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Nuclear Fragment Emission in High-Energy *p*-Xe and *p*-Kr Collisions and a Description of Their Production Mechanism

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We have studied the energy distributions of Li, Be, B, C, N, O, F, Ne, Na, Mg, Al, and Si emerging from high-energy proton-xenon and proton-krypton collisions in the $20 < p_{\rm inc} < 400$ GeV/c momentum range. Based on the fragment mass dependence of the slope characterizing these energy distributions, there is a natural division of the fragments into two groups. The production of fragments heavier than carbon can be understood in terms of a two-body disintegration of a residual nucleus possessing a *single* slope parameter.

With the successful operation of the warm-gas-jet facility[1] at Fermi National Accelerator Laboratory (FNAL) providing thin targets of heavy gases, it has become possible to employ electronic techniques to study the production characteristics of low-energy nuclear fragments at the highest available proton energies. In this paper we present data from Kr and Xe targets and discuss an interpretation in terms of a simple model for heavy-fragment emission. From comparisons of these data with previous light-fragment studies, there is evidence for a two-step process in p-nucleus collisions; first, there is a simultaneous emission of a large number of nucleons (~20) which may coalesce into light fragments. The remaining excited nuclear remnant subsequently decays into heavy fragments via a quasi-two-body decay.

This experiment was conducted in the internal-target area of FNAL. Targets of 100 ng/cm^2 were created by injecting hydrogen–noble-gas mixtures through a de Laval nozzle into the circulating proton beam. The pressure pulse was maintained for 2.7 sec, coinciding with the acceleration time of the beam from 20 to 400 GeV/c, during which 10^{18} protons/sec intersected the target. Fragments emerging from the p-nucleus collisions were detected by one of four ΔE-E-veto telescopes, each consisting of three surface-barrier Si detectors. These telescopes were mounted symmetrically around the axis of the internal-target magnetic spectrometer with a direct view of the gas jet. Data were taken at twelve approximately equally spaced intervals between 33° and 76° with respect to the proton beam. Target mixtures for the data reported here were 90% H_2–10% Xe and 82% H_2–18% Kr by partial pressures.

Fragments were accepted which satisfied a $\Delta E \cdot E \cdot \overline{\rm veto}$ trigger within preset energy windows. Discriminator levels were optimized for fragments heavier than lithium with low kinetic energies ($E < 120$ MeV). Identification by AZ^2, where A is the nucleon number and Z the charge, was determined through an empirical function of the energies deposited in the ΔE and E detectors. A typical spectrum indicating the presence of elements B to Si is shown in Fig. 1.

A detailed analysis[2] of fragment energy spectra revealed no dependence upon beam momentum; thus, the data presented here are summed over beam momenta. Furthermore, the angular distributions evidenced only a weak correlation with emission angle. Laboratory kinetic energy distributions of B, N, Na, and Si from p-Xe and p-Kr collisions are shown in Fig. 2. Multiple-scattering corrections have been included. A slow variation of the slopes with fragment mass is apparent; similar spectra are observed from both krypton and xenon targets. To parametrize our data we used the formalism of Goldhaber[3] and Westfall *et al.*,[4] which provides a simple de-

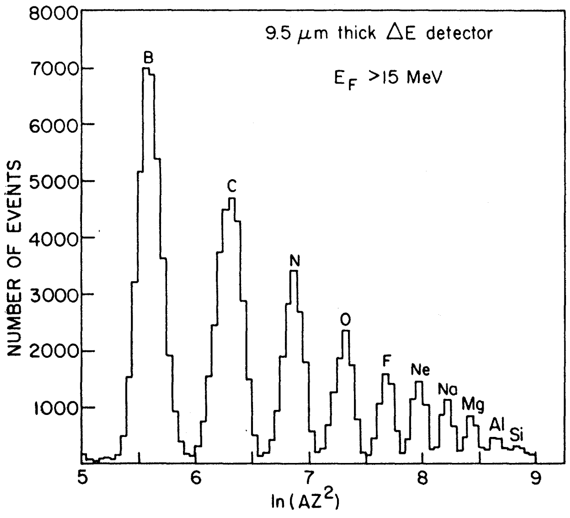

FIG. 1. The AZ^2 distribution of the nuclear fragments produced in p-Xe collision. The proton-beryllium range has not been plotted to avoid compressing the scale.

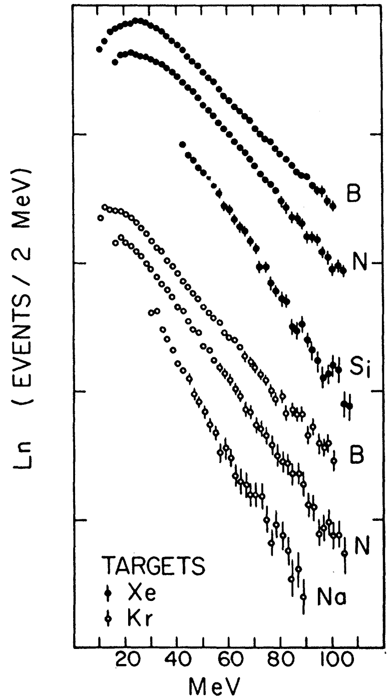

FIG. 2. The natural logarithm of the number of events, corrected for losses due to multiple scattering, is plotted as a function of fragment kinetic energy. Fragment identity is indicated on the distribution curve. curve.

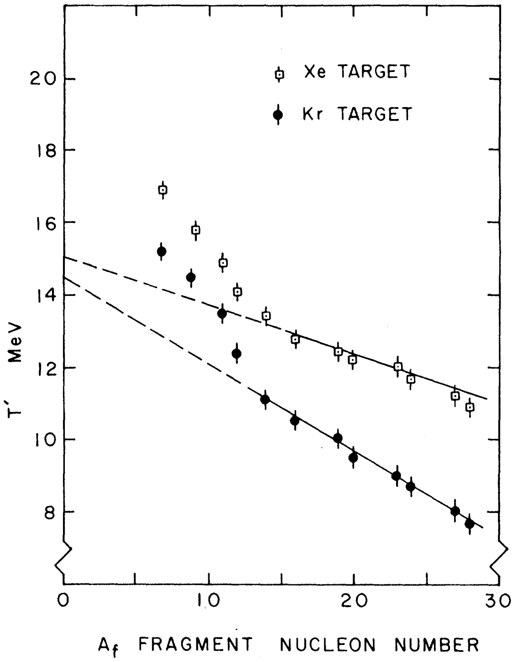

FIG. 3. The inverse logarithmic slope as function of fragment nucleon number. The straight lines represent the functional form $T'=T(1-A_f/A_R)$. The values of T' and A_R were obtained by simultaneously fitting the energy spectra of fragments with $7\leq Z\leq 14$.

scription of fragment production. In this model, the fragments are emitted isotropically in the rest frame of a decaying nuclear remnant. Kinetic-energy spectra from this excited remnant are given by a Maxwell-Boltzmann–type distribution, where E^*, the fragment energy in the remnant rest frame, is shifted by the Coulomb barrier energy B'. When transformed into the laboratory by the small remnant velocity v, along the beam direction, the differential cross section becomes

$$\frac{d^2\sigma}{dE\,d\Omega}=N'\left[\frac{E}{E^*}(E^*-B')\right]^{1/2}\times\exp\left(-\frac{E^*-B'}{T'}\right), \qquad (1)$$

where N', B', and T' represent a normalization constant, the Coulomb barrier energy, and the inverse logarithmic slope of the energy spectrum, respectively. The fragment energy E^* is given by $E^*=E+E_0-2(EE_0)^{1/2}\cos\theta$, with E the measured laboratory energy of the fragment (M_f), E_0 the energy from remnant motion, $E_0=\frac{1}{2}M_f v^2$, and θ the laboratory angle. By fitting the observed differential spectrum to Eq. (1), the constants B', v, and T' were determined for each fragment.

By examining T' as a function of the fragment nucleon number A_f (Fig. 3), we deduce that T' is approximately a linear function of A_f for masses larger than carbon, for both Kr and Xe targets. We interpret this observation as evidence suggestive of a two-body decay process wherein the linear variation of T' with fragment mass is due to two-body kinematics. In contrast to earlier models,[5-8] we conjecture that in the first stage of a p-nucleus collision, a number of nucleons are ejected leaving an excited remnant of A_R nucleons which subsequently decays via a quasi-two-body mode.[4] In this picture

$$T' = T/\nu \equiv T(1 - A_f/A_R), \tag{2}$$

where ν represents the effect of two-body kinematics and T denotes the inverse logarithmic slope of the energy in the remnant frame. Equation (1) is then modified by $E^* \to E^*\nu$, $B' \to B$, and $T' \to T$.

Relying on the above conjecture, we can simultaneously fit the kinetic energy distribution of fragments with $7 \leqslant Z \leqslant 14$ for a common value of A_R, T, and v. We find a confidence level greater than 80% for each fragment and note that the values obtained are in good agreement with the individual fits. However, the spectra of Li, Be, B, and C are not well described with these overall parameters, yielding confidence levels of less than 0.01%. The straight lines in Fig. 3 represent Eq. (2) with A_R and T determined by simultaneous fits for fragment charge in the $7 \leqslant Z \leqslant 14$ range. We conclude that the production of the higher-mass fragments, nitrogen to silicon, is well described by this model with a quasi-two-body decay mode of a remnant with A_R nucleons and inverse logarithmic slope (apparent temperature[9]) T. Values of the parameters obtained are $T(\mathrm{Kr}) = 14.5 \pm 1$ MeV, $T(\mathrm{Xe}) = 15.0 \pm 1$ MeV, $A_R(\mathrm{Kr}) = 60 \pm 5$, $A_R(\mathrm{Xe}) = 110 \pm 10$, $v(\mathrm{Kr}) = (0.007 \pm 0.001)c$, and $v(\mathrm{Xe}) = (0.002 \pm 0.001)c$. The values for T are consistent with a similar analysis at 5 GeV.[4]

A description of light-fragment production is afforded by a rather different model.[6] Particle-yield experiments, soon after the alternating-gradient synchrotons came into operation at CERN and at Brookhaven National Laboratory, revealed a surprisingly high ratio of d and t to proton fluxes in the GeV/c momentum range.[7,10] Subsequently, Butler and Pearson argued theoretically that the observed production of deuterium could be described by the coalesence of the emitted nucleons into light nuclei via final-state interactions.[6] A phenomenological formula was developed to relate fragment distributions to those of protons[7,8]:

$$\frac{d^2\sigma(A)}{dE\,d\Omega} = \frac{1}{A!}\left(\frac{4\pi p_0^3}{3\sigma_0 m[E(E+2m)]^{1/2}}\right)^{A-1}\left[\frac{d^2\sigma(\text{proton})}{dE\,d\Omega}\right]^A,$$

where E is the laboratory kinetic energy per nucleon and A is the nucleon number; the proton nucleus cross section is σ_0 and m is the nucleon mass. This equation gives the probability of observing a fragment that has coalesced from a number of nucleons which have emerged within a momentum sphere of $4\pi p_0^3/3$. We have tested this model using the data of Ref. 4 and find good agreement between H and He spectra suggesting that the coalescence mechanism gives a good description of light-fragment production for low kinetic energies (30 to 60 MeV). Insufficient data for Li to C fragments preclude a similar test for these nuclei. In that this model does not require thermal equilibrium between light fragments formed by coalescence and heavier fragments emitted from the breakup of a nuclear remnant, their apparent temperatures do not have to be the same. All the model requires is the simultaneous emission of nucleons, which may take place promptly. We may speculate, then, the following description for the breakup of a heavy nucleus excited by a high-energy proton: emission of a large number[11] of nucleons which may occur promptly,[12,13] some of which coalesce to form light fragments, followed by a two-body decay of the remnant, which yields the heavier fragments with a characteristic inverse slope of approximately 15 MeV for the kinetic energy distribution in the remnant rest frame. There are clear experimentally testable consequences of this model: (a) there are large numbers of nucleons (20–40) emitted in association with fragment production[11]; (b) with a heavy fragment of mass A_f there is another fragment of mass $A_R - A_f$ produced in coincidence for $A_f > 12$. If these features are shown in future experiments, the intriguing question of possible radial compression and creation of compressed nuclear matter will naturally arise. In a 3-GeV/c emulsion experiment, observation[14] of stars with only two dark tracks was reported. Although they had no fragment mass or residual mass determination, they concluded that the tracks were two-body decays into two approximately equal-mass objects. We observe an *asymmetric* two-body decay.

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Measurement of *g* Factors by Quantum Beats in the OH Free Radical

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Using pulsed optical excitation we have measured the g factors of twelve hyperfine levels ($K=1$ through 6) of the $A^2\Sigma_{1/2}^+$ state of OH by observation of quantum beats. The results are consistent with Hund's case (b) coupling to within the experimental uncertainty of 0.35% (principally limited by magnetic field calibration). However, the ratios of the g factors of a given hyperfine doublet, which are independent of field and accurate to about 0.15%, show significant discrepancies from theory.

Because of the ubiquitous nature of the OH free radical, its properties are of interest to investigators in such diverse fields as astrophysics, combustion studies, atmospheric physics, and molecular spectroscopy. The decay of the lowest-lying electronic excited state via the ultraviolet transition ($A^2\Sigma_{1/2}$ to $X^2\Pi$) has been studied extensively.[1] Recently, the use of tunable dye lasers has introduced a new level of versatility and sophistication in the study of this molecule.[2] In this Letter we report the direct measurement of the g factors of the $v=0$, $A^2\Sigma_{1/2}$ excited state of OH by time-resolved excited-state spectroscopy. This follows the lead of Wallenstein, Paisner, and Schawlow[3] and demonstrates the utility of time-resolved techniques, particularly quantum beats, in molecular spectroscopy. It also provides motivation for further calculations of the magnetic properties of molecules.

The experiment consists of exciting a sample of OH free radicals in a dc magnetic field with a short pulse of light from a dye laser and observing the oscillations superposed on the fluorescence. If the bandwidth of the laser is greater than the Zeeman splitting of the molecular levels, the molecule is excited to a superposition state of several Zeeman components and the resulting fluorescence exhibits quantum beats. The angular frequency of these beats is given by $\omega = 2g_F\mu_B B/\hbar$, where g_F is the g factor of the individual hyperfine states, μ_B is the Bohr magneton, and B is the applied magnetic field. Quan-