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Author
Olmer, C. Scott

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M. E. Ortíz, A. Dacal, A. Menchaca-Rocha,
M. Buenerd, D. L. Hendrie, J. Mahoney, C. Olmer and D. K. Scott

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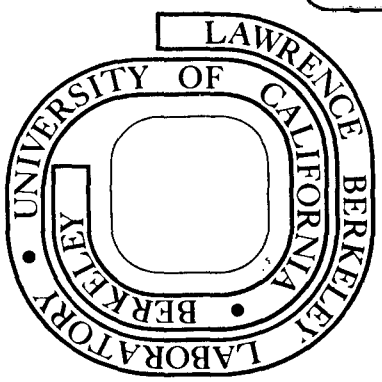

DISCLAIMER

ENERGY DEPENDENCE OF MULTINUCLEON TRANSFER REACTIONS INDUCED BY ^{20}Ne ON ^{12}C

M. E. Ortíz, A. Dacal and A. Menchaca-Rocha
Instituto de Fisíca, UNAM. A. P.20-364
México 20, D.F. Mexico

and

M. Buenerd†, D. L. Hendrie††, J. Mahoney,
C. Olmer††† and D. K. Scott
Lawrence Berkeley Laboratory
Berkeley, California 94720

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† Permanent Address: Institut des Sciences Nucléaires, Cedex 257, 38044 Grenoble, France.

†† Present Address: Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742.

††† Present Address: Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

ABSTRACT

The energy dependence of up to five nucleon transfer reactions induced by ^{20}Ne on ^{12}C has been measured in the energy range 150 to 294 MeV. Good agreement is found between the experiment and both DWBA and semiclassical calculations.

Systematic studies of multi-nucleon transfer reactions induced by heavy ions, involving both variations in incident energy and mass transfer can make a stringent test of heavy-ion reaction mechanisms. We have investigated the energy dependence of multi-nucleon transfer reactions on a light target nucleus through the measurement of reactions of the type $^{12}C(^{20}Ne,x)Y$, where x ranges from ^{19}F to ^{15}N (i.e. from one to five nucleon transfers) at incident energies of 150, 175, 202, 225, 252 and 294 MeV. In this letter we show that the gross features of the incident energy and mass transfer dependences of the reactions can be well reproduced by either DWBA or semiclassical calculations.

The $^{20}Ne^{5+,6+}$ beams from the 88-Inch Berkeley Cyclotron were used to bombard solid ^{12}C targets of thickness 100 $\mu g/cm^2$. The reaction products were detected and identified using a QSD spectrometer and a focal plane detector [1]. The overall energy resolution of 150 keV (fwhm) was mainly determined by kinematics and target thickness.

The energy spectra measured for the reaction product ^{16}O at forward angles are shown in fig. 1 at several incident energies. The other reaction products (^{19}F, ^{18}O, ^{17}O, ^{15}N and ^{14}N) were also present on the focal plane of the spectrometer, but only restricted excitation regions were covered at all energies. Therefore, we shall concentrate on the energy dependence of the following excitation energy windows: ^{19}F, 0 - 5 MeV; ^{18}O, 10 - 15 MeV; ^{17}O, 5 - 10 MeV; ^{16}O, 10-15 and 20-25 MeV (the shaded regions in fig. 1); and ^{15}N, 23-25 MeV. A more detailed description of reactions populating individual levels will be reported elsewhere [2].

The angular distributions do not have any prominent diffractive structure and fall off exponentially as predicted for direct reactions in this energy region [3]. Fig. 2 shows the integrated differential cross sections for the various selected regions plotted as a function of the incident energy. The data follow smooth trends over the observed energy range. The solid and dashed lines represent theoretical calculations which we now describe.

In most cases the excitation windows lie in the unbound region of the spectra, where the density of states is large. The prediction of absolute yields by a DWBA calculation would therefore be difficult. Nevertheless we use the DWBA [4] to understand the observed relative trends. Later, we shall use a simple semiclassical formulation [5] to lend physical insight into the reaction process. In the DWBA calculations we made the following approximations. 1) The optical model parameters (set 1) were based on data at lower energies [6,7] with the values: V = 17 MeV, r_o = 1.35 fm, a = 0.57 fm, r'_o = 1.35 fm, with W = 40 MeV and a' = 0.57 fm for the $^{20}Ne + ^{12}C$ and $^{19}F + ^{13}N$ channels; W=30 MeV and a'=0.49 fm for the $^{18}O + ^{14}O$, $^{17}O + ^{15}O$, $^{16}O + ^{16}O$ and $^{15}N + ^{17}F$ channels. No energy dependence was assumed in the energy range covered. 2) For all cases where the center of the excitation window corresponded to an unbound excitation, the form factors were calculated by making the state just bound by $\simeq$ 0.1 MeV. 3) The energy dependence for the excitation window was assumed to be the same as that of a state lying in the center of the window with an angular momentum equal to that of a state of known J [8] in that region. 4) The particles were assumed to be transferred as a cluster. In fig. 3a we illustrate the effect of using different optical model parameter sets. For these calculations

we assume a hypothetical $J=6^+$ state in ^{16}O, populated in the reaction $^{12}C(^{20}Ne,^{16}O)^{16}O$. The solid line corresponds to the use of energy independent parameters. For comparison we illustrate the effect of including energy dependence in the optical model parametrization. The dashed line represents DWBA calculations using the optical parameters of ref. [6] for the incident channel and of ref. [7] for the outgoing channel (set 2). The third set (set 3) uses the same parameters for the incoming channel as set 2 but takes those of ref. [9] for the exit channel. Although at lower energies there are considerable differences [10] in the theoretical predictions of the different parameter sets, at high energies the predictions are very similar.

Concerning our second approximation we have found that changes in the form factor due to binding have no appreciable effect on the energy dependence (see fig. 3b). As will be discussed later within the framework of a semiclassical model, the choice of an arbitrary J value is justified because the form of the energy dependence seems to be dependent mostly on the Q-value and is insensitive to the value of J (see fig. 3c). Similar effects were found [11] in the $^{208}Pb(^{16}O,^{15}N)^{209}Bi$ system, where a smooth change in shape of the energy dependence as a function of excitation energy is almost identical for adjacent spins 1/2 and 13/2 (see fig. 2, ref. [11]). The results of DWBA calculations for all the different channels are shown (solid lines) in fig. 2. There is good agreement with the observed energy dependence.

Similar results were obtained (dashed lines in fig. 2) with a semiclassical model [5] which gives more physical insight into the energy dependence. In this formalism, the probability for transfer

of a particle of mass m from a projectile state of orbital angular momentum ℓ_1 to a final state of orbital angular momentum ℓ_2 is given by

$$P(\ell_1,\ell_2) \propto \left|Y^{\lambda_1}_{\ell_1}\left(\frac{\pi}{2},0\right)\right|^2 \left|Y^{\lambda_2}_{\ell_2}\left(\frac{\pi}{2},0\right)\right|^2 \exp\left\{-\left|\frac{R\Delta k}{2\pi}\right|^2 - \left|\frac{\Delta L}{\sqrt{\gamma R}}\right|^2\right\} \qquad (1)$$

where

$$\Delta L = \lambda_2-\lambda_1 + \frac{1}{2}\, k_0(R_1-R_2) + \frac{Q_{eff}\, R}{\hbar v} \qquad (2)$$

and

$$\Delta k = \frac{mv}{\hbar} - \lambda_1/R_1 - \lambda_2/R_2 \qquad (3)$$

Here $k_o = mv/\hbar$, λ_1 and λ_2 are the projections of ℓ_1 and ℓ_2 on an axis perpendicular to the reaction plane, v is the relative velocity in the region of transfer and m is the transferred mass; $R = R_1 + R_2$ where R_1, R_2 are the nuclear radii. The parameter $\gamma^2 = 2m\varepsilon/\hbar^2$, where ε is the binding energy. From eq. (1), we see that the only energy dependence in this formulation comes from ΔL and Δk. The maximum transfer probability occurs when $\Delta L \approx 0$ and $\Delta k \approx 0$. The dependence of ΔL with incident energy (E) arises from two terms (see eq. (2)). The middle term is a monotonically increasing function of E; in our case, however, the near equality of R_1 and R_2 minimized the contribution of this term. The last term in eq. (2) is proportional to $1/\sqrt{E}$. This term becomes important at low energies (assuming $Q_{eff} \neq 0$) predicting a low energy fall-off for the transition probability. The dependence on Δk is monotonically increasing with E. As the energy is increased this term becomes dominant resulting in an exponential fall-off (eq. (1)) at high energies.

The dependence on the transferred mass (m) in eq. (1) can also be tested with the present data, which cover values of m from 1 to 6 a.m.u. Our data show a general increase in slope for the high energy fall-off as m is increased. Such a dependence on m is predicted by eq. (2), through the linear dependence of Δk on m. This systematic effect is influenced by the Q value dependence of ΔL. A clear example is the energy dependence of the $^{12}C(^{20}Ne,^{18}O)^{14}O^*$ (10-15 MeV) excitation window where the high negative Q-value of approximately 27 MeV causes the predicted low energy fall-off, due to ΔL, to extend up to high energies. When m is increased as in the $^{12}C(^{20}Ne,^{16}O)^{16}O$, reaction, the large negative Q ($\sim$ -20 MeV) is insufficient to overcome the high energy fall-off due to Δk.

As in the DWBA calculations, the semiclassical calculations, shown in fig. 2 (dashed lines), were done assuming that the energy dependence for a finite window in excitation energy is approximately the same as that of a state lying in the center of the window. We use the same J values as those assumed in the DWBA calculations. The shape of the predicted energy dependence is found to depend only weakly on the choice of J value. This is illustrated in fig. 3d where semiclassical calculations for the cases shown in fig. 3c are presented (assuming J=6 and 8 for a hypothetical state at 22.5 MeV excitation populated in the $^{12}C(^{20}Ne,^{16}O)^{16}O$ reaction). An inspection of eqs, (2) and (3) shows that although a given λ_2 value (the maximum value of λ_2 is J) might shift the energy dependence by a constant factor the shape remains unchanged.

Multinucleon transfer reactions on light targets have been observed [12] to selectively populate multiparticle-multihole rotational bands leading to spectra with states populated with strength proportional to J(J+1). The incident energy dependence of states in such reactions could be a possible signature of J-value [12]. However, although the selectivity and J(J+1) dependence are already strong indications of the internal structure of the states and can be used as circumstantial evidence for J^{π} assignments, the form of the incident energy dependence, being mostly a function of the Q-value, does not seem to be a sensitive tool for absolute spin assignments. It is clear that the simple semiclassical model can be used to explain the features of the data, and therefore it is a very useful and inexpensive means of optimizing the incident energy to enhance a given excitation region.

In conclusion, we have shown that the gross features of the energy dependence of multinucleon transfer reactions induced by heavy ions can be well reproduced by simple one-step DWBA calculations [4] or by semiclassical calculations [5]. We found that this dependence is not very sensitive either to optical model parametrization or form factor details. The observed shapes are well described by simple total angular momentum and linear momentum conservation conditions. They prove to be insensitive to spin assignment and were found to depend mostly on the Q-value. These systematics can be used to infer the optimum incident energy for the population of a given excitation region in heavy-ion transfer reactions. The calculations can be done with a semiclassical formulation. Similar studies in

excitation regions where multi-step processes are expected to occur might make a good testing ground for unified reaction theories [13] in the continuum. Further experiments are required to understand the satisfactory agreement with direct reaction theory reported here, whereas similar studies of single nucleon transfer reactions with ^{16}O on ^{208}Pb give large discrepancies [11].

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FIGURE CAPTIONS

1). The energy spectra for the reaction $^{12}C(^{20}Ne,^{16}O)^{16}O$ measured at forward angles are shown as a function of incident energy. The shaded region represents the excitation energy windows considered for the analysis of the energy dependence.

2). Integrated cross sections as a function of incident energy for excitation energy windows (in parentheses) for the reactions $^{20}Ne + ^{12}C \rightarrow ^{19}F$, ^{18}O, ^{17}O, ^{16}O and ^{15}N. The theoretical predictions are discussed in the text.

3). Validity of the approximations for calculations of the reaction $^{12}C(^{20}Ne,^{16}O)^{16}O^*$ (22.5 MeV). In a) is shown a comparison of different optical model parametrizations; in b) the effect of changing the binding energy of the $^{16}O \rightarrow \alpha + ^{12}C$ system for form factor calculations is shown; in c) and d) the sensitivity to the choice of J value is tested for both DWBA (c) and semiclassical (d) calculations.

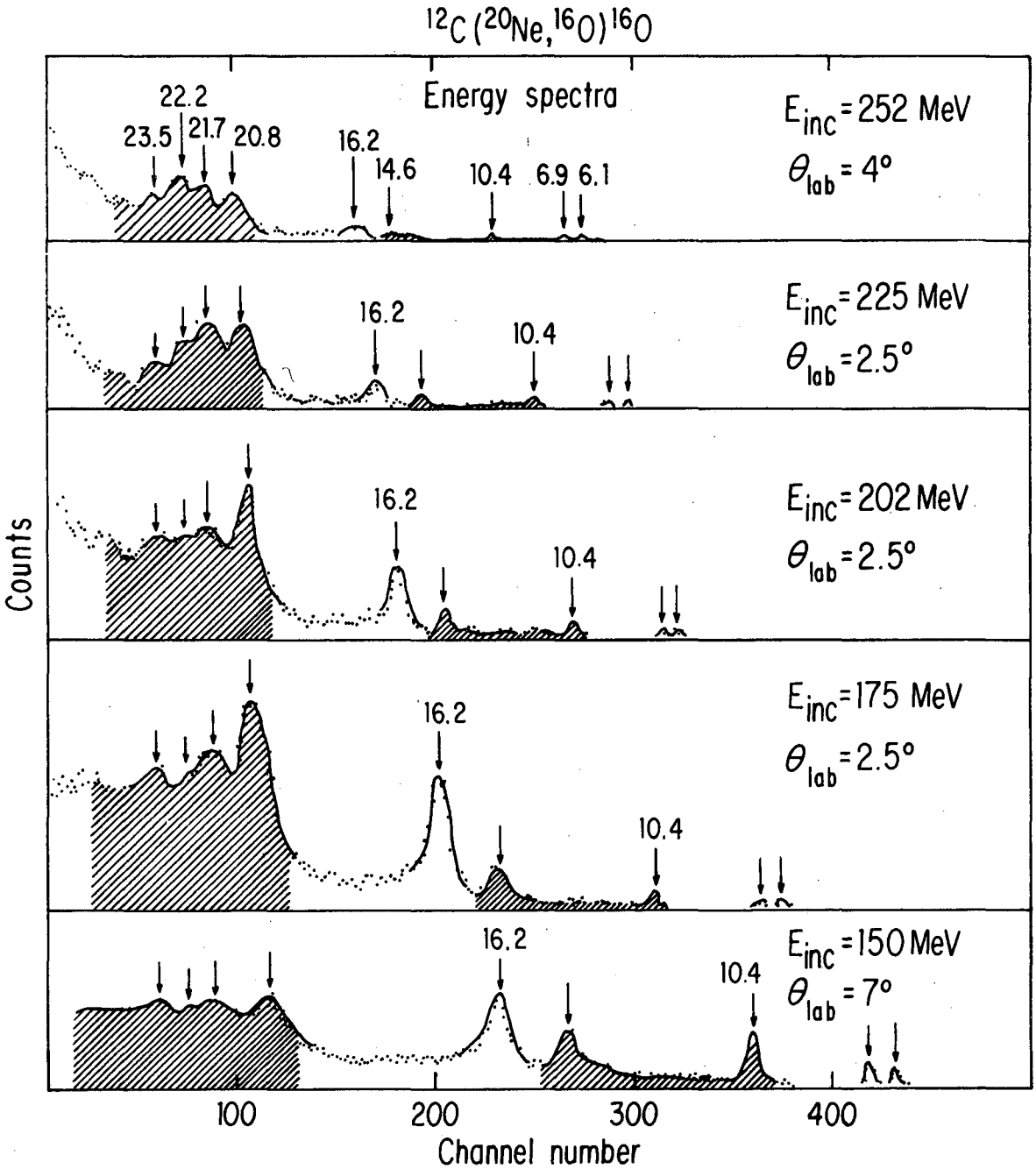

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Fig. 1

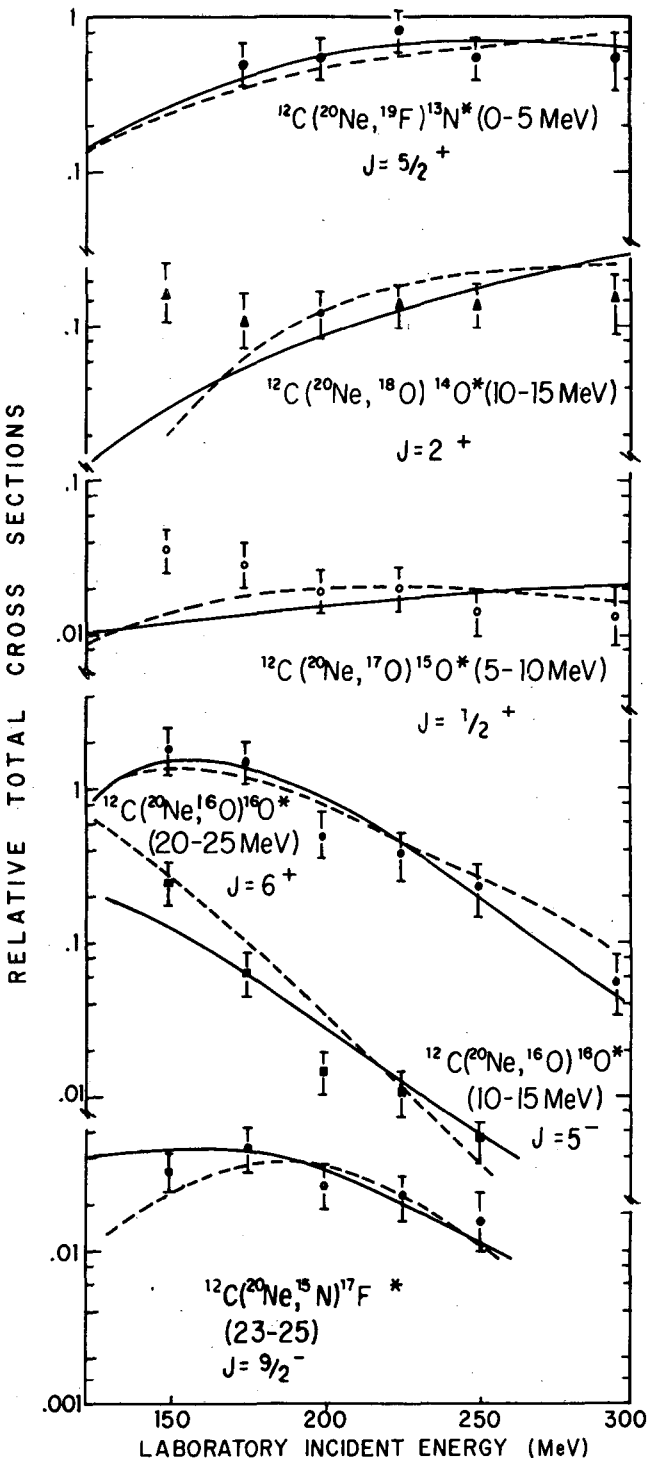

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Fig. 2

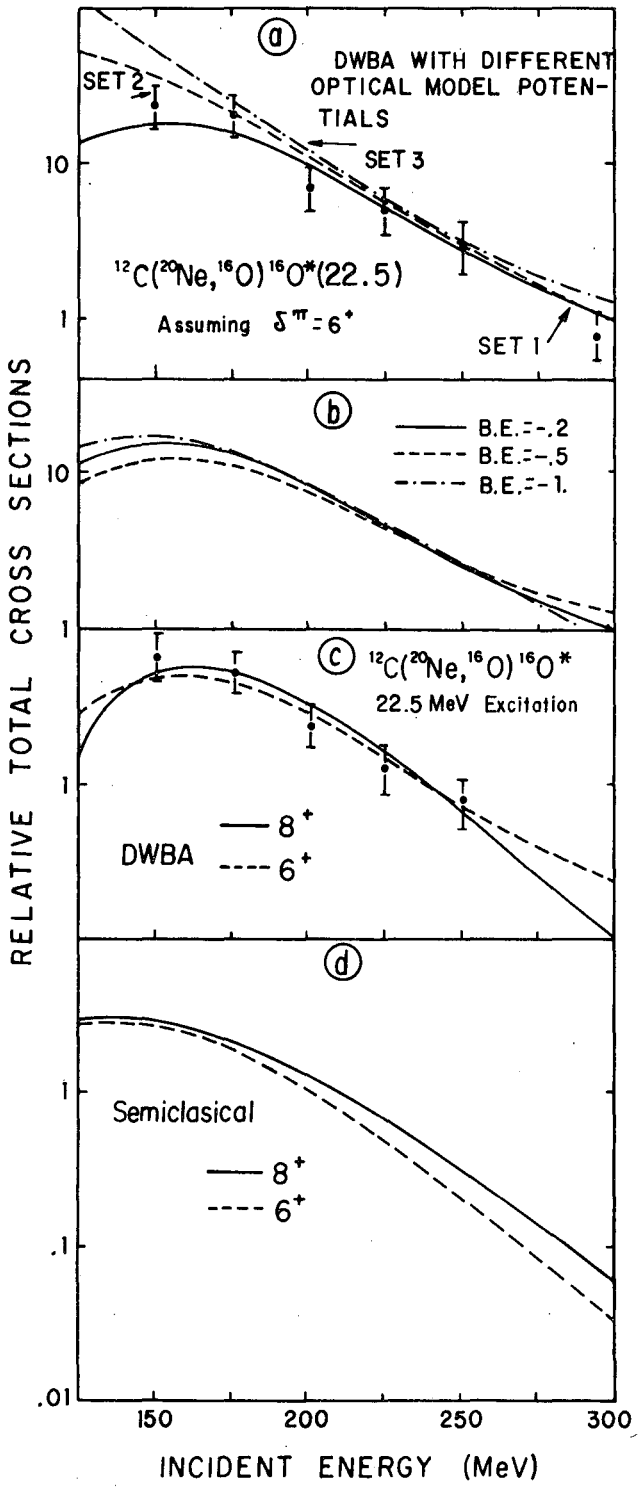

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Fig. 3

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