(p, t) Excitations of Removal and Addition Types of Quadrupole-Pairing Vibrational States in Even Nd Isotopes

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Strong $L=2$ transitions to the removal type of quadrupole-pairing vibrational states with $Q=-(8-10)$ MeV, observed in (p,t) reactions on all stable Nd isotopes with 52-MeV protons, are shown to be well accounted for by one-step distorted-wave Born-approximation calculations. Compared with these, the transitions to the 2_1^+ (addition type of quadrupole pairing) states of $N\geq 82$ isotopes, which are found to be much weaker and have quite different angular distributions, are shown to be reasonably accounted for in terms of two step coupled-channel Born-approximation calculations.

In our previous work, monopole- and quadrupole-type pairing (QP) excitations were studied in (p, t) reactions on even Nd isotopes ($N=82-90$) with 52-MeV protons.[1] A strong $L=0$ transition to an excited 0^+ state was observed in the reaction ^{144}Nd(p, t)^{142}Nd(2.97 MeV),[2] but on heavier isotopes no such 0^+ states were strongly excited[1,3] in the energy region where the pairing vibrational state[4] is expected to lie; see Fig. 1. It was therefore concluded[1] that the monopole-pairing vibrational strength is largely fragmented so that the simple zero-order picture[4] breaks down for $N=84-88$ nuclei.[5] Contrary to the case with $L=0$, however, rather strong $L=2$ transitions with $Q=-(8-10)$ MeV were observed in all the Nd isotopes studied,[1] as is seen also in Fig. 1, and the 2^+ states thus excited were intepreted[1] as being the removal-type quadrupole-pairing (RQP) vibrational state. In addition to these QP states, excitation cross sections of the 2_1^+ states, which are the addition-type QP vibrational states (AQP),[6] were also measured, and it is the purpose of the present Letter to give a comparative analysis of these two kinds of $L=2$ transitions. The data were taken by using a proton beam of 52 MeV from the INS Tokyo synchrocyclotron.[7] Emitted tritons were detected with a broad-range magnetic spectrometer.[8] Overall energy resolutions were 80 keV.

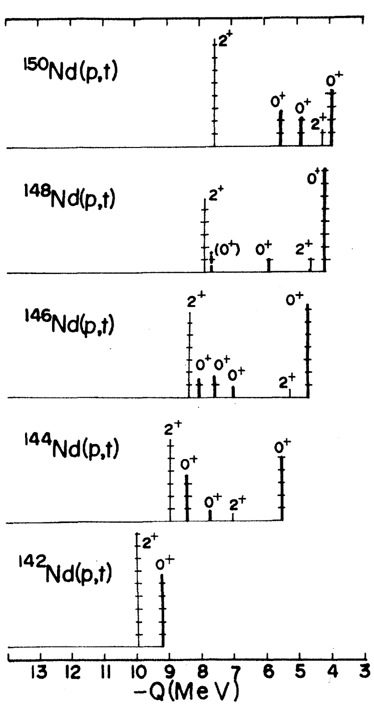

FIG. 1. Summed cross sections for $L=0$ and 2 transitions in the reaction Nd(p,t) with 52.1-MeV protons. The relative errors in the cross sections between different targets are estimated to be $\pm 10\%$.

As far as the strong QP-type $L=2$ transitions are concerned, the analysis is quite easy. As is seen in Fig. 2(a), the angular distribution from these 2^+ (RQP) states can be fitted quite easily with standard distorted-wave Born-approximation (DWBA) calculations.[9] A similar fit can also be obtained with the coupled-channel Born-approximation (CCBA). This was indeed shown in recent CCBA calculations of the reaction ^{142}Nd(p, t)^{140}Nd.[10]

Compared with these RQP 2^+ transitions, the AQP 2^+ transitions are much more inhibited, and also have angular distributions that are quite different, particularly at smaller angles, as can be seen by comparing Fig. 2(b) with 2(a). Therefore,

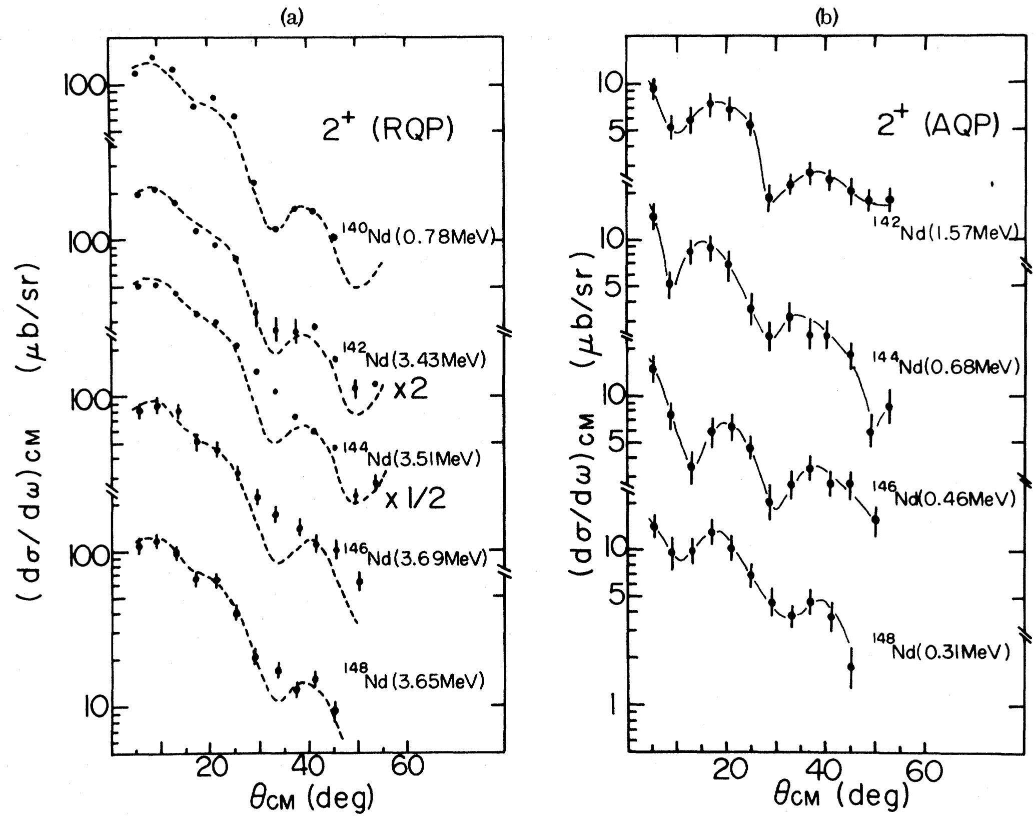

FIG. 2. Angular distributions of $L=2$, Nd(p,t) transitions (a) to the quadrupole-pairing vibrational states ($-Q \simeq 8$–10 MeV), and (b) to the first excited 2^+ states of the $N \geq 82$ isotopes. Each final state is indicated. The dashed curves are one-step–process DWBA predictions. The solid curves in (b) are drawn to guide the eye.

DWBA is not expected to work here. We thus attempt to fit these cross sections by extending DWBA to CCBA calculations, which have recently been used rather successfully in analyzing ^{142}Nd(p, t) data.[10] In the following calculation we take ^{144}Nd(p, t) as an example.

In carrying out the CCBA calculation, we first need to construct explicitly the wave functions of relevant states in both target and residual nuclei. As for the residual nucleus ^{142}Nd, we have constructed such wave functions in our previous work,[10] and they can be used here just as they stand. In particular, the 2_1^+ wave function, which was obtained by using the random-phase approximation (RPA), can be written as

$$|2_1^+\rangle = C_{2q}^\dagger|0\rangle, \tag{1}$$

where $C_{2q}^\dagger$ is the creation operator of the collective, particle-hole- (p-h) type phonon. The vacuum $|0\rangle$ plays the role of the wave function of the 0_g^+ state.

The target nucleus ^{144}Nd has two neutrons outside the $N=82$ core. The 0_g^+ and 2_1^+ states are thus primarily pairing vibrational states of the "addition type."[4] For our purpose of performing CCBA calculations, however, somewhat more sophisticated wave functions are needed for these states, and we apply the same technique as was used in Ref. 10 in obtaining the wave functions for states in ^{140}Nd, which has two neutron holes. The resultant wave functions can be written as

$$|0_g^+\rangle_i = \alpha_1 A_0^\dagger|0\rangle + \alpha_2 (A_2^\dagger C_2^\dagger)_0|0\rangle, \tag{2a}$$

$$|2_1^+\rangle_i = \gamma_1 A_2^\dagger|0\rangle + \gamma_2 A_0^\dagger C_2^\dagger|0\rangle + \gamma_3 (A_2^\dagger C_2^\dagger)_2|0\rangle, \tag{2b}$$

where $A_0^\dagger$ and $A_2^\dagger$ are, respectively, the creation operators of the 0^+ and 2^+ pairing-vibrational phonons. As in Ref. 10, they were obtained by using RPA, together with the simple pairing-force model. The second and third terms of (2) represent states which are formed by the superpositions of the pairing-vibrational and p-h phonons. Their mixing with the purely pairing-vibrational state, the first term in (2), is treated as being caused by the H_{31} term of the quadrupole-

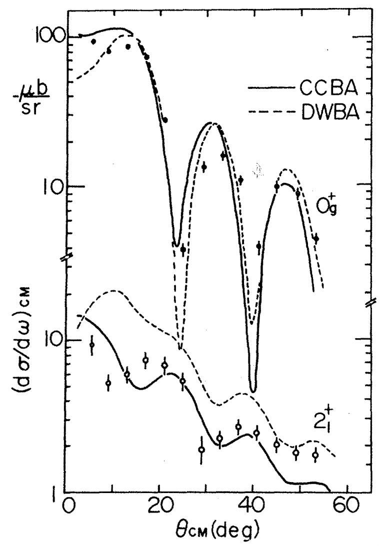

FIG. 3. Cross sections for the reaction ^{144}Nd(p, t)^{142}Nd at 52 MeV.

quadrupole interaction, which has been ignored in the step of constructing the phonon operators $C_2^\dagger$, $A_0^\dagger$, and $A_2^\dagger$. With these approximations and with the use of the same parameters as in our previous work,[11] the coefficients in (2) were found to be $\alpha_1 = 0.90$, $\alpha_2 = 0.43$, $\gamma_1 = 0.82$, $\gamma_2 = 0.48$, and $\gamma_3 = -0.21$.

Using Eqs. (1) and (2), together with these coefficients, the form factors to be used for various (p, t) processes are obtained as

$$F_0(0^+ \to 0^+) = \alpha_1 F_0 = 0.90 F_0, \tag{3a}$$

$$F_0(2^+ \to 2^+) = \gamma_2 F_0 = 0.48 F_0, \tag{3b}$$

$$F_2(0^+ \to 2^+) = (\alpha_2/5) F_2 = 0.086 F_2, \tag{3c}$$

$$F_2(2^+ \to 0^+) = \gamma_1 F_2 = 0.82 F_2, \tag{3d}$$

$$F_2(2^+ \to 2^+) = (\gamma_3/\sqrt{5}) F_2 = -0.094 F_2. \tag{3e}$$

Here F_0 and F_2 are $L=0$ and $L=2$ form factors for the (p, t) transitions from, respectively, the purely pairing-vibrational 0^+ and 2^+ states to vacuum.

By using Eqs. (1) and (2) one can also evaluate the β_2 values to be used in the inelastic scattering part of CCBA, in the same way as was done in Ref. 10. We found that $\beta_2 = 0.132$ and 0.097, respectively, for the incident and exit channels.

The CCBA cross section thus obtained is compared with that of DWBA as well as with experiment in Fig. 3. As is seen, the agreement of the CCBA result with experiment is good. Note that DWBA predicts too large a cross section at forward angles, meaning that in CCBA the direct and multistep processes interfere destructively, a situation which was also experienced in the analysis[12] of (p, t) data from deformed nuclei, but is opposite to that seen in the ^{142}Nd(p, t). There the 0_g^+ cross section was increased by CCBA over what it was in DWBA.

Combining the results of the present calculation with that of Ref. 10, we see that CCBA, fits the 0_g^+ and 2_1^+ cross sections rather well, both for $N \leq 82$ and $N \geq 84$ case, in spite of the fact that the magnitude of the 2_1^+ cross section in the former is more than one order of magnitude larger than it is in the latter. This difference in magnitude can be traced back to the fact that the form factor to be used for the direct $L=2$ transition in the $N \leq 82$ case is (3d) (after changing F_2 into the removal type) which is large, in place of (3c) which is small and is to be used in the $N \geq 84$ case.

It is thus seen that CCBA is capable of explaining (p, t) data from nuclei across the $N = 82$ magic number, and then all the way into the deformed region, although for nuclei in the transition region ($N = 88$–90), a somewhat more sophisticated model may have to be introduced in order to describe the relevant states.

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Four-Nucleon Transfer from ^{16}O to ^{90}Zr near the Coulomb Barrier*

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The transfer of two neutrons and two protons is found to be the dominant reaction process in $^{16}O + ^{90}Zr$ near the Coulomb barrier. The reaction was identified from γ-ray spectra measured in coincidence with backward-angle charged particles. A band of excited states in the residual nucleus is found to be selectively populated. The energy dependence of the centroid energy of this band is studied and compared with theories of sub-Coulomb transfer reactions.

We have combined the techniques of charged-particle and γ-ray spectroscopy to study heavy-ion–induced transfer of particles at bombarding energies near the Coulomb barrier. Since at such energies reaction products are expected to emerge preferentially at backward angles,[1] an annular particle detector placed close behind the target will span the most intense part of the angular distribution with large solid angle. This permits the detection of coincident γ rays with very good coincidence efficiency and identification of the dominant reaction processes by analysis of the coincident γ spectra.

Employing this technique in studying the $^{16}O + ^{90}Zr$ system,[2] we find that the dominant reaction channel near the Coulomb barrier is the transfer of two neutrons and two protons, which we will henceforth refer to as "α" transfer. We find that in the residual nucleus ^{94}Mo a narrow band of states is selectively populated and has unusual γ-ray decay properties. The back-angle transfer cross section to these states becomes observable at bombarding energies characteristic of the interference minimum of Coulomb excitation and nuclear inelastic scattering (48 MeV lab) and reaches a maximum estimated to be 0.28 mb/sr at a bombarding energy of 51 MeV (lab). At the latter energy the energy centroid of the band of states populated in the residual nucleus is at 6.5 MeV excitation.

In the present experiment a beam of ^{16}O ions from the München MP tandem accelerator was focused onto a 98% enriched metallic ^{90}Zr target of 0.8 mg/cm^2 thickness. A 60-μm annular detector—covered by a 0.45-mg/cm^2 Ni foil—was placed 4.5 cm behind the target, so it spanned an angular range of 166° to 175.5°. γ rays were observed at 90° to the beam axis at 4 cm distance from the target. Particle and γ energies and particle-γ time differences for each coincident event were recorded on magnetic tape by the on-line PDP 8/10 computer system. Single-parameter spectra were accumulated simultaneously. The beam was integrated in a Faraday cup and