0^+ States in Mo Isotopes from (p,t) Reactions and Anomalies in the New Transitional Region

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(Received 7 July 1971)

We have used ^{92,94,96,98,100}Mo(p,t) reactions to investigate the 0^+ states in even Mo isotopes. The appearance of low-lying excited 0^+ states in ^{98,100,102}Mo with large two-neutron transfer strengths, together with the systematics of the lowest 2^+ states, suggests the existence of a new transitional region. The large cross section for the excited 0^+ state in the reaction ^{100}Mo$(p,t)^{98}$Mo may be able to explain the anomaly in the $l=0$ spectroscopic factors in ^{98}Mo(d,p) and ^{100}Mo(d,t) reactions.

There is evidence, both theoretical[1] and experimental,[2,3] that the heavier Mo isotopes (^{102}Mo), ^{104}Mo, and ^{106}Mo may have permanent deformations. Since the lightest isotope ^{92}Mo is a closed-shell nucleus with $N=50$ and is spherical, the midway isotopes ^{98}Mo, ^{100}Mo, and (^{102}Mo) are expected to show the characteristics of typical transitional nuclei. In well-known experiments on Sm,[4] excited 0^+ states, whose wave functions are similar to those of the ground states of neighboring even isotopes, were excited strongly by (p,t) and (t,p) reactions. The same sort of selective process may be expected in Mo(p,t) and Mo(t,p) reactions also.

Another aim of the present experiment is to investigate the so-called pairing vibrational states[5] in Mo isotopes. Ball, Auble, and Roos[6] have investigated the pairing vibrational states in Zr isotopes by (p,t) reactions and have found that the pairing vibrational picture is visualized only for isotopes with $N \leq 52$. It is of interest to see how the additional two protons in Mo isotopes disturb the systematics of the pairing vibrational states.

Targets of enriched Mo isotopes (^{92,94,96,98,100}Mo, 1–3 mg/cm^2) were bombarded by 52-MeV protons from the Institute for Nuclear Study–Tokyo synchrocyclotron. Outgoing tritons were detected with a broad-range magnetic spectrometer.[7] Overall energy resolutions including the effect of target thickness were 80–100 keV. Angular distributions of tritons were measured for levels with excitations energies up to about 5 MeV. The $l=0$ angular distributions obtained are shown in Fig. 1. Of particular interest is the fact that the cross section for the 0.735-MeV 0^+ state in ^{98}Mo from the ^{100}Mo(p,t) reaction is about 24% of that for the ground-state transitions. With the present energy resolution the 0.735-MeV 0^+ state could not be resolved from the close-lying 0.787-MeV 2^+ state. However, as shown in Fig. 1, the summed angular distribution for these two states still shows the characteristic $l=0$ pattern; and hence the 2^+ component in the summed cross section seems to be much smaller than the 0^+ component. Assuming that the shape of the angular distribution for the 0.787-MeV 2^+ state in ^{98}Mo was identical to that for the 0.778-MeV 2^+ states in ^{96}Mo from the ^{98}Mo(p,t) reaction, the $l=0$ components of the differential cross sections

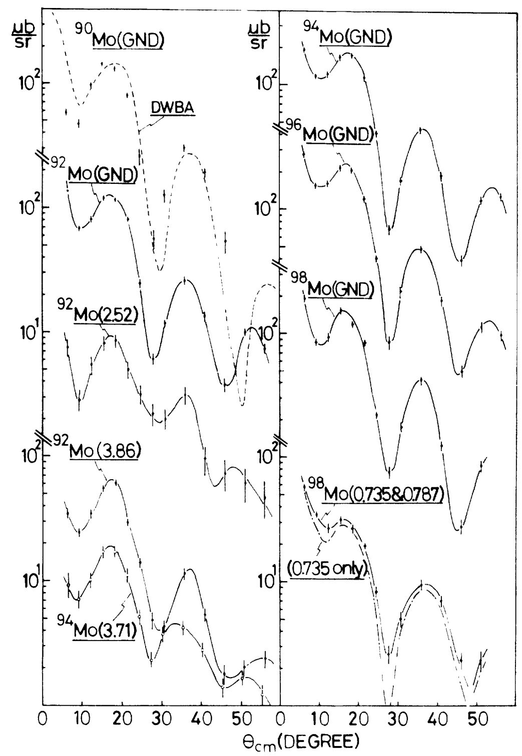

FIG. 1. The $l=0$ differential cross sections of the Mo(p,t) reactions leading to the final nuclei and states indicated. Each of the solid curves serves only as a guide to the eye. For the reaction ^{100}Mo$(p,t)^{98}$Mo(0.735 and 0.787 MeV), the solid curve represents the summed cross sections while the dashed-dotted curve represents the estimated cross section for the 0.735-MeV state. The dashed curve is a distorted-wave Born approximation fit to the reaction ^{92}Mo$(p,t)^{90}$Mo(g.s.).

were deduced and are shown in Fig. 1 (dashed-dotted curve). On the other hand, the reaction ^{98}Mo(p, t) failed to excite to a detectable degree a proposed 0^+ state in ^{96}Mo at 1.148 MeV.[8] Unfortunately, the Q value for the excitation of 1.148-MeV state in ^{96}Mo is very close to that of the reaction ^{96}Mo(p, t)^{94}Mo(g.s.) arising from the isotopic impurity of ^{96}Mo (~0.6%) in the ^{98}Mo target. After subtracting the possible contribution from the reaction ^{96}Mo(p, t)^{94}Mo(g.s.), the peak differential cross section (at $\theta = 15°$) of the reaction ^{98}Mo(p, t)^{96}Mo(1.148 MeV) was found to be less than 1 μb/sr.

Levels in ^{100}Mo and ^{102}Mo have recently been investigated by ^{98,100}Mo(t, p) reactions.[9] Strong excitations of the excited 0^+ levels at nearly the same energies (~0.7 MeV) were found for both of the nuclei. The 0.700-MeV 0^+ level of ^{100}Mo was also observed in the reaction ^{100}Mo(p, p')^{100}Mo.[10] The (t, p) cross sections for the excited 0^+ states with respect to those for the 0^+ ground states are about 20% (^{100}Mo) and 50% (^{102}Mo), respectively.

For the heaviest isotopes, ^{104}Mo and ^{106}Mo, data on fission products are available.[2,3] Both nuclei show apparent rotational-like level structures.

Figure 2 summarizes the available data on Mo isotopes. Except for ^{104}Mo and ^{106}Mo, only the 0^+ states and the lowest 2^+ states are shown.

The decreasing trend (from 0.787 MeV in ^{98}Mo to 0.172 MeV in ^{106}Mo) of the excitation energies of the lowest 2^+ states and the increasing trend[3] (from 10 to 150) of the value

$$\frac{B(E2:\ \text{lowest } 2^+ \rightarrow \text{g.s. } 0^+)_{\text{expt}}}{B(E2:\ \text{single particle})}$$

from ^{98}Mo to ^{106}Mo suggest that the isotopes ^{98,100,102}Mo may form a series of transitional nuclei whose shapes change gradually from spherical to deformed.

The (p, t) cross section to the excited 0^+ state of ^{98}Mo and the (t, p) cross sections to the excited 0^+ states of ^{100}Mo and ^{102}Mo mentioned above are unusually large since in most even nuclei two-neutron–transfer cross sections are of the order of a few percent of the cross sections for the corresponding ground-state transitions except for some special cases. Up to the present, three regions of the periodic table are known in which the excited 0^+ states are strongly excited by two-neutron–transfer reactions.[11] The first of these regions is in the vicinity of the closed shells where the energy gap in single-particle states exists and for which the concept of pairing vibration is more or less applicable. The second is for some deformed nuclei, for which there is also a gap in the energy spacing of Nilsson orbits. The third is the transitional region where the equilibrium shape is changing as is

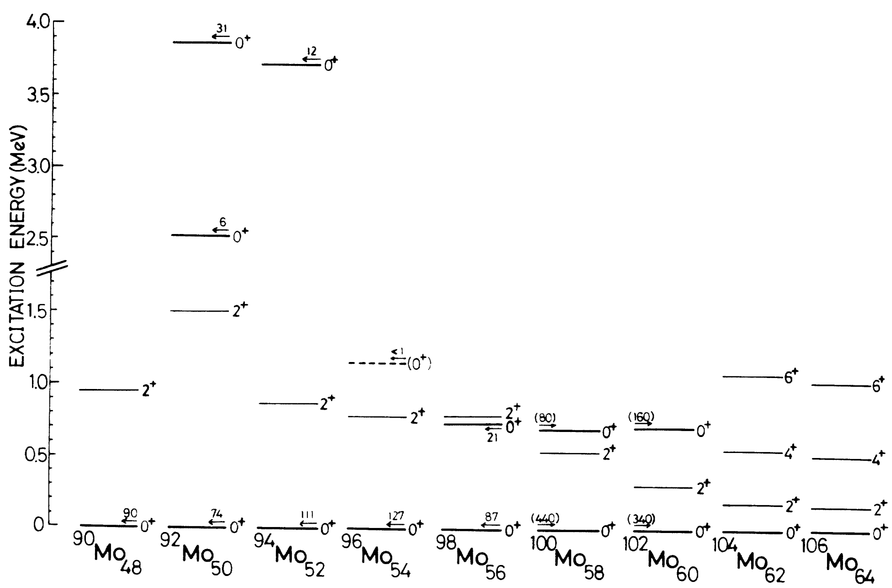

FIG. 2. The systematics of the 0^+ and the lowest 2^+ states in even Mo isotopes. For ^{104,106}Mo, rotational-like levels up to 6^+ are indicated. The numbers on the left-pointed arrows show the integrated (p,t) cross sections (μb) from 6 to 55°, while those (in parentheses) on the right-pointed arrows show the peak differential cross sections (in μb/sr) at 35° of (t, p) reactions (Ref. 9).

found near $N=90$. The first of these three categories is not applicable for ^{98}Mo since ^{98}Mo is not a good closed-neutron-shell nucleus, as is described below. The data on the reactions ^{98}Mo$(d,p)^{99}$Mo [12] and ^{98}Mo$(d,t)^{97}$Mo [13] show that six neutrons outside the $N=50$ core are in a state of a complicated mixture of $d_{5/2}$-, $g_{7/2}$-, $s_{1/2}$-, and $d_{3/2}$- orbitals. The ^{98}Mo(p,p) and ^{98}Mo(p,p') reactions, through isobaric analog resonance,[14,15] also show that ^{98}Mo is not a good closed-shell nucleus. These facts make a sharp contrast to the case of ^{96}Zr in which six neutrons outside the $N=50$ core are mostly in $d_{5/2}$ and form a fairly good closed-neutron-shell nucleus.[15,16] The second category is not applicable either since ^{98}Mo is not a deformed nucleus. Accordingly, the large (p,t) and (t,p) cross sections to the excited 0^+ states in ^{98,100,102}Mo are attributed to one of the peculiar features of the third category, i.e., the transitional region.

It is surprising that only the ground state of ^{96}Mo was excited as a 0^+ state in the reaction ^{98}Mo$(p,t)^{96}$Mo while both 0^+ states (the ground and the 0.735-MeV states) of ^{98}Mo were excited to a comparable degree in the reaction ^{100}Mo$(p,t)^{98}$Mo, in view of the fact that $N=56$ is not a good shell closure in ^{98}Mo. The data on the reaction ^{98}Mo$(p,t)^{96}$Mo show that the structure of the ground state does not change appreciably after transferring two neutrons while the structure of the 1.148-MeV state of ^{96}Mo may be quite different from that of the ground state of ^{98}Mo. The data on the reaction ^{100}Mo$(p,t)^{98}$Mo indicate that the wave function of the 0.735-MeV state of ^{98}Mo, which is expected to contain a deformed component, has a fairly large overlap with that of the ground state of ^{100}Mo. The zero-point oscillation[17] in the target ground state, however, causes comparable transfer strengths for both the ground and the 0.735-MeV states of ^{98}Mo.

Other evidence which supports the above interpretation has been reported by Diehl, Cohen, and Moyer.[18] They compared the $l=0$ spectroscopic factors in ^{98}Mo(d,p) and ^{100}Mo(d,t) reactions leading to the same final states ($J^\pi=\frac{1}{2}^+$) in ^{99}Mo and found that the ratio $S(d,t)/S(d,p)$ for the ground state ($\frac{1}{2}^+$) of ^{99}Mo was only about $\frac{1}{20}$ of those for other $\frac{1}{2}^+$ states at 0.526 and 0.906 MeV of the same nucleus. This is because the (d,p) spectroscopic factors for the 0.526- and 0.906-MeV states of ^{99}Mo are an order of magnitude smaller than that for the ground state of ^{99}Mo in spite of the fact that the (d,t) spectroscopic factors for these three states are on the same order of magnitude. Such an anomaly in one-nucleon spectroscopic factors is the first and only case among hundreds of cases they have treated so far. The center of gravity of the 0.526- and 0.906-MeV states in ^{99}Mo is estimated to be 0.650 MeV, which is very close to 0.735 MeV. Then it seems quite natural to assume that these two $\frac{1}{2}^+$ excited states in ^{99}Mo are largely due to single-neutron states based on the 0.735-MeV 0^+ state of ^{98}Mo. The spectroscopic factors for these two states in ^{99}Mo are then expected to be much smaller than that for the ground state since the former need core excitation. On the other hand, the (d,t) spectroscopic factors for these two states need not be small since the wave function of the target state ^{100}Mo(g.s.) seems to have a large overlap with the 0.735-MeV 0^+ state in ^{98}Mo.

We have a few comments on the pairing vibrational states. In the reaction ^{94}Mo$(p,t)^{92}$Mo, two excited 0^+ states were found: one at $E_x=2.52\pm0.02$ MeV ($Q=-11.66\pm0.2$ MeV) and another at $E_x=3.86\pm0.02$ MeV ($Q=-13.00\pm0.2$ MeV). The cross sections for these two states are approximately 7% (at 2.52 MeV) and 35% (at 3.86 MeV), respectively, of that for the reaction ^{92}Mo$(p,t)^{90}$Mo(g.s.). The Q value corresponding to the center of gravity of these two levels is -12.83 ± 0.2 MeV which is 1.39 MeV less negative than that of the reaction ^{92}Mo$(p,t)^{90}$Mo(g.s.) (-14.22 ± 0.2 MeV). In the reaction ^{96}Mo$(p,t)^{94}$Mo, only one excited 0^+ state was found at $E_x=3.71\pm0.02$ MeV ($Q=-11.64\pm0.2$ MeV) with a cross section approximately 13% of that of the reaction ^{92}Mo$(p,t)^{90}$Mo(g.s.). The rest of the 0^+ transfer strengths may be distributed over the ground state and many other fragmented levels, but most of the latter states probably are not detectable with the present energy resolution. For heavier isotopes, no 0^+ states were found in the expected energy region. Pairing vibration, therefore, does not seem to be a good approximation for Mo isotopes.

The authors are grateful to F. Tanaka, R. Namai, and Y. Fukushima for their help in taking the data, and to the Institute for Nuclear Study cyclotron crew for the operation of the cyclotron. The authors are also indebted to the late K. Matsuda and to S. Takeda for information on the (t,p) reactions. One of us (H.T.) would like to thank M. Sano for useful discussions.

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[1]D. A. Arseniev, A. Sobiczewski, and V. G. Soloviev, Nucl. Phys. A139, 269 (1969).

[2]E. Cheifetz *et al.*, Phys. Rev. Lett. 25, 38 (1970).

[3]E. Cheifetz *et al.*, in CERN Report No. 70-30, 1970 (unpublished), Vol. 2, p. 883.

[4]J. H. Bjerregaard *et al.*, Nucl. Phys. 86, 145 (1966); W. McLatchie, W. Darcey, and J. E. Kitching, Nucl. Phys. A159, 615 (1970), and references therein.

[5]A. Bohr, in *Nuclear Structure, Dubna Symposium, 1968* (International Atomic Energy Agency, Vienna, Austria, 1969), p. 179.

[6]J. B. Ball, R. L. Auble, and P. G. Roos, Phys. Lett. 29B, 172 (1969).

[7]K. Yagi *et al.*, Nucl. Instrum. Methods 52, 29 (1967).

[8]D. Heck *et al.*, Nucl. Phys. A165, 327 (1971).

[9]K. Matsuda *et al.*, to be published.

[10]Y. Awaya *et al.*, to be published.

[11]J. V. Maher *et al.*, Phys. Rev. Lett. 25, 302 (1970).

[12]J. B. Moorhead and R. A. Moyer, Phys. Rev. 184, 1205 (1969).

[13]S. A. Hjorth and B. L. Cohen, Phys. Rev. 135, B920 (1964); H. Ohnuma and J. L. Yntema, Phys. Rev. 178, 1855 (1969).

[14]J. J. Kent, C. F. Moore, and C. E. Watson, Phys. Rev. C 1, 346 (1970).

[15]W. J. Courtney and C. F. Moore, Phys. Lett. 31B, 131 (1970).

[16]B. L. Cohen and O. V. Chubinsky, Phys. Rev. 131, 2184 (1963).

[17]K. Kumar and M. Baranger, Nucl. Phys. A110, 529 (1968).

[18]R. C. Diehl, B. L. Cohen, and R. A. Moyer, Phys. Lett. 30B, 637 (1969).

Magnetic Moment of the Lowest 6^+ State in ^{42}Ca and Effects of the Deformed States

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(Received 10 May 1971)

With the time-differential angular-distribution method the g factor of the lowest ($\nu f_{7/2}^2$) 6^+ state in ^{42}Ca has been determined to be $-0.50^{+0.02}_{-0.03}$, which is closer to the Schmidt value for the $0f_{7/2}$ neutron than is that of the ^{41}Ca ground state. Strong violation of the additivity of the effective magnetic moment for these states is interpreted by a larger mixing of the core-excited deformed states into the ^{41}Ca ground state.

In the present Letter we report a g-factor measurement of the lowest 6^+ state ($t_{1/2} = 5.52$ nsec) in ^{42}Ca made by means of the time-differential perturbed angular distribution (PAD) method, which yields a g factor significantly different from the previously reported value.[1] From the shell-model point of view the 6^+ state is considered to be mainly of the $\nu f_{7/2}^2$ configuration. In fact recent measurements of the $E2$ transition probability between the 6^+ and 2750-keV 4^+ states proved the very pure character of this configuration.[2] The g factor of the 6^+ state, giving the $0f_{7/2}$ neutron g factor in its two-particle state, is expected to throw new light on the magnetic moment of the ^{41}Ca ground state ($-1.59460\mu_N$[3]) which is known to deviate largely from the Schmidt value ($-1.91314\mu_N$). Since the ^{40}Ca core is closed in the L-S coupling scheme, the correction due to configuration mixing vanishes according to first-order perturbation theory.[4] The deviation from the Schmidt value therefore comes from the higher-order configuration mixing and from some other possible effects such as mesonic exchange currents and $L \cdot S$ and tensor interactions. If these effects can be renormalized into the effective magnetic moment of the $0f_{7/2}$ neutron, we expect $g(6^+, {}^{42}\mathrm{Ca})$ to be nearly equal to $g(\frac{7}{2}^-, {}^{41}\mathrm{Ca})$. Such an additivity of the renormalized magnetic moment has recently been shown to hold well for the protons in the ^{208}Pb and ^{88}Sr regions[5] in which the spin core polarization (the first-order configuration mixing) is an important contribution to the deviation from the Schmidt value.

The experimental method used in this work is essentially the same as described earlier.[6] The 6^+ state in ^{42}Ca was excited by the reaction ^{40}Ca(α, $2p$)^{42}Ca with 25-MeV α particles from the cyclotron at the Institute of Physical and Chemical Research. A thick metallic Ca (natural) target was used. Time distributions of γ rays were measured by the use of the natural cyclo-