process (A1), we have

$$E_b + A_t m_N = E_{b*} + (A_t m_N + T_A) \qquad (A4)$$

which is equivalent to

$$m_b \cosh y_b \simeq m_{b*} \cosh y_{b*} \qquad (A5)$$

to a good approximation in the DE process since the nuclear recoil kinetic energy plus the energy transferred to the internal restructuring of b*, if there is any, $T_A = q^2/2A_t m_N < 0.001$ GeV can be neglected due to Eqs. (A2) and (A3).

For interactions of $E_b > 10$ GeV/nucleon (or 10 GeV for a hadron), Eq. (A5) can be well approximated as $m_b(\exp y_b)/2 \simeq m_{b*}(\exp y_{b*})/2$, indicating

$$\Delta y = y_b - y_{b*} \simeq \ln(m_{b*}/m_b). \qquad (A6)$$

Now, secondly from the conservation of longitudinal momenta for the process (A1), we have

$$p_b = p_{b*L} + q_L \qquad (A7)$$

which corresponds to

$$m_b \sinh y_b = (m_{b*}^2 + q_T^2)^{1/2} \sinh y_{b*} + q_L$$
$$\simeq m_{b*} \sinh y_{b*} + q_L. \qquad \text{(A8)}$$

Multiply both sides of Eqs. (A4) and (A8) by $\cosh y_b$ and $\sinh y_b$, respectively, and subtracting the two resulting equations, we have

$$m_b + q_L \sinh y_b \simeq m_{b*} \cosh(-\Delta y). \qquad \text{(A9)}$$

Also multiplying both sides of these same equations by $\sinh y_b$ $\cosh y_b$ and subtracting the two resulting equations, we have

$$q_L \cosh y_b \simeq m_b \sinh(\Delta y) \qquad \text{(A10)}$$

After squaring Eq. (A9) and Eq. (A10), we add the two resulting equations to obtain Eq. (1)

$$m_{b*} \simeq m_b (1 - q_L^2/m_b^2 + 2q_L \sinh y_b/m_b)^{1/2}$$

in the text.

Now to understand the mechanism how large mass m_{b*} can be created from the projectile of mass m_b *without transfering large energy* (in fact, little energy) to the target nucleus, our picture of these DE process at high energy attribute it to the intrinsic "wave" nature of the incident and the *diffracted* beam. The diffractive condition of Eq. (A1), $q_T R \simeq 1$, implies the deviation angle of $\theta_{b*}(\neq 0)$ for b^*, since $q_T = q \sin \theta_{b*}$.

From Eq. (A5), where $y_{b*} = \tanh^{-1} (\beta_{b*} \cos \theta_{b*})$,[14] $\cos \theta_{b*} < 1$

(and $\beta_{b*} \simeq \beta_b \sim 1$) assures $y_{b*} < y_b$ ($\Delta y \simeq y_b - y_{b*} = \ln(m_{b*}/m_b) > 0$) and consequently $m_{b*} > m_b$ from the approximate equality of Eq. (A5). Thus, we insist that the increase of m_{b*} (as much as up to $m_{b*} \simeq 10m_b$ easily at RHIC energy) comes from the intrinsic wave nature due to the opaque or semi-opaque disk represented by the target nucleus. In other words, the *relativistic* effect played the cardinal role of increasing the rest mass of projectile nucleus. Thus, the large mass excitation with the small momentum transfer(or energy transfer) to the target, i.e., Δm (in GeV/c^2) >> ΔE (in GeV) of our picture, may imply that the prevailing calculation of electromagnectic dissociation may be at fault *especially* at *large* sinh $y_b (\simeq \gamma_b)$, since the authors in Ref. 9 assume Δm (in GeV/c^2) $\sim \Delta E$ (in GeV) universally. There are two consequences which can be checked experimentally: The first is the high-energy augmentation of DE process because, for us, it would require less q_L and the absorption of the lower-energy ($E_\gamma < 1$ MeV) part of the virtual-photon spectrum($\propto \ln\gamma_b Z_T^2/E_\gamma$) than for the authors of Ref.9 ($E_\gamma \simeq 10 - 30$ MeV), even in using the Weizacker-Williams method[26] for the electromagnetic contribution of the DE process (the predominant dependences on $A_t^{1/3}$ and Z_T have been well investigated by J. Barrette *et al.* in Ref. 9). In this respect, our observation of increase in DE interactions *with pions* for large γ_b supports our view, since they involve $E_\gamma > 280$ MeV and can not be produced directly by the giant dipole resonance of $E_\gamma \simeq 10 - 30$ MeV. The preliminary evidence of abundant production of Δ for high-energy μ (as it should) in nuclear emulsion,[23 - 25] will also support our view since Δm ($\simeq 200$ GeV/c^2) $> \sim 20$ MeV, which should be the energy that the predominant role of giant dipole resonance is solely assumed. For the μ, it will be far more important to investigate this phenomena further, since the DE processes is induced due purely to electromagnetic field. This is more so since $\Delta m \simeq \gamma_b q_L$ remains independent of E_b from our observation.

The second consequence may be for us to prove the existence of b^* states with their long LS lifetimes $\simeq 10^{-21}$sec in the *continuum, which is partially proven by our data indicating the universal validity of Eq. (3).*
Since our observed lifetime is $\gamma_b\tau \simeq 10^{-21}$ sec, more states with the intrinsic *short* lifetime τ will be allowed to leave and to decay outside the target, where the very DE interactions take place, as γ_b increase. For example, in order to create Δ *on the mass shell*, γ_b must be fairly large, which is the alternative way of explaining seeing the DE process.

APPENDIX II

The Relation between LS rapidity y and Pseudorapidity η

There has been a good approximate relation between the LS rapidity y and the pseudorapidity η, $y \simeq \eta + \ln(p_T/m_T)$.[14] The parameter $u = p_T/m_T$ ($= \exp(y - \eta)$) can also be expressed as $u = \bar{\gamma}_b \bar{\beta}_b \sin\bar{\theta} \simeq \bar{\beta}_T$ for p or α fragments in the rest system of incident heavy ions (the antilaboratory system, ALS) and, since $\bar{\beta} \ll 1$, $\bar{\gamma} \sim 1$ for p or α fragments.[21] As shown for 2,188 α fragments produced in Fe - C and Fe - Pb collisions at 1.88 GeV/nucleon,[17] the inclusive distribution of $\bar{\beta}_T \simeq u$ may be well expressed by

$$dN = \exp(\ c + \kappa/\bar{\beta}_T\ )\ d(1/\bar{\beta}_T) \qquad \text{(A11)}$$

with $\kappa = 0.0457 \pm 0.0011$. On the other hand, the relation

$$\exp(\ \eta - y_b\ ) = \exp[(y - y_b) - (y - \eta)]$$

becomes

$$\exp(\ \eta - y_b\ ) \simeq 1/u \simeq 1/\bar{\beta}_T,$$

since $\langle y - y_b \rangle = \langle \bar{y} \rangle = 0$ on the average, individually for each interaction in the ALS. Thus, in terms of $\exp(\eta - y_b)$, Fig. A1 shows frequencies of occurrence of the α fragments, produced in 135 $N_h = 0$ interactions of 14.6-GeV/nucleon ^{28}Si nuclei in nuclear emulsion,[16] (filled circles), and 344 interactions of 1.88-GeV/nucleon ^{56}Fe nuclei in nuclear emulsion[18] (unfilled circles), which gave, respectively, $\kappa = 0.050 \pm 0.006$ and 0.048 ± 0.003(χ^2/DOF = 9/5 and 24/8 for the fits). The combined value of $\kappa = 0.046 \pm 0.0010$ from the above three data attests the 'limiting fragmentation'.[15, 32]

By combining Eqs. (3) and (6) of Ref. 17, the median angle $\theta^{1/2}$ is obtained as $(\cot\theta)^{1/2} = \ln(2\gamma_b\beta_b/\kappa)$, which give $\theta^{1/2} =$ arc $\cot[(\cot\theta)^{1/2}]$ the with plausible assumption of $\gamma\beta \simeq \gamma_b\beta_b$. Thus we obtain $< \ln u > = 2.71$.

As for singly-charged shower particles, there are roughly two kinds of produced secondaries: p (possibly d or t) fragments and pions (or kaons) of 'pionization'. In view of our success of finding a law of emission, for α fragments, Eq. (A11), shown in Fig. A1 and in Ref. 16, the differential frequency of occurrence of singly-charged shower particles, produced in 135 14.6 GeV/nucleon ^{28}Si nuclei in nuclear emulsion,[16] is shown in Fig. A2 in terms of $\exp(\eta_p - y_b)$. The general trends can be well fitted with two linear regression functions in the semi-log plots, resulting in the best fitted values of $\kappa = -2.5 \pm 0.2$ (χ^2/DOF = 2/7 for the interval, $0.1 < \exp(\eta_p - y_b) < 1$) and $\kappa = -0.138 \pm 0.008$ (χ^2/DOF = 13/14 for the interval, $2 < \exp(\eta_p - y_b) < 34$). From the latter value of κ, we obtained, as in the above for α fragments, $< \ln u > = 1.61$.

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Conference on High Energy Physics, Singapore, 2 - 8, August 1990.

+A visiting professor at LSU from Korea Univ. (Aug., 1987 - May, 1988).

++KOSEF fellow (1987 - 1988) on leave of absence at LSU from Gyeongsang National Univ., (Dec., 1987 - Dec., 1988).

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[19]Selection of DE events in Ref. 11 was carried out not exactly by our present mothod of applying the criteria of Eq. (3), and, nevertheless, the *same* trends of the Δm distribution as ours are shown in Fig. 4. As stated in the text (II), identification of DE events can be routinely achieved by inspection under the microscope only.

[20]In m, our values of MFP for the various channels coincide largely with those of Ref. 10, as seen in Table I. However, there is no available data from experiments other than those in nuclear emulsion that can be compared directly with our results. To an order of magnitude, our results match favorably also with $\sigma(^{16}O$ - Al at 200 GeV/nucleon) of the counter experiments by P. D. Barnes *et al.*, Phys. Lett. B206, 146 (1988).

[21]There is one exception seen in Table I (a), due probably to the detection efficiency: The ratio of frequency of the mode p + ^{15}N to that of α + ^{12}C is 4 ~ 5 at 200 GeV/nucleon but only 0.4 at 14.6 GeV/nucleon. The detection efficency of the latter mode should be ~ 100 %, while the usage of 125 x magnification at 14.6 GeV/nucleon might have hindered full detection of the minimum-ionizing particle of p for the former mode. In addition to the fact that their emission angles θ_p at 14.6 GeV/nucleon are fairly large, which makes their detection harder. Nevertheless, because we used 750 x magnification, the same is not true for 14.6 GeV/nucleon ^{28}Si, as seen from Table I (b). The ratio of the frequency of the mode p + ^{31}P to that of α + ^{28}Si in Table I (c)

is more than 10. This is definitely proven by J. Barrette *et al.*, in Ref. 9.

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Table I (continued)

(b) ^{28}Si

E_b(GeV/nucleon)	14.6		
MODE		$\langle\langle\eta_p\rangle\rangle$	$\langle\langle\eta_\alpha\rangle\rangle$
^{24}Mg+α(10.0)	4		6.8
^{27}Al+p(11.6)	15	5.8	
^{20}Ne+2α(19.8)	2		6.2
^{23}Na+α+p(21.7)	4	6.2	6.4
^{16}O+3α(24.0)	1		6.6
^{20}Ne+Li+p(36.7)	1	7.9	
^{20}Ne+α+2d(43.2)	1	5.2	6.2
^{23}Na+2d+p(45.6)	3	5.9	
^{16}O+2α+2d(47.9)	1	6.0	6.6
^{24}Mg+2d(48.7)	10	6.1	
^{14}N+2α+3d(68.6)	2	5.1	6.5
^{16}O+α+4d(71.8)	1	5.7	15.6
3α + 9p	1	5.4	7.2

(c) ^{32}S (Ref. 11)

E_b(GeV/nucleon)	200
MODE	
^{28}Si+α(6.949)	(12)
^{31}P+p(8.865)	(150)
^{27}Al+α+p(18.532)	(11)
^{23}Na+2α+p(28.625)	(2)
^{28}Si+2d(30.797)	(52)
^{24}Mg+α+2d(40.781)	(4)
^{27}Al+2d+p(42.383)	(8)
^{23}Na+α+d+t(46.996)	(1)
^{19}F+2α+2d+p(62.939)	(2)
^{24}Mg+4d(64.629)	(3)
^{20}Ne+α+4d(73.984)	(1)
^{16}O+2α+4d(78.672)	(2)
^{19}F+α+4d+P(86.787)	(1)
^{20}Ne+6d(97.832)	(1)
^{14}N+2α+5d(99.408)	(1)
^{16}O+α+6d(102.512)	(2)
^{12}C+^{7}Li+α+4d+p(103.182)	(1)
^{12}C+2α+6d(109.682)	(3)
^{7}Li+4α+4d+p(110.457)	(1)

Table I. The number of *identified* DE events.

(a) ^{16}O

E_b(GeV/nucleon)	200			60			14.6		
MODE		$\langle\langle\eta_p\rangle\rangle$	$\langle\langle\eta_\alpha\rangle\rangle$		$\langle\langle\eta_p\rangle\rangle$	$\langle\langle\eta_\alpha\rangle\rangle$		$\langle\langle\eta_p\rangle\rangle$	$\langle\langle\eta_\alpha\rangle\rangle$
$\alpha+^{12}C$(7.2)	6(37)		9.2	2		8.2	12		6.3
$p+^{15}N$(12.1)	25(194)	8.7		3(5)	7.5		5	5.4	
4α(14.4)	3(5)		9.4	1		8.8	1		7.4
2d+C(31.8)	11(50)	7.8		-(3)			2	5.6	
p+2α+Li(31.8)	1(4)	7.8	9.2	1	7.4	8.0	-		
$d+\alpha+^{10}B$(32.4)	6(13)	7.8	8.8	1	5.3	8.6	5	5.8	6.6
$^{3}He+\alpha+^{9}Be$(33.4)	1(1)		8.9	-			-		
2d+3α(38.3)	4(19)	8.1	9.9	1	7.5	7.8	2	5.6	7.4
2d+α+Be(38.9)	2(5)	8.4	9.1	-			-		
$p+2d+^{11}B$(47.0)	-(3)								
p+2d+α+Li(55.6)	-(4)			-			1	5.2	6.9
4d+2α(62.1)	2(11)	7.8	9.3	-			1	4.6	6.5
p+4d+Li(79.5)	1(1)	7.3		-			-		
6d+α(86.0)	1(2)	8.3		1(1)	6.6		2	5.0	
p+N+2π(>320)	1	8.2		-			-		
2d+C+2π(>320)	1	7.5		-			-		
2d+3α+2π(>320)	2	7.8	10.0	1	6.3	7.3	-		
3d+α+Li+2π(>320)	1	7.5	8.3	-			-		

Figure Captions

Fig. 1. Distributions of $\langle\eta_p\rangle$ and $\langle\eta_\alpha\rangle$.

Fig. 2. The 'apparent' DE MFP in m versus E_b.

Fig. 3. Proportion of decay modes according to the 'nominal threshold energy' for $^{16}O^*$. Filled circle, shaded one, and unfilled one, respectivly, for 14.6, 60, and 200 GeV/nucleon.

Fig. 4. Proportion of decay modes according to the 'nominal threshold energy'.

Fig. A1. Frequencies of occurrence of a fragments versus $\exp(\eta_\alpha - y_b)$ in nuclear emulsion.

Fig. A2. Frequencies of occurrence of singly-charged secondaries of 14.6-GeV/nucleon ^{28}Si in nuclear emulsion.

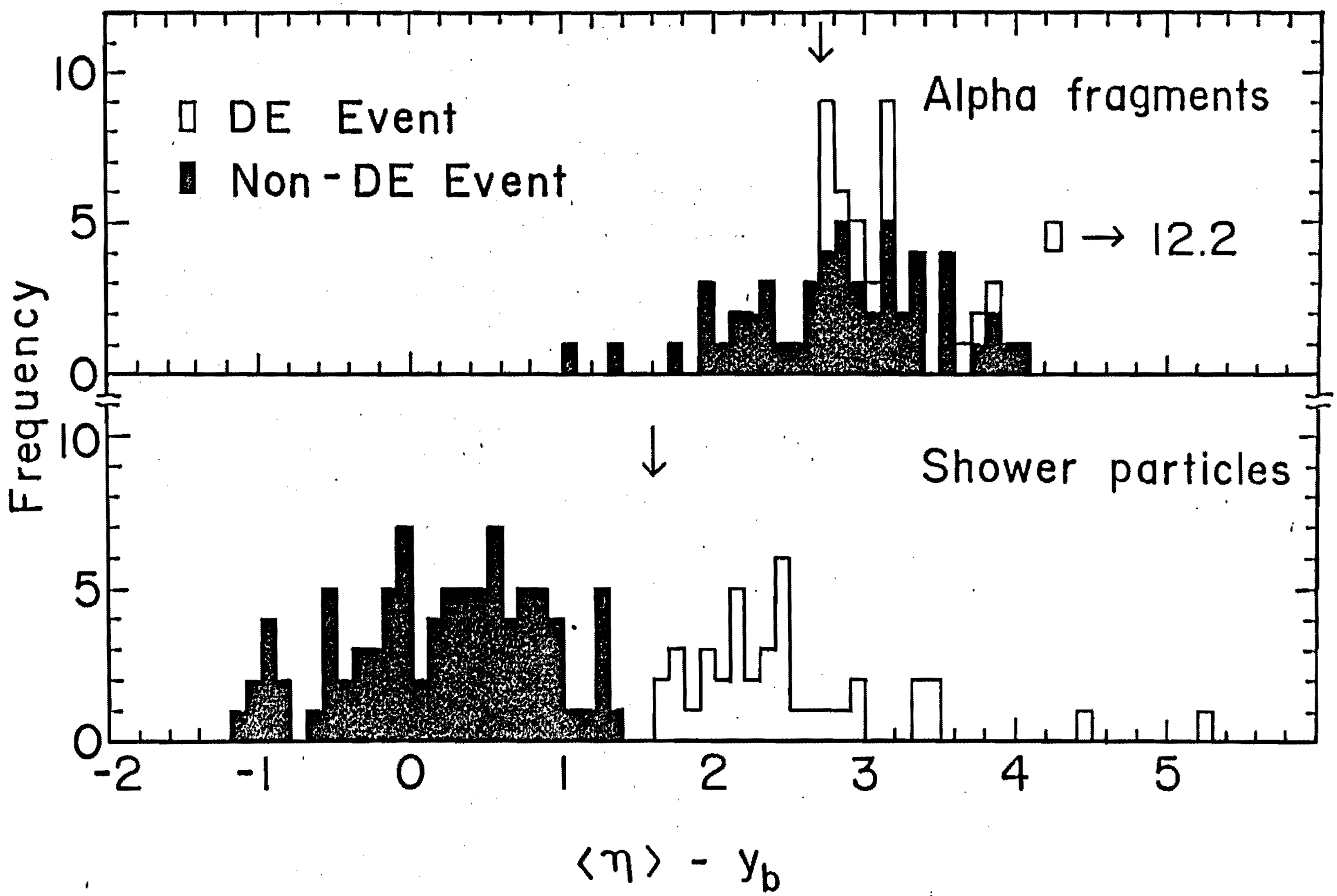
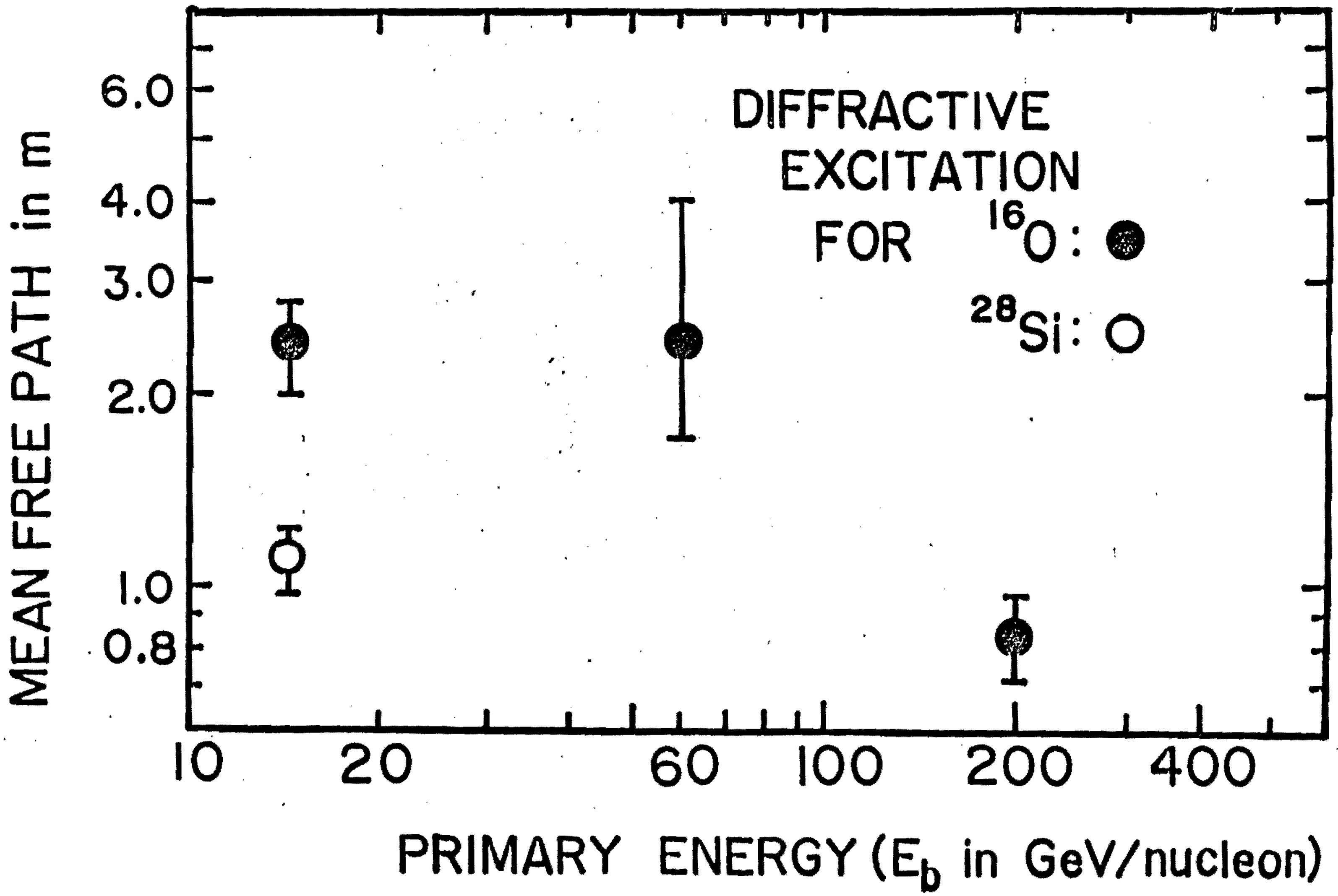
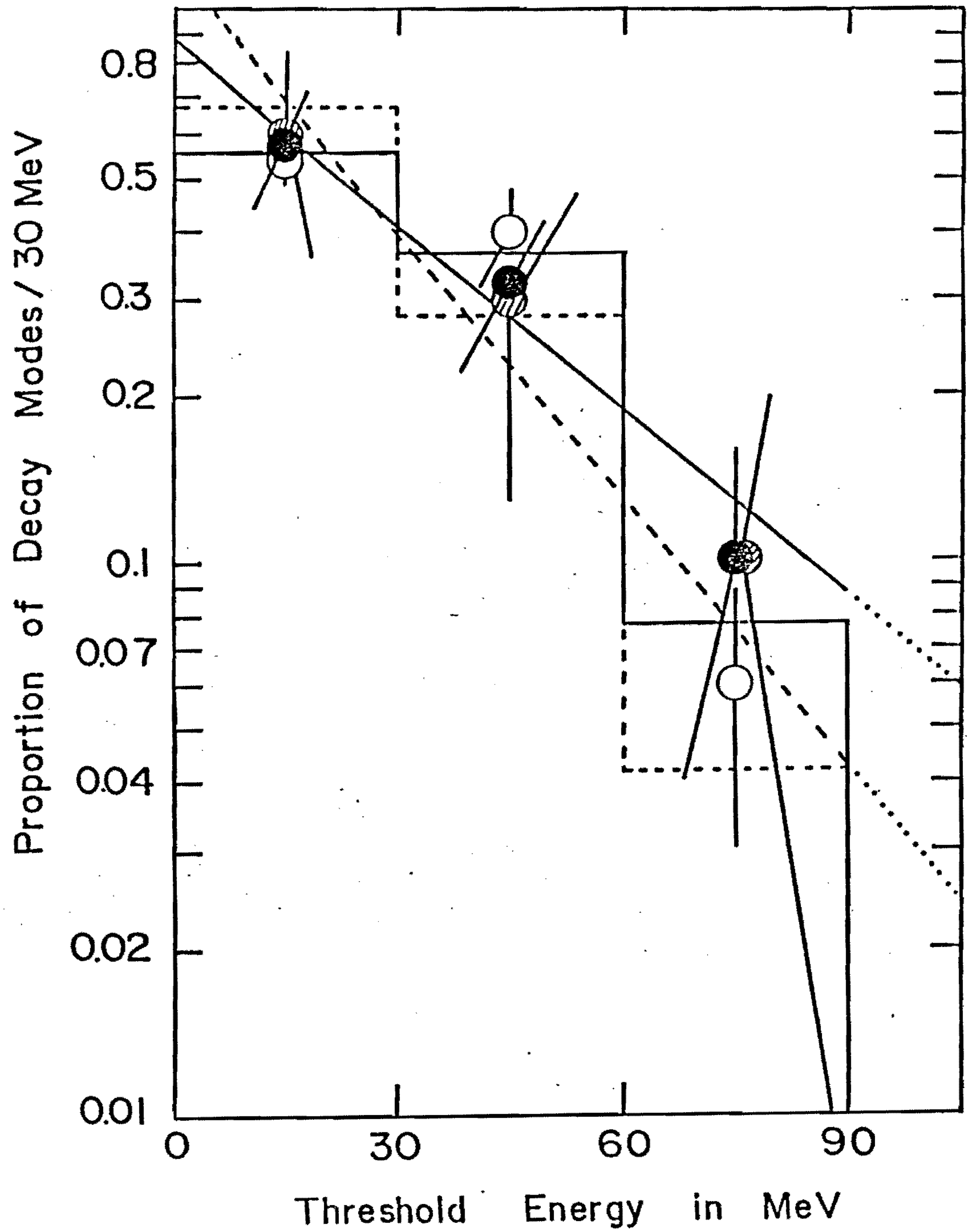

Frequency
10
5
0
DE Event
Non-DE Event
Alpha fragments
→ 12.2
Shower particles
-2
-1
0
1
2
3
4
5
⟨η⟩ - y_b

Fig. 1



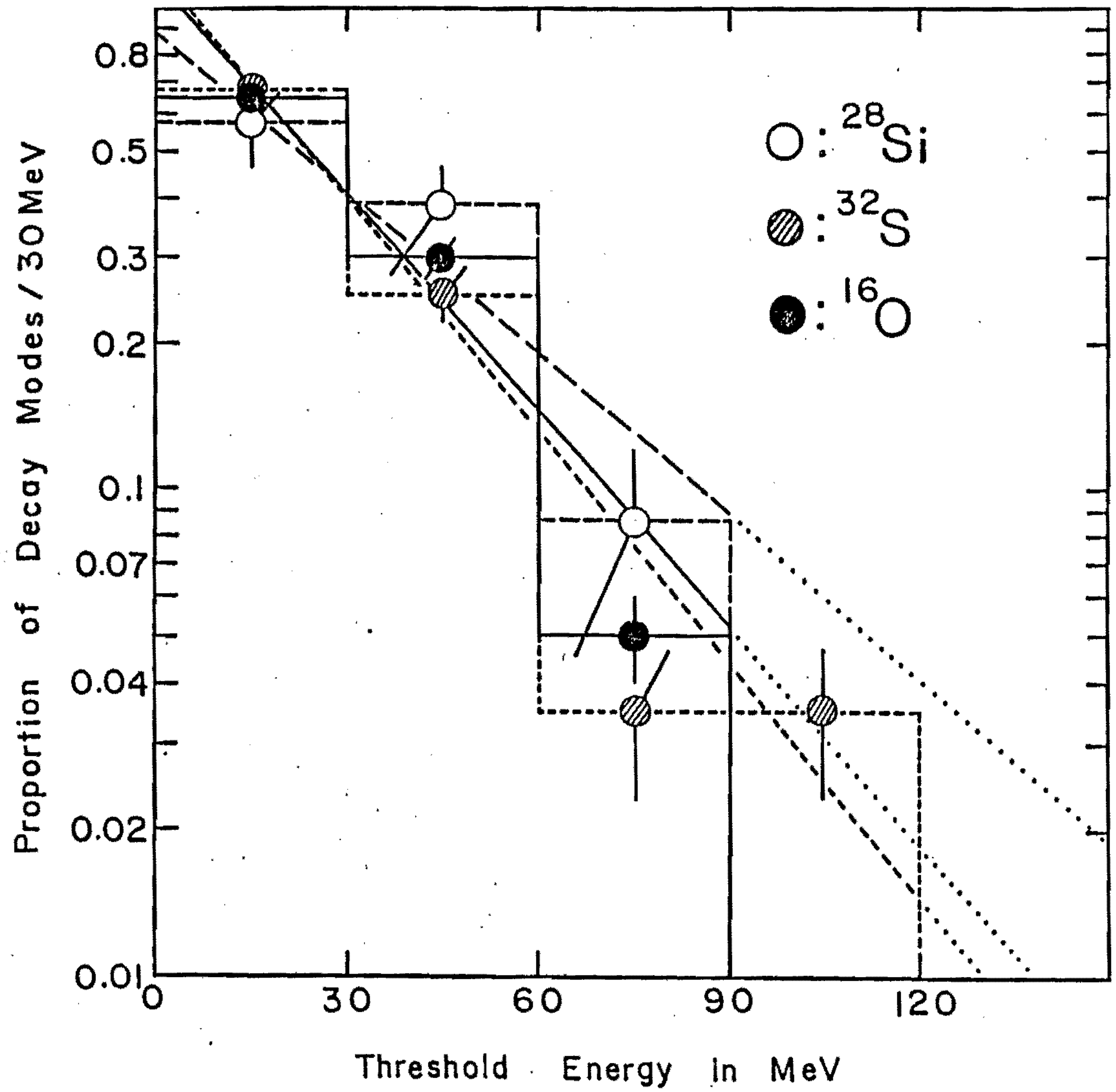
DIFFRACTIVE EXCITATION FOR
16O:
28Si:
MEAN FREE PATH in m
6.0
4.0
3.0
2.0
1.0
0.8
10
20
60
100
200
400
PRIMARY ENERGY (Eb in GeV/nucleon)

Fig. 2



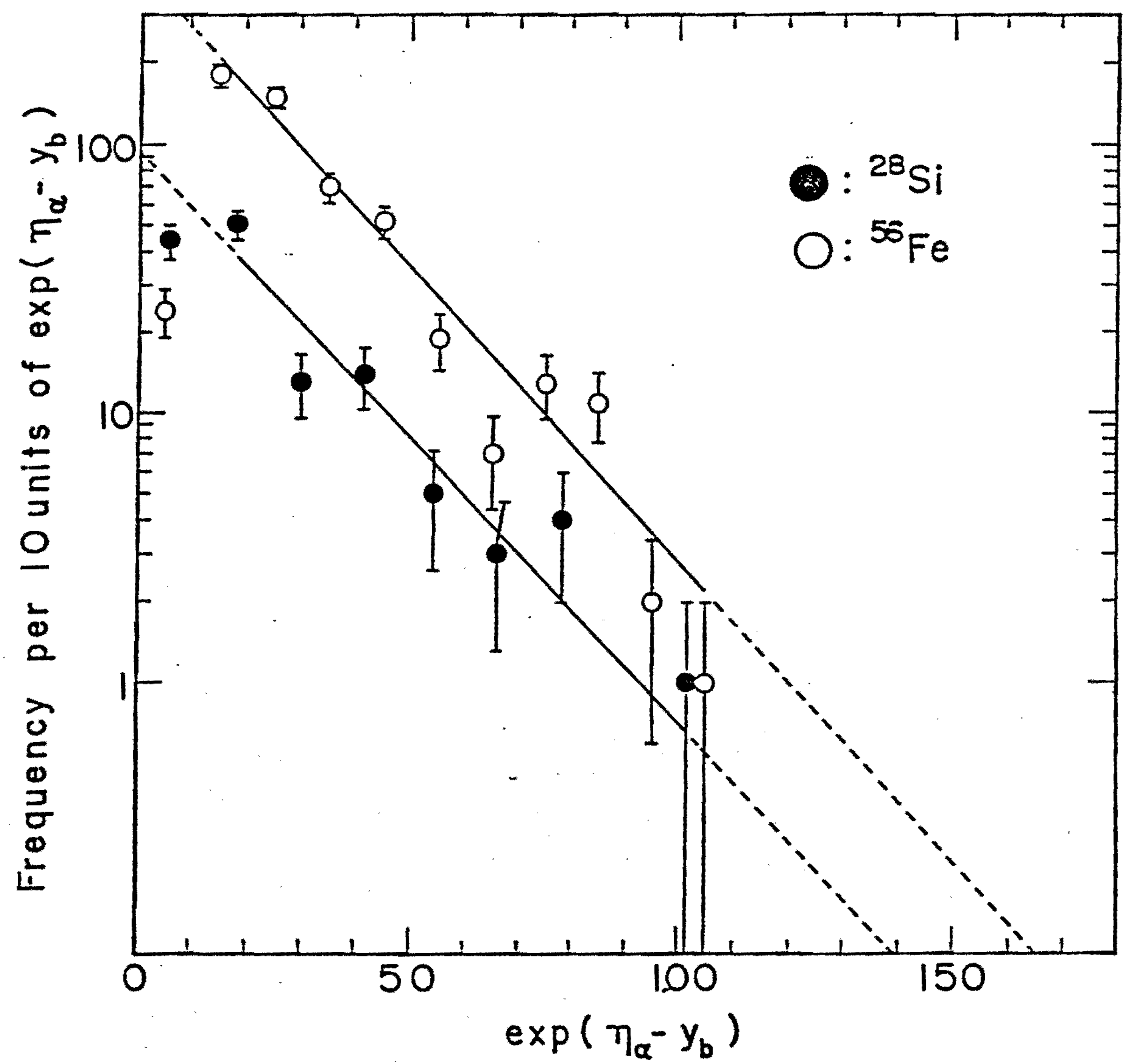
0.8
0.5
0.3
0.2
0.1
0.07
0.04
0.02
0.01
Proportion of Decay Modes / 30 MeV
0
30
60
90
Threshold Energy in MeV

Fig. 3



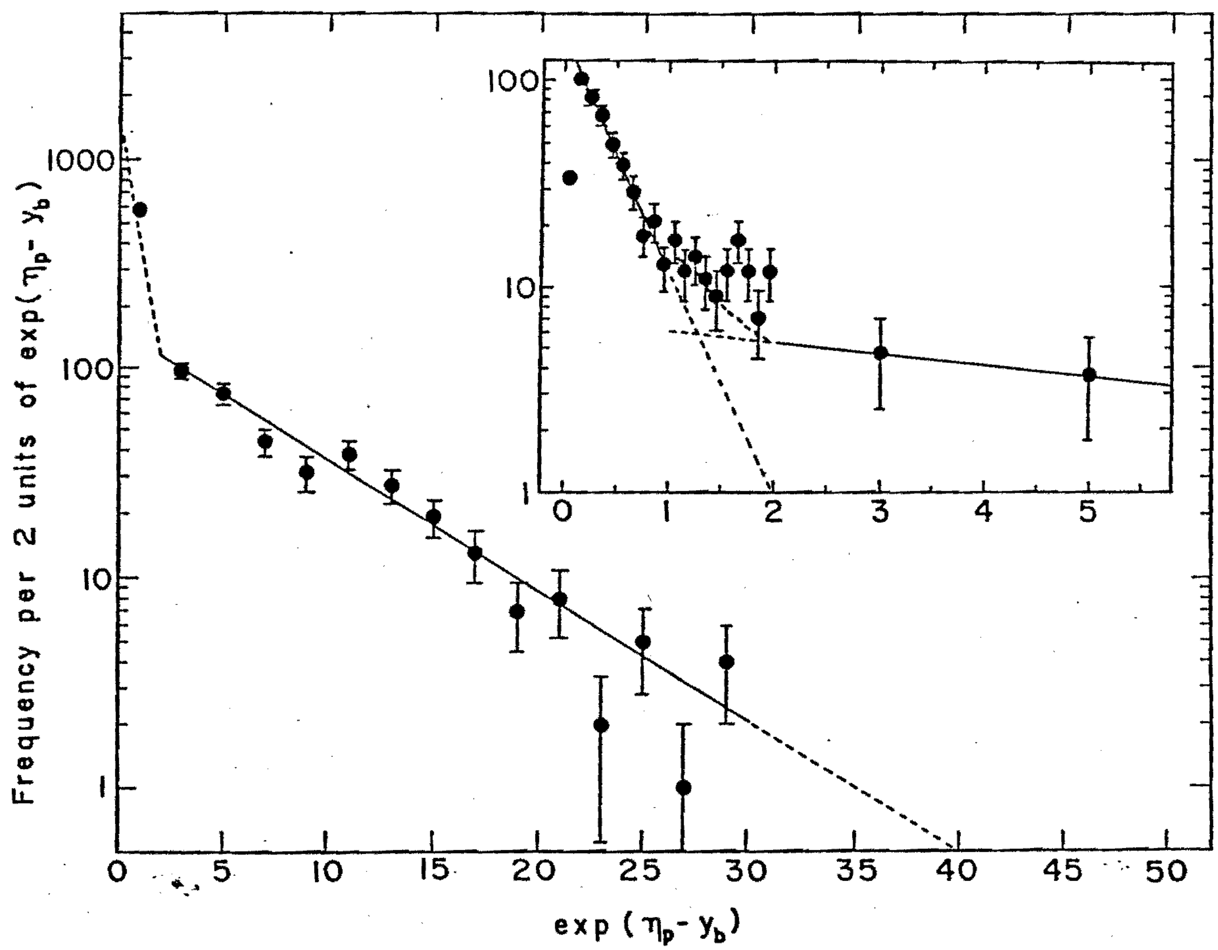
Proportion of Decay Modes / 30 MeV
0.8
0.5
0.3
0.2
0.1
0.07
0.04
0.02
0.01
0
30
60
90
120
Threshold Energy in MeV
O : ^{28}Si
: ^{32}S
: ^{16}O

Fig. 4



Frequency per 10 units of exp(η_α - y_b)
100
10
1
0
50
100
150
exp(η_α - y_b)
: ^{28}Si
: ^{56}Fe

Fig. A1



Frequency per 2 units of exp(η_p - y_b)
1000
100
10
1
0
5
10
15
20
25
30
35
40
45
50
exp (η_p - y_b)
100
10
1
0
1
2
3
4
5

Fig. A2