Analog (p,n) cross sections of the zirconium isotopes at 18 and 25 MeV

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The differential cross sections for the (p,n) reaction to the ground-state analogs of the lightest four stable zirconium isotopes (90, 91, 92, and 94) have been measured at proton energies of 18 and 25 MeV. Integrated cross sections are found to deviate from the expected linear dependence on neutron excess as was previously found for the molybdenum isotopes. The observed dependence is in quantitative agreement with calculations, including inelastic couplings used to explain the molybdenum results. The energy dependence of the zirconium analog cross sections confirms the resonant-type enhancement of the low energy (p,n) excitation function observed previously for the molybdenum isotopes.

I. INTRODUCTION

In a study[1,2] of the (p,n) reaction on the isotopes of molybdenum, the analog cross section departed considerably from the Lane-model[3] prediction of near proportionality to $(N\text{-}Z)$. Coupled-channel calculations[4] indicated that the $(N\text{-}Z)$ effect can be explained by couplings to the low-lying collective states and their analogs. These calculations confirmed that the excitation of analogs of strong collective states proceed primarily by two two-step mechanisms, the one-step process being negligibly small.[4] For the O^+ ground-state analog transition the dominant one-step amplitude is reduced by the destructive addition of the three-step amplitudes that are nearly in phase with each other. Therefore, when the 2^+ states are coupled, for example, the cross section for the O^+ analog state decreases by an amount that is roughly proportional to the inelastic (p,p') 2^+ cross sections. The zirconium isotopes extend the molybdenum measurements to lower deformation parameters (β) in the same mass region.

In addition, the (p,n) analog cross-section measurements at 18 and 25 MeV allowed confirmation of the previously observed anomalous energy dependence of the analog excitation function.[1,2,5,6]

II. EXPERIMENTAL RESULTS

The experimental method used here has been described previously.[7] The experiment was performed with the 25.0±0.1 and 18.0±0.1 MeV proton beams of the Lawrence Livermore National Laboratory cyclograaff accelerator.[8] The energy spread represents an average of the energy losses in the various targets. The 24.93 MHz repetition rate of the AVF cyclotron was scaled down with two external sweepers by a factor of 10 to allow for neutron time-of-flight (TOF) spectroscopy with 10.75 m flight paths in the neutron energy range under consideration ($E_n > 3.5$ MeV for $E_p = 18$ MeV and $E_n > 5.4$ MeV for $E_p = 25$ MeV) without ambiguities due to overlapping bursts.

Neutron TOF spectroscopy was performed simultaneously at 16 angles between 3.5° and 159°. The detectors consist of 11.4-cm diameter by 5.1-cm length NE213 scintillators behind water collimators of 2-m length and are surrounded by a shield of earth and concrete. Pulse-shape discrimination was used to reduce background from pulses produced by gamma rays. A typical time-of-flight spectrum is shown in Fig. 1. Further experimental details are given elsewhere.[9]

Isotopically separated targets were supplied by the Isotopes Division of Oak Ridge National Laboratory. The targets were self-supporting metallic foils of 2.38-cm diameter and nominal thicknesses ranging from 5.3 to 6.2 mg/cm^2. The effective thickness in the region of the beam spot of about 6-mm diameter was measured from the energy loss of ^{241}Am α particles ($E_\alpha = 5.48$ MeV). The isotopic abundance of the predominant isotope in the even zirconium targets was greater than 95%. For the odd mass target it was only 88.5%. Since the principal contaminant was ^{90}Zr and the ^{90}Zr and ^{91}Zr cross sections were essentially equal, no correction was applied to the data to correct for isotopic impurities.

Peaks in the time-of-flight spectra corresponding to excitation of the isobaric analog state are superimposed on a neutron continuum. In order to determine the counts in the peak the continuum was fitted by a straight line and the peak was assumed to have a Gaussian shape. Errors quoted include the combined statistical error of the signal and background measurements and an error estimated in extracting the peak from the continuum.

Differential cross sections were calculated from the counts in the peaks using the previously determined detector efficiencies[10] and the known target thicknesses. Figures 2 and 3 show the differential cross sections in the center-of-mass system for each isotope at the two bom-

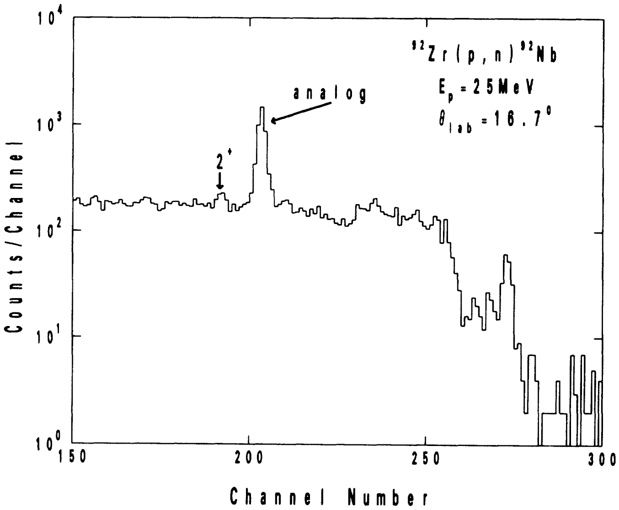

FIG. 1. Time-of-flight spectrum for $^{92}Zr(p,n)$ at $E_p = 25$ MeV and $\theta_{lab} = 16.7°$ with increasing flight time towards the left. The time calibration was 0.75 ns/channel. The positions of the ground-state analog ($E_n = 12.8$ MeV) and 2^+ state analog ($E_n = 11.9$ MeV) are indicated by arrows.

barding energies. The error bars include statistical contributions and an estimated peak fitting error, and the minimum error was taken to be 7% in order to account for the uncertainty in the absolute detector efficiency.

Each of the angular distributions was fitted with a series of Legendre polynomials in order to determine the

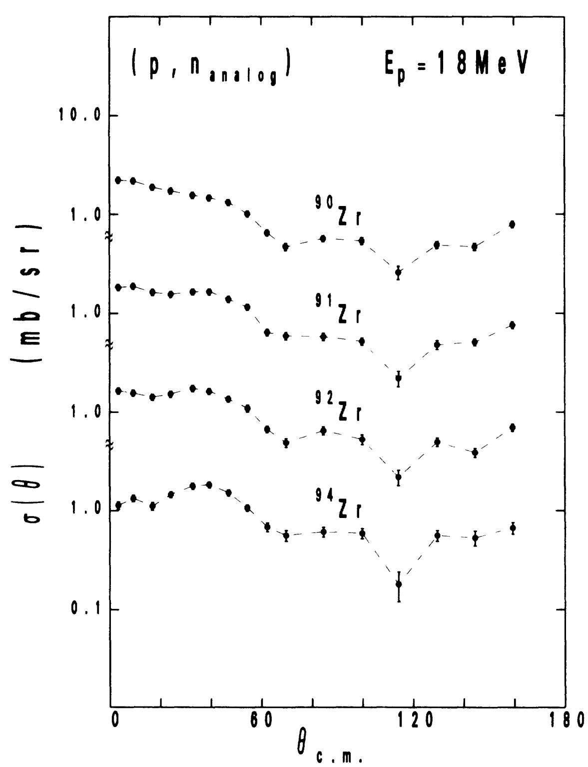

FIG. 2. Angular distributions for the (p,n) reaction to the ground-state analog at 18 MeV for the zirconium isotopes. The absolute cross section is shown.

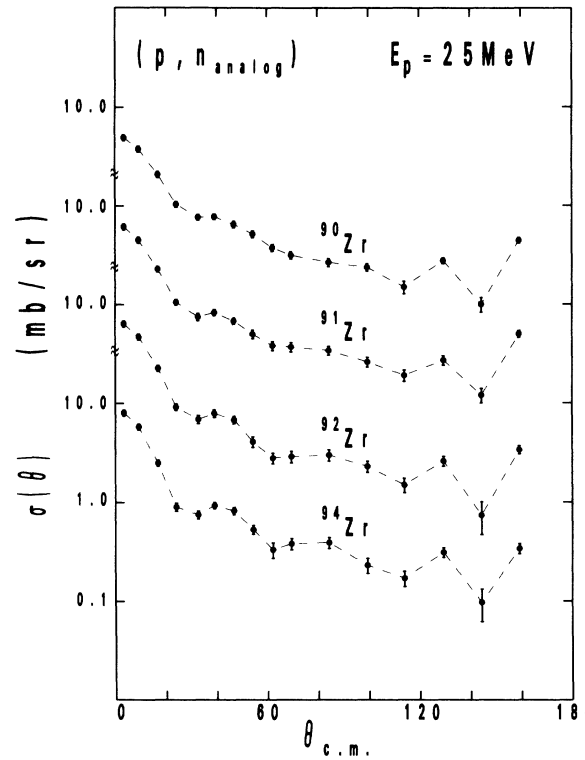

FIG. 3. Same as in Fig. 1 for a bombarding energy of 25 MeV.

integrated cross section. Errors in the integrated cross sections were determined from both the relative errors in the individual data points and from the goodness of fit of the polynomial series to the data. The results are presented in Table I. Figure 4 shows the results for ^{91}Zr as well as other data obtained by detecting the proton decay ($\tilde{p}$) of the analog state. The lower energy data are from Miller and Garvey[11] while the higher energy data are from Hoffmann *et al.*[5] Our data clearly confirm the energy dependence reported by the University of California at Los Angeles (UCLA) group[5] and is quantitatively similar to the previously published molybdenum data.[2]

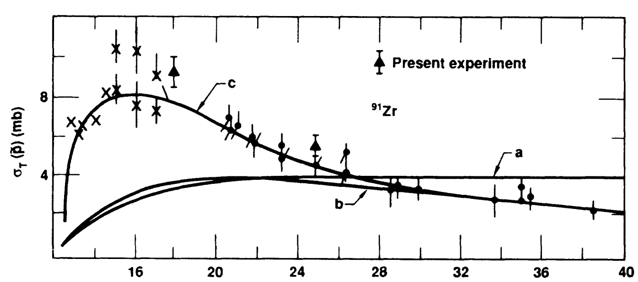

FIG. 4. Integrated cross section for the ^{91}Zr (p,n) ground-state analog reaction as a function of proton bombarding energy. The calculated curves are taken from Ref. 5. Curve (*a*) is a DWBA calculation with a constant isovector potential ($V_1 = 96$ MeV, $W_1 = 48$ MeV). For curve (*b*) the isovector potential is linearly decreasing with bombarding energy ($V_1 = 120 - E_p$, W_1, $= 60 - 0.75E_p$). Curve (*c*) represents a fit to the previously measured data.

TABLE I. Integrated Zr(p,n) ground-state cross sections in mb at 18 and 25 MeV.

Isotope	(N-Z)	$\sigma(18)$	$\sigma(25)$	$\sigma(18)/(N\text{-}Z)^a$	$\sigma(25)/(N\text{-}Z)$
90	10	9.2±0.5	5.5±0.3	0.57±0.03	0.55±0.03
91	11	9.3±0.5	5.8±0.3	(0.53)	(0.53)
92	12	8.9±0.5	5.5±0.3	0.46±0.03	0.46±0.03
94	14	9.4±0.5	6.1±0.3	0.42±0.03	0.44±0.03

[a]Normalized to the 25-MeV average cross sections ($f=0.62$).

III. DISCUSSION

Figure 5 shows the reduced O^+ analog cross section ($\sigma/N\text{-}Z$) for the three even isotopes of zirconium plotted as a function of the square of the deformation parameter β_2. Also shown are three molybdenum isotopes and the coupled-channel results[4] which fit them. In order to make this comparison we have normalized the 18-MeV Zr data to the 25-MeV Zr cross section. No normalization was required for the Mo data because the 16-MeV data were below the resonancelike structure in the excitation function such that the 16- and 26-MeV cross sections were roughly equal. It was argued in Ref. 4 that although the absolute cross sections could not be reproduced over the resonance, the effect of the collective transitions should be quantitatively the same, hence it is reasonable to normalize the ratios shown in Fig. 5.

For ^{90}Zr the deformation parameters are fairly well studied, and the systematic results among deformation parameters determined from different probes are completely consistent with predictions from a core-polarization model.[12] The $\beta_{pp'}$ used in Fig. 5 for ^{90}Zr is taken from the careful study of Ref. 13. Existing empirically determined deformation parameters for the Zr isotopes are consistent with ^{92}Zr and ^{94}Zr being rather similar and more collective than ^{90}Zr, but the precise values of these parameters are rather uncertain. For example, there is a wide variation[14] in β_{em} for these isotopes. The values (0.12) used in Fig. 5 are taken from the analysis with complex potential 1 of the only available (p,p') data[15] done on both isotopes. Recent work[16] on ^{92}Zr at 103.5 MeV yields a smaller $\beta_{pp'}$ than that of Ref. 15, which is in the direction expected from core-polarization results. However, since ^{94}Zr was not examined, we have used the earlier results from Ref. 15. A more precise determination of the deformation parameters in ^{92}Zr and ^{94}Zr is needed for a detailed comparison with coupled-channels calculations but is not required for our general conclusions in this paper. Since the Mo and Zr isotopes are in the same mass region we would expect semiquantitative agreement which we do indeed observe.

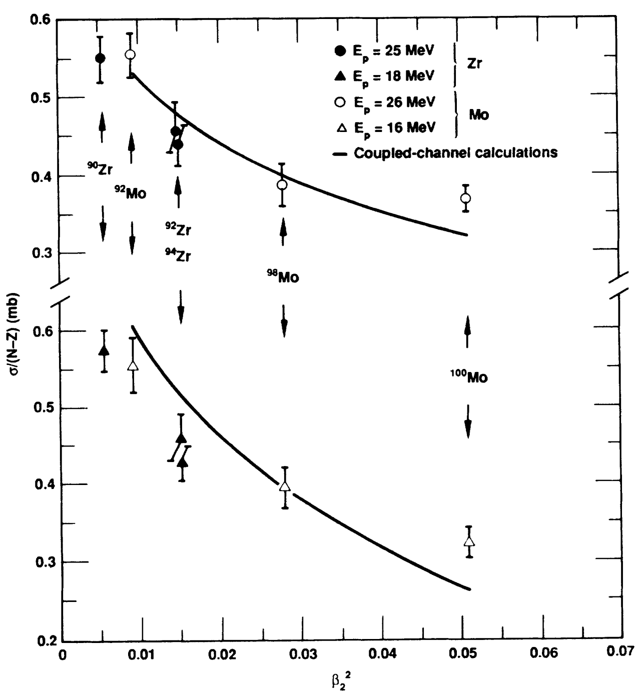

FIG. 5. Total reduced cross section $\sigma/(N\text{-}Z)$ as a function of β_2^2, showing the effect of a variation in the deformation parameter β_2 on the O^+ analog cross section. The molybdenum data and calculations are from Madsen *et al.* (Ref. 4). The 18-MeV data have been normalized to the 25-MeV cross section average.

The current data support the "resonancelike" behavior previously observed for the molybdenum isotopes[2] and for zirconium 91.[5] These two data sets are consistent in requiring a 50% increase in the isospin potential as the bombarding energy decreases from 25 MeV to 16–18 MeV. The direct (p,n) measurements on molybdenum decrease at 16 MeV, whereas the $(\tilde{p})$ measurements on zirconium 91 continue to rise. This apparent discrepancy could arise through the presence of $(\tilde{p})$ decays from excited states which, in the extreme weak-coupling model, would have the same $(\tilde{p})$ energies as the ground-state decays.[17] That this indeed could be the case was demonstrated by Fitzgerald *et al.*,[18,19] where the $(p,n\tilde{p})$ measurements gave the same energy dependence for the ^{119}Sn analog state as the direct (p,n) measurements and one could also see the excited state analogs in the coincidence measurements. At lower energies one might then expect the $(\tilde{p})$ measurements to diverge from the direct (p,n) measurements with the $(\tilde{p})$ measurements being the larger.

All attempts to explain the observed resonancelike behavior have been relatively unsuccessful. Discussions of several possible mechanisms including single particle resonances and giant couplings to collective giant resonances are discussed in Ref. 1. We propose an additional mechanism which may play an important role. It has recently been pointed out that there is a strongly energy-dependent contribution to the real optical potential due to the energy dependence of the imaginary optical potential.[20] This strong energy dependent part of the real potential has been calculated for neutron potentials for several nuclei.[21–24] It follows from the presence of an imaginary component of the isospin potential that there should be an analogous rapidly varying isospin potential.

Because many of the features of the (p,n) cross section used to infer the imaginary part of the isospin potential can be equally well explained by a surface peaking of the real potentials, and self-consistent Hartree-Fock calculations indicate a surface peaking for the zirconium isotopes,[25] we currently do not have good self-consistent estimates of the imaginary isospin potential. One can however estimate that this analog of the Fermi surface anomaly should be the order of a MeV. This would be roughly a 20% increase in V_1 compared to the 50% we need.

IV. SUMMARY

The surprisingly large variation ($>50\%$) of the reduced O^+ analog cross section $\sigma/(N-Z)$ in the (p,n) reaction in the even molybdenum isotopes was well accounted for by the coupling to the strong inelastic states and their analogs.[4] The zirconium data also confirm the steeper β dependence of the reduced cross section at the lower bombarding energy. Although it is quite clearly predicted by calculations it is noteworthy that variations in β_2 from 0.10 to 0.12 do indeed alter the reduced cross sections by $\sim 30\%$.

The absolute ^{91}Zr (p,n) analog cross sections are in excellent agreement with the UCLA measurements[5] of the $(\bar{p})$ decay cross section. These measurements together with previous measurements on the molybdenum isotopes indicate a resonancelike energy dependence of the (p,n) cross section a few MeV above the (p,n) threshold. No satisfactory explanation for this behavior exists although it is clear that several possible mechanisms may play an important role. The most likely contributors are the analog of the Fermi surface anomaly, the presence of single-particle resonances and the coupling to giant resonances. We are currently attempting to quantify the potential contribution of each of these mechanisms.

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