PHYSICAL REVIEW C VOLUME 28, NUMBER 1 JULY 1983

Brief Reports

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract.*

Momentum widths of heavy-ion reaction products at 27.4 MeV/nucleon

Martin J. Murphy* and Robert G. Stokstad
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 11 January 1983)

The inclusive energy spectra of ^{6,7}Li ejectiles from the reaction ^{9}Be + Au at 27.4 MeV/nucleon have been measured. The quasielastic peaks for ^{6}Li and ^{7}Li have reduced momentum widths σ_0 of 65 and 60 MeV/c, respectively. When plotted in conjunction with similar measurements, these new results clarify the behavior of the reduced momentum width in the important region between 10–100 MeV/nucleon.

[NUCLEAR REACTIONS ^{9}Be + Au $\rightarrow$ ^{6,7}Li + X. $E(^9$Be$)$ = 27 MeV/ nucleon. Measured momentum widths of ^{6,7}Li ejectiles. Deduced reduced width σ_0. Discuss σ_0 over energy range 10–2000 MeV/nucleon.]

The inclusive momentum spectra of ejectiles emitted at forward angles in heavy-ion reactions exhibit a characteristic "quasielastic" peak. This peak has a mean velocity approximately equal to the beam velocity, and is observed for laboratory bombarding energies of 5 to 2000 MeV/nucleon. Its characteristics have been extensively analyzed for an understanding of heavy-ion reaction mechanisms. In this paper we report an inclusive measurement of the energy spectra of ^{9}Be + Au reaction products at 27.4 MeV/ nucleon, and discuss the status of the currently available body of similar data. Particular attention is devoted to the widths of the spectra.

At high energies ($\geq$200 MeV/nucleon) the quasielastic (QE) peak is consistent with a Gaussian momentum distribution in the rest frame of the projectile[1,2] and is associated with projectile fragmentation. The width σ of this Gaussian distribution has been observed[3] to have a mass dependence of the form

$$\sigma^2 = \frac{A_F(A_P - A_F)}{A_P - 1}\sigma_0^2 \ . \qquad (1)$$

Here A_P and A_F are the projectile and fragment mass numbers and σ_0 is a "reduced" width that, for a given bombarding energy, is approximately independent of projectile, target, and ejectile masses. For these high-energy fragmentation reactions, the shape of the QE momentum distribution, the mass dependence of Eq. (1), and the observed[3] values of σ_0 can be explained[4] by both a process that samples the Fermi momentum of nucleons in the projectile, and a process that produces a fully equilibrated projectile nucleus with a temperature $kT = \sigma_0^2/M_N$. M_N is the mass of the nucleon.

In order to look for evidence of fragmentation reactions at lower energies, the measurement of the quasielastic peak width, σ, and the reduced width, σ_0, has been extended to energies as low as 7.5 MeV/nucleon. At these low energies the ejectile momentum spectrum shows a low energy tail in addition to the QE peak. (This tail evolves into the deep-inelastic peak at larger angles.) Nevertheless, the high energy (QE) side of the spectrum still has a Gaussian shape in the projectile rest frame, and the widths σ and σ_0 may be obtained.

Upon extending the measurements down to 10 MeV/nucleon the reduced width was observed to change dramatically with energy.[5] At energies from 2 GeV/nucleon to 213 MeV/nucleon the average value of σ_0 is ~86 MeV/c, while at energies below 10 MeV/nucleon the reduced widths have decreased to ~20 MeV/c. However, owing to very limited data and inadequacies of the early measurements, the energy dependence in the intervening region has been the subject of discussion for several years. In an early investigation of σ_0 at energies from 10 to 20 MeV/nucleon using the ^{16}O + Pb reaction, Scott[5] reported a rapid rise to the value characteristic of relativistic bombarding energies. Egelhaaf *et al.*,[6] pointed out that this measurement combined the energy spectra of all isotopes of a particular ejectile charge, which obviously leads to peaks wider than would be the case for a single isotope. Egelhaaf's measurement of the energy spectra for separated isotopes in

$^{20}Ne + Au$ reactions in the same energy range yielded reduced widths much smaller than those reported by Scott and Gelbke[5]; at 20 MeV/nucleon the reduced widths[6] did not exceed 40 MeV/c. When plotted on a linear scale they appeared to reach a plateau at ~20 MeV/nucleon. Subsequently, Harvey[7] noted that the values of σ_0 in Ref. 5 referred to by Egelhaaf represented an average over ejectile charges as well as isotopes, although variations of σ_0 with charge were significant.

The previously available measurements of σ_0 leave unexplored an interval between 20 and 40 MeV/ nucleon. We report here a new measurement of σ_0 which contributes a data point in the middle of this gap.

We have measured energy spectra for the reactions $^9Be + Au \rightarrow {}^{6,7}Li + X$, at a laboratory energy of 27.4 MeV/nucleon. A 246 MeV ^9Be beam from the LBL 88-Inch Cyclotron was used to bombard a 3.25 mg/cm^2 Au target. A Si(Li) particle telescope with elements 87 μm, 500 μm, and 5 mm thick, located at $\theta_{lab} = 12°$, was used to detect and identify reaction products. All of the different ejectile isotopes were resolved, and complete inclusive energy spectra for ^6Li and ^7Li were obtained. The spectra for other isotopes suffered from energy biases or low counting statistics.

The inclusive energy spectra for ^6Li and ^7Li are shown in Fig. 1. A Gaussian momentum distribution in the projectile rest frame was transformed to a laboratory energy distribution and used to fit the QE peak. The fitting region encompassed the peak and the high energy side and avoided the low energy tail. The fitted curves are also shown in Fig. 1, along with the resulting centroids and widths. The energy centroids correspond approximately to the beam velocity. We obtained values for σ_0 of 65.4 ±2.9 MeV/c and 60.2 ±1.4 MeV/c for ^6Li and ^7Li, respectively.

Figure 2 is a summary of several measurements of σ and σ_0 at various energies. It includes the results of Eglehaaf *et al.*,[6] the high energy points at 213 MeV/nucleon and 2.1 GeV/nucleon, the data of Scott *et al.*[5] reanalyzed by Harvey,[7] and our new measurement at 27.4 meV/nucleon. In all cases the reported widths are for the total (parallel plus perpendicular) momentum distributions at the grazing angle, and are obtained from the energy spectra of single isotopes. The fits in each case cover the apparent quasielastic part of the energy spectrum. (At energies below 50 MeV/nucleon this region excludes the obvious low energy tail. At higher energies, where no low energy tail is evident, the fit extends over the full spectrum.) The measurements at 213 MeV/nucleon and 2.1 GeV/nucleon provided widths for a large number of different isotopes. Rather than plot all of the individual points, the full ranges of observed widths are indicated, as well as the mean values.

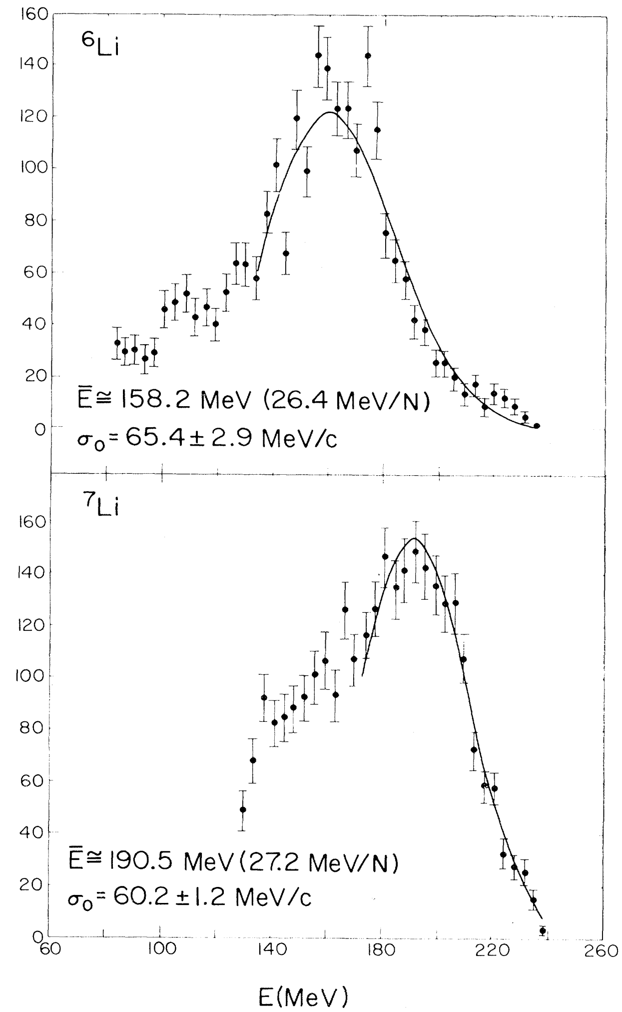

FIG. 1. Inclusive laboratory energy spectra at 12° lab for ^6Li and ^7Li ejectiles from $^9Be + Au$ at 27.4 MeV/nucleon. The solid curves are fits to the quasielastic parts of the spectra.

The data compiled in Fig. 2 show an obvious energy evolution for both σ and σ_0. The transition from the low to the high energy limit is not as abrupt as originally suggested,[5] but it is fully realized over the energy range of 10–200 MeV/nucleon. The factorization of σ according to Eq. (1) reduces the mass dependence of the width at most energies, but leaves a residual mass dependence in σ_0 that is more pronounced below 100 meV/nucleon than at higher energies. The limited amount of data available at energies below 100 MeV/nucleon makes more quantitative statements on the mass dependence of σ_0 difficult.

One must be cautious when using the data for $\sigma_0(E)$ in Fig. 2 as evidence for or against the occurrence of particular reaction mechanisms (e.g., fragmentation, breakup, transfer, etc.). Although the high energy measurements show a persuasive agree-

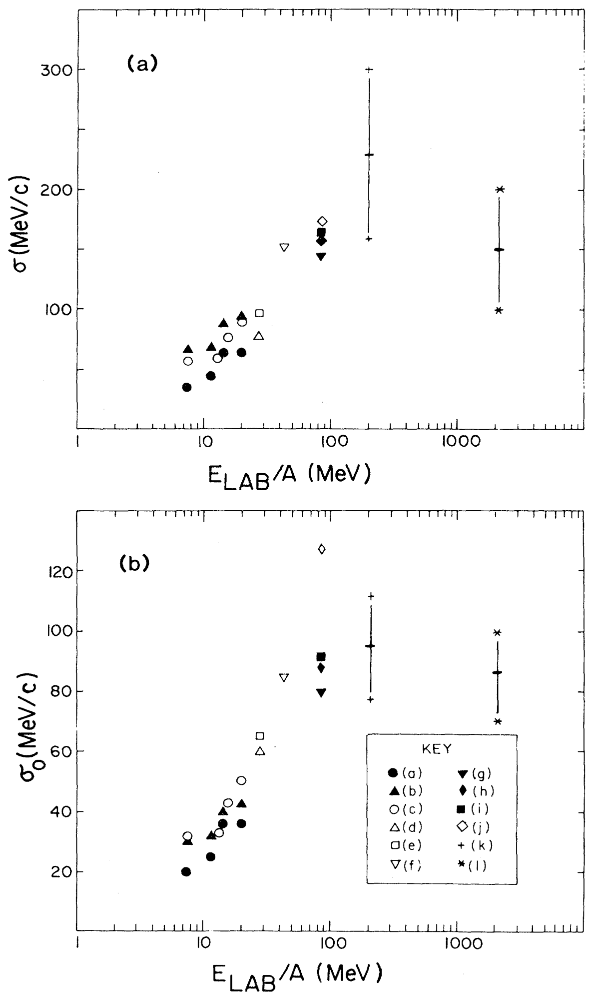

FIG. 2 (a) and (b): A compilation of several different measurements of the momentum widths σ and the reduced momentum widths σ_0 of ejectiles from heavy-ion reactions. In (b), the key to the reactions is as follows: (a) ^{197}Au-(^{20}Ne,^{16}O), Ref. 6; (b) ^{197}Au(^{20}Ne, ^{12}C), Ref. 6; (c) ^{208}Pb(^{16}O, ^{12}C), Ref. 7; (d) ^{197}Au(^{9}Be, ^{7}Li), this work; (e) ^{197}Au(^{9}Be, ^{6}Li) , this work; (f) ^{181}Ta(^{20}Ne, α), Ref. 8; (g) ^{12}C(^{12}C, ^{6}Li), Ref. 9; (h) ^{12}C(^{12}C, ^{7}Li), Ref. 9; (i) ^{12}C(^{12}C, ^{7}Be), Ref. 9; (j) ^{12}C(^{12}C, ^{10}B), Ref. 9; (k) ^{232}Th(^{40}Ar,X), Ref. 10; (l) Be-Pb(^{16}O,X), Ref. 3. A large number of widths were measured at 213 and 2100 MeV/nucleon; the figure indicates the range and mean value of the results.

ment with Eq. (1), the data below 100 MeV/nucleon suffer from several problems which affect the interpretation of σ and σ_0. For instance, all of the results summarized in Fig. 2 have been obtained from inclusive measurements of the reaction spectra. A variety of reaction mechanisms could be represented in these spectra, each contributing its own isotope and energy dependence to the total width. For example, it is known that both transfer and breakup reactions occur at the lower energies.[11] Secondly, the available data below 100 MeV/nucleon only provide the width of the total momentum distribution. There is evidence that below 200 MeV/nucleon only the longitudinal momentum dispersion has the mass dependence of Eq. (1). It has been shown by Van Bibber[12] that at 100 MeV/nucleon the transverse momentum dispersion has a form more like

$$\sigma_{P_\perp}^2 \simeq \frac{A_F(A_P-A_F)}{A_P-1}\sigma_0^2 + \frac{A_F(A_F-1)}{A_P(A_P-1)}\sigma_2^2 \ . \qquad (2)$$

This new parametrization still does not account fully for the isotope dependence of the data compiled in Fig. 2(b)—although Eq. (2) accounts for the widths at 86 meV/nucleon,[9] it does not describe the isotope dependence between 7 and 45 meV/nucleon. At these lower energies the trend is contrary to Eq. (2). As a final point, we note that the fitting procedure to obtain σ is itself quite subjective. It requires assumptions about the effect of the low energy tail and qualitative decisions about the part of the spectrum to be included in the fit. Even among the data presented here there are certainly systematic differences due to these necessary judgments.

Our measurement of quasielastic momentum widths at 27.4 MeV/nucleon yields results that support a relatively smooth transition in the reduced width σ_0 between 10 and 200 MeV/nucleon. Upon reexamining all of the similar data available at energies from 5 to 2000 MeV/nucleon, we have noted that this transition is just as evident in the "unreduced" width σ. However, there are problems with the interpretation of σ_0; it not only conceals a known anisotropy in the longitudinal and transverse momentum dispersions, but also a variety of reaction mechanisms. Therefore, any conclusions about the reaction dynamics at low energies based upon the currently known values of σ_0 are premature. The reliable deduction of physical information from measurements of σ at low energy must await the systematic measurement of each momentum component and separation of the inclusive spectra according to reaction mechanism.

We would like to thank Karl Van Bibber and Peter Countryman for discussions and assistance with the measurements. This work was supported by the Director, U.S. Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics, and by Nuclear Sciences of the Basic Energy Sciences Program of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

*Present address: Nuclear Physics Laboratory, University of Washington, Seattle, WA 98195.

[1]H. H. Heckman *et al.*, in *Proceedings of the 5th International Conference on High Energy Physics and Nuclear Structure,* edited by G. Tibell (Almquist and Wiksell, Uppsala, 1974).

[2]H. Feshbach and K. Huang, Phys. Lett. 47B, 300 (1973).

[3]D. E. Greiner, P. J. Lindstrom, H. H. Heckman, B. Cork, and F. S. Beiser, Phys. Rev. Lett. 35, 152 (1975).

[4]A. S. Goldhaber, Phys. Lett. 53B, 306 (1974); G. Bertsch, Phys. Rev. Lett. 46, 472 (1981).

[5]D. K. Scott, M. Bini, P. Doll, C. K. Gelbke, D. L. Hendrie, J. L. Laville, J. Mahoney, A. Mechaca-Rocha, M. C. Mermaz, C. Olmer, T. J. M. Symons, Y. P. Viyogi, K. Van Bibber, H. Weiman, and P. J. Siemens, Lawrence Berkeley Laboratory Report No. LBL-7729, 1978 (unpublished); C. K. Gelbke, D. K. Scott, M. Bini, D. L. Hendrie, J. L. Laville, J. Mahoney, M. C. Mermaz, and C. Olmer, Phys. Lett. 70B, 415 (1977).

[6]Ch. Egelhaaf, G. Bohlen, H. Fuchs, A. Gamp, H. Homeyer, and H. Kluge, Phys. Rev. Lett. 46, 813 (1981).

[7]B. G. Harvey, Phys. Rev. Lett. 47, 454 (1981).

[8]J. B. Natowitz, M. N. Namboodiri, L. Adler, R. P. Schmitt, R. L. Watson, S. Simon, M. Berlanger, and R. Choudhury, Phys. Rev. Lett. 47, 1114 (1981).

[9]J. Mougey, R. Ost, M. Buenerd, A. J. Cole, C. Guet, D. Lebrun, J. M. Loiseaux, P. Martin, M. Maurel, E. Monnand, H. Nifenecker, P. Perrin, J. Pinston, C. Ristori, P. de Saintignon, F. Schissler, L. Carlen, B. Jakobsson, A. Oskarsson, I. Otterlund, B. Schroder, H. A. Gustafsson, T. Johansson, H. Ryde, J. P. Bondorf, O. B. Nielsen, and G. Tibell, Phys. Lett. 105B, 25 (1981).

[10]Y. P. Viyogi, T. J. M. Symons, P. Doll, D. E. Greiner, H. H. Heckman, D. L. Hendrie, P. J. Lindstrom, J. Mahoney, D. K. Scott, K. Van Bibber, G. D. Westfall, H. Wieman, H. J. Crawford, C. McParland, and C. K. Gelbke, Phys. Rev. Lett. 42, 33 (1979).

[11]M. J. Murphy, B. G. Harvey, D. L. Hendrie, W. W. Pang, K. Van Bibber, and R. Legrain, Phys. Lett. 120B, 75 (1983).

[12]K. Van Bibber, D. L. Hendrie, D. K. Scott, H. H. Wieman, L. S. Schroeder, J. V. Geaga, S. A. Chessin, R. Treuhaft, J. Y. Grossiord, J. O. Rasmussen, and C. Y. Wong, Phys. Rev. Lett. 43, 840 (1979); C. Y. Wong and K. Van Bibber, Phys. Rev. C 25, 2990 (1982).