3629 (1973); T. B. Grimley, Proc. Phys. Soc. (London) 92, 776 (1967); D. M. Newns, Phys. Rev. 178, 1123 (1969); J. W. Gadzuk, in *Surface Physics of Crystalline Materials*, edited by J. M. Blakely (Academic, New York, 1974).

[4]B. Feuerbacher and B. Fitton, Phys. Rev. B 8, 4890 (1973).

[5]E. W. Plummer, to be published.

[6]T. Gustafsson, P. O. Nilsson, and L. Wallden, Phys. Lett. 37A, 121 (1971); N. V. Smith and M. M. Traum, Phys. Rev. Lett. 31, 1247 (1973); M. M. Traum, N. V. Smith, and F. J. Di Salvo, Phys. Rev. Lett. 32, 1241 (1974).

[7]N. V. Smith, M. M. Traum, and F. J. Di Salvo, Solid State Commun. 15, 211 (1974).

[8]T. E. Madey, private communication.

[9]For a detailed discussion of hydrogen on W(100) see T. E. Madey, Surface Sci. 36, 281 (1973).

[10]L. W. Anders, R. S. Hansen, and L. S. Bartell, J. Chem. Phys. 59, 5277 (1973).

[11]P. J. Estrup and J. Anderson, J. Chem. Phys. 45, 2254 (1966).

[12]No peaks are plotted in Fig. 2 below $-7$ eV for $h\nu=26.9$ eV due to interference of the 19.8-eV spectral line of neon.

[13]A. Liebsch, Phys. Rev. Lett. 32, 1203 (1974).

[14]E. W. Plummer, private communication.

[15]J. G. Endriz, Phys. Rev. B 8, 3464 (1973); B. Feuerbacher and B. Fitton, Solid State Commun. 15, 295 (1974).

[16]W. F. Egelhoff, J. W. Linnett, and D. L. Perry, unpublished results.

# One- and Multi-Step Processes in the Reaction $^{144}$Nd($^{12}$C, $^{14}$C)†

K. Yagi,* D. L. Hendrie, L. Kraus,‡ C. F. Maguire, J. Mahoney, D. K. Scott, and Y. Terrien§
*Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720*

and

T. Udagawa, K. S. Low, and T. Tamura
*Center for Nuclear Studies,‖ University of Texas, Austin, Texas 78712*
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Two very different types of angular distributions, one having a normal bell shape and the other being much more constant with angle were observed in the reaction $^{144}$Nd($^{12}$C, $^{14}$C) for two well-known $2^+$ states of $^{142}$Nd. The fits to these angular distributions using the distorted-wave Born approximation and/or coupled-channel Born approximation confirms the conclusion that the data give definite evidence for the importance of multistep processes. A comparison with the reaction $^{144}$Nd($p,t$) is also discussed.

In previous work[1,2] on the reaction $^{144}$Nd($p$, $t$)$^{142}$Nd, the excitation of the ground ($0_g^+$) state, the first excited ($2_1^+$) state, the 2.98 MeV ($0_2^+$) state, and the 3.49 MeV ($2_2^+$) state in $^{142}$Nd ($N=82$) was investigated. The purpose of the present work is to study these and additional states via the reaction $^{144}$Nd($^{12}$C, $^{14}$C)$^{142}$Nd. Our interests are to learn to what extent the light-ion– and heavy-ion–induced, two-neutron pickup reactions are similar and to determine the effects of multi-step processes in heavy-ion transfer reactions.

The most remarkable feature found in the previous ($p,t$) work[1,2] was that the transitions to the $0_g^+$, $0_2^+$, and $2_2^+$ final states were strong and were of a one-step nature, while the transition to the $2_1^+$ state was much weaker and also had an anomalous angular distribution markedly different from what was expected for a one-step $L=2$ transition. The difference in the behavior of the $2_1^+$ and $2_2^+$ transitions was attributed to the following distinct properties of those states.[2] The $2_2^+$ state is a collective state of two-particle, two-hole nature in the $N=82$ closed shell, i.e., a superposition of monopole and quadrupole pairing vibrations.[3] Therefore, it can be excited strongly by a direct-($L=2$)-type two-neutron pickup reaction. On the other hand, the $2_1^+$ state consists dominantly of a proton particle-hole quadrupole vibrational configuration; thus a direct two-neutron transfer process is substantially inhibited and higher-order processes may contribute significantly. Indeed, the anomalous behavior of the $2_1^+$ cross section, which defied explanation in terms of distorted-wave-Born-approximation (DWBA) calculations, was well accounted for by coupled-channel-Born-approximation (CCBA) calculations, which took into account the effect of inelastic scattering.[2]

The $^{144}$Nd($^{12}$C, $^{14}$C) experiment was performed

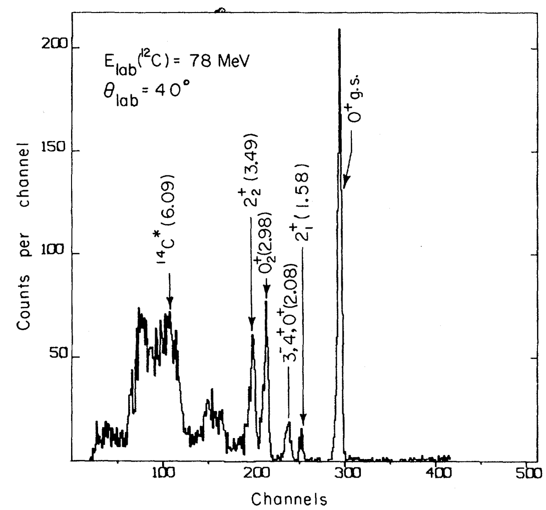


FIG. 1. Energy spectrum of the reaction $^{144}$Nd($^{12}$C, $^{14}$C). Excitation energies in $^{142}$Nd are shown in parentheses in MeV. The peak corresponding to the first excited state in $^{14}$C is also shown.

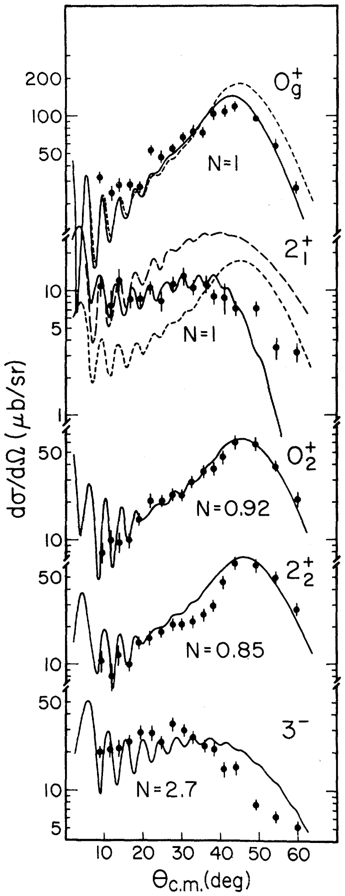


FIG. 2. Experimental and theoretical angular distributions of the reaction $^{144}$Nd($^{12}$C, $^{14}$C) at $E_{lab} = 78$ MeV. Each curve is labeled with a normalization factor $N$, so chosen that $N = 1$ for the $0_g^+$ state. (Without this renormalization, all the theoretical cross sections are to be reduced by a factor 9.)

using a 78-MeV $^{12}$C beam from the Berkeley 88-in.-cyclotron. Reaction products were detected in the focal plane of a magnetic spectrometer.[4] Particle identification and energies of the reaction products were obtained by a combination of magnetic rigidity, $dE/dx$, total energy, and time of flight. Figure 1 shows an energy spectrum of the $^{14}$C ions. A 300-$\mu$g/cm$^2$ self-supporting isotopically pure metallic $^{144}$Nd target gave a resolution of 200 keV. Angular distributions of the $^{14}$C groups leading to $0_g^+$, $2_1^+$, $0_2^+$, and $2_2^+$ states and a group at about 2.08 MeV consisting of $3_1^-$, $4_1^+$, $0_1^+$ were measured from $\theta_{lab} = 8°$ to 55° in 2.5° steps.

Figure 2 gives the measured differential cross sections of the five $^{142}$Nd groups, and one may conclude that the data have the following properties: (i) The $0_g^+$, $0_2^+$, and $2_2^+$ states are excited strongly and have bell-shaped angular distributions which are characteristic of one-step transitions, with peaks appearing at $\theta_{c.m.} \approx 45°$; (ii) the $2_1^+$ transition is strongly inhibited and has a quite anomalous (flattened) angular distribution; (iii) below the excitation energy of 3.5 MeV, $0_g^+$, $0_2^+$, and $2_2^+$ are the only states that are excited strongly, in spite of the fact that there are about 25 states in this energy range known from other experiments.[5] All these features are very much reminiscent of the situation for the $(p,t)$ reaction.[1,2]

Since the elastic scattering of $^{12}$C by $^{142}$Nd was not available, we began our analysis by using the Körner *et al.* potential,[6] which has $V = 100$ MeV, $W = 25$ MeV, $r_0 = 1.22$ fm, and $a = 0.50$ fm, and searched on radius and diffuseness so as to give the best overall fit to our transfer data. The resulting potential ($r_0 = 1.18$, $a = 0.55$ fm) was used in all theoretical calculations. The elastic cross-section predictions did not change much from that obtained with the unaltered Körner *et al.* parameters, nor differ very much from that obtained by using the parameters of Becchetti *et al.*[7] We may therefore say that the conclusion we derive below is rather insensitive to the choice among optical potential parameters which are currently accepted.

In constructing the form factor(s) to be used in the DWBA and/or CCBA calculations,[8,9] the wave functions of $^{142}$Nd and $^{144}$Nd were constructed in exactly the same manner as they were in Ref. 2 and by Udagawa, Tamura, and Izumoto.[10] The overlap of these two wave functions gives the wave function of the two extra neutrons in $^{144}$Nd. A corresponding wave function for the two extra neutrons in $^{14}$C can be obtained by using the results of Cohen and Kurath[11] and after transforming each of these two-neutron wave functions into the center of mass and relative parts, only the term that involved the relative motion which had no node and $^1S$ coupling was retained. The radial part of the corresponding c.m. part was then smoothly connected to the appropriate tail that corresponded to a Woods-Saxon potential with a radius parameter $r_0 = 1.2$ fm and a diffuseness $a = 0.65$ fm.

The cross sections for the $0_g^+$ and $2_1^+$ final states were obtained by performing exact finite-range (EFR)-CCBA calculations, in which $0^+$ and $2^+$ Nd states were coupled in both incident and final channels, with $\beta_2 = 0.125$ and 0.096 for $^{144}$Nd and $^{142}$Nd, respectively. As is seen in Fig. 2 good simultaneous fits to both bell-shaped $0_g^+$ and flattened $2_1^+$ angular distributions are obtained. A corresponding EFR-DWBA cross section is also given by a dotted line for the $2_1^+$ state, which is seen to have a completely different shape from the experimental angular distribution. The DWBA $0_g^+$ cross section, which is also given by a dotted line, will be discussed later.

It is worth emphasizing that not only the angular distribution, but also the relative magnitude of the EFR-CCBA $0_g^+$ and $2_1^+$ cross sections were obtained correctly. It is worth noting further that the CCBA $2_1^+$ cross section (solid line) was obtained as a result of destructive interference between the one-step DWBA process and the two-step processes, $0_g^+(^{144}\text{Nd}) \to 0_g^+(^{142}\text{Nd}) \to 2_1^+(^{142}\text{Nd})$ and $0_g^+(^{144}\text{Nd}) \to 2_1^+(^{144}\text{Nd}) \to 2_1^+(^{142}\text{Nd})$. The $2_1^+$ cross section given by a broken line was obtained by considering *only* these two-step processes. The very anomalous angular distribution results from this interference. Such a result is rather similar to what was experienced in the corresponding $(p,t)$ work, where the contributions of the two-step and the one-step processes were comparable to one another and their strong interference made the $2_1^+$ angular distribution also anomalous.[2]

A similar EFR-CCBA calculation was made considering a $0_g^+$-$3_1^-$ coupling in $^{142}$Nd, and the resultant $3_1^-$ cross section, shown in Fig. 2, agrees rather well with the experimental angular distribution to the group at 2.08 MeV. The predicted magnitude obtained with $\beta_3 = 0.106$ is, however, too small by a factor of $N = 2.7$. Since the experiment includes the $3_1^-$, $4_1^+$, and $0_1^+$, cross sections, however, we do not attach much significance to this comparison.

The calculation of the $0_2^+$ and $2_2^+$ cross sections was made in terms of EFR-DWBA, assuming that the excitation takes place only via pairing vibrational components in these states which have monopole and quadrupole nature, respectively.[12] As is expected the resultant cross sections (Fig. 2) are basically bell shaped, and agree satisfactorily with experimental angular distributions. The relative normalization factors $N = 0.92$ and $N = 0.85$, respectively, for these two states are sufficiently close to unity, indicating that the wave functions we used to describe these two states are basically correct.

It should be finally noted that, both experimentally and theoretically, the peak of the bell-shaped angular distribution for the $0_2^+$ state appears at 45°. On the other hand, the experimental peak for the $0_g^+$ state appears at 43°, i.e., a shift by 2° to forward angle takes place, and our CCBA calculations explain this. The corresponding DWBA cross section, however, has the peak at 45° (in agreement with that for the $0_2^+$ state) and the angular distribution (dotted line) fits the experiment rather poorly. The origin of the shift of 2° of the peak position in going from DWBA to CCBA is the destructive interference in the latter between the two-step $0_g^+(^{144}\text{Nd}) \to 2_1^+(^{144}\text{Nd}) \to 0_g^+(^{142}\text{Nd})$ amplitude and the one-step $0_g^+(^{144}\text{Nd}) \to 0_g^+(^{142}\text{Nd})$ amplitude. This destructive interference is stronger (weaker) for partial waves whose orbital angular momentum $l$ is smaller (larger) than the grazing angular momentum $l_g$. Thus, the effective value of $l_g$ for CCBA is larger than that for DWBA which results in the shift of the peak position to a smaller angle.

In summary, (i) the mechanism of the reaction $^{144}$Nd($^{12}$C, $^{14}$C) is quite analogous to that of the reaction $^{144}$Nd$(p,t)$; (ii) the comparison of the transitions to the two types of $2^+$ states gives a definite evidence for the importance of two-step processes[9,13]; (iii) since the direct transfer signature for this system is a clear bell-shaped angular distribution, the anomalous nature of the $2_1^+$ excitation is much more conspicuous than that observed in the $(p,t)$ case[1,2]; (iv) the coupling effect can be significant in predicting the correct angular distribution, in particular the peak position, even when the angular distribution has a simple bell shape. This was exemplified in our $0_g^+$ cross section.

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*On leave from Osaka University, Osaka, Japan.

‡On leave from Centre de Recherches Nucléaires and Université Pasteur, Strasbourg, France.

§On leave from Centre d'Etudes Nucléaires de Saclay, Saclay, France.

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[1]K. Yagi, Y. Aoki, J. Kawa, and K. Sato, Phys. Lett. 29B, 647 (1969).

[2]K. Yagi, K. Sato, Y. Aoki, T. Udagawa, and T. Tamura, Phys. Rev. Lett. 29, 1334 (1972).

[3]A. Bohr, in *Proceedings of the International Symposium on Nuclear Structure, Dubna, 1968* (International Atomic Energy Agency, Vienna, Austria, 1968), p. 179.

[4]B. G. Harvey, J. Mahoney, F. G. Pühlhofer, F. S. Goulding, D. A. Landis, J. C. Faivre, D. G. Kovar, M. S. Zisman, J. R. Meriwether, S. W. Cosper, and D. L. Hendrie, Nucl. Instum. Methods 104, 21 (1972).

[5]J. F. Lemming and S. Raman, Nucl. Data, Sect. B 10, 309 (1973).

[6]H. J. Körner, G. C. Morrison, L. R. Greenwood, and R. H. Siemssen, Phys. Rev. C 7, 107 (1973).

[7]F. D. Becchetti, D. G. Kovar, B. G. Harvey, J. Mahoney, B. Mayer, and F. G. Pühlhofer, Phys. Rev. C 6, 2215 (1972).

[8]T. Tamura and K. S. Low, Phys. Rev. Lett. 31, 1356 (1973); K. S. Low and T. Tamura, Phys. Lett. 48B, 285 (1974); T. Tamura, to be published.

[9]T. Tamura, K. S. Low, and T. Udagawa, Phys. Lett. 51B, 116 (1974).

[10]T. Udagawa, T. Tamura, and T. Izumoto, Phys. Lett. 35B, 129 (1971).

[11]S. Cohen and D. Kurath, Nucl. Phys. A101, 1 (1967).

[12]The probability of the pairing vibrational components in $0_2^+$ and $2_2^+$ states we used are 73 and 75%, respectively. These numbers were taken from the experimental fact that $\sigma(^{144}\mathrm{Nd}(p,t)^{142}\mathrm{Nd}, 0_2^+)/\sigma(^{142}\mathrm{Nd}(p,t)^{140}\mathrm{Nd}, 0_g^+) = 0.73$ and $\sigma(^{144}\mathrm{Nd}(p,t)^{142}\mathrm{Nd}; 2_2^+)/\sigma(^{142}\mathrm{Nd}(p,t)^{140}\mathrm{Nd}, 2_1^+) = 0.75$. See Ref. 2 for the experimental data.

[13]R. J. Ascuitto and N. K. Glendenning, Phys. Lett. 45B, 85 (1973).

## Observation of the Yrast and Statistical Cascades in (Heavy-Ion, $xn\gamma$) Reactions

J. O. Newton, J. C. Lisle,* G. D. Dracoulis, J. R. Leigh, and D. C. Weisser
*Department of Nuclear Physics, Australian National University, Canberra, Australian Capital Territory, 2600, Australia*

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The energy spectra and angular distributions of the yrast and statistical cascades in $^{160,162}$Yb have been obtained from measurements of the reactions $^{147,149}$Sm($^{16}$O, 3$n$) and $^{148,150}$Sm($^{16}$O, 4$n$). An average of about six yrast and six statistical $\gamma$ rays occur in the 4$n$ reaction. The data suggest that the yrast $\gamma$ rays are mostly stretched $E2$.

In recent years the study of discrete lines from low-lying states of final-product nuclei formed in (heavy-ion, $xn\gamma$) reactions has led to new and valuable information on nuclear states of high angular momentum.[1] However little effort has been devoted to the study of the $\gamma$-ray cascade resulting from the decay of the highly excited states. Because of the high level density in this region these $\gamma$ rays cannot be resolved and they form a continuum.

The present view of the continuum decay[1] is briefly outlined below. States of high angular momentum ($\gtrsim 20\hbar$) lying below about 1 neutron binding energy above the yrast line are expected to decay to states within a region of a few hundred keV above the line, mainly by a few dipole transitions, carrying away on the average little angular momentum but considerable energy. These transitions may have an energy distribution related to a statistical evaporation spectrum. States in the yrast region are forced to decay along this region mainly by stretched transitions to states of lower spin and energy until the ground-state band (gsb) is reached. Decay then proceeds through the gsb. The time of ~10 psec between the initial formation of the compound nucleus and entry to the gsb[1] implies that the states in the intersection region must be heavily admixed and that the transitions in the yrast region must be mainly $E1$, $M1$, or $E2$ and must have little dispersion in energy. The theoretical work of Stephens and Simon[2] suggests that the transitions should be mainly $E2$. Little direct experimental evidence has been presented to support this model although recently Tjøm *et al.*[3] and der Mateosian, Kistner, and Sunyar[4] reported measurements which determine the average numbers of continuum $\gamma$ rays for several cases without sep-