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Momentum Widths of Heavy-Ion Reaction Products at 27.4 MeV/n

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ABSTRACT

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

NUCLEAR REACTIONS: ^{9}Be+Au ^{6,7}L+X.
E(^{9}Be) = 27 MeV/n. Measured momentum widths of
^{6,7}Li ejectiles. Deduced reduced width σ_o .
Discuss σ_o over energy range 10-2000 MeV/n.

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The inclusive momentum spectra of ejectiles emitted at forward angles in heavy-ion reactions exhibit a characteristic "quasi-elastic" 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/n. Its characteristics have been extensively analyzed for an understanding of heavy-ion reaction mechananisms. In this paper we report an inclusive measurement relevant to this subject, and discuss the status of the currently available body of similar data.

At high energies ($\geqslant$ 200 MeV/n) the quasi-elastic (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 of this Gaussian distribution has been observed[3] to have a mass dependence of the form

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

Here A_P and A_F are projectile and fragment mass numbers and σ_o 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_o can be explained[4] both by a process that samples the Fermi momentum of nucleons in the projectile, and by a process which produces a fully thermalized momentum distribution with a temperature $kT= \sigma_o^2/M_o$

In order to look for evidence of fragmentation reactions at lower energies, the measurement of the quasi-elastic peak width, σ, and the "reduced" width, σ_0, has been extended to energies as low as 7.5 MeV/n. 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 and may be obtained.

Upon extending the measurements down to 10 MeV/n the reduced width was observed to change dramatically with energy.[5] At energies from 2 Gev/n to 213 MeV/n the average value of σ_0 is $\sim$86 MeV/c while at energies below 10 MeV/n 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 up to 20 MeV/n 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/n the reduced widths[6] did not eceed 40 MeV/c. When plotted on a linear scale they appeared to reach a plateau at ∿20 MeV/n. Subsequently, Harvey[7] noted that the values of σ_o in ref. 5 referred to by Egelhaaf represented an average over ejectile charges as well as isotopes, and variations of σ_o with charge were significant.

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

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

The inclusive energy spectra for ^{6}Li and ^{7}Li 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 ± 4.7 MeV/c and 60.2 ± 1.4 MeV/c for ^{6}Li and ^{7}Li, respectively.

Figure 2 is a summary of several measurements of σ and σ_0 at various energies. It includes the results of Egelhaaf, et al.,[6] the high energy points at 213 MeV/n and 2.1 GeV/n, the data of Scott, et al.[5] reanalyzed by Harvey[7], and our new measurement at 27.4 MeV/n. In all cases the reported widths are for the total momentum distributions at the grazing angle, and are obtained from the energy spectra of single isotopes. The fits in each case cover the apparent quasi-elastic part of the energy spectrum. (At energies below 50 MeV/n 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/n and 2.1 GevV/n 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.

The data compiled in Fig. 2 show an obvious energy evolution for both σ and σ_o. 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/n. The factorization according to eq. 1 reduces the mass dependence of the width at most energies, but leaves a residual mass dependence in σ_o that is more pronounced below 100 MeV/n than at higher energies. The limited amount of data available at energies below 100 MeV/n makes more quantitative statements on the mass dependence of σ_o difficult.

One must be cautious when using the data for σ_o (E) in Fig. 2 as evidence for or against the occurance of particular reaction mechanisms (e.g., fragmentation, breakup, transfer,etc.). Although the high energy measurements show a persuasive agreement with eq. 1, the data below 100 MeV/n suffer from several problems which affect the interpretation of σ and σ_o. 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/n only provide the width of the total momentum distribution. There is evidence that below 200 MeV/n only the longitudinal momentum dispersion has the mass dependence of eq. 1. It has been shown by Van Bibbber[12] that at 100 MeV/n the transverse momentum disperison has a form more like

$$\sigma_1^2 \approx \frac{A_F(A_P-A_F)}{A_P-1}\,\sigma_o^2 + \frac{A_F(A_F-1)}{A_P(A_P-1)}\,\sigma_2^2$$

This new parameterization still does not account fully for the isotope dependence of the data compiled in Fig. 2b; although eq. 2 accounts for the widths at 86 MeV/n,[9] it does not describe the isotope dependence between 7 and 45 MeV/n. At these lower energies the trend is generally 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 judgements.

Our measurement of quasi-elastic momentum widths at 27.4 MeV/n yields results that support a relatively smooth transition in the reduced width σ_o between 10 and 200 MeV/n. Upon re-examining all of the similar data available at energies from 5 to 2000 MeV/n, we have noted that this transition is just as evident in the "unreduced" width σ. There are problems with the interpretation of σ_o; 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 presently known values of σ_o , 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.

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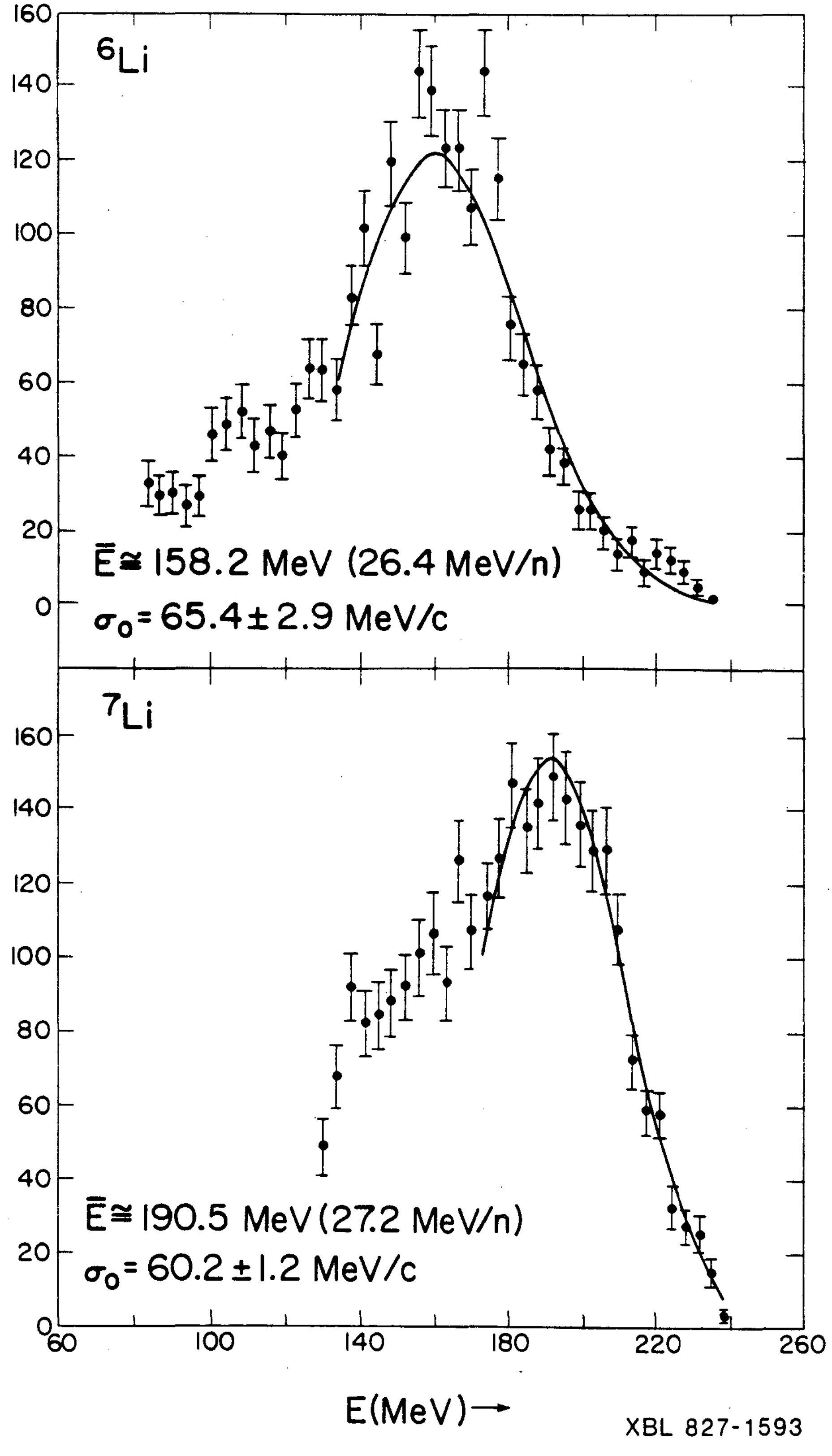
FIGURE CAPTIONS

1) The inclusive laboratory energy spectra for ^{6}Li and ^{7}Li ejectiles from ^{9}Be+Au at 27.4 MeV/n. The solid curves are fits to the quasi-elastic parts of the spectra.

2a and b) A compilation of several different measurements of the momentum widths and the reduced momentum widths of ejectiles from heavy-ion reactions. The key to the reactions is

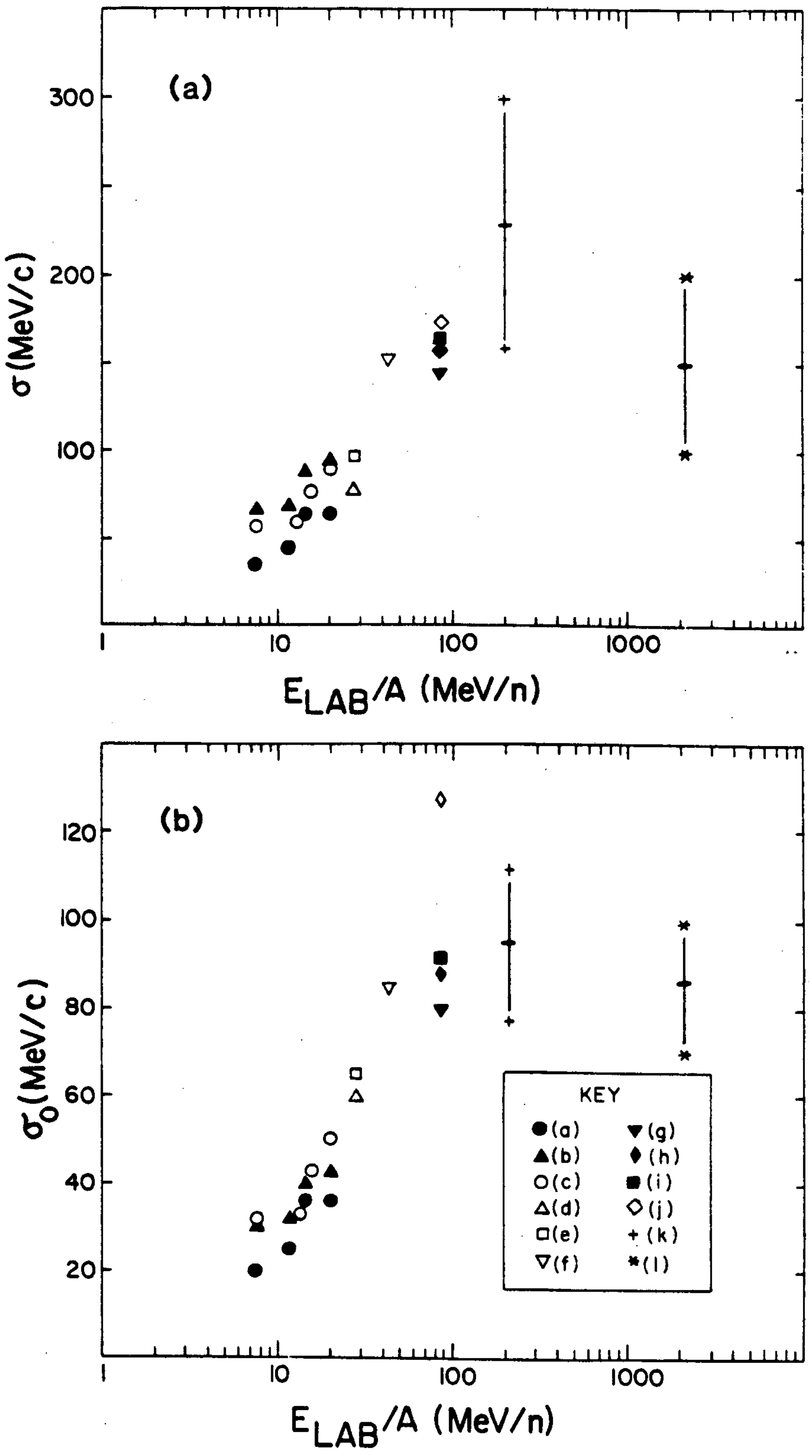
a) ^{197}Au(^{20}Ne,^{16}O), Ref. 6
b) ^{197}Au(^{20}Ne,^{12}C), Ref. 6
c) ^{208}Pb(^{16}O,^{12}C), Ref. 7
d) ^{nat}Au(^{9}Be,^{7}Li), This work
e) ^{nat}Au(^{9}Be,^{6}Li), This work
f) ^{181}Ta(^{20}Ne, α), Ref. 8
g) ^{12}C(^{12}C,^{6}Li), Ref. 9
h) ^{12}C(^{12}C,^{7}Li), Ref. 9
i) ^{12}C(^{12}C,^{7}Be), Ref. 9
j) ^{12}C(^{12}C,^{10}B), Ref. 9
k) ^{232}Th(^{40}Ar,X), Ref. 10
l) ^{16}O+X, Ref. 3

A large number of widths were measured at 213 and 2100 MeV/n; the Figure indicates the range and mean value of the results.



^{6}Li
160
140
120
100
80
60
40
20
0
$\bar{E} \cong 158.2$ MeV (26.4 MeV/n)
$\sigma_0 = 65.4 \pm 2.9$ MeV/c
^{7}Li
160
140
120
100
80
60
40
20
0
$\bar{E} \cong 190.5$ MeV (27.2 MeV/n)
$\sigma_0 = 60.2 \pm 1.2$ MeV/c
60
100
140
180
220
260
E(MeV) →
XBL 827-1593

Fig. 1



XBL 829-9684

Fig. 2

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