Measurement of the static quadrupole moments of the first 2^+ states in ^{94}Mo, ^{96}Mo, ^{98}Mo, and ^{100}Mo†

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(Received 3 March 1976)

The static quadrupole moments Q_{2^+} and the $B(E2; 0^+ \rightarrow 2^+)$ values of the first 2^+ excited states in ^{94}Mo, ^{96}Mo, ^{98}Mo, and ^{100}Mo have been determined by Coulomb excitation experiments performed by resolving elastically and inelastically backward scattered ^{4}He and ^{16}O projectiles detected in four surface barrier detectors. The measurements yielded for Q_{2^+} and $B(E2; 0^+ \rightarrow 2^+)$: (-0.13 ± 0.08) e b or $(+0.01 \pm 0.08)$ e b and (0.196 ± 0.003) e^2b^2 for ^{94}Mo; (-0.20 ± 0.08) e b or $(+0.04 \pm 0.08)$ e b and (0.270 ± 0.004) e^2b^2 for ^{96}Mo; (-0.20 ± 0.09) e b or $(+0.16 \pm 0.09)$ e b and (0.266 ± 0.005) e^2b^2 for ^{98}Mo; (-0.42 ± 0.09) e b or (-0.10 ± 0.09) e b and (0.511 ± 0.009) e^2b^2 for ^{100}Mo.

[NUCLEAR REACTIONS ^{94,96,98,100}Mo(α, α'), $E = 8.0$ MeV; ^{94,96,98,100}Mo$(^{16}$O$, ^{16}$O$')$, $E = 36.0$ or 36.5 MeV; measured $\sigma(E, E_{^{16}O'})$. ^{94,96,98,100}Mo deduced Q_{2^+}, $B(E2; 0^+ \rightarrow 2^+)$. Enriched targets.]

I. INTRODUCTION

In recent years the nuclear structure of the even molybdenum nuclei has been the subject of extensive experimental investigation.[1-7] The study of these nuclei has been motivated primarily by the observation that with the exception of ^{92}Mo, which with 50 neutrons is a good closed-shell nucleus,[8,9] all the other even Mo nuclides show departures from shell-model expectations which cannot be described by relatively simple considerations. Indeed, the study of fission product decay[10] revealed that the low-lying levels of ^{102}Mo, ^{104}Mo, and ^{106}Mo show features corresponding to deformed nuclei, in agreement with theoretical calculations[11-13] predicting the onset of deformations in the neutron rich Mo nuclides (as well as in the neighboring Zr and Ru nuclei). Moreover, (p, t) and (t, p) reaction experiments[14-17] seemed to indicate that the ^{98,100,102}Mo nuclei form a transitional region between the more spherical ^{94,96}Mo nuclei and the ^{104,106}Mo rotational ones. To complicate even further the already hazy picture of these nuclei, low-lying $0^{+\prime}$ levels are known to exist in ^{96}Mo, ^{98}Mo, ^{100}Mo, and ^{102}Mo with rather puzzling properties. In spite of the fact that the $B(E2; 0^{+\prime} \rightarrow 2^+)/B(E2; 2^+ \rightarrow 0^+)$ ratio in ^{96}Mo and ^{100}Mo shows an apparent agreement with the vibrational model,[4] the position of these $0^{+\prime}$ states in the level structure is such that they cannot be considered as members of the second phonon triplet. In ^{98}Mo the $0^{+\prime}$ level is even lower in energy than that of the first 2^+ excited state. It was proposed that these $0^{+\prime}$ levels could be the bandheads of strongly deformed bands built on them.[12] However, the results of two recent investigations on ^{98}Mo and ^{102}Mo showed that it is highly unlikely that these levels can be considered as bandhead of rotational bands.[16,17] This holds also for the $0^{+\prime}$ levels of ^{96}Mo and ^{100}Mo, since these states decay by fast $E2$ transitions to the first 2^+ excited states. Thus their nuclear shape cannot be very different from that of the possible ground-state band.

Perhaps the level schemes of the even molybdenum isotopes could be described in terms of the collective model of Gneuss and Greiner,[18] which treats all types of nuclei from spherical to deformed in a uniform manner. The principal outcome of this model is that ground-state, β, and γ bands should appear in the structure of nuclei (of the same type as those found for $N = 88$ and $N = 90$).[19] Such an interpretation was tried by Heck *et al.*[20,21] for ^{96}Mo and ^{98}Mo, and by Sharma *et al.*[16] for ^{98}Mo with encouraging results. Unfortunately, a more complete comparison with this model cannot be carried out since $B(E2)$ values and two-particle transfer spectroscopic factors have not been predicted within the framework of this model.

From the aforementioned points it is clear that the level structure of the even molybdenum nuclei is far from being well understood and that more data are needed as an experimental basis for comparison with more refined calculations. The present work was undertaken with this purpose in mind i.e., to obtain the experimental determination of an important nuclear parameter as the static quadrupole moments Q_{2^+} which may be very useful for future theoretical calculations.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Targets of ^{94}Mo, ^{96}Mo, ^{98}Mo, and ^{100}Mo were bombarded with 36 MeV (or 36.5 MeV) ^{16}O ions and 8 MeV ^{4}He projectiles from the University of Montreal tandem Van de Graaff accelerator. The targets had a thickness varying from 10 to 30 μg/cm^2 and were prepared by vacuum evaporation of molybdenum metal or molybdenum oxide (MoO_3) on 10 or 20 μg/cm^2-thick carbon backings. The excitation probabilities for ^{4}He and ^{16}O projectiles were obtained by comparing resolved elastically and inelastically scattered particle groups detected in four surface barrier detectors placed at scattering angles of $\pm 157.5°$ and $\pm 172.5°$. The energy resolution was approximately 30 keV for the α particles and varied from 100 to 140 keV for the ^{16}O ions depending on the target thickness and scattering angle. Typical ^{16}O spectra are shown in Fig. 1 (^{94}Mo) and Fig. 2 (^{100}Mo), and a typical α spectrum (^{100}Mo) is presented in Fig. 3. The ratios $R_{exp} = d\sigma_{inel}/d\sigma_{el}$ were extracted from the data after the contributions from the isotope impurities were subtracted from the spectra. The subtractions were made employing the Oak Ridge isotopic analysis which is given in Table I.

To derive the static quadrupole moments Q_{2^+} and the reduced transition probabilities $B(E2; 0^+ \rightarrow 2^+)$ of the first excited states of ^{94}Mo, ^{96}Mo, ^{98}Mo, and ^{100}Mo, the measured cross-section ratios R_{exp}, which are given in Table II, were fitted with the cross-section ratios R_c calculated with the

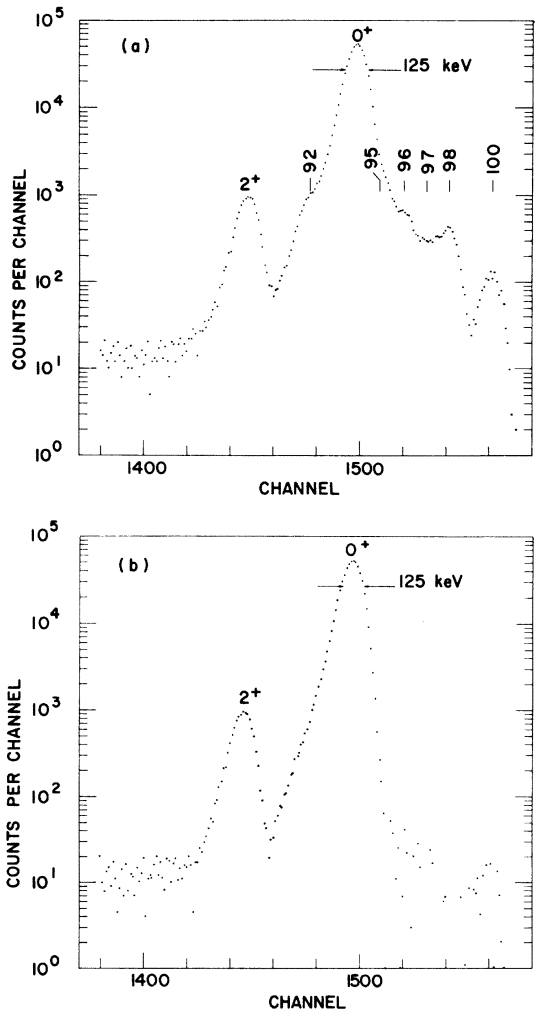

FIG. 1. ^{16}O (36.5 MeV) spectra from ^{94}Mo at scattering angle $\theta_{lab} = +157.5°$. (a) The raw spectrum showing the elastic contributions due to the Mo impurities. (b) The spectrum after subtraction of the Mo impurities.

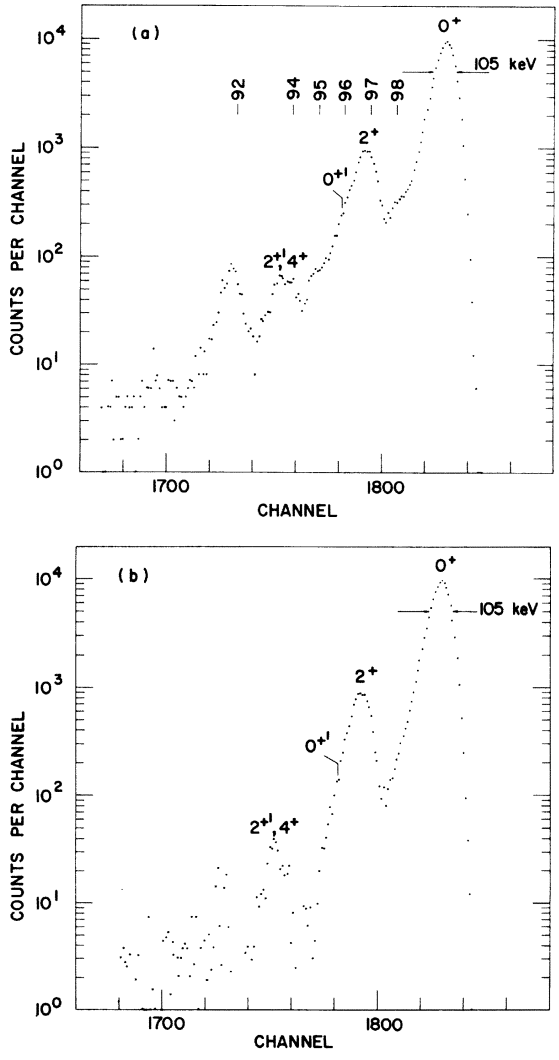

FIG. 2. ^{16}O (36.0 MeV) spectra from ^{100}Mo at scattering angle $\theta_{lab} = +157.5°$. (a) The raw spectrum showing the elastic contributions due to the Mo impurities. (b) The spectrum after subtraction of the Mo impurities.

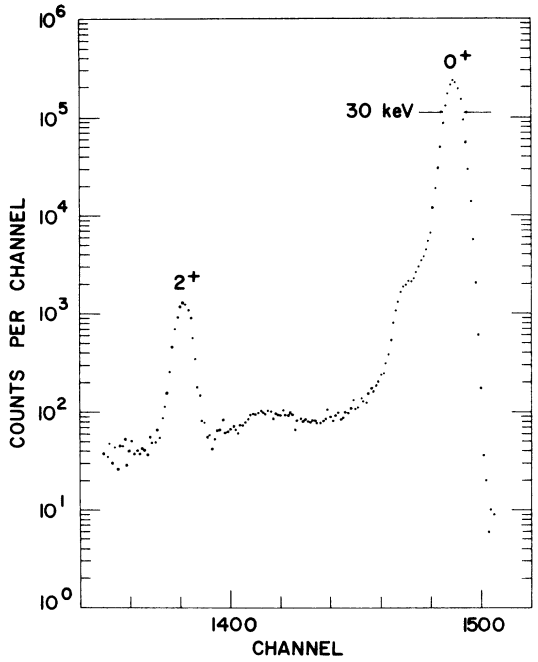

FIG. 3. α (8.0 MeV) spectrum of ^{100}Mo at scattering angle $\theta = +157.5°$. The shoulder on the left of the elastic peak is due to the presence of the other molybdenum isotopes in the enriched target (95.9% ^{100}Mo).

coupled channel computer code of Winther and de Boer,[22] with appropriate reduced matrix elements M_{rs} of the quadrupole operator. These matrix elements were obtained from the $B(E2)$ values determined by Coulomb excitation measurements previously performed in this laboratory.[4] The energy levels included in the analysis are shown in Fig. 4 and the matrix elements used are given in Table III. The final results for the static quadrupole moments and reduced transition probabilities are presented in Table IV.

III. DISCUSSION

From an inspection of Table IV, it is apparent that the $B(E2; 0^+ \rightarrow 2^+)$ values measured in this work are lower than those determined in a Coulomb excitation (thick target yield method) experiment previously performed in this laboratory.[4] The difference is approximately 5%, 4.5%, 6.5%, and 3% for ^{94}Mo, ^{96}Mo, ^{98}Mo, and ^{100}Mo, respectively. In a recent investigation by Bohn *et al.*[30] on the structure of the excited states of ^{100}Mo and ^{102}Mo (the states of ^{100}Mo were excited by Coulomb excitation and those of ^{102}Mo by the two-neutron transfer reaction induced by ^{18}O ions on a ^{100}Mo target) the $B(E2; 0^+ \rightarrow 2^+)$ of the first 2^+ excited state in ^{100}Mo was measured as $(0.475 \pm 0.024)\ e^2\ b^2$, which is 10% smaller than the value determined in Ref. 4. Since the maximum "safe" energy for pure Coulomb excitation by oxygen ions of the 2^+ state in ^{100}Mo was found to be 40 MeV by these authors, they claimed that this small discrepancy was due to the too high ^{16}O energy used in our previous experiment, so that nuclear forces may have interfered significantly with the Coulomb interaction. However, we do not believe that this is the essential reason which could explain the difference in the $B(E2; 0^+ \rightarrow 2^+)$ values measured here and in Ref. 4. Apart from the fact that the present $B(E2; 0^+ \rightarrow 2^+)$ value for ^{100}Mo does not disagree (within the error limits) with that determined by Barrette *et al.*,[4] it should not be forgotten that in our previous Coulomb excitation measurements oxygen ion beams of 36 to 44.8 MeV were employed and no appreciable difference was found in the $B(E2; 0^+ \rightarrow 2^+)$ values for all molybdenum isotopes. Furthermore, it is well known that employing the thick target yield method in determining the reduced electromagnetic transitions, the so-called "safe" energy can be slightly exceeded since the γ rays result from an integration of the differential cross section and only approximately 10% of the total cross section results from scattering angles larger than 135° which are the close collisions where some perturbing effects may occur. We believe that the most likely explanation in the variance of the $B(E2)$ values should be searched in some systematic error present in the thick target yield method,[4] as for instance an erroneous choice of the $dE/d\rho x$ stopping power function which for oxygen ions is not

TABLE I. Isotope composition of targets in percent. All material was obtained from Oak Ridge Separated Isotopes Divisions.

Target	Isotopes 92	94	95	96	97	98	100
94	0.87±0.05	93.9 ±0.10	2.85±0.05	1.04±0.05	0.40±0.05	0.75±0.05	0.22±0.05
96	0.18±0.05	0.18±0.05	0.94±0.05	96.8 ±0.10	0.96±0.05	0.82±0.05	0.10±0.02
98	0.32±0.02	0.22±0.02	0.45±0.02	0.59±0.02	0.69±0.02	97.18±0.10	0.55±0.02
100	0.6 ±0.02	0.23±0.02	0.4 ±0.02	0.81±0.02	0.36±0.01	1.69±0.05	95.9 ±0.10

TABLE II. Values of the experimental and least-square-fitted ratios.

Isotope	Beam energy (MeV)	Lab angle (deg.)	$R_{exp} \times 10^3$ [a]	$R_{fit} \times 10^3$ [b]
94	8 (^{4}He)	157.5	0.794 ± (0.8)	0.792
		172.5	0.810 ± (0.9)	0.810
	36.5 (^{16}O)	157.5	18.08 ± (1.0)	18.15
		172.5	18.55 ± (1.5)	18.52
96	8 (^{4}He)	157.5	1.481 ± (0.8)	1.474
		172.5	1.505 ± (0.9)	1.514
	36.5 (^{16}O)	157.5	30.80 ± (1.3)	31.25
		172.5	31.10 ± (1.9)	31.98
	36.0 (^{16}O)	157.5	29.30 ± (0.9)	28.95
		172.5	29.60 ± (1.1)	29.61
98	8 (^{4}He)	157.5	1.427 ± (0.9)	1.421
		172.5	1.460 ± (1.0)	1.460
	36.5 (^{16}O)	157.5	30.80 ± (0.9)	30.93
		172.5	31.50 ± (1.1)	31.68
100	8 (^{4}He)	157.5	5.550 ± (1.4)	5.588
		172.5	5.906 ± (1.2)	5.807
	36.0 (^{16}O)	157.5	94.50 ± (1.1)	94.16
		172.5	96.67 ± (1.1)	96.95

[a] The experimental errors for R_{exp} are statistical only and are quoted in percent.

[b] The fitted ratios are those obtained for a positive value of $P_3 = M_{02'} M_{2'2} M_{02}$ and $P_3' = M_{02''} M_{2''2} M_{02}$.

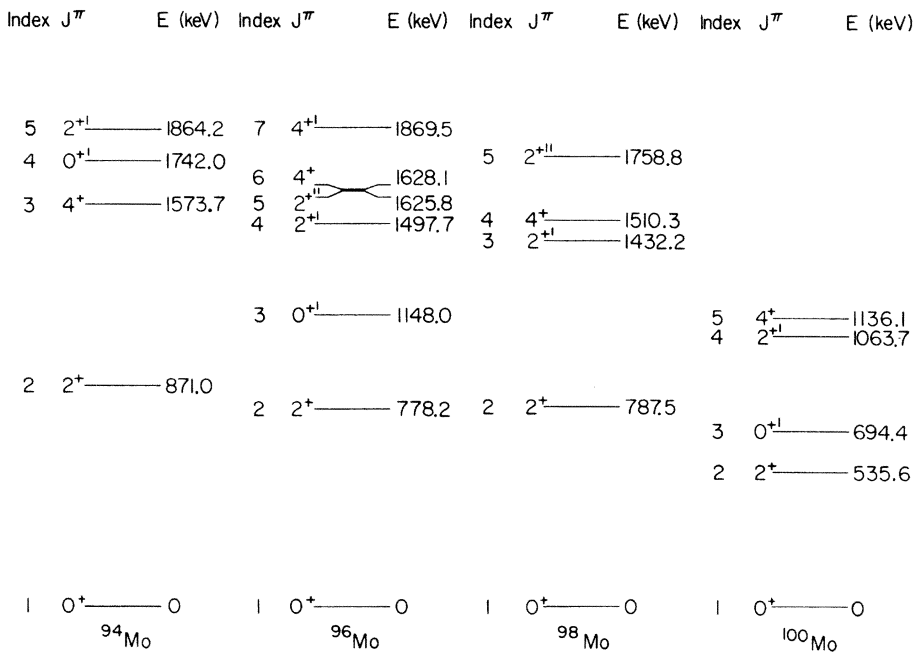

FIG. 4. Energy levels of ^{94}Mo, ^{96}Mo, ^{98}Mo, and ^{100}Mo included in the analysis. These level schemes have been taken from Ref. 4 with the exception of the 1742 keV ($0^{+\prime}$) level in ^{94}Mo whose existence has been definitely established by McEllistrem *et al.* (Ref. 6). For analysis purposes the $B(E2; 0^{+\prime} \rightarrow 2^+)/B(E2; 2^+ \rightarrow 0^+)$ ratio was taken equal to 2, in agreement with the general trend found for the $0^{+\prime}$ states in the other even Mo isotopes (Ref. 4). However, the Q_{2^+} value in ^{94}Mo is not practically affected, even excluding the $0^{+\prime}$ level from the analysis. For the δ values of the $2^{+\prime} \rightarrow 2^+$ transitions in ^{94}Mo and ^{96}Mo and the $2^{+\prime\prime} \rightarrow 2^+$ transition in ^{96}Mo; see Refs. 23 and 20. The δ values of the $2^{+\prime} \rightarrow 2^+$ and $2^{+\prime\prime} \rightarrow 2^+$ transitions in ^{98}Mo were taken from Ref. 21. The $2^{+\prime} \rightarrow 2^+$ γ ray in ^{100}Mo was considered as a pure $E2$ transition.

TABLE III. Reduced $E2$ matrix elements (in e b) used in the analysis. The matrix elements are defined by $M_{rs} = \langle s \| i^{\lambda} \mathfrak{M}(E\lambda) \| r \rangle$, where $\mathfrak{M}(E\lambda)$ is the multipole operator and $\lambda = 2$; $M_{rs}^2 = (2I_r + 1)\, B(E2;\ r \rightarrow s)$, and the quadrupole moment of the first 2^+ excited state is given by $Q_{2^+} = -0.758 M_{22}$.

				^{94}Mo				
Level	(J^{π})	$1(0^+)$	$2(2^+)$	$3(4^+)$	$4(0^{+\prime})$	$5(2^{+\prime})$		
1	0^+	0	$\pm M_{12}$	0	0	−0.056		
2	2^+	$\pm M_{12}$	M_{22}	−0.774	−0.295	−0.761		
3	4^+	0	−0.744	0	0	0		
4	$0^{+\prime}$	0	−0.295	0	0	0		
5	$2^{+\prime}$	−0.056	−0.761	0	0	0		
				^{96}Mo				
Level	(J^{π})	$1(0^+)$	$2(2^+)$	$3(0^{+\prime})$	$4(2^{+\prime})$	$5(2^{+\prime\prime})$	$6(4^+)$	$7(4^{+\prime})$
1	0^+	0	$\pm M_{12}$	0	−0.125	−0.038	0	0
2	2^+	$\pm M_{12}$	M_{22}	−0.367	−0.49	−0.474	−0.972	−0.212
3	$0^{+\prime}$	0	−0.367	0	0	0	0	0
4	$2^{+\prime}$	−0.125	−0.49	0	0	0	0	−0.741
5	$2^{+\prime\prime}$	−0.038	−0.474	0	0	0	0	0
6	4^+	0	−0.972	0	0	0	0	0
7	$4^{+\prime}$	0	−0.212	0	−0.741			
				^{98}Mo				
Level	(J^{π})	$1(0^+)$	$2(2^+)$	$3(2^{+\prime})$	$4(4^+)$	$5(2^{+\prime\prime})$		
1	0^+	0	$\pm M_{12}$	−0.113	0	−0.022		
2	2^+	$\pm M_{12}$	M_{22}	−0.845	−1.086	−0.283		
3	$2^{+\prime}$	−0.113	−0.845	0	0	0		
4	4^+	0	−1.086	0	0	0		
5	$2^{+\prime\prime}$	−0.022	−0.283	0	0	0		
				^{100}Mo				
Level	(J^{π})	$1(0^+)$	$2(2^+)$	$3(0^{+\prime})$	$4(2^{+\prime})$	$5(4^+)$		
1	0^+	0	$\pm M_{12}$	0	−0.106	0		
2	2^+	$\pm M_{12}$	M_{22}	−0.467	−0.943	−1.325		
3	$0^{+\prime}$	0	−0.467	0	0	0		
4	$2^{+\prime}$	−0.106	−0.943	0	0	0		
5	4^+	0	−1.325	0	0	0		

not known very precisely.

As is usual in the kind of experiments reported here, the various solutions quoted in Table IV for Q_{2^+} reflect the ambiguity in the unknown relative signs of the excitation amplitudes to the higher 2^+ states (or the so-called sign of the interference term). Even though in some of the Mo isotopes more than one interference term must be taken into account in the analysis (see Table IV), the following discussion will be carried out considering only the interference term due to the second 2^+ excited states (or $2^{+\prime}$ states), since the presence of higher 2^+ states (or $2^{+\prime\prime}$ states) do not alter appreciably the determined Q_{2^+} values. It is not possible from the present experiments alone to decide on the sign of the interference term since the quality fit is good for either sign. However, the general trend of the results on nuclei in this mass region[31] strongly favors the Q_{2^+} values given by considering the positive sign of the interference term (or constructive interference). We will see that the theoretical predictions on the Q_{2^+} values of the even molybdenum isotopes are also in agreement with this assumption.

Very few theoretical calculations on the sign and magnitude of Q_{2^+} of the molybdenum nuclei exist in the literature. Only very recently Paar[32] has calculated the level structure and nuclear properties of ^{94}Mo and ^{95}Mo using the particle-vibrational coupling model. The Q_{2^+} value calculated by this author for ^{94}Mo is (− 0.26) e b. Even though this value is larger than that found experimentally, the sign and magnitude are consistent with those determined with the positive sign of

TABLE IV. Summary of results for the $B(E2; 0^+ \rightarrow 2^+)$ and Q_{2^+} values obtained in the present study and from other measurements.

Isotopes	P_3	P_3 [a]	$B(E2; 0^+ \rightarrow 2^+)$ (e^2b^2)	Q_{2^+} $(e\,b)$ [b]	χ^2/d.f.	Ref.
94	+		0.196±0.003	−0.13±0.08	0.5	Present work
	−		0.196±0.003	+0.01±0.08	0.5	Present work
			0.206±0.011 [c]			Ref. 4
96	+	+	0.271±0.004	−0.20±0.08	1.3	Present work
	+	−	0.270±0.004	−0.15±0.08	1.3	Present work
	−	+	0.270±0.004	−0.01±0.08	1.3	Present work
	−	−	0.269±0.004	+0.04±0.08	1.3	Present work
			0.284±0.014			Ref. 4
98	+	+	0.267±0.005	−0.20±0.09	0.2	Present work
	+	−	0.266±0.005	−0.18±0.09	0.2	Present work
	−	+	0.265±0.005	+0.14±0.09	0.2	Present work
	−	−	0.265±0.005	+0.16±0.09	0.2	Present work
			0.286±0.014			Ref. 4
100	+		0.512±0.009	−0.42±0.09	2.1	Present work
	−		0.511±0.009	−0.10±0.09	2.1	Present work
			0.526±0.026			Ref. 4
			0.475±0.024			Ref. 30
				−0.40±0.10		Ref. 31

[a] P_3 is the matrix element product $M_{02'}\,M_{2'2}\,M_{02}$, and P_3' is the triple product $M_{02''}\,M_{2''}\,M_{02}$.

[b] The errors in the measured values of Q_{2^+} were calculated considering counting statistics, uncertainty in the exact value of the average beam energy passing through the targets (this is mostly due to the lack of a precise value for the target thickness), atomic screening, and vacuum polarization effects. The possible correction due to the giant dipole resonance (Refs. 24 and 25) was not considered whereas the small quantum-mechanical correction (Ref. 26) was included in the Q_{2^+} values.

[c] This is not the value reported in Ref. 4 (which was 0.218±0.011). However, subsequent work on the Coulomb excitation of levels in ^{95}Mo and ^{97}Mo (Refs. 27 and 28) showed the presence of a strong impurity peak at 870 keV. Thus the presence of this impurity was corrected in the original ^{94}Mo spectra, giving as a result the $B(E2)$ reported here. Furthermore, we take this occasion to report on the correction (see Ref. 29) of some errors present in the work of Ref. 4.

the interference term. It appears, however, that the magnitude of Q_{2^+} (and also its sign but to a lesser extent) depends strongly on the competition among the contributions of the available shell model levels of the two valence neutrons. In turn these contributions are crucially dependent on the positions of some single particle states. For instance, in ^{94}Mo the Q_{2^+} value is very sensitive to the position of the $s_{1/2}$ state with respect to the $d_{5/2}$ state. By slightly raising the position of the $s_{1/2}$ state (the neutron single-particle levels are taken by Paar as determined by a ^{92}Mo (d,p) ^{93}Mo reaction[33]) the Q_{2^+} decreases in absolute value, and for a large displacement of the $s_{1/2}$ level the Q_{2^+} could even become positive and small ($Q_{2^+} = 0.1\ e$ b).

Thus it seems that for ^{94}Mo (and probably also for the other even molybdenum isotopes) there exists a situation similar to that found in the cadmium and tellurium nuclei.[34] Bindal, Youngblood, and Kozub[35] have calculated recently the absolute values of the static quadrupole moments of the first 2^+ states in ^{96}Mo, ^{98}Mo, and ^{100}Mo. These values are in e b units: 0.25 (^{96}Mo), 0.26 (^{98}Mo), and 0.46 (^{100}Mo). (actually, the values given in Ref. 35 are slightly larger but since they were calculated from the $B(E2; 0^+ \rightarrow 2^+)$ as determined in Ref. 4, they were corrected considering the new and more precise $B(E2; 0^+ \rightarrow 2^+)$ values found in the present work.) More recently, Bindal *et al.*[36] did calculate again the magnitude, together with the sign of Q_{2^+} for ^{98}Mo, as (− 0.266) e b. All these values agree very well with the static quadrupole moments determined here using the positive sign of the interference term. Thus this is another reason which supports the assumption that the static quadrupole moments of the first 2^+ excited states of the even molybdenum isotopes are, most likely, those determined with $M_{02'}M_{2'2}M_{02}$ positive. Finally, it should be remarked that the only reported value in the literature for Q_{2^+} (^{100}Mo)[31] agrees very well with our Q_{2^+} found employing the positive sign of the interference term.

†Work supported by the National Research Council of Canada.

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*Much of this material is derived from a thesis submitted by P. Paradis in partial fulfillment of the requirements for the M.Sc.

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