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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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ABSTRACT

We have studied the low 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 $20 < P_{inc} < 400$ GeV/c momentum range. The energy spectra of fragments heavier than Carbon, when interpreted as a two-body disintegration of single nuclear remnant, are characterized by a single slope parameter. Thus, the evolutionary end point of a p-nucleus collision is a two body break up of a lighter residual nucleus.

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With the successful operation of the warm gas jet facility[1] at 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 ($\sim$ 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 nanograms/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, 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° & 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 $\Delta E \cdot E \cdot \overline{VETO}$ 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. Futhermore, 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 Refs 3 and 4, which provides a simple description 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-Boltzman 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

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

where N', B', and T' represent a normalization constant, the Coulomb barrier energy and the inverse logarithmic slope of the energy spectrum. The fragment energy E^* is given by $E^* = E + E_o - 2\sqrt{EE_o}\cos\theta$, with E the measured laboratory energy of the fragment (M_f), E_o the energy from remnant motion, $E_o = \frac{1}{2}M_f v^2$, and θ the laboratory angle. By fitting the observed differential spectrum to equation (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 suggesstive 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,[5,6,7,8] 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

$$T' = T/\nu \equiv T(1-A_f/A_R) \qquad (2)$$

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 $E^* \rightarrow E^*\nu$, $B' \rightarrow B$ and $T' \rightarrow T$.

Relying on the above conjecture, we can simultaneously fit the kinetic energy distribution of fragments with $7 \leq Z \leq 14$ 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 $7 \leq Z \leq 14$ 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 $T(Kr) = 14.5 \pm 1$ MeV, $T(Xe) = 15.0 \pm 1$ MeV, $A_R(Kr) = 60 \pm 5$, $A_R(Xe) = 110 \pm 10$, $v(Kr) = (0.007 \pm .001)c$, and $v(Xe) = (0.002 \pm .001)c$. 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 BNL, 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 that of protons.[7,8]

$$\frac{d^2\sigma(A)}{dEd\Omega} = \frac{1}{A!}\left(\frac{4\pi p_o^3}{3\sigma_o m[E(E+2m)]^{\frac{1}{2}}}\right)^{A-1} \frac{(d^2\sigma(prot))^A}{dEd\Omega}$$

where E is the laboratory kinetic energy per nucleon and A is the nucleon number; the proton nucleus cross section is σ_o 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 $4\pi p_o^3/3$. 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 precludes a similar test for these nuclei. In that this model does not require thermal equilibrium between light fragements formed by coalescence and heavier fragments emitted from the break up 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 emergy 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 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 remnan 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.

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FIGURE CAPTIONS

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.

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 indentity is indicated on the distribution curve.

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 $7 \leq Z \leq 14$.

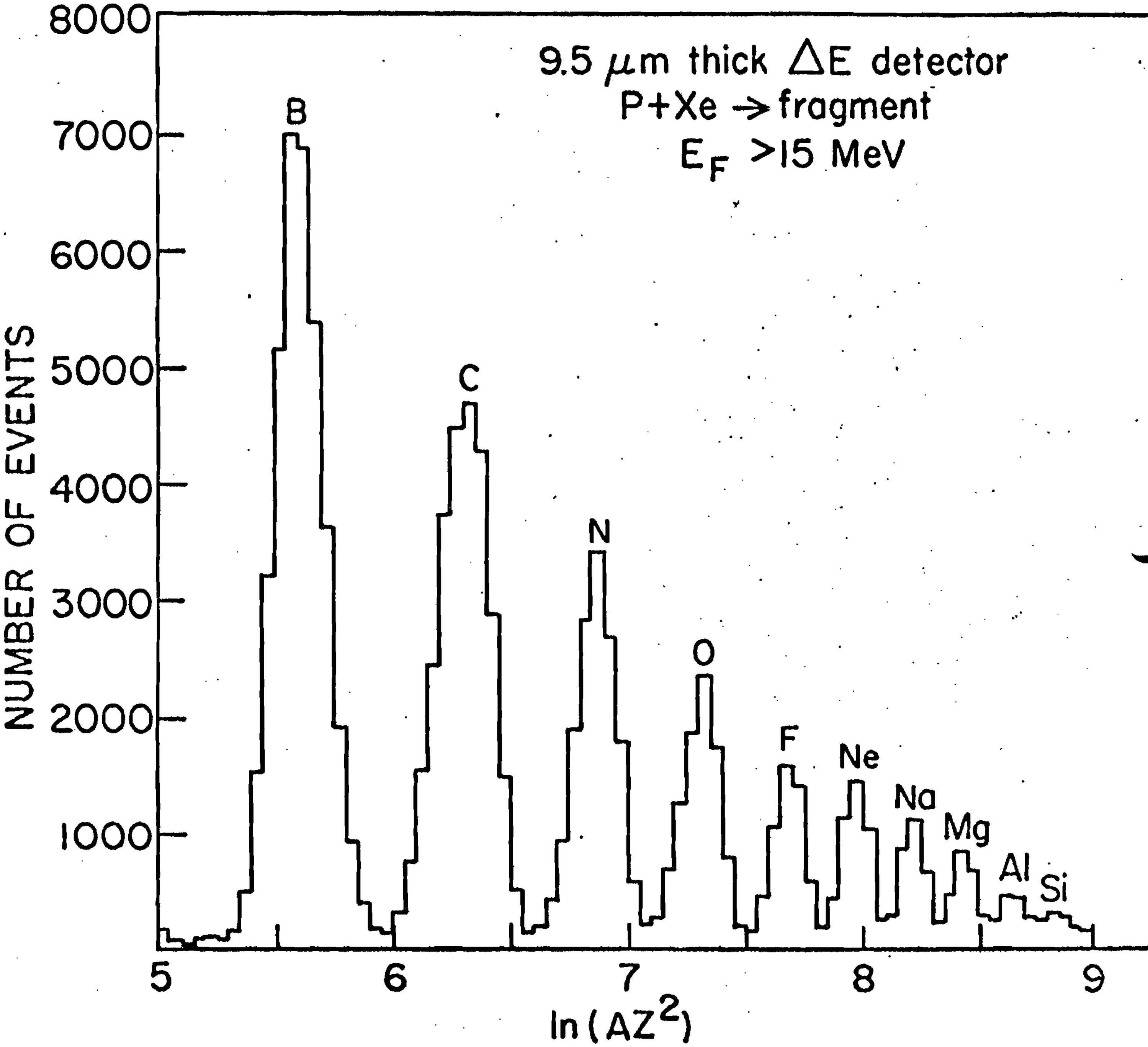

Fig 1
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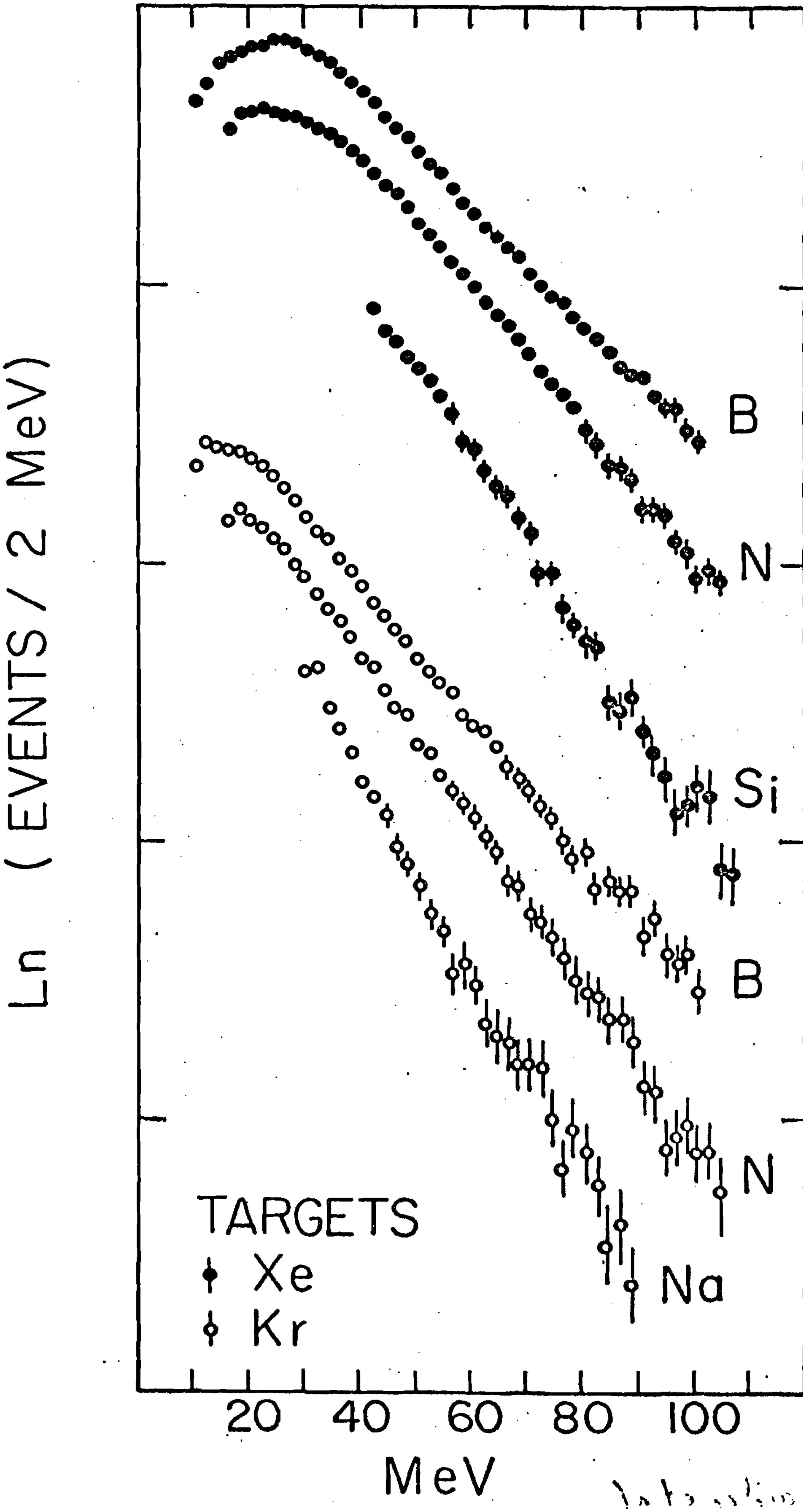
Ln (EVENTS / 2 MeV)
B
N
Si
B
N
Na
TARGETS
Xe
Kr
20
40
60
80
100
MeV

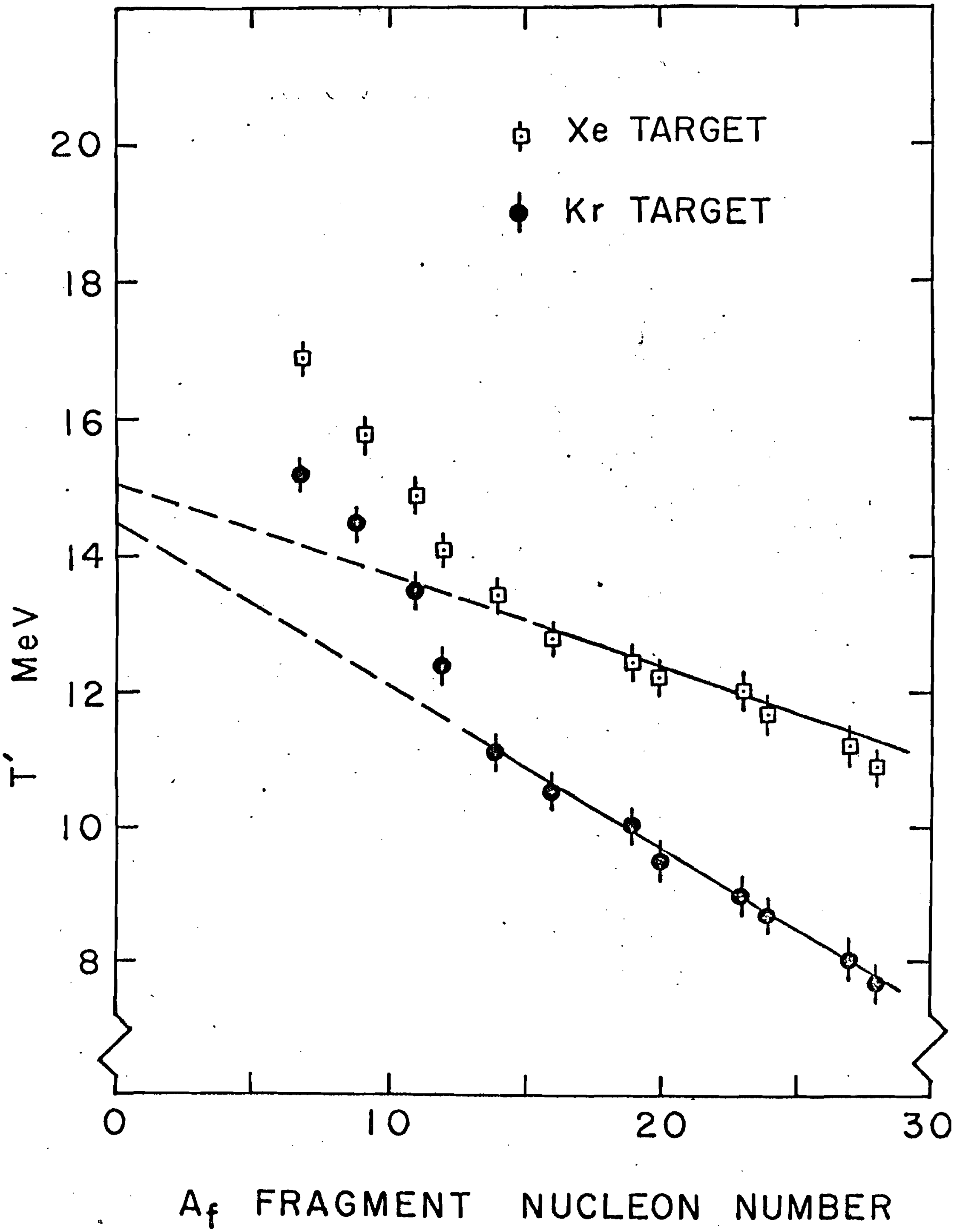

Fig 3
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