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FOLDED POTENTIALS FOR THE DESCRIPTION OF HEAVY ION

ELASTIC SCATTERING AND TRANSFER REACTIONS*

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We present a simple model for the heavy ion optical potential based on the convolution of target and projectile densities with a suitably chosen nucleon-nucleon effective interaction. This model is shown to be appropriate for a number of low energy peripheral processes, such as elastic scattering and one and two particle transfer reactions. Application of the method to cluster states in light nuclei and relativistic heavy ion interactions is also considered.

The optical potential is of central importance for heavy ion interaction processes, since it is widely used to describe elastic scattering as well as more complicated reactions through the DWBA formalism. In principle, one would like to relate the optical potential for composite particle scattering to the fundamental nucleon-nucleon (NN) interaction, in an approach that systematically includes many body corrections. Several such microscopic models are available for nucleon-nucleus scattering [1-3]. However, some phenomenological adjustments are usually necessary in order to obtain good fits to experimental data. We recognize that a quantitative microscopic theory of nucleus-nucleus interactions is somewhat beyond our reach at present. Hence we propose a compromise which retains the more important physical features of a microscopic approach, but is flexible enough to fit data. We are thus able to preserve much of the predictive power of a fundamental theory. The essential ingredients are

- 1) the neutron and proton density distributions of the interacting nuclei, and
- 2) the nucleon-nucleon effective interaction in the two nucleus medium.

We present here a sample of results from a folding model which relates this input information to the optical potential $V_{\text{opt}}(r)$:

$$V_{\text{opt}}(r) = \int \rho_A(\mathbf{r}_1) \rho_B(\mathbf{r}_2) G(\mathbf{r} + \mathbf{r}_1 - \mathbf{r}_2) d\mathbf{r}_1 d\mathbf{r}_2 \quad (1)$$

where ρ_A and ρ_B are the total densities of nuclei A and B, and G is the NN effective

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interaction. In Eq. (1), we assume for simplicity a local interaction $G(r)$ which is averaged over spin and isospin. Various models which are similar in form to Eq. (1) have also been employed in the discussion of atom-atom collisions and hadron-hadron interactions at very high energy [4]. Several similar treatments of composite particle processes also exist [5], but these involve the folding of a nucleon-nucleus optical potential with the density of the target (or the projectile). By this means, one hopes to phenomenologically include the effects of some higher order correlation terms, but the target and projectile are not treated symmetrically. We prefer to use the symmetric form (1), which is the first term in a consistent density expansion of the optical potential. This form of the folding model enables us to identify G as the underlying NN amplitude. Note that G is an amplitude rather than an NN potential; i.e., G includes rescattering corrections to all orders with Pauli restrictions and other many body effects. Thus Eq. (1) does not correspond to treating the NN potential in perturbation theory, which would be quite inadequate [6].

In fitting experimental elastic scattering data, we parametrize G in terms of an adjustable complex strength constant $\bar{f}$ and a fixed range parameter r_0 . Thus, higher order corrections to Eq. (1) are absorbed by suitably modifying $\bar{f}$. As we shall see later, at higher energies one obtains good agreement between the phenomenological value of $\bar{f}$ and the value obtained from a microscopic estimate. In addition, we show that with an adjustable $\bar{f}$, Eq. (1) remains a useful model for the potential for peripheral processes at low energies.

The main features of the potential model of Eq. (1) are the following: a) it relates the geometry of the nucleus-nucleus potential to the geometries of the projectile and target nuclei. It thus represents a very strong theoretical prejudice as to the radius and effective diffuseness of the heavy ion optical potential. b) by construction, the folded potential has no continuous geometrical ambiguities. One can also show that there are no discrete ambiguities (in potential depth). c) the fixed geometry of the model greatly reduces the amount of computing time necessary to obtain a fit.

Some comments on the validity of the folding model are in order. Such an expansion is expected to converge at high energies [1] or low densities. The latter condition is the key to the present situation. For heavy ion elastic scattering or relatively simple particle transfer processes, the interaction is primarily restricted to the surface region, where the effective densities are low. If the two nuclei interpenetrate appreciably, more complicated many particle transfer and breakup channels will be populated. The folding model would be quite inappropriate for a particular complicated channel (5 particle transfer, say). However, the total reaction cross section σ_R should be well described by the folding model, or any other reasonable model for that matter, if it is close to the geometric limit.

The applicability of the folding model at low energies is thus restricted to peripheral processes, which are sensitive to the surface and tail region of the opti-

cal potential $V_{\text{opt}}(r)$. In the tail region, the folded potential should be closer to the truth than phenomenological Woods-Saxon potentials. However, the present elastic scattering data do not provide a sufficient constraint to determine the rate of fall-off of $V_{\text{opt}}(r)$ in the tail region, so one cannot reject phenomenological potentials. Of course, the folding model is quite wrong in the nuclear interior, since it neglects Pauli restrictions and correlation corrections. However, this fact is largely irrelevant, since the processes which we consider are known to be insensitive to the form of the real potential for small r [6]. One could probably obtain better fits to some of the transfer data (particularly two particle), while preserving the quality of the elastic fit, by using a phenomenological ansatz (a Woods-Saxon, say) for the interior region, and joining it smoothly to a folded potential in the surface region.

We now outline the scope of our efforts. In previous work, the use of the folding method has been restricted mainly to elastic and inelastic scattering [5,6]. However, for heavy ion processes, elastic and inelastic scattering place a rather weak constraint on the form of the potential. For instance, elastic scattering only determines the value of the real potential near a critical radius $r \approx 1.5 (A^{1/3} + B^{1/3})$ fm., where A and B are the projectile and target mass numbers [6]. Hence, to see if our model has non-trivial content, it is necessary to test it for a wide range of phenomena at various energies and for different nuclei. The crucial test is whether the folded shape, with the strength determined by a fit to elastic scattering, also reproduces one and two particle transfer data in the DWBA. We provide several illustrative examples. We also mention briefly the application of the model to cluster states in light nuclei [7], which tests the extrapolation of the method from continuum to bound state problems, and also to relativistic heavy ion interactions [8]. The details pertaining to the various ramifications of the model are to be found in refs. [7-11].

We now discuss the ingredients of our calculations. For nuclear densities, two prescriptions were tested, in order to determine the sensitivity of the potential to the tail region of the densities: a) proton densities $\rho_p(r)$ taken from electron scattering analyses, and neutron density $\rho_n(r)$ assumed proportional to proton density; b) $\rho_p(r)$ and $\rho_n(r)$ obtained from Hartree-Fock or shell model calculations; total density obtained from $\rho(r) = \sum_i W_i |\varphi_i(r)|^2$, where i runs over all occupied neutron and proton bound states, $\varphi_i(r)$ is the single particle wave function and W_i is the statistical weight ($2j+1$ for filled shell). To obtain $\varphi_i(r)$ we used Hartree-Fock results [12] or wave functions corresponding to Woods-Saxon potentials which give a best fit to empirical single particle binding energies [13] for a range of nuclei. This latter recipe is expected to provide a reasonable representation of $\rho(r)$ in the tail region, since the large r behavior will be dominated by the least bound orbits whose binding energies are well known. On the other hand, electron scattering analyses do not provide a sufficiently accurate density for large r . We find in fact that the quality of our elastic scattering fits depends fairly sensitively on having an adequate description of the tail region of the density. Fits obtained with pre-

scription b) above are consistently better than those obtained using a). We show later that the use of proper densities is essential to establish contact between the best fit and theoretical values of the potential strength.

For the parametrization of the NN effective interaction G , we use the ansatz

$$G = \bar{f}(N e^{-r^2/r_0^2}) \quad (2)$$

where $\bar{f}$ is a complex depth parameter and N is a normalization constant chosen so that $N/d^3 \int \exp(-r^2/r_0^2) = -2\pi\hbar^2/M$, where M is the nucleon mass. This choice of N enables us to relate $\bar{f}$ to the usual NN forward scattering amplitude. If we neglect many-body effects, the simplest theoretical estimate for $\bar{f}$ is

$$\bar{f} = \sum_k \bar{f}_k \quad (3)$$

where $\bar{f}_k$ is a spin and isospin averaged partial wave amplitude. For example, for s -waves we have

$$\begin{aligned} \bar{f}_0 &= (1-\frac{1}{2})\bar{f}_{1S_0} + 3\frac{1}{2}\bar{f}_{3S_1} \\ \bar{f}_{SJ} &= \frac{2J+1}{k} \exp(i\delta_{SJ}) \sin\delta_{SJ} \end{aligned} \quad (4)$$

where δ_{SJ} is the free space NN phase shift for spin S , orbital angular momentum l and total spin J . The factor $\frac{1}{2}$ (1/2 for $N=Z$ projectiles) yields the proper spin-isospin average, and k is the lab NN wave number, evaluated at the incident lab energy per particle. A range parameter $r_0 = 1.4\text{fm}$ was chosen. This value is consistent with what we expect from the long range part of the NN potential; it also corresponds to a sharp minimum in the χ^2 function as a function of r_0 for a number of α scattering cases which we examined.

We now present some typical numerical results. For elastic scattering, the two parameter fits with a complex $\bar{f}$ are of uniformly good quality. For α scattering, we only try to fit the data in the region of strong diffraction oscillations, consistent with the limitations of a first order model. The high quality of the fits in the diffraction region is illustrated in Fig. 1 for the $\alpha + {}^{208}\text{Pb}$ reaction. Also shown in Fig. 1 is a typical fit to heavy ion elastic scattering, in this case ${}^{18}\text{O} + {}^{60}\text{Ni}$. For heavy ion processes, we employ the entire angular range in the fit, since the measured data only extend down to $\sigma/\sigma_R \approx 0.01$, which still corresponds to a peripheral process. It is not clear that a local single channel optical model description remains physically meaningful in the region far below $\sigma/\sigma_R \approx 0.01$. The fits to the heavy ion data are comparable to those obtained with conventional Woods-Saxon potentials with 4-6 parameters. This indicates that the folding model provides a succinct description of those features of the geometry of the optical potential which are important for peripheral processes. This is perhaps its greatest merit for

Fig. 1 The top curve shows the fit to the Brookhaven $^{18}\text{O} + ^{60}\text{Ni}$ elastic data [14] at 62.92 MeV with $\bar{r} = 1.27 \pm 0.91$ fm. The lower curve displays the fit to the Maryland $\alpha + ^{208}\text{Pb}$ data [16] at 139 MeV with $\bar{r} = 1.79 \pm 1.21$ fm.

low energy applications.

The real and imaginary parts of the folded potential corresponding to the $^{18}\text{O} + ^{60}\text{Ni}$ fit are shown as solid lines in Fig. 2. A Woods-Saxon (WS) potential used to fit the transfer data is also shown as a set of dashed lines [14]. Several observations are in order: The real part of the folded and WS potentials agree well in the region of the critical radius $r \approx 1.5 (A^{1/3} + B^{1/3})$, indicated by an arrow in Fig. 2. This is the part of the potential which is determined by elastic scattering. The behavior of the two potentials is quite different in the interior; the folded potentials are characteristically very deep near $r=0$. The imaginary potentials also differ in the surface region, so it is clear that the elastic scattering data is much less sensitive to the details of the absorption. Particle transfer reactions, on the other hand, are more sensitive to the magnitude of the absorption. It is only with the aid of such reactions that we are able to begin to sort out different potential models.

Fig. 2 The solid curves V and W are the real and imaginary parts of the folded potential corresponding to the $^{18}\text{O} + ^{60}\text{Ni}$ fit of Fig. 1. The dashed curves correspond to Woods-Saxon potentials of Levine *et al.* [14] which yield a good fit to the $^{60}\text{Ni}(^{18}\text{O}, ^{16}\text{O})^{62}\text{Ni}$ reaction.

Another observation is that the shape of a folded potential differs from that of a WS potential, in that it cannot be characterized by a single diffuseness parameter in the crucial surface region. At any radius r , we can define an "equivalent" WS potential by matching the folded potential to the tail $V_0 \exp(R/a) \exp(-r/a)$ of a WS potential. This procedure generates the ambiguity plot shown in Fig. 3. Such a plot can be used to generate a respectable first guess to a WS potential which will fit the elastic data. The main point here is that the effective diffuseness " a " of the folded potential is radius dependent. However, the folding model gives values of a for heavy targets which are in the usual range $0.4 \lesssim a \lesssim 0.6 \text{ fm}$, when the matching to a WS form is done in the region of the critical radius for elastic scattering. For bound state problems, such as the $\alpha + ^{16}\text{O}$ cluster states in ^{20}Ne [7,9], the effective diffuseness is considerably larger ($\approx 1 \text{ fm}$) in the region where the α cluster is localized. This large diffuseness enables one to obtain close to the correct energy

Fig. 3 Ambiguity plot from folding model analysis of 166 MeV Orsay data for $\alpha + {}^{40}\text{Ca}$ [5]. Families of equivalent Woods-Saxon parameters for the real depth V , the imaginary depth W and the diffuseness a are shown. Each curve is labelled by r_0 , where $R = r_0(A^{1/3} + B^{1/3})$ is the radius parameter of the well.

splittings within the ground and first excited rotational bands with a single strength parameter $\bar{f}$ for each band, whereas WS potentials with a conventional diffuseness of 0.6 fm require a considerable renormalization of the depth for each state.

Another crucial test is the energy dependence. For the case of α particle scattering, there is sufficient data (from 40-166 MeV) to study empirically the energy dependence of the real and imaginary parts of the folded potential. For heavy ions, it is difficult to make such a systematic study at the present time, since most of the data are restricted to the low energy region of 5-10 MeV per particle. Higher energy data would be most welcome.

In Fig. 4, we show as dots the real and imaginary parts of $\bar{f}$, empirically adjusted at each energy to provide a best fit to α elastic scattering data. The real part of the potential is found to decrease with increasing energy, as is familiar

Fig. 4 Energy dependence of the real and imaginary parts of the depth parameter $\bar{f}$. Empirical values of $\bar{f}$ determined by best fits to α scattering data are shown as dots, circles and triangles, as a function of the lab energy/particle E_L/A_1 . The theoretical curves labelled by k_F are calculated as described in the text.

from proton-nucleus scattering analyses [15]. Correspondingly, the imaginary depth increases with energy, as expected in general from arguments based on density of states. The fits shown in Fig. 4 refer to three different target nuclei, ${}^{40}\text{Ca}$, ${}^{58}\text{Ni}$, and ${}^{208}\text{Pb}$. No significant target dependence of $\bar{f}$ is seen, which reassures us that the folding of densities correctly accounts for the variation of cross sections with target at the same energy.

The comparison of these results with a theoretical calculation of $\bar{f}$ is provided by the solid curves in Fig. 4. These theoretical estimates are obtained in a simple interacting Fermi gas model, starting from the free space NN amplitude of Eq. (3). We pass from the free NN amplitude to an effective amplitude in the medium by applying the following series of corrections:

- a) we first perform the spin-isospin average as in Eq. (4), including s,p, and d waves in Eq. (3).
- b) we next perform a Fermi average of the forward scattering NN amplitude over

the internal motion of nucleons in the projectile and target, both being characterized by the same Fermi momentum k_F . This average assumes the form

$$\langle \bar{f} \rangle = (16/\rho^2) \sum_{\substack{|\underline{k}| < k_F \\ |\underline{k}'| < k_F}} \bar{f}(\underline{k}+\underline{p}, \underline{k}'; \underline{k}+\underline{p}, \underline{k}') \quad (5)$$

in the LAB system. Here $\rho = 2k_F^3/3\pi^2$ is the total density and p is the lab momentum corresponding to the projectile energy per particle.

c) Using $\langle \bar{f} \rangle$, we now apply an off-shell correction which takes account of the fact that nucleons propagate in a single particle potential in the nucleus, and hence the NN scattering takes place off the energy shell. One may also think of this as a binding correction. It is well established that the effective interaction G depends smoothly on the off-shell energy. Including the off-shell effect via a Taylor expansion about the on-shell point, we obtain a corrected amplitude f_R given by

$$f_R(E) = \langle \bar{f}(E) \rangle - (\langle u_1 \rangle + \langle u_2 \rangle) \left. \frac{d}{d\omega} \langle \bar{f}(\omega) \rangle \right|_{\omega=E} \quad (6)$$

where E is the lab kinetic energy per particle and $\langle u_1 \rangle$ and $\langle u_2 \rangle$ are average potential energies for particles 1 and 2. We take $\langle u_1 \rangle = \langle u_2 \rangle \approx -15$ MeV for surface nucleons. This correction is not very large and, like the Fermi motion average, tends to smooth out the energy dependence of the amplitude.

d) Using $f_R(E)$, we now supply a correction for the Pauli principle. Our final approximation for the amplitude $\bar{f}$ is then

$$\bar{f}(E) = f_R(E)/(1-f_R(E)F(E, k_F)) \quad (7)$$

where F is complicated function [11] which ensures that the two nucleons always propagate above the Fermi sea in intermediate states. A detailed discussion of the many body and Pauli corrections to the NN amplitude is given in ref. [11].

The results shown in Fig. 4 display the sensitivity of the calculated $\bar{f}$ to the choice of k_F . Typical values characteristic of local densities in the nuclear overlap region are $k_F = 0.45\text{fm}^{-1}$ and 0.90fm^{-1} . The values of $\bar{f}$ obtained using the free space amplitude of Eq. (3) ($k_F = 0$) are also shown for comparison.

From Fig. 4, we see that the calculated real part of $\bar{f}$ agrees well with the empirical values for $k_F = 0.45\text{fm}^{-1}$. No single value of k_F reproduces both the real and imaginary parts of $\bar{f}$. Our calculation does reproduce the general trends of $\bar{f}$ as a function of energy, however. Note that the free space amplitude ($k_F = 0$) is a rather poor approximation to $\bar{f}$, particularly at low energies. The many body effects, in particular the Pauli principle corrections, are crucial in obtaining any sort of reasonable agreement with empirical values of $\bar{f}$. At low energies (below 40 MeV/particle), there is considerable spread in the theoretical predictions, depending on

which k_F is chosen. The small spread in the best fit values, however, and the high quality of the fits suggests that a more careful treatment of the many body effects would be worthwhile. The quality of the fits demonstrates that the folding model, even in its present simple form, is useful in the low energy region. Note that above 40 MeV per particle, the many body corrections become small, and the calculated and empirical values of $\bar{f}$ agree well, in both the real and imaginary parts. Thus our microscopic model should have considerable predictive power for intermediate and high energy heavy ion processes. In this region, there is very close contact between the underlying effective NN amplitudes and the nucleus-nucleus potential.

Before proceeding to discuss a variety of applications, it is worthwhile to dwell for a moment on the simplicity of our approximation to the lowest order potential. The only dependence on the projectile and target (except ξ) is through their ground state mass distributions. The entire energy dependence and the influence of many-body effects are incorporated in $\bar{f}$. While it may be desirable to eliminate some of these approximations later, this simple form yields a single theoretical curve for $\bar{f}(E)$ which expedites a comparison between the empirical and theoretical results for a variety of projectile-target situations. We note in passing that such a comparison is only meaningful when high quality fits to the data are obtained. This requirement demands a careful treatment of the densities and the finite range of the effective NN force.

We now show some examples of transfer reactions, calculated with distorted waves generated by the folded potential which fits elastic scattering. We thank A.J. Baltz for assistance in these computations. We have chosen non-trivial examples [14] which exhibit some forward peaking, in order to provide a proper challenge to the model. Semiclassical bell-shaped angular distributions do not provide a very strong constraint on the theory. In Fig. 5, we show some results for one particle transfer [14]. The folded model provides a good account of the data, both for the ground and excited state transitions. In this and several other cases, the results are comparable in quality to those obtained with Woods-Saxon potentials [14]. The fine details could be improved by weakening the absorption a bit, since this would have much less influence on the elastic than on the transfer data, and would enhance the forward peaking for the transfer reaction.

An example of two neutron transfer [14] is shown in Fig. 6. Here again the folding model provides a reasonable description of the data, if we weaken the absorption somewhat from the elastic best fit value. As we transfer more and more particles, we start to probe the interior of the potential, where the folding model is expected to break down. We see some evidence for this if we compare Figs. 5 and 6; the fit to one particle transfer is considerably more quantitative than that for two neutron transfer. Some of this effect may be due to the limitations of the DWBA.

One can also look for bound states of a folded potential [7,9]. For example,

Fig. 5 One particle transfer cross sections [9] obtained using the folded potential which best fits elastic scattering. Data is from Brookhaven [14]; the DWBA code was supplied by A. J. Baltz.

bound states or single particle resonances of an α cluster in the potential generated by an ^{16}O core can be identified with members of the ^{20}Ne ground or excited state rotational bands. The folding model with a single $\bar{f}$ per band yields close to the experimental energy splittings as well as the correct α widths for continuum states and $B(E2)$ values for transitions within the ground state band. The folding model can also be used to predict the positions of high spin states populated in three particle transfer reactions [17]. In many cases, the spins of such levels are not well established, so the folding model performs a useful predictive function. The folding model approach to cluster states will be treated in detail by B. Buck at this conference, so we omit further discussion here.

Very high energy heavy ion cross sections (≥ 1 GeV/particle) have also been calculated using an impact parameter representation for the scattering amplitude and a folding model to generate the potential [8]. The folded potential with a free NN estimate for $\bar{f}$ should be valid at high energy, since the many-body corrections to $\bar{f}$

Fig. 6 Two particle transfer cross section (dashed line) for the $^{60}\text{Ni}(180,160)^{62}\text{Ni}$ reaction at 62.92 MeV obtained using the best fit folded potential of Fig. 1. The data is from Levine et al. [14]. Numerical densities obtained from a single particle model [13] were used. Similar calculations using electron scattering densities are shown in ref. [9]. The solid line shows the effect of decreasing the absorption by 50%; a reasonable fit to the elastic data is maintained.

are small. The folding model yields a set of predictions for high energy cross sections and factorization ratios based on methods of standard nuclear theory. We thus obtain a useful set of predictions to be compared with those arising from more sophisticated particle physics concepts. These results have been reviewed in detail recently [10].

In summary, the folding model for nucleus-nucleus interactions correlates a wide range of data within a single framework capable of being extrapolated to make predictions in new situations. The model is still partly phenomenological in the low energy region ($\lesssim 40$ MeV/particle), since the strength of the potential is not reliably given by our crude form of many body theory, and must be adjusted empirically in order to fit data. However, the model gives a good account of one and two particle transfer data as well as elastic scattering. It is expected to work well for any peripheral process, since such processes are insensitive to the potential in the nuclear interior. For intermediate and high energy reactions, the folding model pro-

vides an optical potential with no free parameters, assuming the nuclear densities ρ are given; the data may then place constraints on the behavior of ρ in the tail region.

We feel that there is some hope for a basic theory in which one tries to utilize one's knowledge of NN interactions and the geometrical properties of nuclei to derive a potential for nucleus-nucleus scattering. In this way, one tries to achieve a consistent description of as wide a class of phenomena as possible. In any case, the folding model may indicate a more economical way of parametrizing the potential; phenomenology is best tempered with some guidance from theory.

A number of other applications of the method are under study: a) α and heavy ion inelastic scattering [18]; b) use of the folded potential as an input into a coupled channel formalism; c) systematic predictions of the energies of high spin states populated in three and four particle heavy ion transfer reactions; d) calculation of multiplicities of particles produced in very high energy nucleus-nucleus collisions [10]; e) calculation of fusion barriers. We are also examining a number of refinements to the model, such as a more careful treatment of the density dependence of the effective interaction G . In general this will lead to somewhat different geometries for the real and imaginary parts of the optical potential. We may also parametrize the interior of the potential separately, and join on to the folded potential in the surface region; this should enable us to improve the description of the transfer data, while retaining a high quality fit to elastic scattering.

REFERENCES

1. A.K. Kerman, H. McManus and R.M. Thaler, Ann. Phys. (N.Y.) 8 (1959) 551.
2. J. Hüfner and C. Mahaux, Ann. Phys. (N.Y.) 73 (1972) 525.
3. G.W. Greenlees, G.H. Pyle and Y.C. Tang, Phys. Rev. 171 (1968) 1115.
4. T.T. Chou and C.N. Yang, Phys. Rev. Letters 20 (1968) 1213; Phys. Rev. 170 (1968) 1591.
5. B. Tatischeff and I. Brissaud, Nucl. Phys. A155 (1970) 89; A.M. Bernstein and W.A. Seidler, Phys. Letters 34B (1971) 569; P. Mailandt, J.S. Lilley and G.W. Greenlees, Phys. Rev. Letters 28 (1972) 1075; Phys. Rev. C 8 (1973) 2189; R.S. Mackintosh, Nucl. Phys. A210 (1973) 245; L. West, S. Cotanch and D. Robson in Proceedings of Munich Conference (1973), Vol. I, p. 383.
6. G.R. Satchler, Invited talk at International Conference on Reactions Between Complex Nuclei, Nashville, Tennessee June 1974.
7. B. Buck, C.B. Dover and J.P. Vary (to be published).
8. S. Barshay, C.B. Dover and J.P. Vary, Phys. Letters 51B (1974), 5 and BNL preprint 18972, May 1974.
9. J.P. Vary and C.B. Dover, Phys. Rev. Letters 31 (1973) 1510.
10. J.P. Vary and C.B. Dover, invited paper for the Second High Energy Heavy Ion Summer Study, Lawrence Berkeley Lab (July 15-26, 1974).
11. C.B. Dover and J.P. Vary (to be published).
12. J. Negele, private communication.
13. D.J. Millener and P.E. Hodgson, Nucl. Phys. A209 (1973) 59.
14. E.H. Auerbach et al., Phys. Rev. Letters 30 (1973) 1078; M.J. Schneider et al., Phys. Rev. Letters 31 (1973) 320; C. Chasman, S. Kahana and M. Schneider, Phys. Rev. Letters 31 (1973) 1074; P. Bond et al., Phys. Letters 47B (1973) 231; M.J. Levine et al., to appear in Phys. Rev. Comments.
15. W.T.H. van Oers and J.M. Cameron, Phys. Rev. 184 (1969) 1061.
16. D.A. Goldberg and S.M. Smith, Phys. Rev. Letters 29 (1972) 500; D.A. Goldberg, S.M. Smith and G.F. Burdzik, University of Maryland Technical Report No. 74-107, June (1974) and private communication.
17. K. Nagatani et al., Phys. Rev. Letters 31 (1973) 250.
18. C.B. Dover, P. Moffa and J.P. Vary (in preparation).