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Destructive interference between direct and indirect processes in (p,t) reactions on spherical vibrational nuclei and strong resemblance to that in (p,t) reactions on well-deformed nuclei

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As evidence of a phase transition of the interference between direct and inelastic multistep processes in two-neutron pickup reactions exciting the first 2^+ state of spherical vibrational nuclei, a destructive interference has been observed in $^{A+2}$Pd$(p,t)^{A}$Pd(2_1^+) reactions. A strong similarity between the ^{104,108,110}Pd$(p,t)^{102,106,108}$Pd(2_1^+) cross sections and the ^{158}Gd$(p,t)^{156}$Gd(2_1^+) cross section is discussed.

[NUCLEAR REACTIONS ^{104,108,110}Pd(p,t), $E = 52$ MeV; measured $\sigma(\theta)$, coupled channel analysis.]

The interference between a direct process and inelastic multistep processes exciting the collective first 2^+ state via two-neutron transfer reactions has been extensively studied both with light ions[1-4] and heavy ions.[5-7] As far as spherical vibrational nuclei are concerned, a destructive interference was observed for pickup reactions from target nuclei in the beginning of the closed shell [^{144}Nd(p,t) ^{142}Nd[2] and ^{144}Nd(^{12}C, ^{14}C) ^{142}Nd[7] were such cases of $N > 82$], while a constructive interference was found for target nuclei at the upper end of the closed shell [^{142}Nd(p,t) ^{140}Nd[8] and $^{A+2}$Te(p,t) ^{A}Te[3] were such cases of $N < 82$]. Compared with vibrational nuclei, pickup reactions from well-deformed nuclei showed the destructive nature of the interference: (p,t) reactions on the isotopes of Gd,[9] Yb, and W.[1] In this communication the neutron number dependence of the interference[4,10] is investigated so as to detect the *destructive* interference near the *beginning* of a major shell of $N = 50-82$ by using (p,t) reactions on Pd isotopes. Since the Pd isotopes have very large deformation parameters ($\beta_2 \approx 0.25$[11]), it is quite interesting to compare the result with that of the (p,t) reactions on the well-deformed nuclei in the rare-earth region.

The (p,t) experiment on ^{104,108,110}Pd was done by using a proton beam of 52 MeV from the Institute for Nuclear Study Tokyo synchrocyclotron. Emitted tritons were detected with a broad-range magnetic spectrometer.[12] Overall energy resolutions were 80 keV. Differential cross sections obtained are shown in Fig. 1 together with theoretical curves which will be explained later.

The (p,t) transitions to the ground state (0_g^+) and the first excited 2^+ (2_1^+) state are analyzed in terms of coupled channel (CC) calculations.[13] Optical potential parameters are essentially the same ones which have been successfully used in the analyses of (p,t) reactions on the isotopes of Te, Sn, and Cd with 52-MeV protons.[3] Form factors for the transfer processes are constructed on the basis of the quasiparticle-RPA (random phase approximation) wave functions by using both the monopole pairing interaction and the Q-Q interaction. Details on the procedure are found in Ref. 10. We consider 8-proton and 15-neutron single-particle orbits[4] and the following force parameters (in MeV): $G_0^{(P)} = 20.5/A$, $G_0^{(n)} = 16.5/A$, $\kappa_2(QQ) = 0.075$. Form factors for the inelastic scattering processes are calculated from the first derivatives of the optical potentials. The deformation parameters (β_2) used are the same ones obtained from Coulomb-excitation experiments.[11] The dynamical element that determines the destructive or constructive nature of the interference is the relative sign of the $L = 0$, $0_g^+ \to 0_g^+$ and $L = 2$, $0_g^+ \to 2_1^+$ transfer form factors in the nuclear surface region under a fixed phase convention. So we defined the ratio $R = F_2(0_g^+ \to 2_1^+)/F_0(0_g^+ \to 0_g^+)$ at the nuclear surface of $r = 6$ fm. The phase of the wave function is determined in such a way that we always have a positive (transition) deformation parameter and also a positive value of the form factor $F_0(0_g^+ \to 0_g^+)$ in the surface region.

The differential cross sections of the ^{104}Pd$(p,t)^{102}$Pd (0_g^+ and 2_1^+) reaction are calculated by using the form factors mentioned above and shown in Fig. 1(a). As is expected, the net theoretical curve for the 2_1^+ cross section (solid line denoted by D) shows an interference of destructive type, but it does not reproduce the experimental

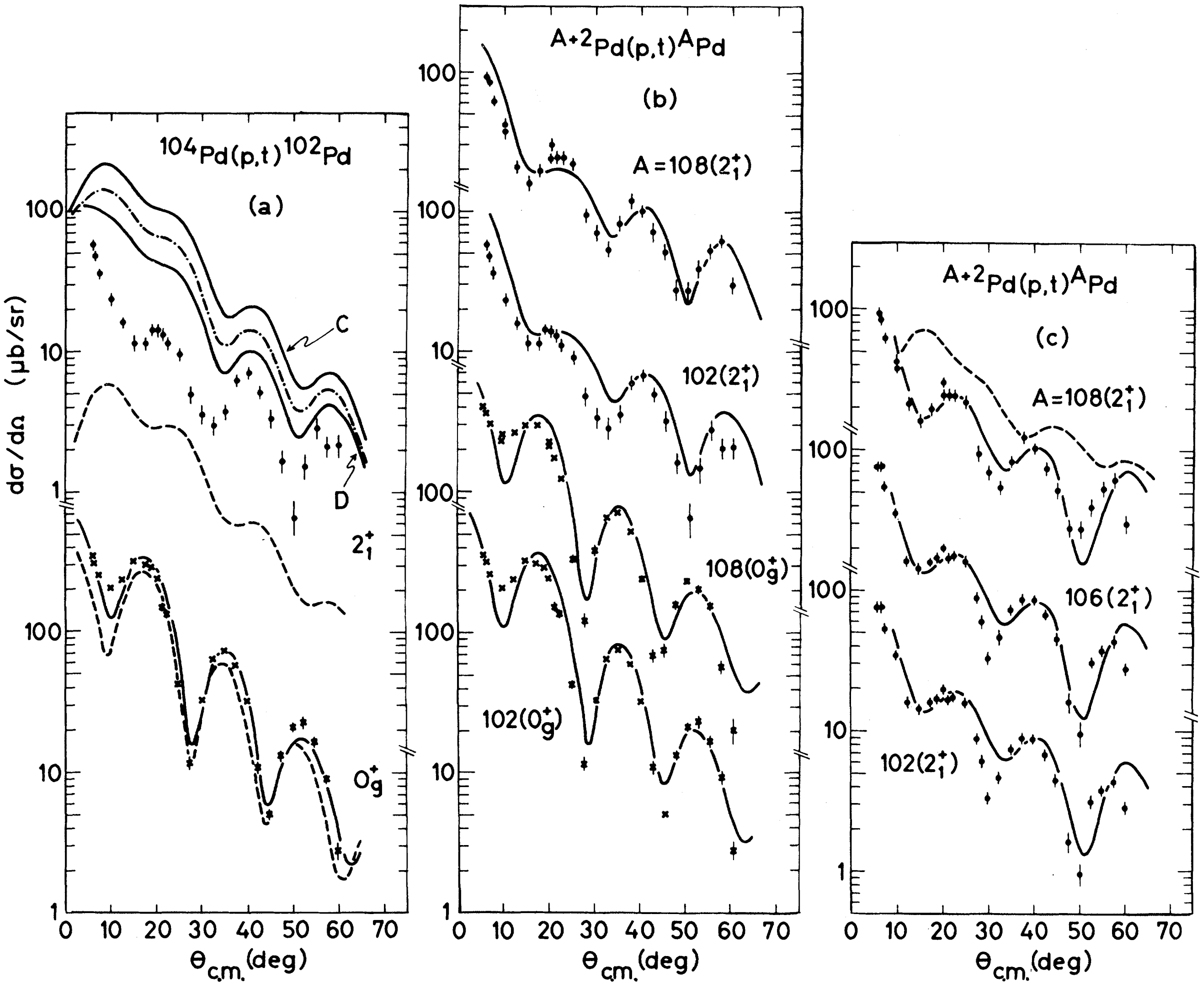

FIG. 1. Experimental and calculated cross sections of ${}^{A+2}\mathrm{Pd}(p,t){}^{A}\mathrm{Pd}(0_g^+$ and $2_1^+)$ at $E_p = 52$ MeV. A unique normalization constant is used in both (a) and (b). (a) Dashed lines are predictions by direct process only, dash-dot line by multistep processes only, and solid lines by the net CC result. A solid line denoted by D is a true prediction with $R = +0.12$ for the 2_1^+, while the one denoted by C is obtained by artificially assuming a constructive interference with $R = -0.12$. (b) Solid lines are due to the net CC results; $R = +0.41$ for ${}^{104}\mathrm{Pd}(p,t)$ and $+0.47$ for ${}^{110}\mathrm{Pd}(p,t)$. (c) Solid lines are the CCBA predictions for ${}^{158}\mathrm{Gd}(p,t){}^{156}\mathrm{Gd}(2_1^+)$, while a dashed line is due to the distorted wave Born approximation prediction.

cross sections. It is worthwhile to point out that a constructive interference which can be obtained artificially by inverting the phase of R from $R = +0.12$ to -0.12 gives a much worse fit for the 2_1^+ cross section (solid line denoted by C).

The fault in the fit of the case of the destructive interference [Fig. 1(a)] can be traced to the fact that the RPA is not very good approximation for the Pd isotopes because of a large cancellation between the forward and backward scattering amplitudes of the RPA wave functions of the 2_1^+ states of the Pd isotopes.[10] The reason why the 2_1^+ cross section of the direct process [dashed line in Fig. 1(a)] is very small is the smallness of the form factor $F_2(O_g^+ \to 2_1^+)$ due to this cancellation. This cancellation causes a phase transition of the interference from the constructive type to the destructive type [a change of the sign of the $F_2(O_g^+ \to 2_1^+)$ or the ratio R] at the neutron number a little bit heavier nuclei than the Pd isotopes.[10] In this situation the form factor $F_2(O_g^+ \to 2_1^+)$ based on the RPA wave functions is quite unstable for the choice of the values of the parameter involved. Therefore the best way to pin down the form factor $F_2(O_g^+ \to 2_1^+)$ is to search $F_2(O_g^+ \to 2_1^+)$ empirically which gives the best fit to the experimental 2_1^+ cross section, by varying the ratio R as a free parameter subject only to keeping R positive (destructive interference). This parametrization is very reasonable because the behavior of the 2_1^+ cross section relative to that of the O_g^+ cross section is well determined by the ratio R calculated at the nuclear surface.

From this point of view the cross sections of the O_g^+ and 2_1^+ transitions in the ^{104,110}Pd(p,t) reactions are calculated and very good fits are obtained as shown in Fig. 1(b). A normalization constant (coupling strength in Ref. 13) $D_0=-530$ MeV fm$^{3/2}$ is used throughout. The ratios R thus determined are $R=+0.41$ and $+0.47$ for ^{104}Pd(p,t) and ^{110}Pd(p,t) reactions, respectively. A dip at $\theta\approx 15°$ together with a rapid increase of the cross section for $\theta<15°$, which is a characteristic feature of the destructive interference for the 2_1^+ cross section, is nicely reproduced by the CC calculations (solid lines). In addition absolute values of the cross sections are well reproduced both for the 2_1^+ and O_g^+ transitions.

The ratios R experimentally determined are larger by a factor of 4 than those determined with the quasiparticle-RPA method. A more refined method for treating spherical vibrational nuclei is necessary.

It is interesting to note at this stage that the observed 2_1^+ angular distributions for nuclei with $50<N\leq 64$ (Pd isotopes) have a strong resemblance to those observed for deformed nuclei ($N>90$) taken as targets. Actually a coupled channel Born approximation (CCBA) curve for the ^{158}Gd(p,t)-^{156}Gd(2_1^+) transition,[9] for example, which has reproduced the experimental 2_1^+ cross section with 52-MeV protons is compared with the 2_1^+ cross sections of the ^{102,106,110}Pd(p,t) reactions after making a kinematical correction for a factor q(momentum transfer)R(nuclear radius); see Fig. 1(c). Again, the characteristic dip together with the rapid increase of the cross section for $\theta<15°$ is reproduced quite well.

The reason why such similar behavior (destructive interference) in the cross sections occurs, in spite of the fact that the two types of nuclei ^{A}Pd and ^{158}Gd have quite different structure, can be traced to the fact that the form factors that appear in both reactions have a strong similarity in the nuclear surface region. More specifically, the ratios $R=F_2(O_g^+\rightarrow 2_1^+)/F_0(O_g^+\rightarrow O_g^+)$ and $R'=F_0(2_1^+\rightarrow 2_1^+)/F_0(O_g^+\rightarrow O_g^+)$ both evaluated at the nuclear surface are quite similar in each other. Indeed we have $R=+0.5$ and $R'=+1.0$ for the deformed nuclei,[9] while $R=+0.45$ and $R'=+0.8$ [10] for the Pd isotopes. These values are indeed of similar magnitude and, more significantly, have the *same sign*.

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