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Systematics of $L=0$ Transitions Observed in the (p, t) Reaction of Nuclei near $N=50$*

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(Received 29 June 1972)

We present excitation energies and transition intensities observed for 0^+ states populated by the (p,t) reaction on nuclei near $N=50$. Comparison of results on selected isotopes of Sr, Zr, Mo, and Ru shows an unexpected loss of neutron $L=0$ transfer strength with increasing proton number.

Excited 0^+ states in even-even nuclei are generally difficult to observe experimentally. Recently, with the advent of high-resolution (p, t) and (t,p) reaction studies, much more data on such states has become available. Only limited information is available, however, on nuclei in any particular mass region. We report here the first systematic study of the behavior of excited 0^+ levels in nuclei in the region of the major shell closure at $N=50$. The data have been selected from a series of (p, t) reaction studies on the strontium, molybdenum, and ruthenium isotopes, all performed at a proton energy of 31 MeV. In addition, previous work on the zirconium isotopes has been repeated at this energy to facilitate comparison. For this report we will consider only the $L=0$ transitions observed in the (p, t) reactions leading to or from nuclei with $N=50$.

Two classes of excited 0^+ levels are expected among the low-lying excited states of the $N=50$ nuclei. The first class arises from simple recouplings of the valence protons. It has been shown that ^{88}Sr can be regarded as a reasonably inert core for the low-lying levels of nuclei in the mass 90 region. The ground states of the heavier $N=50$ isotopes will, in such a model, contain protons distributed in the $2p_{1/2}$ and $g_{9/2}$ orbitals and be of the form

$$\alpha(\pi p_{1/2})_0^{\,2}(\pi g_{9/2})_0^{\,n-2}+\beta(\pi g_{9/2})_0^{\,n}.$$

The orthogonal configuration will result in a low-lying 0^+ excited state. If this linear combination is unchanged by addition of neutrons to the $N=50$ core, such 0^+ states cannot be populated by the (p, t) reaction. However, if slight configuration changes due to the added neutrons occur, such 0^+ states will be populated weakly by the (p, t) reaction. A second class of 0^+ states consists of the so-called pairing vibrations. They are states consisting of pairs of particles excited from the core into the valence shell. They occur at somewhat higher excitation energies and are generally of considerable strength. They are excited in the (p, t) reaction by removal of a neutron pair from the closed core.

All of the reactions reported here were studied with 31-MeV protons from the Oak Ridge isochronous cyclotron. For most targets, energy spectra were taken at 5-deg intervals over an angular range from 5 to 45 deg. The tritons were detected with nuclear emulsions in the broad-range spectrograph facility with an overall experimental resolution of about 20 keV. Energy spectra and angular distributions published previously[1] for ^{90}Zr are typical of the data obtained. Relative uncertainties in the measured cross sections are estimated to be less than ±5% for the stronger states.

The $L=0$ transitions observed in the reactions ^{90}Zr(p, t) and ^{92}Zr(p, t) are summarized in Fig. 1. The intensities indicated for each transition are obtained by matching the angular distributions in the region of the maximum near 40 deg. These

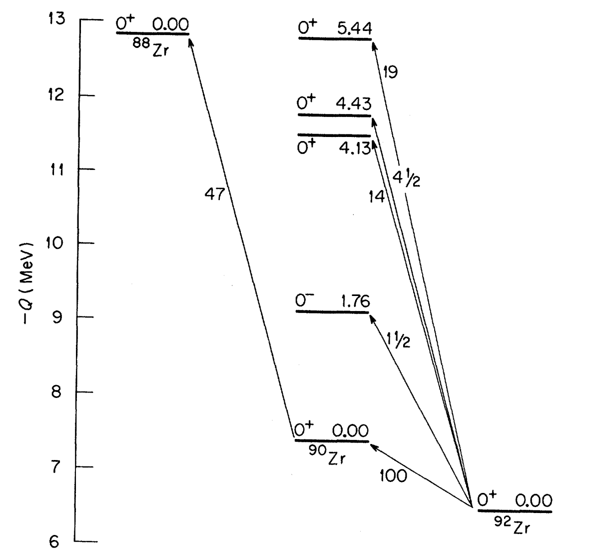

FIG. 1. Relative intensities for 0^+ states populated by (p,t) reactions on ^{90,92}Zr targets.

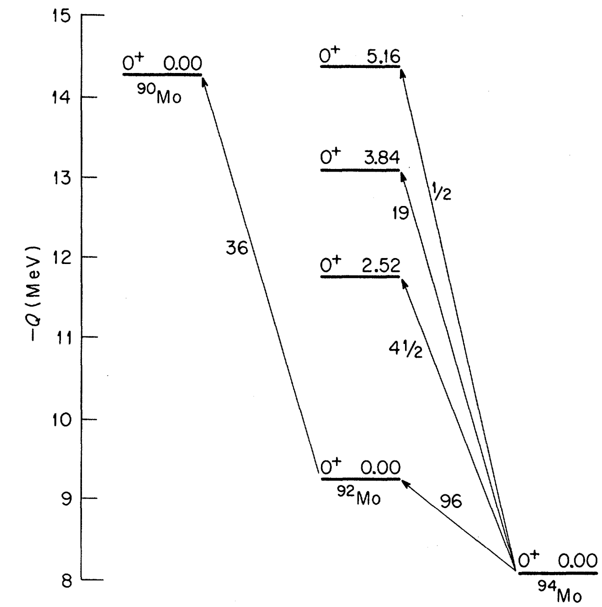

FIG. 2. Relative intensities for 0^+ states populated by (p,t) reactions on ^{92,94}Mo targets.

numbers thus reflect only the relative cross sections measured and are uncorrected for effects of reaction dynamics and configuration changes. Only the ground-state transition is shown for the reaction ^{90}Zr(p, t),[1] since this represents the bulk of the $L = 0$ transition strength for pickup from the $N = 50$ core. In the case of the reaction ^{92}Zr(p, t), examination of the spectra up to 8.5 MeV of excitation in ^{90}Zr revealed no 0^+ states above 5.44 MeV with detectable intensity ($< 2\%$ of the ground state).

The level at 1.76 MeV in ^{90}Zr is generally attributed to the proton excitation discussed above.[2,3] This type of state has been observed with the (p, t) reaction on all of the zirconium isotopes and the observed strengths shown to be consistent with such an interpretation.[4]

The transition strength to the three higher levels is attributed to removal of neutron pairs from the $N = 50$ core. These levels thus represent the "pairing-vibration" strength observed in this nucleus. There are several interesting points to note about these levels: (1) The total intensity sums to only about $\frac{2}{3}$ of that for the ^{90}Zr(p, t) ground-state transition. (2) Although the most intense level is found at the same reaction Q value as the ^{90}Zr(p, t) ground-state transition, the center of gravity of the transition strength is of less negative Q value with appreciable intensity to the 4.13-MeV level. (3) There is a distinct separation between the low-lying "valence" 0^+ levels and the levels carrying the pairing-vibration strength.

Similar zirconium data obtained at a proton energy of 38 MeV have been discussed previously.[5] The principal result was to show that, for these nuclei, major deviations are found from the predictions of the simple harmonic form of the pairing-vibration model.[6] Recently, Sørensen has shown that by including the effects of particle-hole correlations the observed energy shifts, loss of intensity, and fractionation of pairing strength in ^{90}Zr can be accounted for within the framework of the pairing-vibrational model.[7]

The $L = 0$ transitions observed in the reactions ^{92}Mo(p, t) and ^{94}Mo(p, t) are summarized in Fig. 2. Part of the motivation for this work was to locate the level corresponding to the excited 0^+ expected from the proton configuration. The level observed at 2.52 MeV is proposed for such a description since it agrees well with the excitation energy predicted by simple shell-model calculations for the $N = 50$ nuclei.[8,9] This level has also been observed in (p, t) studies at higher energies reported recently.[10,11]

The pattern of the pairing vibration strength in ^{92}Mo is changed significantly from ^{90}Zr. Although there is a 0^+ level observed near the energy expected for the pairing vibration (in the harmonic form of the model), it carries almost none of the expected strength. Instead, the major transition intensity is observed to a level over 1 MeV less

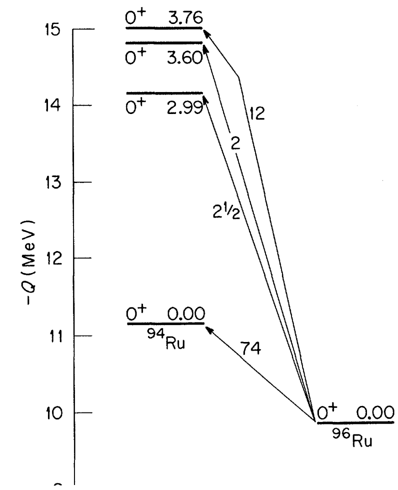

FIG. 3. Relative intensities for 0^+ states populated by the (p,t) reaction on ^{96}Ru.

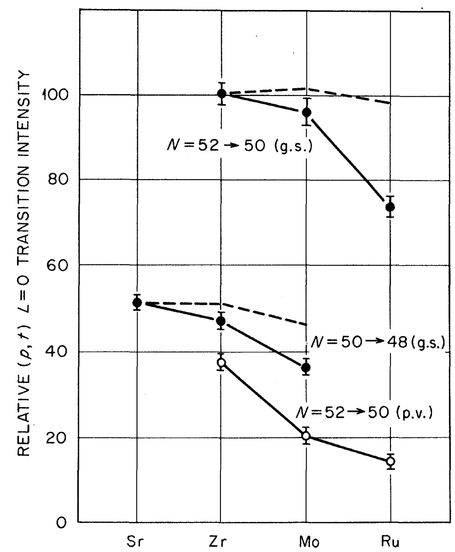

FIG. 4. Relative $L=0$ transition intensities observed for nuclei near $N=50$. The "pairing-vibration" points are summed intensities over all excited 0^+ levels except the state attributed to proton recoupling. The dashed lines indicate the intensity changes expected on the basis of two-nucleon–transfer distorted-wave Born-approximation calculations.

bound. In addition, the observed 0^+ levels are rather evenly spaced, with the excited proton state being somewhat closer to the pairing vibration than to the ground state. The pattern ob served here closely resembles that observed previously for the neodymium isotopes at $N=82$.[12]

The $L=0$ transitions observed in the reaction ^{96}Ru(p,t) are shown in Fig. 3. In this case the (p,t) reaction on $N=50$ cannot be studied since ^{94}Ru is not stable. Of the levels observed in ^{94}Ru, the best candidate for the excited proton 0^+ appears to be the level at 2.99 MeV.

Since the mass of ^{92}Ru is unknown, we cannot determine the energy shift of the pairing vibration strength. We do observe, however, that the excited 0^+ levels have now become rather tightly grouped.

The intensities shown in Figs. 1–3 have all been normalized to the ^{92}Zr(p,t) ground-state transition. These results are summarized and compared in Fig. 4. Also included in this figure is the result for the ^{88}Sr(p,t) ground-state transition.

The most striking feature of these results is the rapid decrease of $L=0$ transition intensity with increasing proton number. We have chosen to quote observed intensity ratios in this Letter since these are related directly to our experimental measurements and not affected by any uncertainties in distorted-wave Born-approximation analysis. We have also performed two-neutron–transfer distorted-wave Born-approximation calculations for these reactions, and the predicted intensity behavior for these transitions is included in Fig. 4. As seen from the figure, the observed trends cannot be accounted for by the reaction dynamics and therefore suggest changes in the neutron structure as protons are added.

The drop in ground-state transition intensity for the $N=52$ nuclei probably indicates a significantly increased population of the $1g_{7/2}$ orbital by the "extra-core" neutron pair. This orbital contributes so little to the (p,t) intensity, compared with the $2d_{5/2}$ and $3s_{1/2}$ orbitals, that such a decrease can be easily reproduced. The required increased binding of the neutron $1g_{7/2}$ orbital is not particularly surprising since the protons are filling the $1g_{9/2}$ orbital.

The drop in intensity for the pickup from the closed core is more difficult to understand. The implied loss of coherence in these wave functions would require the transfer strength to appear in other levels. In view of the loss of strength in the $N=52$ ground-state cross sections, it seems unlikely that much of the core pickup strength for these nuclei has been transferred into the ground-state transitions. The other possibility is that additional strong $L=0$ transitions will appear at much higher excitation energies. To date, no evidence of this has been found. For example, in the reaction ^{92}Mo(p,t) no excited 0^+ levels with appreciable strength are observed up to 5 MeV of excitation.[13] Thus, such levels must be located still higher in excitation or another mechanism is responsible for the observed loss in (p, t) intensity.

*Research sponsored by the U. S. Atomic Energy Commission under contract with Union Carbide Corporation.

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Calculation of the Coupling Constant for Deuteron Exchange in p-^{3}He Scattering*

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(Received 10 August 1972)

A simple extrapolation technique is used to determine the normalization C of the proton-deuteron tail of the ^{3}He wave function. With a wave function calculated using the Faddeev equations and the Reid soft-core potential we find $|C|^2 \approx 2.8$, in fair agreement with the value $|C|^2 \approx 2.2 \pm 0.3$ estimated by Bolsterli and Hale in a modified phase-shift analysis of p-^{3}He elastic scattering data.

In a recent paper,[1] Bolsterli and Hale (BH) applied the so-called "modified phase-shift analysis" to p-^{3}He elastic scattering data at 4.00, 5.51, 6.82, and 8.82 MeV. For l values 2, 3, 4, and 5, which correspond to impact parameters greater than the sum of the proton and ^{3}He radii, phase shifts were calculated from Born terms associated with deuteron and $(^1S_0)$ np exchange graphs (Fig. 1). The exchanged $(^1S_0)$ np system was assumed to be in a zero-energy bound state. The strengths of these exchange contributions are proportional to $|C|^2$ and $|C'|^2$, the normalization constants squared of the p-d and p-$(^1S_0)$ np tails, respectively, of the ^{3}He wave functions. C and C' were assumed to be equal.[2] The $l = 0,1$ phase shifts were determined from a least-squares fit to the data. It was found that the inclusion of peripheral phase shifts in partial waves for $l > 1$ significantly decreased the weighted variance below the value obtained when these phase shifts were not included in the analysis. The best fit to the data corresponded to a value of around 2.2 for $|C|^2$.

The technique of using peripheral values for high partial-wave phase shifts was originally employed by Cziffra *et al.*[3] to improve the analysis of nucleon-nucleon scattering data and to extract from it a value for the pion-nucleon coupling constant. Shanley[4] applied the method to the analy-

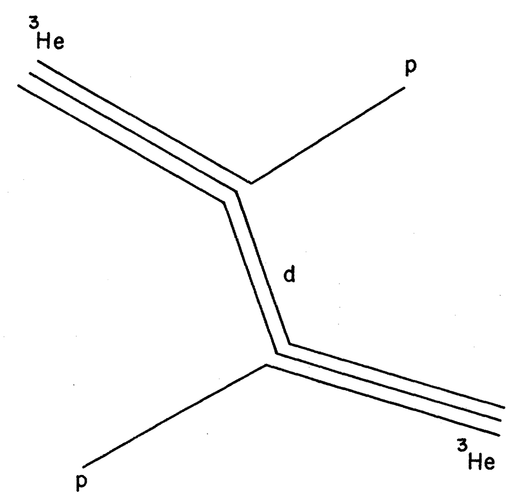

FIG. 1. Deuteron-exchange diagram.