Hadronic excitation of the second 0^+ state in ^{90}Zr

J. P. Delaroche,* Y. Wang, and J. Rapaport
Department of Physics, Ohio University, Athens, Ohio 45701
(Received 3 July 1986)

Coupled-channel analyses of new (n,n′) and existing (p,p′) as well as (α,α') scattering measurements for the second 0^+ state (1.761 MeV) in ^{90}Zr are described. Macroscopic form factors are assumed for the $E0$ and $E2$ transitions. Multistep $E2$ transitions are found to dominate the direct inelastic excitations. Compound (n,n′) and (p,p′) scattering processes are also found to be important at incident energies up to 16 MeV. A rather good description of shapes and magnitudes of the differential cross sections is achieved.

The hadronic excitation of the $J^\pi=0_2^+$ first excited state in ^{90}Zr at 1.761 MeV has been extensively studied during the past twenty years. So far a complete and satisfactory explanation has not been achieved. Microscopic distorted-wave Born approximation (DWBA) calculations have been performed to fit the (p,p′) differential cross section measured[1] at $E_p=12.7$ MeV by Love and Satchler.[2] They were able to reproduce only the shape below $\theta \lesssim 100°$ with the DWBA predictions an order of magnitude lower than the measurements. More recently, new microscopic DWBA calculations[3] for the $0_1^+\rightarrow 0_2^+$ transition have been performed at $E_p=25$ MeV and compared with high precision measurements.[3] The predicted angular distribution has the right order of magnitude but not the same phasing as the data. Similar DWBA calculations performed at $E_p=40$ MeV were not successful either.[4] Some of the discrepancies were attributed to neglecting core polarization effects.[4] On the other hand, CC calculations in which the first derivative of the optical potential was used as a form factor for the $0_1^+\rightarrow 0_2^+$ transition were unable to describe these measurements.[4]

Love[5] has also studied the role played by multistep processes in the excitation of the 0_2^+ via the first $2^+(2_1^+)$ state. However, the reported CC calculations were not very successful in reproducing the (p,p′), (d,d′), (t,t′), and (α,α') data; large factors were needed to renormalize the calculations to the measurements. Similar conclusions have been reported for the (p,p′) analysis at $E_p=25$ MeV. These studies[3,5] rely heavily upon the assumption that the $2_1^+\rightarrow 0_2^+$ transition is strong. However, this assumption is questionable since it has never been firmly established that this $E2$ transition carries a significant amount of strength.[6,7] On the other hand, the electromagnetic transitions $2_3^+\rightarrow 0_2^+$ and $2_4^+\rightarrow 0_2^+$, observed[6] in (n,n′γ) and (p,p′γ) measurements have never been considered as alternative steps in the multistep excitation of the 0_2^+ state. It is the main purpose of the present study to show that these $E2$ transitions dominate the multiple excitation of the 0_2^+ level in hadronic scattering experiments. Statistical model calculations have also been performed for (n,n′) and (p,p′) scattering to achieve a complete description of the nucleon scattering measurements available below 40 MeV. The (p,p′) and (α,α') scattering measurements under consideration have been performed at $E_p=12.7$ (Ref. 1), 18.8 (Ref. 8), 25.0 (Ref. 3), and 40 MeV (Ref. 4), and at $E_\alpha=65$ MeV (Ref. 9), respectively. The (n,n′) scattering measurements have been performed at $E_n=8$ MeV at Ohio University and will be described elsewhere.[10]

The CC calculations have been conducted using the coupling scheme shown in Fig. 1. The 2_1^+ level ($\beta_2=0.07$), which is not coupled to the 0_2^+ level, has been included for the sake of completeness. Its inclusion in the coupled scheme does not alter at all the calculated angular distributions for the 0_2^+ state. The radial shapes for the $E2$ transitions have been taken as the first derivatives of the optical potential $U(r)$. The prescription (i.e., monopole form factor, version 1) given in Ref. 11 has been adopted for the $E0$ transition potential. All the central terms of the optical potential have been chosen as channel-energy dependent[12] in the CC calculations performed using ECIS79 (Ref. 13) as operated in the external input mode.

Important ingredients for these calculations are the reduced matrix element

$$M_{IJ}^{(\lambda)}=i^\lambda\langle J||M(E\lambda)||I\rangle$$

of the electric multipole operator $M(E\lambda)$, $\lambda=0$ and 2,

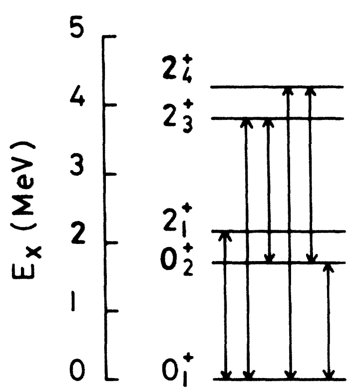

FIG. 1. Coupling scheme for ^{90}Zr used in the present CC calculations.

and their relative phases. The relative phases adopted for the $E2$ transitions are those obtained recently[14] from the diagonalization of the full Bohr's Hamiltonian for ^{90}Zr. The collective masses as well as moments of inertia of this Hamiltonian were determined from constrained Hartree-Fock-Bogoliubov calculations.[15] With these relative phases as adopted for the $E2$ transitions, the $E0$ matrix element $\langle 0_2^+ || M(E0) || 0_1^+ \rangle$ is found to be positive from empirical adjustments. Its value defined here as β_0 is the vibration amplitude for the $0_1^+ \rightarrow 0_2^+$ transition. We have checked that these relative phases lead to optimum fits to the angular distribution measurements. We have also checked that the important relative phases for getting good fits are ψ_3 and ψ_4. These ψ_i are the relative phases between $\langle 2_3^+ || M(E2) || 0_2^+ \rangle$ and $\langle 2_3^+ || M(E2) || 0_1^+ \rangle$, and between $\langle 2_4^+ || M(E2) || 0_2^+ \rangle$ and $\langle 2_4^+ || M(E2) || 0_1^+ \rangle$, respectively. With appropriate values for ψ_3 and ψ_4, β_0 takes on a positive value as mentioned above.

The absolute value of the ratio $R_i = M^{(2)}_{2_i 0_2} (M^{(2)}_{2_i 0_1})^{-1}$ may be extracted from the γ-decay intensities $I_\gamma(2_i^+ \rightarrow 0_2^+)$ and $I_\gamma(2_i^+ \rightarrow 0_1^+)$, $i=3$ and 4, respectively. With our phase convention, the value $R_3 = -3.95$ is inferred from the γ-decay properties of the 2_3^+ level.[6] R_4($R_4 > 0$ in our phase convention) cannot be determined in this manner because experimental values of $I_\gamma(2_4^+ \rightarrow 0_2^+)$ and $I_\gamma(2_4^+ \rightarrow 0_1^+)$ do not exist. Therefore, R_4 has been treated as a parameter and adjusted to optimize the fit to the angular distribution measured at $E_p = 40$ MeV. This value is $R_4 = 5.00$ and has been held constant.

The CC analyses are based on spherical optical potential parameters taken from Refs. 1, 8, 16, and 4 ($E_p = 12.7$, 18.8, 20.0, and 40 MeV, respectively), Ref. 9 ($E_\alpha = 65$ MeV), and Ref. 10 ($E_n = 8$ MeV). The absorptive potentials have been reduced by 10% to compensate for the couplings, and the quadrupole deformation parameters β_i as well as the central real potentials have been tuned to maintain good fits to the elastic and 2_i^+ differential cross sections, $i=1$, 3, and 4, respectively. Coulomb excitation has been included only for $E2$ transitions in (p,p′) and (α,α') scattering calculations. Finally, the channel-energy dependent potentials for nucleon scattering have been determined by following the empirical formula given in Ref. 16. For α-particle scattering, we have used the energy dependences inferred from Fig. 5 of Ref. 17. The effect of these channel-energy dependent potentials is an increase of the 0_2^+ differential cross section predictions by 40% for incident nucleon energies lower than 20 MeV. At higher energies, the effect is negligible for (p,p′) and (α,α') scattering.

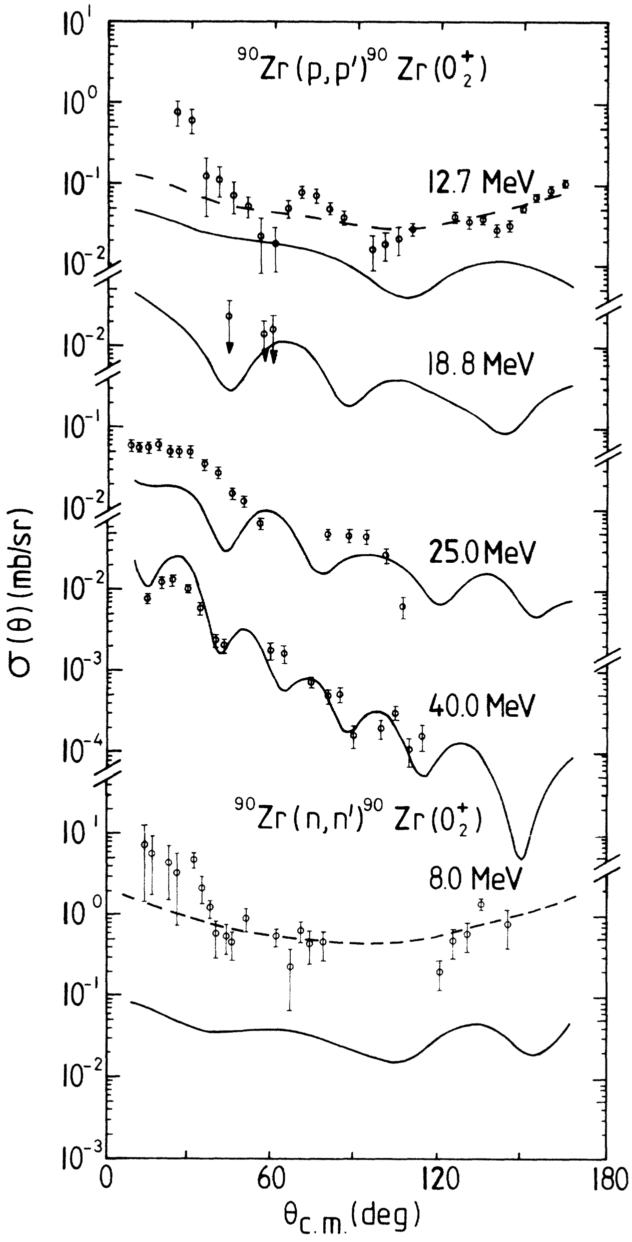

FIG. 2. Present results for the CC analysis for the excitation of the 0_2^+ state in ^{90}Zr with hadronic probes at the indicated energies. The dashed lines at $E_p = 12.7$ MeV and $E_n = 8.0$ MeV represent the sum of compound processes and CC calculations.

The results of the present CC analysis for (p,p′) and (n,n′) scattering are shown as continuous curves in Fig. 2. The value $\beta_0 = 0.004$ used throughout these calculations is about an order of magnitude smaller than the β_2 values adopted for the $2_3^+ \rightarrow 0_1^+ (\beta_2 = 0.058)$ and $2_4^+ \rightarrow 0_1^+ (\beta_2 = 0.043)$ vibration amplitudes. The agreement between the CC calculations and the measurements is rather good at $E_p = 40$ MeV, and is seen worsening as the incident energy decreases. At $E_n = 8$ MeV, for instance, the CC calculations are 10 times lower than the measurements.

Since the angular distributions measured at $E_p = 12.7$ MeV and $E_n = 8$ MeV are roughly symmetric with respect to $\theta = 90°$, we have also performed statistical model calculations using the code HELENE (Ref. 18) to estimate the importance of the compound (p,p′) and (n,n′) processes. These are found to be large at these incident energies, and completely negligible above 16 MeV. This is illustrated in Fig. 2, where the dotted curves represent the sum of direct interaction (DI) and compound processes. These curves compare well with the measurements at $E_p = 12.7$ MeV and $E_n = 8$ MeV.

Although an overall good agreement between the calculations and the nucleon scattering data is achieved over a large energy range, the angular distributions at angles

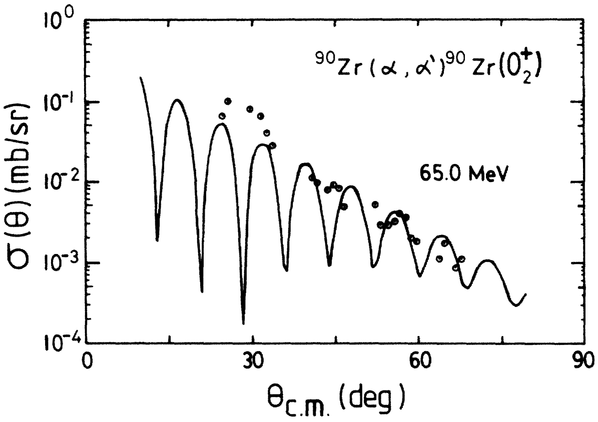

FIG. 3. Present results for the CC analysis for the ^{90}Zr$(\alpha,\alpha')^{90}$Zr(0_2^+) cross section at $E_\alpha=65$ MeV.

$\theta<40°$ are not very well described (see Fig. 2). To trace the origin of this systematic feature, we have performed new CC calculations at $E_p=25$ and 40 MeV with β_0 set to zero and R_4 slightly readjusted from $R_4=5.0$ to $R_4=4.0$. The result (not shown here) is precisely a change in magnitude and shape of the calculated angular distribution in this angular range. The new CC values are lower at $\theta<40°$ and almost unaltered at larger angles when compared with the previous CC results. This sensitivity study shows that the DI predictions for the 0_2^+ angular distribution are dominated by multistep processes. It also indicates that the forward angle region of the differential cross section is influenced by the assumptions made on the radial shape of the $E0$ transition. It is quite possible that the present choice for the $E0$ form factor be questionable, as suggested by Satchler,[11] for low energy monopole transitions. Although $L=0$ Coulomb excitations are expected to be small, it could be that including this transition potential would slightly alter the calculated differential cross section at small angles as well.

The results of our CC calculations for (α,α') scattering are shown in Fig. 3. Like in the nucleon scattering analyses, the potential depths and deformation parameters[9] at $E_\alpha=65$ MeV have been fine tuned to optimize the fits to the measurements[9] for elastic scattering and inelastic scattering to the 2_1^+ and 2_3^+ levels. The deformation $\beta_2=0.017\pm0.002$ for the 2_4^+ level has been obtained from our analysis of the angular distribution shown in Fig. 6 of Ref. 9 for the unresolved multiplet at $E_x=4.35$ MeV. As can be seen on Fig. 3, the CC calculations (solid curve) are in good agreement with the measurements at $\theta\gtrsim40°$. Below $\theta=40°$ the calculations are lower than the data. As for nucleon scattering, the deficiency may be related to the radial shape adopted for the $0_1^+\to0_2^+$ transition form factor. Finally, we have checked from sensitivity calculations (i.e., β_0 has been varied by $\pm50\%$ that multistep processes also dominate the inelastic excitation of the 0_2^+ level in (α,α') scattering ($E_\alpha=65$ MeV).

To summarize, we have shown that multistep $E2$ processes dominate the direct excitation of the 0_2^+ level in ^{90}Zr by nucleons and α particles. This reaction mechanism should be supplemented by compound processes to also achieve a rather good overall description of the existing nucleon scattering measurements below 16 MeV. All the calculated differential cross sections have the right order of magnitude, which is gratifying. However, some deficiencies are observed in our calculations at $\theta\lesssim40°$. These deficiencies might originate, to a large extent from the inadequacy of the radial shape adopted for the $0_1^+\to0_2^+$ transition form factor. More experimental information on this $E0$ transition [for instance, from (e,e') scattering] are desirable to better understand the role of the $0_1^+\to0_2^+$ transition in the hadronic excitation of the 0_2^+ level in ^{90}Zr. Finally, the phase relations between the $E0$ and $E2$ transitions as well as between the $E2$ contributions were found to be critical. More experimental information on these relative phases is also desirable to verify the values obtained in the present CC analyses.

This study was supported in part by grants from the National Science Foundation and from the National Cancer Institute, Department of Health and Human Services.

*Permanent address: Service de Physique et Techniques Nucleaires, Centre d'Etudes de Bruyères-le-Châtel, Bôite Postale No. 12, 91680 Bruyères-le-Châtel, France.

[1]J. K. Dickens *et al.*, Phys. Rev. **168**, 1355 (1968).
[2]W. G. Love and G. R. Satchler, Nucl. Phys. **A159**, 1 (1970), and references therein.
[3]L. T. van der Bijl *et al.*, Nucl. Phys. **A393**, 173 (1983), and references therein.
[4]R. A. Hinrichs *et al.*, Phys. Rev. **7**, 1981 (1973).
[5]W. G. Love, Phys. Lett. **42B**, 13 (1972).
[6]D. C. Kocher, Nucl. Data Sheets **16**, 55 (1975).
[7]S. Raman and N. B. Gove, Phys. Rev. C **7**, 1995 (1973); H. Petterson *et al.*, Nucl. Phys. **A108**, 124 (1968); A. B. Tucker and S. O. Simmons, *ibid.* **A156**, 83 (1970); S. Beshai *et al.*, *ibid.* **A296**, 151 (1978); P. M. Endt, Atomic Data Nucl. Data Tables **23**, 547 (1979); E. K. Warburton *et al.*, Phys. Rev. C **31**, 1184 (1985).
[8]W. S. Gray *et al.*, Phys. Rev **142**, 735 (1966); M. B. Johnson *et al.*, *ibid*, **142**, 748 (1986).
[9]C. R. Bingham *et al.*, Phys. Rev. **148**, 1174 (1966).
[10]Y. Wang and J. Rapaport (unpublished).
[11]G. R. Satchler, Part. Nucl. **5**, 105 (1973).
[12]A. S. Meigooni *et al.*, Nucl. Phys. **A445**, 304 (1985).
[13]J. Raynal, International Atomic Energy Agency Report No. IAEA-SMR-918, 281, 1972 (unpublished).
[14]M. Girod and J. P. Delaroche (unpublished).
[15]M. Girod and B. Gammaticos, Phys. Rev. C **27**, 2317 (1983).
[16]Ch. Lagrange and A. Lejeune, Phys. Rev. C **25**, 2278 (1982).
[17]L. W. Put and A. M. J. Paans, Nucl. Phys. **A291**, 93 (1977).
[18]S. K. Penny, Oak Ridge National Laboratory Report No. ORNL-TM-2590, 1969 (unpublished).