Title
MOMENTUM DISTRIBUTIONS OF ISOTOPES PRODUCED BY FRAGMENTATION OF RELATIVISTIC 12C AND l6O PROJECTILES

Permalink
https://escholarship.org/uc/item/61d374rt

Authors
Greiner, D.E.
Lindstrom, P.J.
Heckman, H.H.
et al.

Publication Date
1975-03-01

Submitted to Physical Review Letters

LBL-3651
Preprint c.1

MOMENTUM DISTRIBUTIONS OF ISOTOPES PRODUCED BY FRAGMENTATION OF RELATIVISTIC ^{12}C AND ^{16}O PROJECTILES

D. E. Greiner, P. J. Lindstrom, H. H. Heckman,
Bruce Cork, and F. S. Bieser

March 1975

Prepared for the U. S. Atomic Energy Commission
under Contract W-7405-ENG-48

DISCLAIMER

MOMENTUM DISTRIBUTIONS OF ISOTOPES PRODUCED BY FRAGMENTATION OF RELATIVISTIC ^{12}C AND ^{16}O PROJECTILES.*

D. E. Greiner, P. J. Lindstrom, H. H. Heckman,
Bruce Cork and F. S. Bieser

Lawrence Berkeley Laboratory and Space Sciences Laboratory
University of California, Berkeley, California 94720

ABSTRACT

Presented are results on the momentum distributions for isotopes produced within 12.5 mr of the beam direction from the fragmentation of beams of ^{12}C at 1.05 and 2.1 GeV/n and ^{16}O at 2.1 GeV/n. In the projectile rest frame the momentum distributions are, typically, Gaussian shaped. For fragments $A \geq 2$, the momentum distributions are isotropic, depend on fragment and beam, and have no significant correlation with target mass or beam energy.

We present here the first comprehensive measurements of the momentum distributions for isotopes produced by the fragmentation of heavy-ion beams at the Bevatron. These results apply to the fragmentation of ^{12}C nuclei with energies 1.05 and 2.1 GeV/n, and ^{16}O at 2.1 GeV/n. The evaluation of the isotopic production cross sections given by Lindstrom et. al.[1] is based on these data.

The momentum and cross section measurements were performed using a single-focusing magnetic-spectrometer with a half-angle acceptance of 12.5 mr about zero degrees.[2] Targets were Be, CH_2, C, Al, Cu, Ag and Pb. The charge and mass of the fragments were obtained by measuring their rigidity (Pc/Ze), energy loss in solid state detectors, and time-of-flight. Particle trajectories were determined with multiple-wire proportional chambers. The longitudinal and transverse momenta, $P_{\parallel}$ and $P_{\perp}$, were obtained from the rigidity and direction of the particle at the focal plane of the spectrometer. The rigidity range was scanned in 0.1 GV steps from 0.8 to 10.2 GV for the 2.1 GeV/n ^{12}C and ^{16}O beams and 0.2 to 6.3 GV for the ^{12}C beam at 1.05 GeV/n. Because the velocities of the projectile fragments are near the beam velocity,[3] these rigidity ranges allowed us to observe all particles produced having a mass to charge ratio, A/Z, between 0.2 and 3.4.

For each isotope the longitudinal-momentum distribution, in the projectile rest frame, was fit to a Gaussian dependence on $P_{\parallel}$. The fitted variables are amplitude, central momentum, $\langle P_{\parallel} \rangle$, and standard deviation $\sigma_{P_{\parallel}}$. Fig. 1 illustrates the Gaussian fit and the variables $\langle P_{\parallel} \rangle$ and $\sigma_{P_{\parallel}}$ for the case of ^{10}Be produced by the fragmentation of 2.1 GeV/n ^{12}C on a Be target. It is emphasized that this analysis applies to the central portion of the momentum spectrum in the projectile rest frame. The fits were restricted to the interval -400 MeV/c to +400 MeV/c which cover typically 1 to 2 decades in the magnitude of the differential cross section. The spectra of all the observed fragments exhibit properties similar to those shown in Fig. 1, namely: the momentum distributions have standard deviations of only 50-200 MeV/c, and the average momentum is slightly negative relative to the projectile.

We find that the Gaussian shape provides a good fit to the observed spectra for all isotopes regardless of beam, energy, or target except for the hydrogen isotopes. The ^{2}H and ^{3}H spectra are fit by a Gaussian curve in the region $-300 \leq P_{\parallel} \leq 400$ MeV/c, but exhibit an enhancement for $P_{\parallel} \leq -300$ MeV/c. The ^{1}H spectrum cannot be fit by a Gaussian shape in the central region $|P_{\parallel}| \leq 150$ MeV/c. In this region a fit to the ^{1}H spectrum is obtained with the exponential relation $d\sigma/dp_{\parallel} \propto \exp(-|P_{\parallel}|/65)$.

The $P_{\perp}$ distributions are based on the measurement of small angles and are less accurate than the $P_{\parallel}$ values. From measurements of the widths of the $P_{\perp}$ distribution for $A \geq 2$ fragments, we find $\sigma_{P_{\perp}} = \sigma_{P_{\parallel}}$ to an accuracy of 10% which indicates that these fragments are produced isotropically.

If these reactions are examples of limiting fragmentation, the large separation in rapidity between the target and the fragment distributions requires the shape of the momentum distributions be independent of target and beam energy.[4] For all reactions the target and energy dependence of the variables $< P_{||} >$ and $\sigma_{P_{||}}$ were examined. Within the accuracy of this experiment we conclude there is no dependence on target mass above the 5% level for $\sigma_{P_{||}}$ and above the 10% level for $< P_{||} >$. Because of this observed target independence we shall refer to the target-averaged values of $\sigma_{P_{||}}$ and $< P_{||} >$ in the remainder of this Letter. To determine if $\sigma_{P_{||}}$ and $< P_{||} >$ are independent of energy we compare the measurements of these variables for the ^{12}C beam at 2.1 and 1.05 GeV/n. The weighted averages over all fragments of the quantities $\sigma_{P_{||}}$ (2.1 GeV/n)/$\sigma_{P_{||}}$ (1.05 GeV/n) and $< P_{||} >$(2.1 GeV/n) - $<P_{||}>$(1.05 GeV/n) are 1.02±0.02 and -1.0±2.0 MeV/c, respectively. This independence of beam energy and target lead to the conclusions that the ^{12}C reactions satisfy the limiting fragmentation hypothesis and the limiting energy region is reached before 1.05 GeV/n.

In the limiting energy region the fragment distributions depend on the identity of the projectile and fragment.[4] We begin discussion of this dependence by presenting in Table I the measured values of $\sigma_{P_{||}}$ and $< P_{||} >$ for all fragments produced with sufficient signal. In Fig. 2 we have plotted the values of $\sigma_{P_{||}}$ for ^{16}O at 2.1 GeV/n versus the fragment mass in amu. The charge of each fragment is used as the plotting symbol. In an attempt to parameterize the mass dependence we have fit the data to the function $\sigma^2_{P_{||}}(B,F) = 4\,\sigma_o^2 F(B-F)/B^2$ where B and F are the mass numbers of the beam and fragment nuclei respectively, and σ_o is the fitted variable. The best-fit curve for ^{16}O is shown in Fig. 2. The fitted values of σ_o for all beams are listed in

Table II. Although the parabola shape displays the general trend of the data, in no case does it provide a good fit to the observed values of $\sigma_{P_{\parallel}}$.[5] The poor fit is demonstrated by the fact that 50% of the data points are over two standard deviations from the curve. Particularly striking is the observation that the same complex variation of $\sigma_{P_{\parallel}}$ with fragment mass is exhibited by both the ^{12}C and ^{16}O fragments, indicating nuclear structure effects are important variables determining the $\sigma_{P_{\parallel}}$ values.

The values of $\langle P_{\parallel} \rangle$ have an approximately linear relationship on $\sigma_{P_{\parallel}}$. In Fig. 3 we show the data representing all fragments from ^{12}C and ^{16}O projectiles at 2.1 GeV/n to exhibit this linear dependence. The general shifts in the momentum distributions toward velocities less than the beam correspond to small energy transfers to the fragment, typically < 130 KeV in the projectile frame. The obvious exceptions are reactions involving charge exchange, such as $^{12}C \rightarrow {}^{12}N$, and charge exchange plus loss of a nucleon, e.g., $^{16}O \rightarrow {}^{15}C$. The reactions involving charge exchange generally have larger negative values of $\langle P_{\parallel} \rangle \simeq -100$ MeV/c. Calculation of the missing mass in these reactions gives values approximately 200 MeV/c^2 after subtraction of the target mass. Thus the data are consistent with the assumption that the charge exchange reactions proceed via pion production, for example $^{12}C \rightarrow {}^{12}N + \pi^-$.

The fragmentation of heavy ions at relativistic energies is a relatively new field of research. There is, therefore, no well developed theory to compare with experimental results. Preliminary attempts, however, have been made to understand the momentum distribution widths. Several authors have derived a dependence of $\sigma_{P_{||}}$ on fragment mass of the form $\sigma^2_{P_{||}} \propto F(B-F)$. The validity and implications of these theories can be determined by comparison with the values of σ_o measured by this experiment. A parabolic dependence of $\sigma^2_{P_{||}}$ on fragment mass was first predicted by Wenzel,[6] later by Lepore and Riddell,[7] and indirectly by Feshbach and Huang[8] as extended by Goldhaber.[9] In general the parabolic shape arises when one assumes: i) the fragment momentum distributions are essentially those in the projectile nucleus, ii) that there are no correlations between the momenta of different nucleons, and iii) momentum is conserved. The work of Lepore and Riddell[7] is a quantum mechanical calculation that employs the sudden approximation with shell-model wave functions to predict $\sigma_o{}^2 = \frac{1}{8} m_p B^{1/3} \left[45B^{1/3} - 25\right]$. This expression, where m_p is the proton mass, gives qualitative agreement with the measured values as shown in Table II. Feshbach and Haung[8] assume sudden emission of virtual clusters and relate σ_o to the Fermi momentum of the projectile, P_f. Using the formulation due to Goldhaber,[9] the relation between P_f and σ_o is $\sigma_o{}^2 = \frac{1}{20} P_f^{\,2} B^2/(B-1)$. The values of P_F determined by quasielastic electron scattering[10] give predicted values of σ_o that are generally 25% higher than the measured values as shown in Table II. An interesting point to note here is that through the predicted relationship between σ_o and P_f, this experiment measures the projectile Fermi momentum via nuclear fragmentation (see Table II). By assuming the projectile has come to thermal equilibrium at an excitation temperature T, Goldhaber[9] has shown that the parabolic shape is again predicted and relates

σ_o to the excitation energy per nucleon by the equation $kT=4\sigma_o^2/m_nB$, where k is Boltzmann's constant and m_n is the nucleon mass. The measured values of σ_o then reflect excitation energies which we have listed in Table II along with the average binding energies per nucleon as determined by the projectile masses.[11,12] Because our measured excitation energies are essentially the binding energy per nucleon of the projectiles, we again conclude that the fragmentation process which results in bound fragments involves very little energy transfer between the target and fragment.

Based on our initial fragmentation studies the following picture emerges: when heavy ions at high velocity interact with matter, a fraction of the reactions emit fragments having essentially the same velocity as the original ion. The probability for this occurrence depends on the target nucleus, ranging from 90% for ^1H to 30% for Pb.[1] Interactions of this type account for the total fragmentation cross sections for fragments $A\geq2$. In these reactions the $(A\geq2)$ fragments are emitted isotropically with Gaussian momentum distributions in the projectile frame. These distributions are independent of target mass and projectile energy, which are basic requirements of the limiting fragmentation hypothesis. Energy transfers to the fragment are small; in fact, the observed excitation energies are remarkably close to the binding energy of the projectile. Finally there is strong and recurring evidence in our data of effects attributable to nuclear structure in both the fragment-momentum distributions and the fragmentation cross sections.

We thank the Bevatron operations staff, under H. A. Grunder and R. J. Force, for their support and effort during this experiment. We commend E. E. Beleal, D. M. Jones, and C. P. McParland for their computer programming efforts and data handling, and R. C. Zink for electronic component construction.

FOOTNOTES REFERENCES

* Work performed under auspices of the U. S. Atomic Energy Commission and the National Aeronautics and Space Administration, Grant NGR 05-003-513.

1. P. J. Lindstrom, D. E. Greiner, H. H. Heckman, Bruce Cork and F. S. Bieser, UCRL 3650 (submitted to Phys. Rev. Lett.)
2. D. E. Greiner, P. J. Lindstrom, F. S. Bieser and H. H. Heckman, Nucl. Inst. and Meth. 116, 21 (1974).
3. H. H. Heckman, D. E. Greiner, P. J. Lindstrom and F. S. Bieser, Phys. Rev. Lett. 28, 926 (1972).
4. W. R. Frazer, et. al., Rev. Mod. Phys. 44, 284 (1972).
5. Preliminary results based on eight isotopes not including ^1H indicated $\sigma_{P_\parallel} \approx 140$ MeV/c, independent of mass (H. H. Heckman, 5th, Intl. Conf. High-Energy Phys. Nucl. Struct., Uppsala, June 1973.) Based on all the data presented here, a constant value of $\sigma_{P_\parallel}=137$ MeV/c gives a goodness-of-fit comparable to that obtained with a parabolic dependence, $\chi^2=1370$ if $\sigma_{P_\parallel}=137$ MeV/c versus $\chi^2=600$ for the parabola with 32 degrees of freedom.
6. W. A. Wenzel, LBL Heavy Ion Seminar, 1973 (unpublished).
7. J. V. Lepore and R. J. Riddell, Jr., LBL 3086, 1974 (unpublished).
8. H. Feshbach and K. Huang, Phys. Lett. 47B, 300 (1973).

9. Alfred S. Goldhaber, Phys. Lett. 53B, 306 (1974). The fragmentation problem has also been studied by Fumiyo Uchiyama, LBL 3318, 1974 (unpublished).

10. E. J. Moniz, I. Sick, R. R. Whitney, J. R. Ficenec, R. D. Kephart and W. P. Trower, Phys. Rev. Lett. 26, 445 (1971).

11. Particle Data Group, Phys. Lett. 50B (1974).

12. C. M. Lederer, J. M. Hollander, and I. Perlman, Table of Isotopes, John Wiley & Sons Inc., New York, N. Y. (1967).

Table I. MOMENTUM DISTRIBUTION WIDTHS AND CENTERS (MeV/c)[a]

		SECONDARY			
BEAM	ENERGY	Z_F	A_F	$\sigma_{P_\parallel}$	$\langle P_\parallel \rangle$
^{16}O	2.10 GeV/n	1	1 [b]	71± 6	-1± 5
		1	2	134± 3	-23± 2
		1	3	150± 3	-41± 5
		2	3	156± 2	-38± 3
		2	4	131± 1	-27± 3
		2	6	167±20	-40±10
		3	6	141± 7	-33± 7
		3	7	163± 4	-46± 6
		3	8	170±13	-24±12
		3	9	188±15	-63±31
		4	7	166± 2	-45± 9
		4	9	166± 7	-47± 7
		4	10	159± 6	-65± 6
		4	11	197±20	-73±27
		5	8	175±22	-57±11
		5	10	175± 7	-40± 7
		5	11	160± 2	-53± 3
		5	12	163± 8	-59±10
		5	13	166±10	-67±23
		6	10	190± 9	-32±15
		6	11	162± 5	-45±13
		6	12	120± 4	-25± 6
		6	13	130± 3	-33± 7
		6	14	125± 3	-38± 7
		6	15	125±19	-132±25
		7	12	153±11	-49±28
		7	13	134± 2	-35± 4
		7	14	112± 3	-27± 3
		7	15	95± 3	-21± 6
		7	16	54±11	-110±15
		8	13	143±14	-57±26
		8	14	99± 6	-31± 7
		8	15	94± 3	-23± 3
^{12}C	2.10 GeV/n	1	1 [b]	67± 5	0± 3
		1	2	134± 4	-27± 3
		1	3	138± 5	-48± 4
		2	3	145± 8	-31± 4
		2	4	129± 1	-25± 4
		2	6	136± 7	-29±15
		3	6	127± 7	-33±10
		3	7	144± 2	-40± 7
		3	8	159± 7	-43±12
		3	9	161± 9	-35±17
		4	7	145± 2	-49± 6
		4	9	133± 3	-38± 9
		4	10	129± 4	-30± 8
		4	11	155±40	-102±82
		5	8	151±16	-39±12
		5	10	134± 3	-35± 7
		5	11	106± 4	-23± 9
		5	12	63± 9	-96±14
		6	9	147±21	-43±30
		6	10	121± 6	-42±11
		6	11	103± 4	-40± 9
		7	12	56±16	-100±11
^{12}C	1.05 GeV/n	1	1 [b]	63± 4	13± 4
		1	2	113±11	-13±12
		1	3	162±14	-25±13
		2	3	132±14	-32± 2
		2	4	125± 3	-27± 2
		2	6	142±20	-32±14
		3	6	122±10	-28± 7
		3	7	142± 7	-44± 4
		3	8	160±26	-35±14
		3	9	139±19	-43±20
		4	7	140± 6	-53± 5
		4	9	131± 9	-35± 5
		4	10	125±11	-37± 5
		4	11	103±37	-104±43
		5	8	139±12	-61±20
		5	10	135± 9	-35± 8
		5	11	102±11	-30± 4
		5	12	88±17	-112±31
		6	9	147±28	-28±17
		6	10	126± 8	-46± 5
		6	11	105±10	-43± 4
		7	12	43±19	-55±19

---

[a] PROJECTILE FRAME PARALLEL MOMENTUM AVERAGED OVER ALL TARGETS (ERRORS INCLUDE SYSTEMATIC AND STATISTICAL CONTRIBUTIONS)

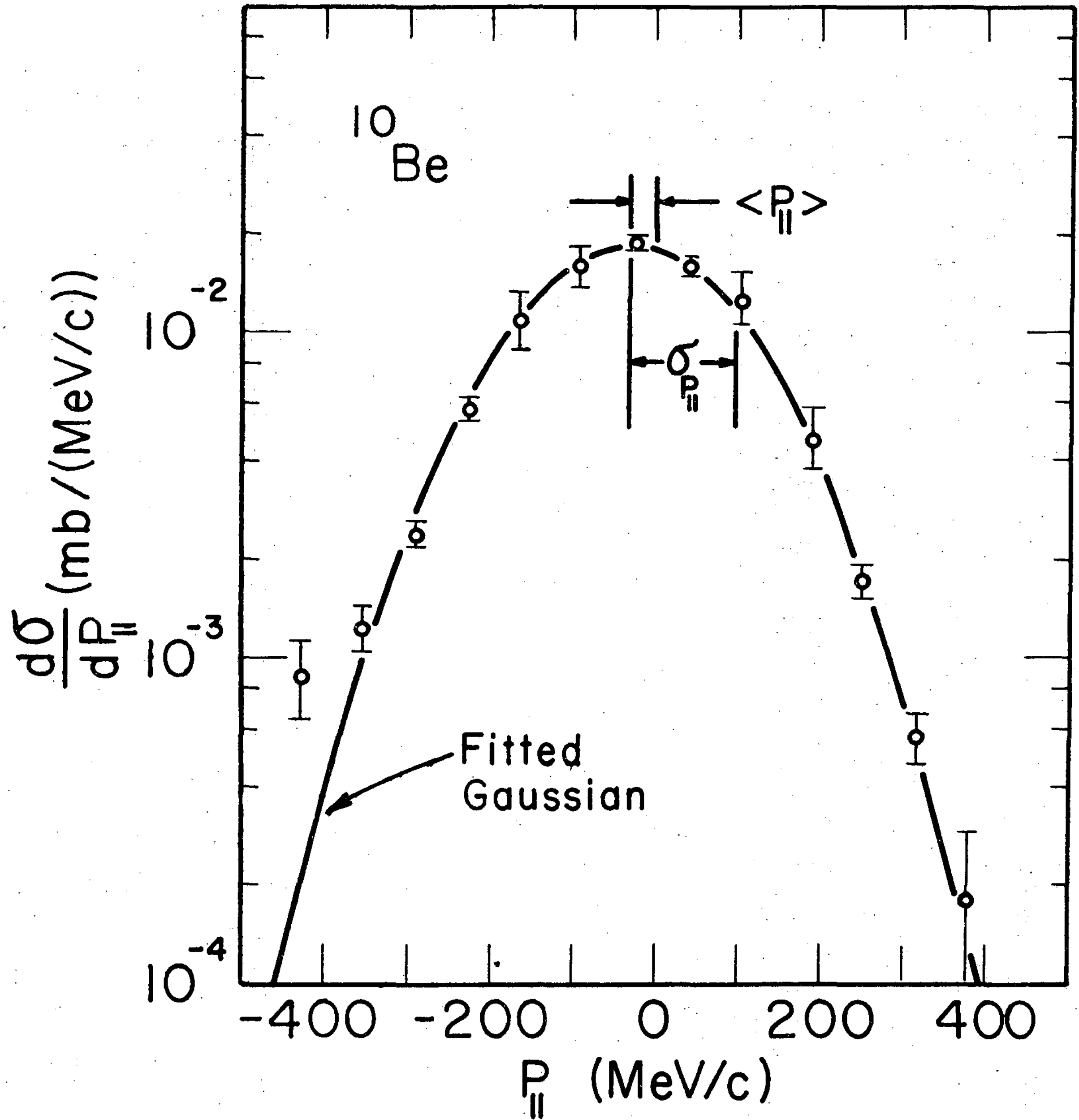
[b] NON-GAUSSIAN DISTRIBUTION

Table II. Comparison with theory and experiment of parameters related to a $\sigma_{P_\parallel}$ mass dependence of the form $\sigma_{P_\parallel}^2=4\sigma_o^2 F(B-F)/B^2$. Derived quantities are Fermi momentum $P_f=20\sigma_o^2(B-1)/B^2$ and average excitation energy $kT=4\sigma_o^2/m_n B$.

		Projectile		
Parameter	Origin	^{16}O 2.1 GeV/n	^{12}C 2.1 GeV/n	^{12}C 1.05 GeV/n
σ_o(MeV/c)	this expt.	171±3	147±4	141±5
"	sudden approximation[7]	162	145	145
"	virtual clusters[8]	212	179	179
P_f(MeV/c)	this expt.	185±3	182±5	174±6
"	electron scattering[10]	230	221	221
kT(MeV/n)	this expt.	7.8±0.3	7.7±0.4	7.1±0.5
average binding energy (MeV/c)	mass measurements[11,12]	8.0	7.7	7.7

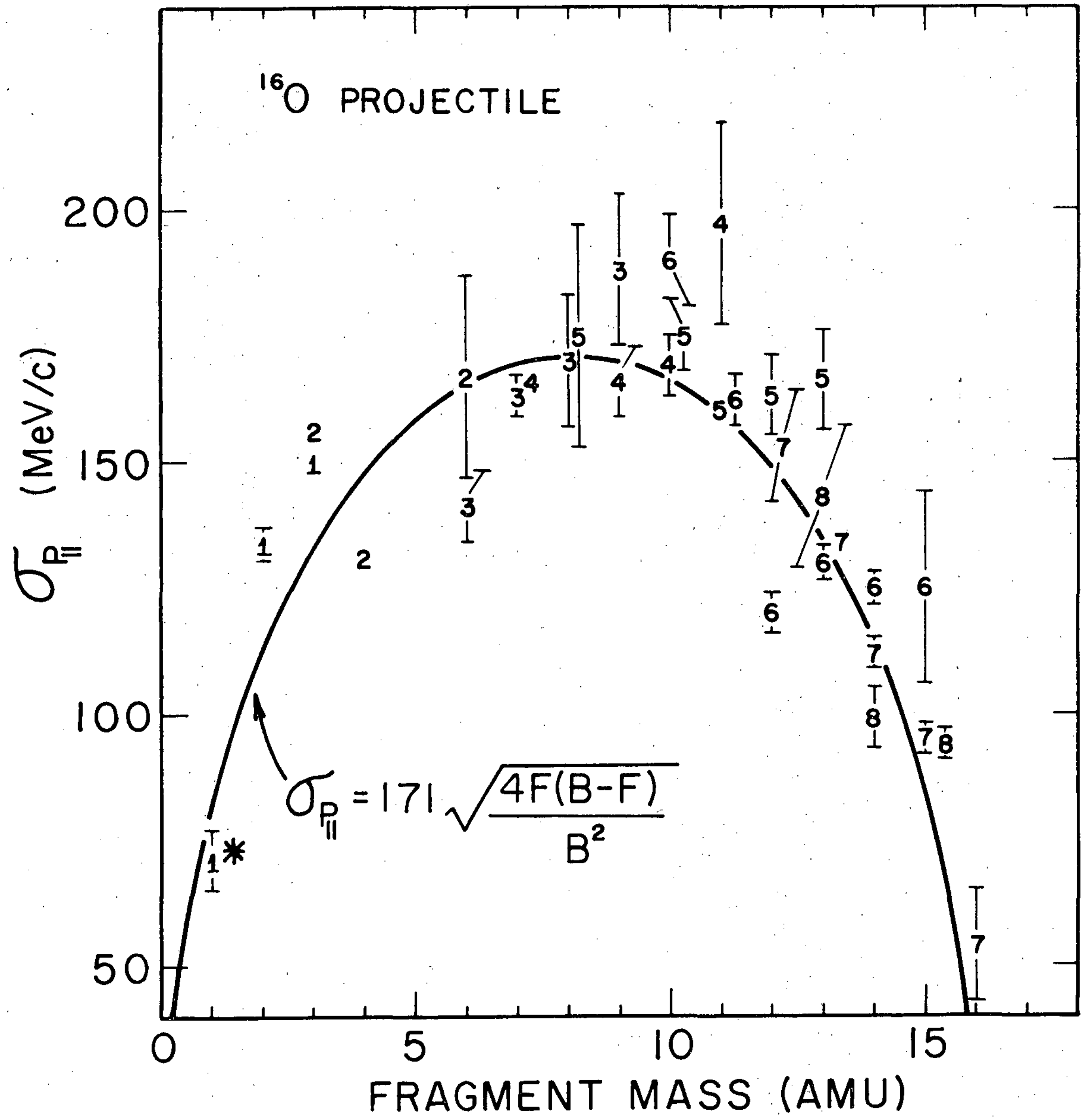
Figure Captions

1. The projectile-frame parallel-momentum distribution for ^{10}Be fragments from ^{12}C at 2.1 GeV/n on a Be target. The mean momentum $\langle P_{\|} \rangle$ = -30 MeV/c and standard deviation $\sigma_{P_{\|}}$ = 129 MeV/c are indicated. The curve shown is the best fit to a Gaussian momentum distribution.
2. Plotted are the target-averaged widths $\sigma_{P_{\|}}$ of the projectile-frame parallel-momentum distributions, in MeV/c, versus fragment mass in amu. The plotted symbol indicates the charge of the fragment. These data represent fragments of ^{16}O at 2.1 GeV/n. The asterisk denotes that the ^{1}H is a non-Gaussian momentum distribution and we have used the central region of this distribution to evaluate $\sigma_{P_{\|}}$. The parabola represents the best fit to the data.
3. Dependence of $\langle P_{\|} \rangle$ on $\sigma_{P_{\|}}$ for all fragments observed from ^{12}C and ^{16}O beams. The average linear relationship is $\langle P_{\|} \rangle = -0.5\ \sigma_{P_{\|}} + 30$. The divergent points with $\langle P_{\|} \rangle \simeq 100$ MeV/c are reactions involving charge exchange.



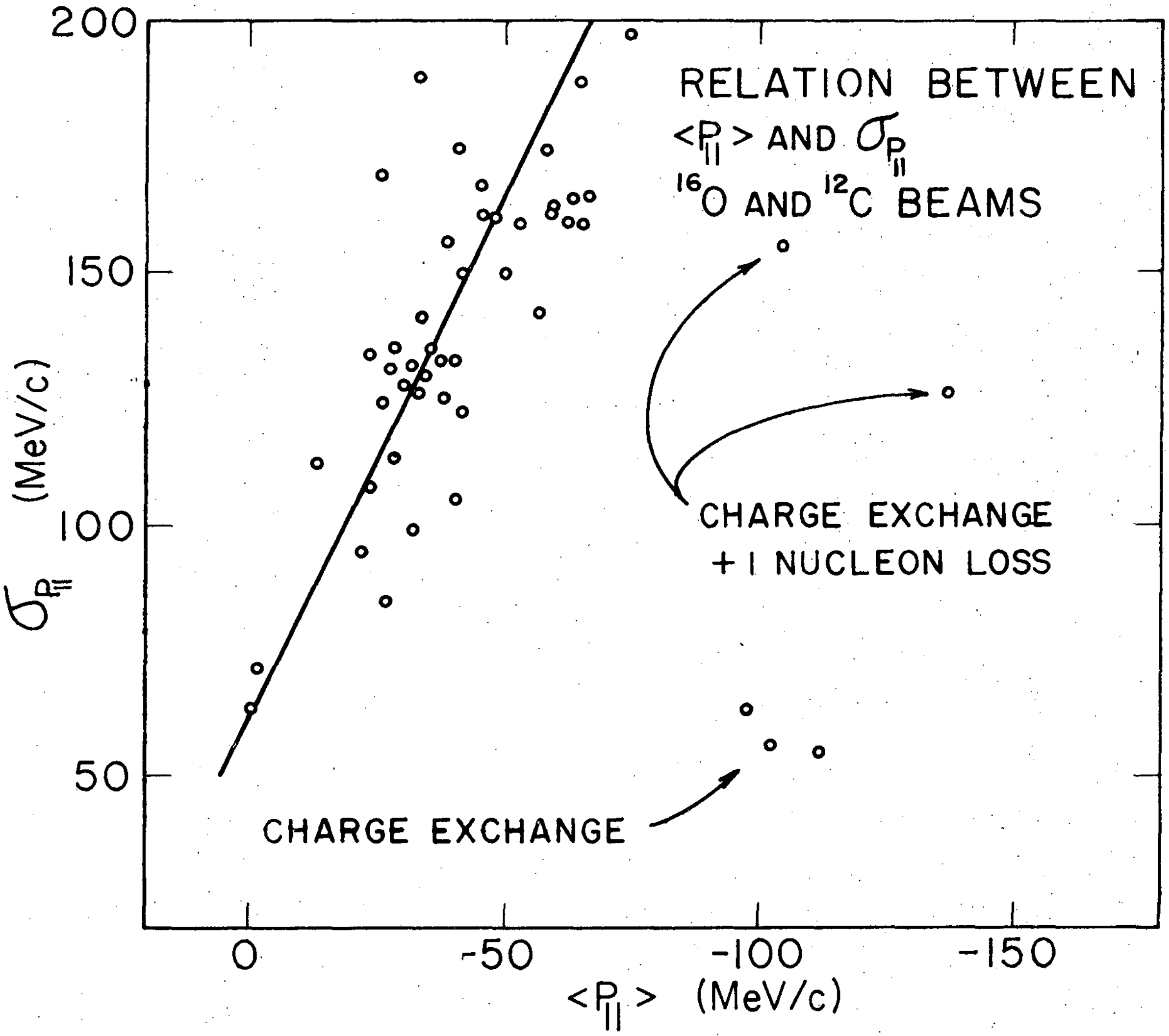
XBL 753-454

Fig. 1



XBL 753-453

Fig. 2



XBL 753-459

Fig. 3

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720