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DOUBLE GAUSSIAN MOMENTUM DISTRIBUTION OF PROJECTILE FRAGMENTS

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When one or two neutrons are lost in the collision of a neutron-rich projectile with a target nucleus, the transverse momentum distribution of the fragment thus produced can be fit with a double Gaussian curve with widely different widths for the two components. It is shown that this phenomenon is not confined to projectiles with more neutrons than protons. It should appear for any fragment for which the momentum arises mainly from a single isotropic source whose value varies from one collision event to another.

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In experiments using 790 MeV/nucleon neutron-rich projectiles interacting with a C target, it was found that the transverse momentum distribution of ^{9}Li fragments from a ^{11}Li projectile could be fit with a double Gaussian curve in which the components had widths, σ, of 80 and 21 MeV/c. (The transverse momentum is defined as the momentum of fragments perpendicular to the bending plane of the analyzing magnet in the projectile frame (1)).

Fragments of ^{4}He and ^{6}He from ^{6}He and ^{8}He projectiles respectively were reported to have only a single broad Gaussian transverse momentum distribution (1). Later work showed that the momentum distribution of ^{4}He fragments from ^{6}He projectiles does in fact have a double Gaussian distribution (2). The case of ^{6}He fragments from ^{8}He is still under study (3).

In other experiments, (^{10}Be from ^{11}Be, ^{12}Be from ^{14}Be), the transverse momentum shows clear evidence of a double Gaussian shape (2,4). In all these cases, the momentum distribution was measured with a bin size of 20 MeV/c. The widths of the broad component range from 80 MeV/c (^{9}Li) to 110 MeV/c (^{4}He), and of the narrow component from 21 MeV/c (^{9}Li) to 43 MeV/c (^{4}He). The ratios of the number of events in the broad peak (B) to those in the narrow peak (N) range from 1.13 ± 0.23 (^{4}He) to 1.50 ± 0.25 (^{9}Li), all with a C target. Thus they are all about the same within error bars.

The parallel and transverse momentum distributions of many fragments from ^{12}C projectiles at 1.05 and 2.1 GeV/nucleon have also been measured. The momentum distributions were found to be isotropic in the projectile rest frame (5). They were fit with single Gaussians using an average bin size of about 53 MeV/c.

In the present work, the collisions between ^{12}C projectile and ^{12}C target nucleons were simulated by a Monte Carlo calculation (6,7) to obtain the yields and approximate exciatation energies of primary fragments. The target nucleus was given a radial Fermi density distribution of protons and neutrons with a half-density radius $\underline{c}$ of 2.222 fm and a diffusivity $\underline{a}$ of 0.521 fm. The effect of varying these parameters for the projectile nucleus was investigated.

A fragment that lost a nucleon was assumed to recoil with the Fermi momentum of the knocked-out nucleon. The Fermi momentum in the center region was taken to be 270 MeV/c, decreasing towards the surface as the cube root of the local density at the radius of the struck nucleon. It was also decreased by a factor F when the local proton and neutron densities were not equal (8):

$$F = 1 - 0.48 \{ [\rho_n(r) - \rho_p(r)]^2 / [\rho_n(r) + \rho_p(r)]^2 \} \qquad (1)$$

Thus the local Fermi momentum of a nucleon at radius r becomes:

$$P_F(r) = 270 \times F \{ [\rho_n(r) - \rho_p(r)] / [\rho_n(0) + \rho_p(0)] \}^{1/3} \text{ MeV/c} \qquad (2)$$

It was assumed to be isotropic.

For projectiles such as ^{11}Li that have a long and dilute neutron "tail" in the density distribution, the calculated probability of knock-out of two neutrons is only about 7% of the probability of one neutron. The detected fragment (e.g. ^{9}Li) is therefore formed almost entirely by decay of the neutron-unbound (N_{proj}-1) primary fragment.

The primary fragments, if excited by recapture of the struck nucleon, by secondary reactions between that nucleon and the projectile remnant, or by formation of a hole in the s-shell, were then allowed to decay by emission of nucleons or of heavier fragments. Particle emission contributed to the momentum of the final fragment: it too was assumed to be isotropic. These calculations are described in detail in Refs. 6,7.

It was found that ^{11}C fragments from ^{12}C projectiles showed a double Gaussian transverse momentum distribution, similar to those measured with the neutron-rich projectile nuclei. The result of the calculation, using a momentum bin size of 20 MeV/c, is shown in Fig. 1. The widths of the two Gaussians are 96 and 35 MeV/c, and the ratio of the number of events in the broad peak to that in the narrow peak is 2.37. These values are similar to those obtained with the neutron-excess projectiles.

When a single Gaussian fit to the same calculation was made with a momentum bin size of 50 MeV/c, the result shown in Fig.2A was obtained. Omitting the narrow Gaussian produces a rather poor fit with two high points near zero momentum. The width, though, is 88 MeV/c, not very different from that of the broad component from the double Gaussian fit.

Fig. 2B shows the result of fitting the experimental parallel momentum distribution (5) in exactly the same way. The similarity between Figs. 2A and 2B is quite striking. (As already mentioned, the experiment showed that the momentum distribution is isotropic: thus parallel and transverse distributions are the same). The experimental parallel momentum width is 105±10 MeV/c for ^{12}C projectiles of 1.05 MeV/nucleon (5). The deviation from the Gaussian curve shown in Fig. 2B strongly suggests that the experimental distribution might well be a double Gaussian if measured with a small enough bin size. The parallel momentum distribution of ^{11}B fragments from ^{12}C has exactly the same deviation from a single Gaussian fit as ^{11}C, but in both cases there are too few data points to allow a meaningful double Gaussian fit to be made. The experimental results for ^{16}O fragmentation are no longer available.

It is perhaps significant that the published momentum distribution of ^{6}He fragments from ^{8}He projectiles shows three experimental points near zero momentum that lie higher than the fitted single Gaussian curve, while the points at about ±100 MeV/c are low (Ref.

1, Fig. 1A).

If the fragment total momentum P in the projectile frame comes from a single isotropic source, then the transverse momentum distribution perpendicular to the bending plane of the magnet is P sin θ cos ϕ , where cos θ is randomly chosen in the range +1 to -1 and ϕ is randomly chosen between 0 and 2π . For any value of P, the distribution will therefore range from +P to -P.

If the value of P is the same for all events, the momentum distribution is flat between -P and +P. In the present calculations, though, the main source of momentum is the Fermi momentum of a struck neutron which varies with the local matter density and the local proton/neutron density ratio (eq. 2). The local value of P_F therefore varies between 270 MeV/c (the Fermi momentum in the full-density region) and nearly zero in the tail of the matter distribution. The transverse or parallel momentum distribution therefore depends on the radial density distributions of neutrons and protons in the projectile. That it can be quite well fit with a double Gaussian is purely coincidental.

Thus the two components of the double Gaussian are not directly related to the binding energies of nucleons in the projectile center and surface, as has been suggested (1). However, these binding energies do, of course, influence the radial density distribution. Weakly bound nucleons are expected to produce a long "tail" in the density distribution (9).

The effect of the radial density distributions of protons and neutrons in ^{12}C projectiles was investigated by changing the half-density radius c and diffusivity a while keeping the volume integral equal to 12 nucleons. The target nucleus retained the usual values of c (2.222 fm) and a (0.521 fm). The results are shown in Table 1.

All the quantities listed in the Table are quite sensitive to the shape of the projectile nucleus. The values in Line 3 (the usual values for ^{12}C) give the best agreement with the experimental cross sections (930 and 46.5 mb). In Line 1, the projectile has a diffuse surface for protons and neutrons: the cross sections are too large and the width of the broad component is much smaller than the experimental value of 105 MeV/c.

In Line 2, the projectile has a diffuse neutron "tail" that extends well beyound the protons. Thus the shape resembles that of neutron-excess nuclei such as ^{11}Li. The Gaussian widths are close to those of ^{9}Li from ^{11}Li projectiles (80 and 21 MeV/c). The ratio B/N, though, is much smaller than for ^{9}Li (1.50±0.50). This is because the proton distribution in ^{12}C (6 protons) extends to larger radii than that of ^{11}Li (3 protons). The broad component comes from interactions in which a single neutron at a small radius is knocked out. The presence of a high proton density at that radius makes this process less probable.

In Line 4, the shape for both protons and neutrons is close to a sharp cutoff in the density distribution. The cross sections, especially σ_c, are too small and the width of the broad component is too large. The narrow component has completely disappeared. Only in Line 3 are all the calculated values in good agreement with experimental results.

If there are additional sources of momentum, such as the formation of the detected fragment from decay of excited projectiles, the width of the Gaussian components is slowly increased. In the formation of ^{11}C from ^{12}C, though, the contribution from decay of ^{12}C is small because excited ^{12}C nearly always decays by emission of ^{4}He rather than by neutron emission to ^{11}C.

Fragments lighter than the projectile nucleus by 3 or moe mass units are mainly formed by decay of heavier excited precursors (7). The addition of several sources of uncorrelated isotropic momenta to the initial Fermi momentum broadens the distribution. Thus ^{8}Li fragments from ^{11}Li projectiles still have a double Gaussian momentum distribution, but the widths of the components are 143 and 42 MeV/c (1), substantially larger than for ^{9}Li (80 and 21 MeV/c respectively).

Thus it seems very likely that double Gaussian momentum distributions are not confined to neutron-excess nuclei. They should be observed for fragments that are formed by knock-out of either a proton or a neutron from any projectile that has a normal or diffuse surface density distribution. The reaction cross section is sensitive only to the matter distribution of the projectile unless the measurements are made at low and high projectile energies with different ratios of the nucleon-nucleon scattering cross sections nn/ np. The inclusive cross sections for one neutron (proton) loss are sensitive to the neutron (proton) density distributions. The widths of the two Gaussian components and the ratio B/N are also sensitive to both the neutron and proton density distributions. Taken together, measurements of the inclusive cross sections and the momentum distributions permit the accurate determination of the radial proton and neutron densities.

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TABLE 1. Effect of changing the shape of the projectile nucleus in the reaction ^{12}C + C, 1000 MeV/nucleon. c and a are the assumed half-density radius and the diffusivity respectively. σ_B, σ_N, σ_R and σ_C are the widths of the broad and narrow transverse momentum distributions, the total reaction cross section and the ^{11}C inclusive cross section respectively. B/N is the ratio of the number of events in the broad (B) and narrow (N) momentum components. r_{av} is the average radius at which a neutron was struck to produce ^{11}C.

c(fm)	a(fm)	σ_B(MeV/c)	σ_N(MeV/c)	B/N	σ_R(mb)	σ_C(mb)	r_{av}(fm)
1.0 (a)	1.271	61	32	1.75	1967	287	6.00
1.0 (b)	1.309	74	22	0.18	1220	204	6.24
2.222 (c)	0.521	96	35	2.37	890	49	3.26
2.50 (a)	0.231	137	(No narrow component)		818	19	2.38

(a) Shape parameters for projectile protons and neutrons.

(b) Shape parameters for projectile neutrons only. For protons, c = 2.222 fm, a = 0.521 fm.

(c) "Standard" values for both protons and neutrons, giving the best agreement with experimental values of σ_B, σ_R and σ_C.

FIGURE CAPTIONS

Fig. 1. Calculated transverse momentum distribution of ^{11}C fragments from ^{12}C + C (1 GeV/nucleon) with half-density radius 2.222 fm and diffusivity 0.521 fm in both projectile and target. Squares are the calculated points. Lines are least squares Gaussian fit to the broad and narrow distributions and their sum.

Fig. 2 (A). Fit to the calculation of Fig. 1, using a single Gaussian and a bin size of 50 MeV/c. Squares are the calculated points. The line is the Gaussian fit.

(B). Experimental parallel momentum distribution of ^{11}C from ^{12}C + C at 1 GeV/nucleon. Squares are the experimental points. The line is a single Gaussian fit.

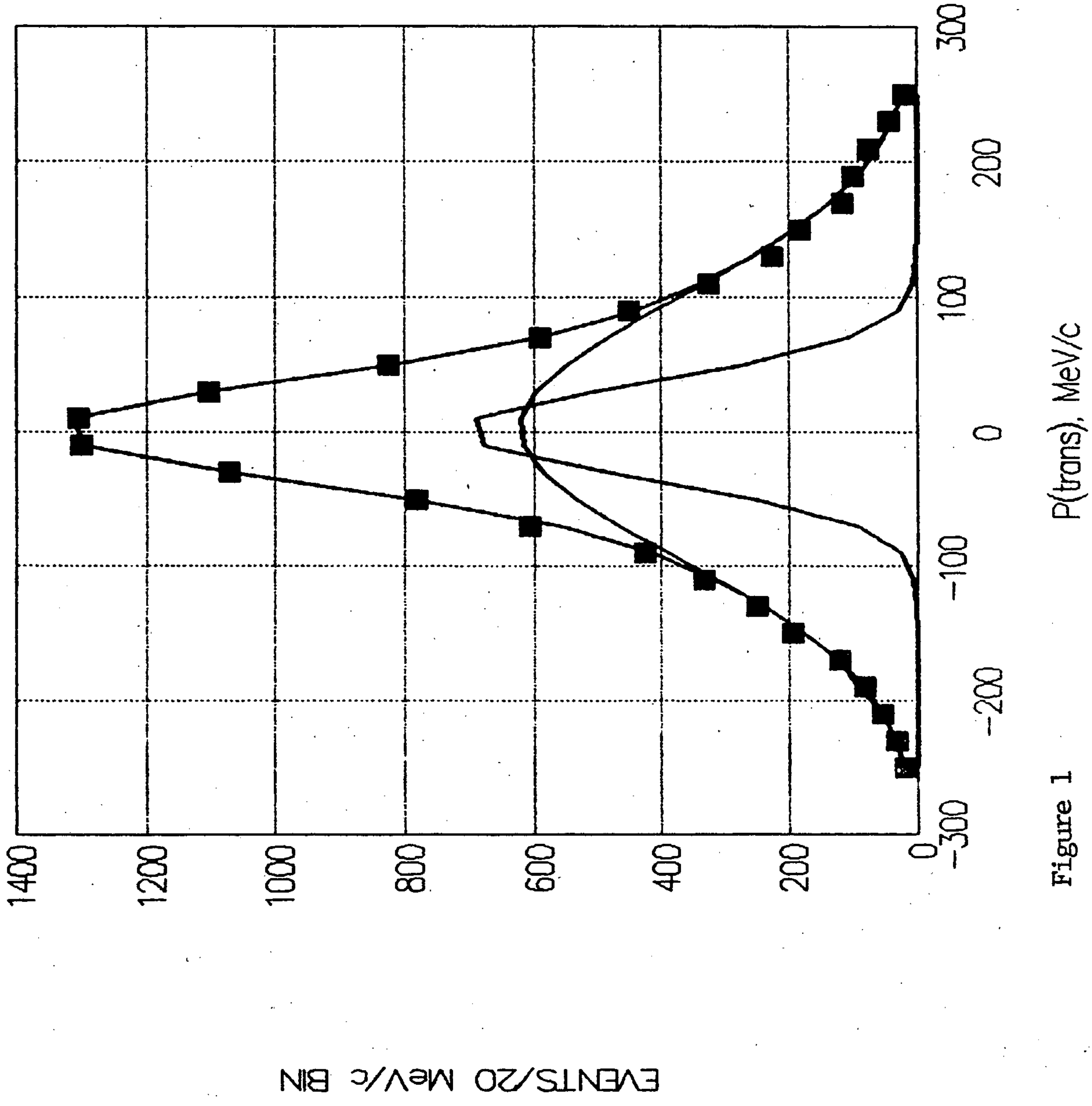
1400
1200
1000
800
600
400
200
0
−300
−200
−100
0
100
200
300
P(trans), MeV/c
EVENTS/20 MeV/c BIN

Figure 1

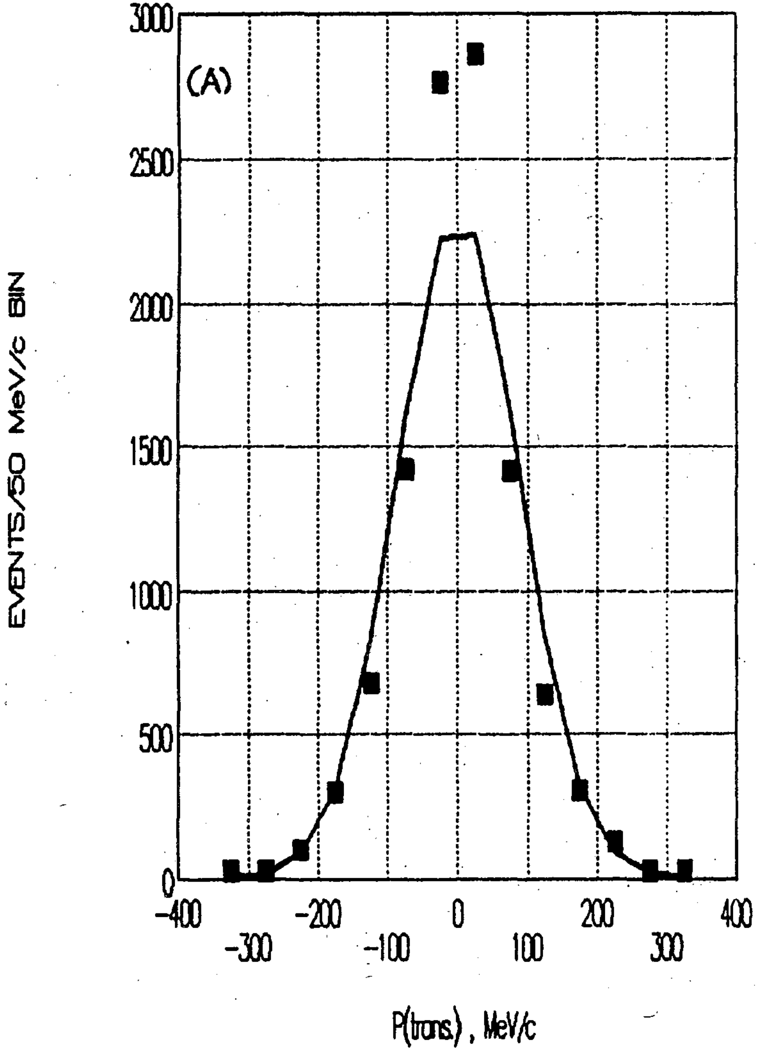

Figure 2A

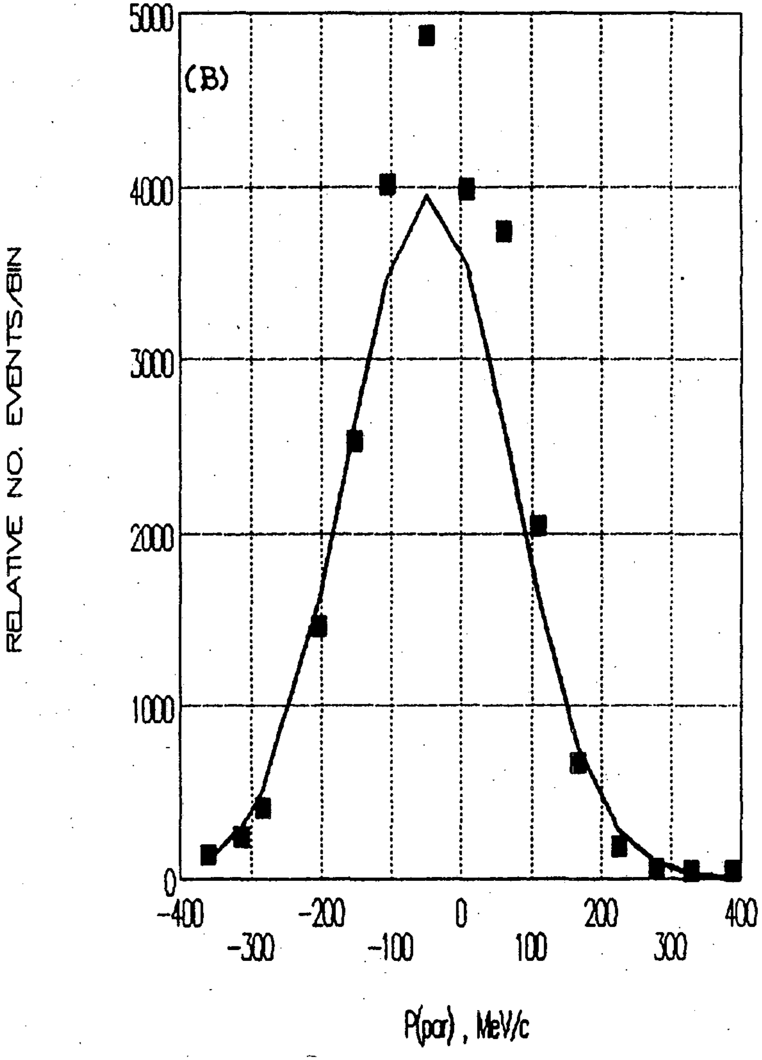

Figure 2B

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