PHYSICAL REVIEW C VOLUME 6, NUMBER 1 JULY 1972

Polarization Effects in the Isospin-Coupled Reaction Channels $p + {}^{91}\mathrm{Zr}$ and $n + {}^{91}\mathrm{Nb}^*_{\mathrm{IAS}}$ †

J. G. Cramer, E. Preikschat, M. P. Baker, M. D. Hasinoff,‡ G. W. Roth, and W. G. Weitkamp
Department of Physics, University of Washington, Seattle, Washington 98195

and

W. J. Braithwaite
Department of Physics, Princeton University, Princeton, New Jersey 08540

and

C. Fred Moore
Center for Nuclear Studies, University of Texas, Austin, Texas 78712
(Received 16 February 1972)

The analyzing-power and differential cross-section excitation functions for the reaction $p + {}^{91}\mathrm{Zr}$ have been measured at 150° in the energy range from 10.0 to 14.9 MeV, which spans the thresholds of the (p,n) quasi-elastic and quasi-inelastic reaction channels leading to the production of the analogs in ${}^{91}\mathrm{Nb}$ of the ${}^{91}\mathrm{Zr}$ target ground state and $\frac{5}{2}^+$ (1.46 MeV) excited state, respectively. A pronounced variation in the analyzing power is observed in the $(\vec{p},d_0)$ exit channel at just the energy regions where charge-exchange coupling is expected to occur due to the opening of the quasi-elastic and quasi-inelastic channels. Somewhat less expected is the change in analyzing power observed in the elastic proton channel in the vicinity of the quasi-elastic and quasi-inelastic thresholds. Sharp resonance structures are observed in the analyzing-power and differential cross-section excitation functions for the $(\vec{p},d_0)$ channel near the quasi-elastic and quasi-inelastic thresholds which are not readily observable in the elastic channel. The analyzing power for the $(\vec{p},n\tilde{p})$ process has been measured at a number of energies in this region and found to be consistent with zero.

The isospin coupling of proton-plus-parent and neutron-plus-isobaric-analog reaction channels was first observed in the excitation function of the reaction ${}^{90}\mathrm{Zr}(d,p_0){}^{91}\mathrm{Zr}(d_{5/2},\ \mathrm{g.s.})$. A pronounced variation in the differential cross section was found near the threshold for the production of the isobaric analog of the final nucleus by the complementary reaction ${}^{90}\mathrm{Zr}(d,n){}^{91}\mathrm{Nb}^*_{\mathrm{IAS}}(d_{5/2},\ 9.94\ \mathrm{MeV})$.[1] This phenomenon has been treated theoretically by a number of workers,[2-7] and such treatments have produced at least qualitative agreement with the observed behavior of the differential cross section. There have also been a number of studies of charge-coupling effects in other nuclei in the mass-90 region, both by (d,p)[8-10] and (p,d) reactions.[11,12] Away from the mass-90 region the isospin-coupling effects are found to be greatly reduced.[10] This has been attributed to the peaking of the p-wave neutron strength function in the mass-90 region, which enhances threshold effects involving neutrons.[3,5,10]

There has also been a measurement of the vector analyzing-power excitation function of the reaction ${}^{90}\mathrm{Zr}(\vec{d},p_0){}^{91}\mathrm{Zr}$ in the vicinity of the $(d,n)_{\mathrm{IAS}}$ threshold which shows strong evidence of isospin-coupling effects.[13] Theoretical efforts to fit this measurement have thus far been unsuccessful.[14] This is not surprising, since direct-reaction theories have not been able to predict reliably the backward-angle analyzing-power measurements in $(\vec{d},p)$ reactions, even in the absence of isospin-coupling effects.[15]

In the present measurements we have used the University of Washington Lamb-shift polarized negative-ion source.[16] The source produced a proton beam with an intensity of 30–45 nA on target and a measured polarization of 70–83%. The polarization of the proton beam was continuously monitored by a ${}^4\mathrm{He}$ polarimeter located behind the primary target of ${}^{91}\mathrm{Zr}$. The target was 92% isotopically enriched and rolled to a thickness of about 900 $\mu\mathrm{g/cm^2}$. The energy loss of the beam in passing through the target was 15–20 keV. This is significantly larger than the estimated beam-energy spread of 2–3 keV.

The polarized proton beam was used to study in detail the reaction ${}^{91}\mathrm{Zr}(p,d_0){}^{90}\mathrm{Zr}$. We have also investigated the elastic proton scattering and the emission of $\tilde{p}$ protons, i.e., protons emitted following the production of the analog of the target by the (p, n) reaction. For all of these processes the analyzing power was measured as a function of energy at a laboratory angle of 150° and for an energy range from 10.0 to 14.9 MeV. This range spans both the (p, n) threshold for production of the analog of the target ground state ($E_{th} = 12.02$ MeV) and that for production of the analog of the $\frac{5}{2}^+$ (1.46 MeV) excited state of the target ($E_{th} = 13.53$ MeV).

The behavior of the analyzing power for the $(\vec{p}, d_0)$ process is very similar to that previously measured for the inverse $(\vec{d}, p_0)$ process[13] (see Fig. 1). In particular, the analyzing-power excitation function has a similar structure occurring at the corresponding place in the excitation function and with the same structural width as that observed in the $(\vec{d}, p)$ measurement. The observed variation in the cross section is also consistent in both cases. Figure 2 shows the measured differential cross section and analyzing-power excitation functions for the various outgoing channels. The quasi-elastic and quasi-inelastic (p, n) thresholds are indicated by arrows, and the striking behavior of the excitation functions in the vicinity of these thresholds is evident.

Shortly after the original $^{90}Zr(d, p_0)$ measurements revealed the presence of charge-exchange effects,[1] several attempts were made to find a similar effect in the elastic proton channel, i.e., $^{91}Zr(p, p_0)$, near the quasi-elastic (p, n) threshold.[17] No effect was observed, however, in the excitation function of the differential cross section. Moreover, a theoretical explanation has been given of the absence of such an effect in the elastic channel.[5] It is therefore of particular interest that the present measurement shows a definite change in analyzing power in the vicinity of the quasi-elastic

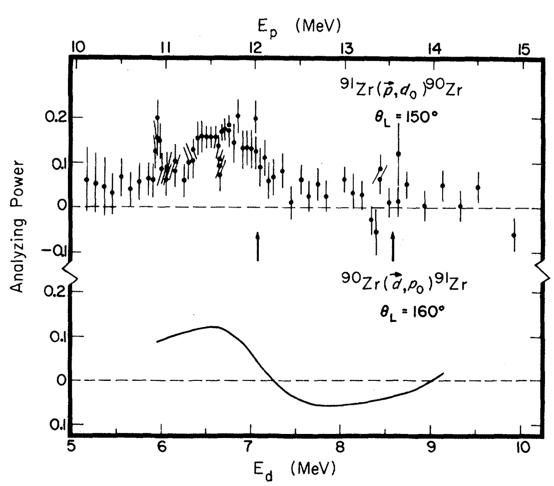

FIG. 1. Comparison of the $^{91}Zr(\vec{p}, d_0)$ and the $^{90}Zr(\vec{d}, p_0)$ analyzing-power excitation functions (see Ref. 13).

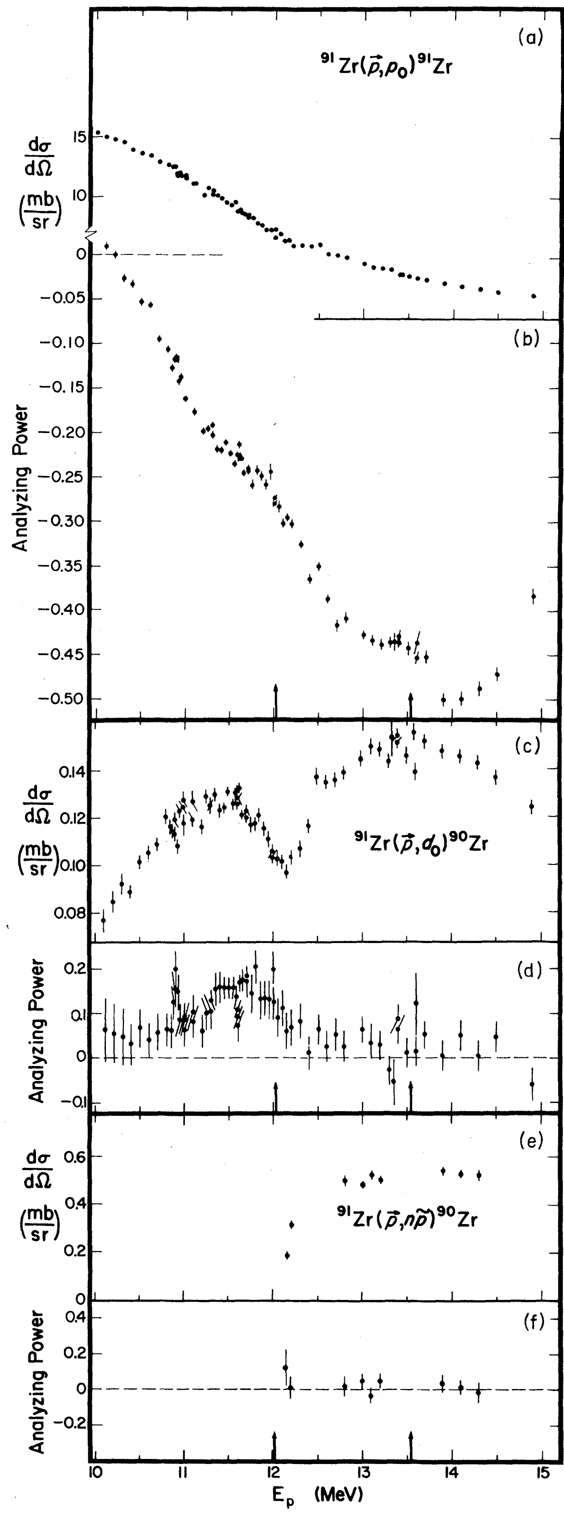

FIG. 2. Excitation functions from $\vec{p} + {}^{91}Zr$ at 150°: (a) $(\vec{p}, p_0)$ elastic differential cross section; (b) $(\vec{p}, p_0)$ elastic analyzing power; (c) $(\vec{p}, d_0)$ differential cross section; (d) $(\vec{p}, d_0)$ analyzing power; (e) $(\vec{p}, n\tilde{p})$ differential cross section; (f) $(\vec{p}, n\tilde{p})$ analyzing power.

threshold, as shown in Fig. 2(b). This is similar to effects observed in the ^{96}Zr$(\vec{p}, p)$ measurement of Wienhard and Graw.[18] These results are of some importance, since the elastic channel is more tractable to theoretical analysis than the (p, d_0) channel and such data should provide a more direct test of present theories.

Another striking phenomenon seen in these data in Figs. 2(b)–2(d) is the behavior of the (p, d_0) cross section and the $(\vec{p}, p_0)$ and $(\vec{p}, d_0)$ analyzing-power excitation functions in the vicinity of the quasi-inelastic (p, n) threshold at $E_p = 13.53$ MeV. This is the threshold for populating the analog state, whose configuration has been described[19] as a $d_{5/2}$ nucleon coupled to the 0^+ first excited core state in ^{90}Zr. The effect observed here at the quasi-inelastic threshold has about the same shape as that observed at the quasi-elastic threshold and roughly $\frac{3}{7}$ its amplitude. The wave functions for the ^{90}Zr ground state and 0^+ excited state are believed to be 70 to 30% and 30 to 70% of $(p_{1/2})^2$ to $(g_{9/2})^2$, respectively. One should notice that the observed amplitudes of the cross-section and analyzing-power variations are in this same proportion.

Sharp structures in the excitation functions of both the cross section and analyzing power of the ^{91}Zr$(\vec{p}, d_0)$ reaction are also observed at energies of 10.9 and 11.6 MeV, and also in the vicinity of 13.5 MeV as seen in Figs. 2(c) and 2(d). These resonance structures have been observed before in studies of charge-exchange-coupling phenomena but have not been satisfactorily explained.[8,9] They have been attributed to either analog[8] or normal[12] resonances in the compound nucleus, and have been compared[8] with the "double-dip" anomalies observed near mass 98 [11] which Lane[6] has suggested to be a charge-exchange-coupling interference phenomenon. It is interesting, however, that the resonance structures observed in the (p, d) channel appear near the quasi-elastic and quasi-inelastic thresholds and are not readily observable in the elastic channel. This gives credence to the idea that they are not normal resonances, but are enhanced by the charge-exchange process and perhaps are related to the large p-wave neutron strength[3,5] in the mass-90 region.

The differential cross-section and analyzing-power data obtained for the $(p, n\tilde{p})$ process are shown in Figs. 2(e)–2(f). For incident energies of 12.3 to 12.7 MeV and 13.3 to 13.7 MeV the $\tilde{p}$ peaks in the proton energy spectra were obscured by inelastic scattering peaks from the ^{16}O contaminant in the target. At those energies where the number of $\tilde{p}$ events could be determined unambiguously, the measured analyzing power is consistent with zero. This result is not surprising, since the simplest form of the average interaction affecting charge exchange does not involve any coupling to the angular-momentum coordinates of the target nucleus. Thus, the excited analog state has the same equal population of magnetic substates as the target-nucleus ground state, and the $\tilde{p}$ differential cross section is expected to be isotropic.

The measurement of polarization effects associated with the charge-exchange-coupling phenomenon in the mass-90 region provides additional information about the processes involved and should serve as a more stringent test of the validity of previous theoretical treatments.

---

†Work supported in part by U. S. Atomic Energy Commission.

‡Present address: University of British Columbia, Vancouver, B. C., Canada.

[1]C. F. Moore, C. E. Watson, S. A. A. Zaidi, J. J. Kent, and J. G. Kulleck, Phys. Rev. Letters 17, 926 (1966).

[2]S. A. A. Zaidi and P. von Brentano, Phys. Letters 23, 466 (1966).

[3]T. Tamura and C. E. Watson, Phys. Letters 25B, 186 (1967).

[4]J. Zimányi and B. Gyarmati, Phys. Letters 27B, 120 (1968).

[5]R. Coker and T. Tamura, Phys. Rev. 182, 1277 (1969); see also H. Bledsoe, R. Coker, and T. Tamura, to be published.

[6]A. M. Lane, Phys. Letters 33B, 274 (1970).

[7]J. Zimányi and J. P. Bondorf, Nucl. Phys. A146, 81 (1970).

Rev. C 2, 1384 (1970).

[9]C. F. Moore, Phys. Letters 25B, 408 (1967); R. Heffner, C. Ling, N. Cue, and P. Richard, Phys. Letters 26B, 150 (1968).

[10]W. R. Coker and C. F. Moore, Phys. Letters 25B, 271 (1967).

[11]R. A. Hinrichs, G. W. Phillips, J. G. Cramer, and H. Wieman, Phys. Rev. Letters 22, 301 (1969); Phys. Rev. C 4, 1366 (1971).

[12]L. S. Michelman, T. I. Bonner, and J. G. Kulleck, Phys. Letters 28B, 659 (1969).

[13]G. Clausnitzer, G. Graw, C. F. Moore, and K. Wienhard, Phys. Rev. Letters 22, 793 (1969).

[14]T. Tamura, private communication.

[15]W. Haeberli, in *Polarization Phenomena in Nuclear Reactions*, edited by H. H. Barschall and W. Haeberli (University of Wisconsin Press, Madison, 1971), p. 235.

[16]E. Preikschat, G. Michel, G. W. Roth, J. G. Cramer, Jr., and W. G. Weitkamp, in *Polarization Phenomena in*

Nuclear Reactions (see Ref. 15), p. 832.
[17]J. A. Nolen, Jr., G. C. Morrison, J. P. Schiffer, and N. Williams, Bull. Am. Phys. Soc. 12, 526 (1967); J. P. Bondorf, C. Ellegaard, J. Kantele, H. Lütken, and P. Vedelsby, Nucl. Phys. A101, 338 (1967).
[18]K. Wienhard and G. Graw, in *Polarization Phenomena in Nuclear Reactions* (see Ref. 15), p. 655.
[19]C. F. Moore, S. A. A. Zaidi, and J. J. Kent, Phys. Rev. Letters 18, 345 (1967).