further detailed analyses of the present data.

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Nuclear Fragment Mass Yields from High-Energy Proton-Nucleus Interactions

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Isotopically resolved nuclear fragments (A_f, Z_f), $3 \leq Z_f \leq 14$, produced by protons in the energy range $80 \leq E_{\rm inc} \leq 350$ GeV incident on krypton and xenon targets have been studied at the Internal Target Laboratory of the Fermi National Accelerator. A power-law dependence, isobaric yield $\propto A_f^{-\tau}$, was found to describe the data over a broad range of yields. The particular value of τ is a signature for the fragment formation mechanism.

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It is well known[1,2] that nuclear fragment production is associated with collisions yielding high-multiplicity final states. The existence of a limiting fragmentation region for energies greater than approximately 10 GeV incident energy establishes fragment production as a distinct high-energy phenomenon.[3] A central question concerns the nuclear state which emits the multiply charged heavy fragments. Previous workers using electronic techniques have focused attention on the characteristics of the fragment kinetic energy spectra and yields without the benefit of isotopic identification for the heaviest fragments observed.[4-6] In this paper we report the results of a high-statistics, high-resolution study of the isotopically resolved fragment kinetic-energy spectra and yields for fragments with charge $3 \leq Z_f \leq 14$, mass $6 \leq A_f \leq 31$, and kinetic energy 5 MeV $\leq E_f \leq 100$ MeV. We find that the fragment mass yields produced in proton-krypton and proton-xenon collisions obey a power law, yield$(A_f) \propto A_f^{-\tau}$, and we have made the first experimental determination of the exponent τ for heavy-fragment data. By study of the isotopically resolved fragment data, a new picture of the fragmentation process emerges.

The combination at the Fermilab Internal Target Laboratory of the circulating proton beam ($\sim 10^{18}$ protons/sec) and the internal gas-jet target[7] ($\sim 10^{14}$ target atoms/cm^3) provides a unique opportunity for studying nuclear fragments from proton-nucleus collisions over an incident energy range from 80 to 350 GeV. In particular, the high counting rate allows the use of a long flight path together with a high-resolution gas ionization detector to obtain isotopically separated fragments whose lifetimes are greater than ~200 nsec. Our detector system was designed to minimize the amount of material between the beam-jet interaction area and our detectors in order to measure the heaviest and slowest fragments possible.

Two single-arm time-of-flight (TOF) spectrometers were designed, one for light ($A_f \leq 20$, $Z \leq 9$) energetic fragments positioned at 76 deg in the laboratory, the other for slower and heavier fragments ($A_f \leq 40$) positioned at 34 deg. Only the 34-deg telescope is shown in Fig. 1. The TOF spectrometer shown consists of three timing devices employing microchannel-plate (CP) detectors based on the design of Zebelmann *et al.*[8] and a gas-semiconductor ionization chamber based on a design by Fowler and Jared.[9] The gas detector was operated at 20 Torr, the equivalent of about 4 μm of silicon.

Hydrogen and noble gases (Ne, Ar, Kr, Xe) were combined to provide targets of up to 100 ng/cm^2. Target gases for the data reported here were mixtures of 90% H_2–10% Xe and 90% H_2–10% Kr. A monitor telescope at 86 deg served to normalize the data against the proton-proton elastic scattering.

Fragment charge was determined by plotting ΔE versus total kinetic energy, E_{Total}. At very

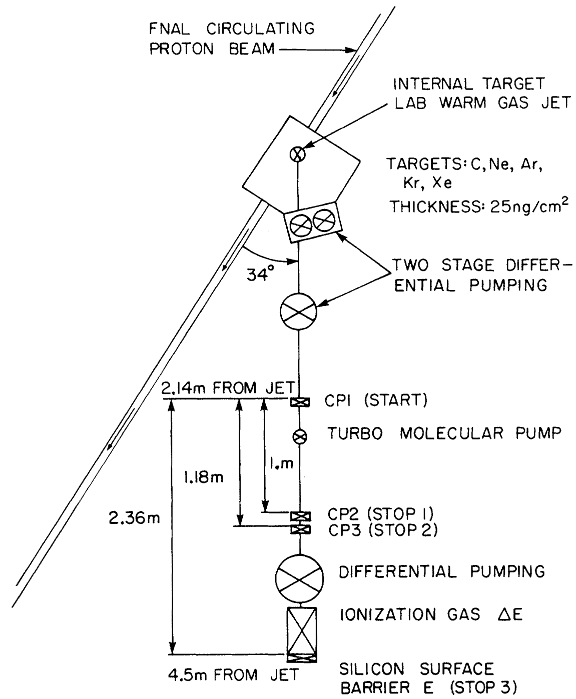

FIG. 1. Experimental apparatus. Only one spectrometer is shown.

low E_{Total} (<10 MeV), the curves of different $A_f Z_f^2$ merge and become inseparable. Thus we introduced a charge-dependent low-energy software cut. Masses for the data reported here were calculated by using the TOF start from CP1 and the stop from the silicon E detector in the gas ionization chamber. Corrections affecting mass resolution were made for the energy loss through the TOF detectors (~20 μg/cm^2 carbon in each CP) and the detector window (~50 μg/cm^2 of stretched polypropylene[10]). The flight time was corrected for the effects of deceleration as the fragment deposited ΔE in the gas detector. The average corrections for a carbon fragment were less than 1 MeV in energy and less than $\frac{1}{3}$ nsec in flight time. A mass resolution of $\Delta M/M \sim 1.5\%$ was achieved over the full range of masses with a cutoff energy of less than 10 MeV. A mass spectrum of the aluminum isotopes is shown in Fig. 2.

The total yield for a given fragment was determined by extrapolating both the low- and high-energy portions of the kinetic energy spectrum. In the worst case, this represented a 39% correction to the yield (charge 12 from krypton). The average correction was less than 10%. Furthermore, the peak in the kinetic energy spec-

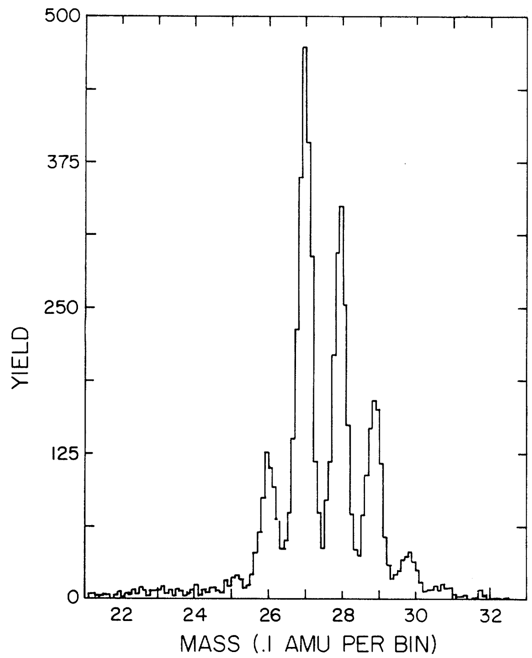

FIG. 2. Aluminum mass spectrum from krypton. The data have been corrected as discussed in the text.

trum was observed for all fragments with $Z_f < 12$ from both targets (see Fig. 3). Since fragment production over this energy range displays little dependence on proton incident energy, the fragment isotopic yields for xenon and krypton, corrected for the above-mentioned effects and for multiple scattering, have been summed over incident proton energies, $80 \leq E_p \leq 350$ GeV. Full experimental details will be discussed in a further publication.

The simplest way to present the data is to sum all the fragments of a given A_f (fragment mass number) and plot the isobaric yields as a function of the fragment mass number. The mass yields for Xe are shown in Fig. 4. The results for krypton are very similar in shape. We estimate the relative error between data points to be on the order of several times the statistical error, which for $A_f = 30$ is approximately 1.5%. In addition, we have included a point for mass 1. This point has been inferred from emulsion data.[2] The neutron contribution was assumed to be 1.3 times that of the proton. In a multigigaelectronvolt proton-nucleus collision an average of twenty tracks of "heavy" charged particles (protons) are found. When this occurs there is an ~8% probability of finding a ^{8}Li fragment (hammer track). Using our own data we find that ^{8}Li represents approximately 7% of the yield of all fragments

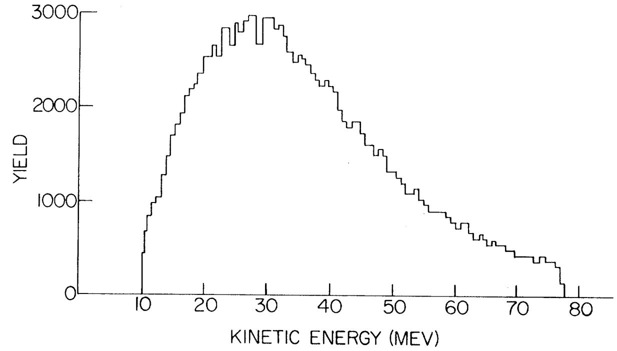

FIG. 3. Kinetic energy spectrum of ^{12}C from xenon.

greater than and including lithium. Thus we believe with some confidence that we are justified in using the emulsion data in order to estimate the mass = 1 yield with ^{8}Li as a cross normalization. Multiple scattering and energy loss in foils and the gas detector window limited the observable fragments to those whose charge was less than or equal to 14. Although our results were obtained at 34°, we believe that they are a fairly accurate reflection of the mass yield integrated over angle. We have observed[11] that for the tar-

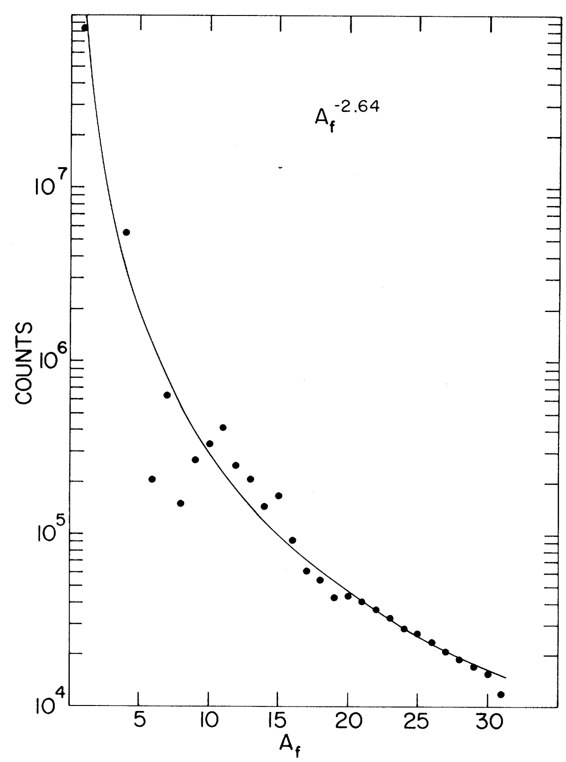

FIG. 4. Mass yield of fragments from xenon vs mass number, A_f, corrected for effects discussed in text.

gets of present interest the fragment angular distributions are isotropic in the laboratory to within 20%.

The data at low masses, say $A_f < 11$, show fluctuations due to the rapidly varying number of observable isobars as a function of fragment mass. For instance, for $A_f = 8$, only ^{8}Li and ^{8}B live long enough to be seen in our apparatus. Thus the data appear smoother as the fragment mass increases since the number of stable isobars approaches a constant. The data below mass 11 have been compared to the isotopically resolved data from an earlier experiment conducted by our group with an entirely different apparatus.[11] The two sets of data are in agreement within our estimated systematic errors. We have fitted the mass distributions by a power law (curve in Fig. 4). Masses between 4 and 12 were excluded from the fit for the reasons stated above. The value of the exponent τ is 2.64 and 2.65 for xenon and krypton, respectively. It is obvious that a power law can fit only the smooth features of the data. The value of τ, however, is well determined by the data, since a change in τ of 0.2 for $A_f = 20$ changes the yield by a factor $20^{0.2} \simeq 1.8$. Indications of such a power law can be seen in the data of Ref. 5 if they are replotted and an average A_f is assumed for a given Z_f. However, no such assumption need be made to determine the parameter τ from isobarically resolved data. It should be pointed out that the mass yield from heavy targets is known to rise after achieving a minimum at about mass 40. This increase, due to several competing processes such as deep spallation and fission, will obscure the power-law falloff in the high-mass region.[12]

We believe that the values found for τ are significant and are characteristic of a system undergoing a statistical clustering. Suppose that following the initial high-energy proton-nucleus collision, the nuclear remnant is left in a state of high excitation, one in which the correlations as evidenced in the shell structure of normal nuclei have been destroyed. As a result of the collision, if the phase space available has increased substantially and if the system has sufficient time prior to disassembly to involve many nucleons, then, through random collisions, the system could undergo cluster formation. We can gain some understanding of the problem by studying the general problem of clustering. Percolation theory[13] deals with the general question of clustering in any number of dimensions. An array of lattice sites, each of which has a probability p of being occupied, is populated randomly. No interaction between lattice sites is assumed. A cluster size is defined by the number of contiguously occupied sites. It is found that the cluster distribution obeys a power law near the percolation (critical) point in analogy with a critical point in matter. The value of the exponent is 2.1 for a three-dimensional lattice. Similarly, theoretical studies of liquid-gas phase transitions indicate that near a critical point, the distribution of cluster sizes, i.e., the number of constituents contained in a droplet, should obey a power law whose exponent is between 2 and 3.[14] Real gases are indeed found to exhibit exponents that lie in this range as determined experimentally.[15] Whether or not we have observed such a phase transition in analogy with classical gases is still an open question. The evidence presented above leads us to conclude that fragments are formed statistically in the multibody breakup of a highly excited nuclear remnant. The state of the remnant must be such that the constituents can form a cluster distribution characteristic of a phase transition near a critical point. This state is therefore distinctly different from the one found in normal nuclei.

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Resonant Behavior in the Projectile X-Ray Yield Associated with Electron Capture in S + Ar Collisions

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Experimental evidence is presented for a new resonant process in ion-atom collisions which is analogous to dielectronic recombination in free-electron–ion collisions. Resonant behavior observed in the yield of projectile K x rays in coincidence with single-electron capture in 70–160-MeV S + Ar collisions is attributed to simultaneous electron capture and K-shell excitation. The data indicate that this resonant process is an important mechanism in inner-shell vacancy production in the energy range studied.

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It was recently suggested that projectile K-shell excitation may occur *simultaneously* with electron capture in ion-atom collisions.[1] Such a process, which is due to the Coulomb interaction of the projectile with the target electrons, is qualitatively analogous to an inverse Auger transition and is expected to be resonant for projectile velocities corresponding to the energy of an exiting electron in the Auger process. Since the captured electron is initially bound in the target, the width of the resonance should be reflective of the distribution of electron momenta in the target.

In the case of free-electron recombination, this process is called dielectronic recombination which occurs when a highly stripped ion captures a continuum electron and simultaneously excites an electron from the ground-state configuration of the ion. Since radiation can be emitted following the formation of this excited state, dielectronic recombination is believed to be an important energy-loss mechanism in high-temperature fusion plasmas.[2] Dielectronic recombination has been identified in plasmas but cross sections for this process have never been successfully meas-