LEVEL STUDIES OF ^{93}Mo VIA $(p, n\gamma)$ REACTION

T. Kakavand, K.P. Singh and I.M. Govil

Department of Physics, Panjab University, Chandigarh-160 014, India

(Received May 18, 1999)

The excited states of ^{93}Mo have been investigated via ^{93}Nb $(p, n\gamma)^{93}$Mo reaction with the proton beam energies from 2.7–4.3 MeV. The angular distributions have been used to assign the spins and the multipole mixing ratios using statistical theory for compound nuclear reactions. The ambiguity in the spin values for the 2181.3, 2247.3 and 2539.3 keV levels have been removed. The multipole mixing ratios eight γ-transitions have been newly measured. The lifetimes of the levels at 2539.3 and 2642.0 keV have been measured for the first time using Doppler shift attenuation method. The experimental results are compared with the existing theoretical models.

PACS numbers: 27.60.+j

1. Introduction

The nucleus ^{93}Mo with one neutron outside its closed shell of 50 neutrons is described as a relatively simple "Shell Model" nucleus. The level properties of this nucleus have been calculated by Auerbach and Talmi [1], Bhatt and Ball [2], Vervier [3], Chuu *et al.* [4] and Itaya [5] on the basis of shell model, and by Choudhury and Clemens [6] using the intermediate coupling model. Most of these calculations have predicted the existence and relative spacing of many of the observed low-lying levels reasonably well.

The excited levels of ^{93}Mo have been studied experimentally via β-decay [7,8] and nuclear reactions with the light ions [9,10] and the heavy-ions [11,12]. Many more levels were observed in ^{93}Nb(p, n) reaction time-of-flight spectroscopy by Finckh and Jahnke [13] but the limited energy resolution in this experiment and also other experiments [10–12] made comparison with the previous work difficult. Rutledge *et al.* [14] and later Mitarai and Minehara [9] also investigated and constructed the level scheme of ^{93}Mo nucleus from the ^{93}Nb$(p, n\gamma)$ reaction but the spins and parities of many levels have not been established. The lifetimes of the low-lying levels in this nucleus have been measured by Gill and Jones [11] and Rutledge *et al.* [14] using Doppler Broadened Line Shape (DBLS) method.

The purpose of the present study was to provide an additional experimental information on the existing level structure [15] of ^{93}Mo and remove the ambiguities in the work reported earlier [11,14,15] through $(p, n\gamma)$ reaction. In this work we have measured the lifetimes of the levels using Doppler Shift Attenuation (DSA) technique. The spin values and the multipole mixing ratios were extracted from the angular distributions of gamma-rays. The branching ratios for various transitions were extracted from the gamma-ray spectra recorded at 55°. Finally from the measured experimental values of lifetimes, spins and multipole mixing ratios for various transitions, the reduced transition probabilities B(M1) and B(E2) were extracted. The experimental level structure and the transition rates are compared with the predictions of the available shell model as well as with the intermediate coupling model calculations. Our results indicate that the low energy excitations are close to the single particle estimates while at higher energies the transitions are more collective in nature, indicating the possible shape coexistence at higher excitation.

2. Experimental procedure

A self-supporting 0.55 mg/cm^2 thick metal foil of natural spectroscopically pure ^{93}Nb was bombarded with proton beam of 2.7–4.3 MeV energy available from the Variable Energy Cyclotron at Panjab University, Chandigarh. The target was placed at an angle of 45^o with respect to the beam direction and was thick enough to stop incident protons. The angular distributions were measured at 0°, 30°, 45°, 55°, 75° and 90°. The γ-rays were detected with a 70 cm^3 coaxial HPGe detector with a resolution of 1.9 keV for the 1332 keV γ-ray of ^{60}Co. The detector was placed at a distance of 10 cm from the target and a graded filter consisting of Pb, Cu and Al was placed infront of the detector to suppress the high flux of x-rays and very low energy gamma-rays. A 5" x 5" NaI(Tl) detector was placed at -90° to act as a monitor for the angular distribution measurements. The target with an electron suppresser acted as a faraday cup. The signals from HPGe detector were stored using a Multichannel Pulse-Height Analyser. Electronic drift in the amplifier gain, if any, was monitored using background photopeaks at 440, 1461, 1779.1 and 2614.1 keV. At each angle a number of spectra were recorded and the drift in the gain was found to be negligible. The peak shifts are measured by first moment analysis to the significant figures which is important for DSAM technique. The excitation functions of various γ-rays have been measured at 55° with respect to the beam direction at 2.7, 3.0, 3.5, 4.0 and 4.3 MeV beam energies to ascertain that the channel of the compound decay is dominant as compared to the Coulomb excitation at the incident proton energy of 4.3 MeV. The energies of the gamma-rays were measured from the spectra recorded at 90° to avoid any shift due to the Doppler effect.

3. Data analysis

The gamma ray spectra were analysed using the computer code PEAK-FIT [16]. A typical gamma-ray spectrum at 90° for incident proton energy of 4.3 MeV is shown in Fig. 1. The peaks corresponding to the background γ-rays in the spectrum are labelled as B, while unidentified peaks are labelled as U. The remaining γ-rays were assigned to the de-excitation of the levels populated in the (p,nγ), (p,p'γ) and (p,γ) reactions. The peaks due to Aluminium placed infront of the detector are marked as Al. The excitation functions of all observed gamma-rays were analysed carefully as a function of energy and those from (p,nγ) reaction were easily identified with a char-

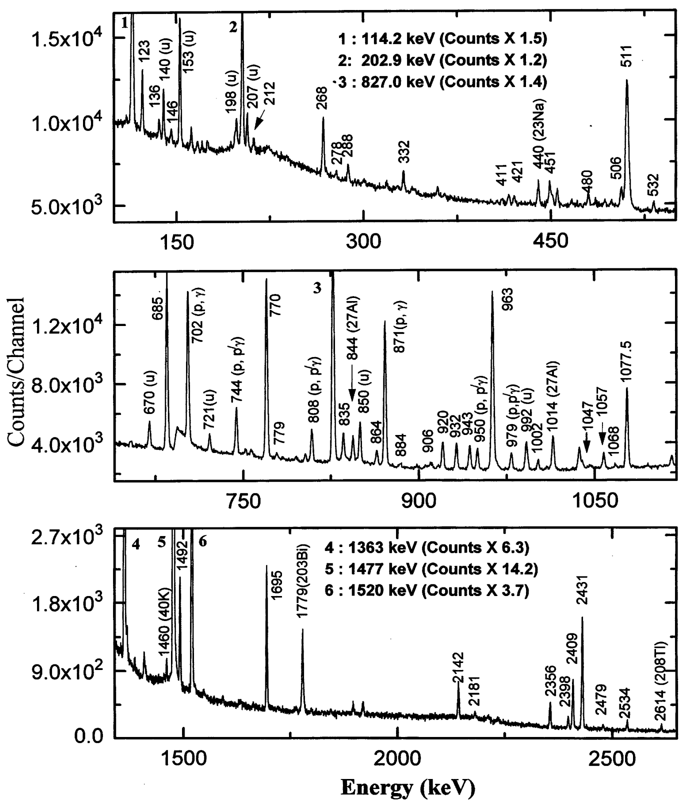

Fig. 1. A typical gamma-ray spectrum from the reaction ^{93}Nb$(p,n\gamma)^{93}$Mo at $E_p = 4.3$ MeV with the detector placed at 90° to the beam direction.

acterstic rise above their threshold energy. The level scheme for ^{93}Mo as established earlier [9,14] is shown in Fig. 2. The gamma-ray energies and the branching ratios measured in the present work are given in Table I.

TABLE I

Summary of level energies, gamma-ray energies and branching ratios for the transitions in ^{93}Mo at $E_p = 4.3$ MeV

S. No.	Level energy (keV)	Gamma ray (keV)	Branching ratios (percent)		
			Present work	Ref. [6]	Ref. [7]
1	943.2	943.2 ± 0.1	100	100	100
2	1363.1	1363.1 ± 0.1	100	100	100
3	1477.3	114.2 ± 0.2	0.9 ± 0.01	0.9 ± 0.1	0.7 ± 0.1
		1477.3 ± 0.1	99.1 ± 0.37	99.1 ± 2	99.3 ± 0.1
4	1492.3	1492.3 ± 0.2	100	100	100
5	1520.3	1520.3 ± 0.1	100	100	100
6	1695.0	331.9 ± 0.2	9.9 ± 1.04	6.8 ± 0.7	6.9 ± 0.7
		1695.0 ± 0.2	90.1 ± 2.0	82.2 ± 3.3	93.1 ± 0.7
7	2142.0	778.9 ± 2.2	15.3 ± 0.2	13.6 ± 0.7	14.7 ± 3.4
		2142.0 ± 0.3	84.7 ± 3.9	86.4 ± 3.5	85.3 ± 3.4
8	2161.9	684.6 ± 0.1	100	100	100
9	2181.3	2181.3 ± 0.4	100	100	100
10	2247.3	770.0 ± 0.2	96.9 ± 1.2	97.8 ± 0.2	96.7 ± 0.5
		884.2 ± 0.2	3.1 ± 0.4	2.2 ± 0.2	3.3 ± 0.5
11	2304.4	827.1 ± 0.2	100	100	100
12	2356.1	835.8 ± 0.2	51.2 ± 2.1	49.9 ± 1.5	47.6 ± 2.5
		863.8 ± 0.2	15.6 ± 1.7	13.2 ± 1.3	15.1 ± 2.1
		2356.1 ± 0.2	33.2 ± 0.7	36.9 ± 1.5	37.3 ± 2.4
13	2398.1	905.8 ± 0.4	14.9 ± 2.7	15.5 ± 3.1	—
		2398.1 ± 0.2	85.1 ± 4.1	84.5 ± 3.4	100
14	2409.1	161.8 ± 0.2	4.8 ± 0.3	6.7 ± 0.6	3.7 ± 0.5
		931.8 ± 0.2	42.0 ± 2.3	34.2 ± 1.0	42.6 ± 2.5
		2409.1 ± 0.2	53.2 ± 1.3	59.7 ± 2.9	53.7 ± 2.6
15	2430.0	268.1 ± 0.2	100	100	100
16	2431.0	1067.9 ± 0.5	2.7 ± 0.9	2.7 ± 0.2	2.5 ± 0.4
		2431.0 ± 0.2	97.3 ± 2.4	97.3 ± 2.1	97.5 ± 0.4
17	2440.4	136.0 ± 0.2	0.2 ± 0.04	—	1.2 ± 0.1
		278.5 ± 0.2	0.3 ± 0.12	—	0.8 ± 0.1
		963.1 ± 0.2	99.5 ± 1.0	100	98.0 ± 0.2
18	2440.6	920.3 ± 0.2	23.3 ± 0.9	4.0 ± 0.2	21.8 ± 1.7
		1077.5 ± 0.2	76.7 ± 1.4	93.3 ± 0.4	78.2 ± 1.7
19	2450.2	145.8 ± 0.2	4.4 ± 1.1	5.9 ± 0.5	4.7 ± 0.6
		202.9 ± 0.2	92.1 ± 3.3	94.1 ± 4.0	92.0 ± 1.1
		288.3 ± 0.2	3.5 ± 0.3	—	3.3 ± 0.3
20	2479.0	1001.7 ± 0.2	38.5 ± 4.2	43.9 ± 3.4	35.8 ± 2.6
		1115.9 ± 0.2	53.5 ± 4.8	40.2 ± 1.4	49.4 ± 2.9
		2479.0 ± 0.2	7.9 ± 1.2	15.9 ± 1.0	14.7 ± 1.9
21	2534.5	287.2 ± 0.5	14.1 ± 1.4	12.8 ± 0.9	13.0 ± 1.6
		1057.2 ± 0.3	53.4 ± 4.5	54.4 ± 1.5	54.6 ± 4.9
		1171.4 ± 0.5	12.9 ± 2.2	12.0 ± 0.5	12.1 ± 2.4
		2534.5 ± 0.3	19.6 ± 1.2	20.8 ± 0.8	20.3 ± 1.0
22	2539.3	1047.0 ± 0.5	100	—	—
23	2573.1	122.9 ± 0.2	76.5 ± 1.2	77.9 ± 6.0	75.6 ± 1.9
		143.1 ± 0.5	0.4 ± 0.11	—	2.6 ± 0.4
		411.2 ± 0.3	23.1 ± 2.3	22.1 ± 1.5	21.8 ± 1.6
24	2642.0	212.0 ± 0.3	29.2 ± 2.9	29.0 ± 1.5	27.5 ± 1.9
		480.1 ± 0.3	70.8 ± 21.9	71.0 ± 3.6	72.5 ± 1.9
25	2667.9	420.6 ± 0.2	21.8 ± 5.3	26.9 ± 1.8	25 ± 5
		506.0 ± 0.2	78.2 ± 12.1	73.1 ± 3.5	75 ± 5

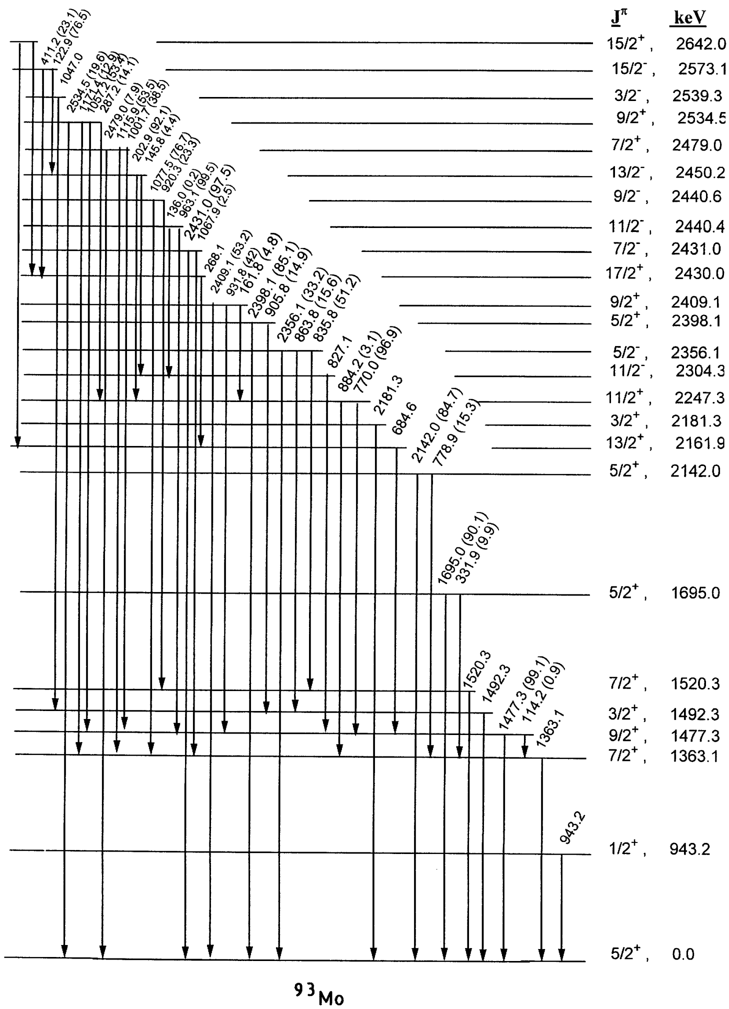

Fig. 2. Level scheme of ^{93}Mo showing the excitation energy and high spin-parity values.

The mean lifetimes were determined using Doppler Shift Attenuation (DSA) method from the singles gamma-ray spectra obtained at various angles between 0° and 90°. As the observed shifts were small because of the low recoil velocity, the drift in the gain of the electronics was continuously monitored with the background photopeaks at 440.0, 1461.0, 1779.1 and 2614.0 keV due to ^{23}Na, ^{40}K, ^{203}Bi and ^{208}Tl, respectively. The plots of the centroids of the photopeaks at different angles versus Cosθ for a few transitions are shown in Fig. 3. The straight line represents the least squar fit. The experimental values of the attenuation factors F(τ) were calculated from

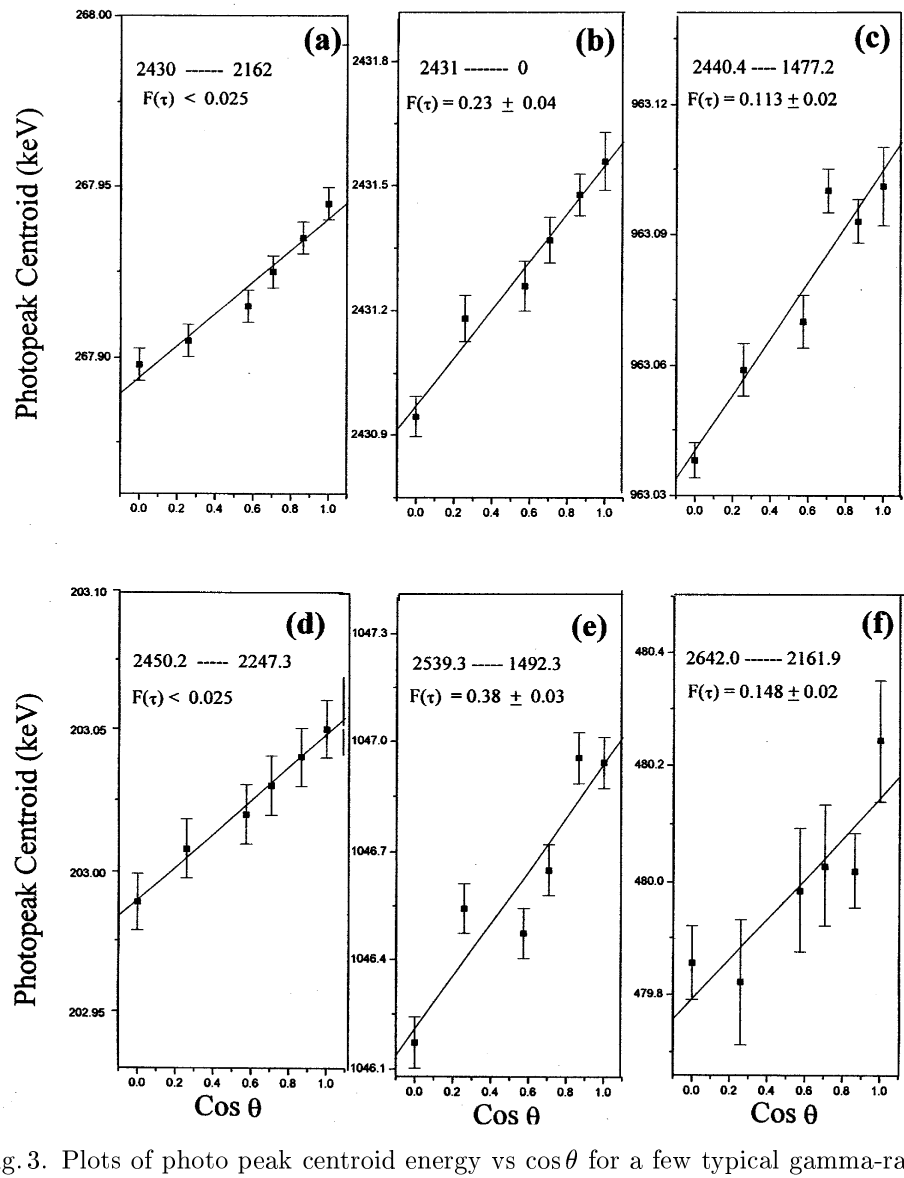

Fig. 3. Plots of photo peak centroid energy vs $\cos\theta$ for a few typical gamma-rays from ^{93}Mo observed in the present work.

the slope of the straight line. The values of theoretical F(τ) were obtained using Lindhard, Scharff and Schiott theory [17] for stopping power alongwith the Blaugrund correction [18] for atomic scattering. The details of the DSAM analysis are given in our earlier publications [19,20]. The values of the measured lifetimes of various levels are given in Table II alongwith their respective experimental $F(\tau)$ values. The mean $F(\tau)$ denotes the average of the $F(\tau)$ values observed for the various transitions from the same level. In the last two columns of this table the values of the lifetimes measured by Rutledge *et al.* [14] are also reported.

TABLE II

Summary of lifetimes and $F(\tau)$ for the excited states in ^{93}Mo.

Level energy (keV)	γ-Ray (keV)	Present experimental $F(\tau)$		Lifetime (fs.)		
		$F(\tau)$	Mean $F(\tau)$	Present work $E_p = 4.3$ (MeV)	Rutledge Ref.[14] $E_p = 4.6$ (MeV)	Rutledge Ref.[14] $E_p = 3.7$ (MeV)
943.2	943.2	< 0.03	< 0.03	> 1000	> 1150	> 610
1363.1	1363.1	0.305 ± 0.030	0.305 ± 0.030	120^{+18}_{-14}	260^{+110}_{-65}	152^{+12}_{-8}
1477.3	1477.3	0.025 ± 0.005	0.025 ± 0.005	950^{+150}_{-200}	> 550	1100^{+900}_{-380}
1492.3	1492.3	0.712 ± 0.141	0.712 ± 0.141	25^{+18}_{-14}	22^{+5}_{-4}	20 ± 3
1520.3	1520.3	< 0.02	< 0.02	> 1200	> 930	1450^{+900}_{-400}
1695.0	331.9	0.338 ± 0.020	0.335 ± 0.025	106^{+9}_{-8}	80^{+15}_{-10}	105^{+15}_{-10}
	1695.0	0.332 ± 0.030				
2142.0	778.9	0.185 ± 0.040	0.187 ± 0.05	220^{+79}_{-48}	175^{+110}_{-35}	—
	2142.0	0.189 ± 0.060				
2161.9	684.6	< 0.03	< 0.03	> 1000	> 800	> 2300
2181.3	2181.3	0.506 ± 0.1	0.506 ± 0.1	55^{+25}_{-17}	53^{+21}_{-15}	—
2247.3	770.0	0.116 ± 0.035	0.116 ± 0.035	380^{+180}_{-97}	380^{+210}_{-105}	405^{+130}_{-85}
2304.4	827.1	0.097 ± 0.01	0.097 ± 0.01	460^{+60}_{-45}	470^{+190}_{-100}	460^{+180}_{-102}
2356.1	835.8	0.095 ± 0.011	0.093 ± 0.015	480^{+96}_{-27}	465^{+185}_{-120}	—
	863.8	0.091 ± 0.019				
	2356.1	0.094 ± 0.015				
2398.1	905.8	0.702 ± 0.1	0.703 ± 0.075	26^{+7}_{-5}	30 ± 5	—
	2398.1	0.704 ± 0.05				
2409.1	161.8	0.065 ± 0.020	0.066 ± 0.015	690^{+106}_{-75}	680^{+140}_{-90}	—
	931.8	0.064 ± 0.015				
	2409.1	0.068 ± 0.011				
2430.0	268.1	< 0.025	< 0.025	> 1200	—	—
2431.0	2431.0	0.23 ± 0.042	0.23 ± 0.042	170^{+50}_{-30}	175^{+25}_{-20}	—
2440.4	963.1	0.113 ± 0.023	0.113 ± 0.023	390^{+110}_{-72}	380^{+425}_{-140}	—
2440.6	920.3	< 0.025	< 0.025	> 1200	> 595	—
	1077.5	< 0.025				
2450.2	145.8	< 0.025	< 0.025	> 1200	—	—
	202.9	< 0.025				
2479.0	1001.7	0.497 ± 0.046	0.501 ± 0.053	56^{+9}_{-6}	49^{+6}_{-5}	—
	1115.9	0.502 ± 0.044				
	2479.0	0.504 ± 0.068				
2534.5	287.2	0.35 ± 0.070	0.355 ± 0.046	97^{+14}_{-10}	100^{+15}_{-6}	—
	1057.2	0.34 ± 0.033				
	1171.4	0.37 ± 0.040				
	2534.5	0.36 ± 0.039				
2539.3	1047.0	0.38 ± 0.03	0.38 ± 0.03	88^{+12}_{-10}	—	—
2573.1	122.9	< 0.025	< 0.025	> 1200	> 260	—
2642.0	480.1	0.148 ± 0.02	0.148 ± 0.02	290^{+50}_{-40}	> 260	—
2667.9	420.6	< 0.03	< 0.03	> 1000	> 425	—

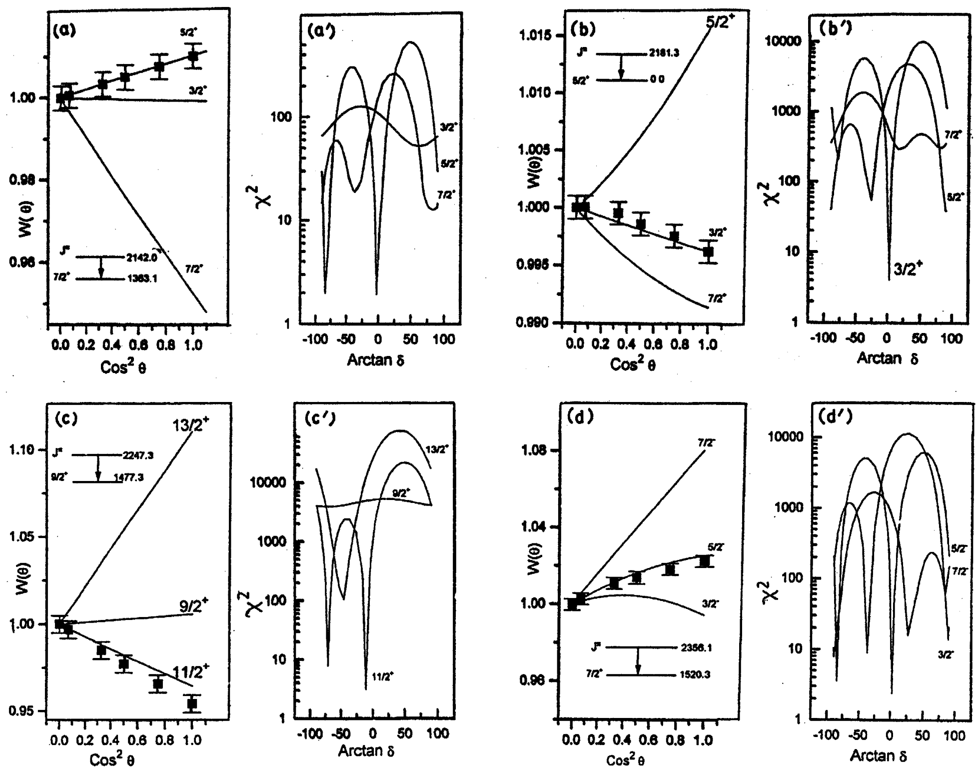

Fig. 4. The angular distributions (a) and χ^2 fit (a') for 778.9 keV transition. Similarly (b,b') for 2181.3 keV transition, (c,c') for 770.0 keV transition and (d,d') for the 835.8 keV transition in ^{93}Mo.

The angular distribution data was used to extract the experimental values of the A_2 and A_4 coefficients by the least-square fit for the expression

$$W(\theta) = 1 + A_2 Q_2 P_2(\cos\theta) + A_4 Q_4 P_4(\cos\theta)\,,$$

where Q_2 and Q_4 are the attenuation factors due to the finite solid angle subtended by the detector. The A_2 and A_4 coefficients were generated theoretically using the computer code CINDY [21] based on the Hauser–Feshbach theory of compound nucleus. The method of analysis of angular distribution data has been described earlier [20]. Figures 4 and 5 show the experimental angular distributions for some of the observed thransitions alongwith theoretical curves for different assumed spins of the decaying states and the respective χ^2 fits as a function of the multipole mixing ratios (δ). The 0.1% confidence limit was used to exclude the unacceptable spin and delta values. The experimental values of the A_2 and A_4 coefficients alongwith multipole mixing ratios are given in Table III.

TABLE III

Summary of angular distribution measurements and multipole mixing ratios (δ) for gamma-rays observed in ^{93}Mo$(p,n\gamma)$ reaction at $E_p = 4.3$ MeV.

Transitions	γ-Rays (keV)	$J_i^\pi \to J_f^\pi$	A_2	A_4	Multipole mixing ratios		
					Present work	Ref. [14]	Ref. [15]
$1363.1 \to 0$	1363.1	$\frac{7}{2}^+ \to \frac{5}{2}^+$	$-0.03(1)$	$-0.01(1)$	$0.5^{+0.9}_{-0.7}$	M1	0.48(7)
$1477.3 \to 1363.1$	114.2	$\frac{9}{2}^+ \to \frac{7}{2}^+$	0.02(2)	0.01(2)	$0.05^{+0.03}_{-0.02}$	M1	< 1.3
$1477.3 \to 0$	1477.3	$\frac{9}{2}^+ \to \frac{5}{2}^+$	0.25(1)	$-0.04(1)$	E2	E2	E2
$1492.3 \to 0$	1492.3	$\frac{3}{2}^+ \to \frac{5}{2}^+$	0.06(1)	0.04(2)	M1	M1	M1
$1520.3 \to 0$	1520.3	$\frac{7}{2}^+ \to \frac{5}{2}^+$	0.34(5)	0.03(5)	$1.2^{+0.5}_{-0.3}$	M1	1.3(6)
$1695.0 \to 1363.1$	331.9	$\frac{5}{2}^+ \to \frac{7}{2}^+$	0.05(20)	0.04(2)	M1	M1	M1
$1695.0 \to 0$	1695.0	$\frac{5}{2}^+ \to \frac{5}{2}^+$	0.08(4)	0.00(5)	M1	M1	M1
$2142.0 \to 1363.1$	778.9	$\frac{5}{2}^+ \to \frac{7}{2}^+$	0.07(2)	0.05(3)	-9.7 ± 0.2	—	—
					$-0.04^{+0.01}_{-0.02}$		
$2161.9 \to 1477.3$	684.6	$\frac{13}{2}^+ \to \frac{9}{2}^+$	$-0.32(1)$	0.05(1)	$-0.15^{+0.04}_{-0.02}$	$-0.11^{+0.03}_{-0.01}$	—
$2181.3 \to 0$	2181.3	$\frac{3}{2}^+ \to \frac{5}{2}^+$	0.04(1)	0.05(1)	M1	M1	M1
$2247.3 \to 1477.3$	770.0	$\frac{11}{2}^+ \to \frac{9}{2}^+$	$-0.34(3)$	0.08(4)	$-0.1^{+0.02}_{-0.03}$	—	—
$2304.4 \to 1477.3$	827.1	$\frac{11}{2}^- \to \frac{9}{2}^+$	$-0.02(0.3)$	$-0.00(0.3)$	$-0.2^{+0.12}_{-0.17}$	$-0.36^{+0.15}_{-0.19}$	—

TABLE III (continued)

1	2	3	4	5	6	7	8
2356.1 → 1520.3	835.8	$\frac{5}{2}^- \to \frac{7}{2}^+$	0.12(2)	0.01(2)	$0.05^{+0.02}_{-0.03}$	—	—
2398.1 → 1492.3	905.8	$\frac{5}{2}^+ \to \frac{3}{2}^+$	0.03(0.3)	0.00(0.4)	M1	M1	—
2398.1 → 0	2398.1	$\frac{5}{2}^+ \to \frac{5}{2}^+$	0.06(3)	0.01(3)	M1	M1	—
2409.1 → 2247.3	161.8	$\frac{9}{2}^+ \to \frac{11}{2}^+$	0.02(2)	0.01(2)	M1	M1	—
2409.1 → 1477.3	931.8	$\frac{9}{2}^+ \to \frac{9}{2}^+$	0.08(4)	0.01(4)	M1	M1	—
2409.1 → 0	2409.1	$\frac{9}{2}^+ \to \frac{5}{2}^+$	0.24(1)	−0.03(1)	E2	E2	E2
2430.0 → 2161.9	268.1	$\frac{17}{2}^+ \to \frac{13}{2}^+$	0.19(1)	−0.00(1)	E2	E2	E2
2431.0 → 1363.1	1067.9	$\frac{7}{2}^- \to \frac{7}{2}^+$	−0.04(1)	0.01(1)	-0.03 ± 0.01 1.2 ± 0.01	—	—
2431.0 → 0	2431.0	$\frac{7}{2}^- \to \frac{5}{2}^+$	−0.06(1)	0.00(2)	$6.5^{+0.14}_{-0.11}$	E2	—
2440.6 → 1363.1	1077.5	$\frac{9}{2}^- \to \frac{7}{2}^+$	−0.02(1)	0.01(1)	-9.7 ± 0.12 0.05 ± 0.11	—	—
2450.2 → 2247.3	202.9	$\frac{13}{2}^- \to \frac{11}{2}^+$	−0.04(2)	0.00(2)	E1	—	E1
2479.0 → 1363.1	1115.9	$\frac{7}{2}^+ \to \frac{7}{2}^+$	0.02(2)	0.02(2)	-0.04 ± 0.04 0.98 ± 0.11	—	—
2534.5 → 1477.3	1057.2	$\frac{9}{2}^+ \to \frac{9}{2}^+$	0.04(2)	0.01(3)	M1	M1	—
2539.3 → 1492.3	1047.0	$\frac{3}{2}^- \to \frac{3}{2}^+$	0.24(3)	0.01(4)	$1.28^{+0.15}_{-0.14}$	—	—
2642.0 → 2430.0	212.0	$\frac{15}{2}^+ \to \frac{17}{2}^+$	0.04(1)	0.03(1)	M1	0.00 ± 0.05	M1
2642.0 → 2161.9	480.1	$\frac{15}{2}^+ \to \frac{13}{2}^+$	−0.21(4)	0.05(5)	0.05 ± 0.07	-0.02 ± 0.05	—

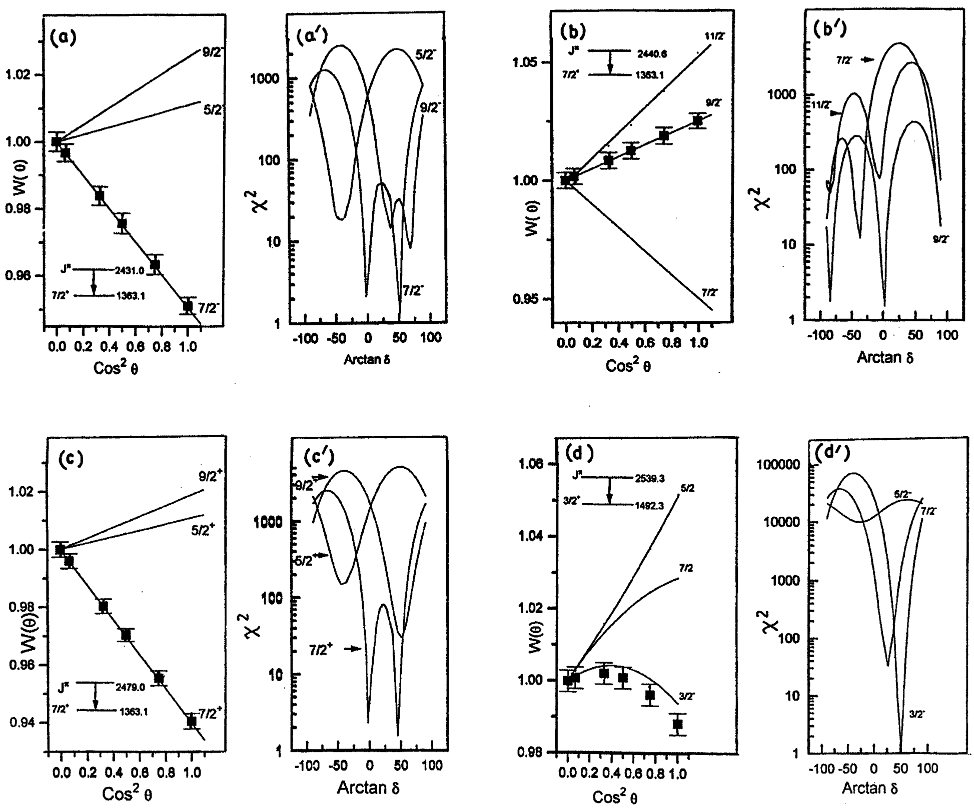

Fig. 5. The angular distributions (a) and χ^2 fit (a') for 1067.9 keV transition. Similarly (b,b') for 1077.5 keV transition, (c,c') for 1115.9 keV transition and (d,d') for the 1047.0 keV transition in ^{93}Mo.

4. Results and discussion

The excitation energies of the various levels in ^{93}Mo were compared with the values available in the literature [9,14,15]. The level energies measured in the present work are in general agreement with the earlier measurements. The weak level at 2539.3 keV not reported earlier [9,14] in $(p, n\gamma)$ reaction but reported in electron capture γ-decay of ^{93}Tc was seen in the present work at 4.0 and 4.3 MeV incident proton energy. The branching ratios for various transitions are compared with the reported values [9,14] and the overall agreement is found to be good. As is evident from Table II, our results for the lifetimes of most of the levels are in good agreement with previous results [14] except for the levels at 1363.1, 2440.6, 2573.1, 2642.0 and 2667.9 keV. This may be attributed due to the poor resolution and the efficiency of the Ge(Li) detector used by Rutledge *et al.* [14]. We were able to measure the lifetimes of the levels at 2539.3 keV and 2642.0 keV as 88^{+12}_{-10} fs and 290^{+50}_{-40} fs, respectively for the first time. Lower limits on the lifetimes of 2430.0 keV and 2450.2 keV levels have also been obtained. The spin velues for most of the levels are consistant with the previous results [15]. The ambiguity in the spin values of the levels at 2181.3, 2247.3, 2356.1 and 2539.3 keV have been removed in the present measurements.

4.1. The 2142.0 keV level

This level has been reported to decay via two γ-rays *i.e.* one to the ground state and other to the 1363.1 keV state with branching ratios [14] of 86.4% and 13.6%, respectively. Our experimental values of the respective branching ratios are 84.7% and 15.3% consistent with the earlier values within experimental errors. The angular distribution of 778.9 keV gamma-ray from this level confirms the spin of this level as $5/2^+$ in Fig. 4(a). Rutledge *et al.* were unable to report mixing ratio for the 778.9 keV transition to the 1363.1 keV state. As evident from the χ^2 fit in Fig. 4(a'), the mixing ratio for this transition is -0.04. This low value of mixing ratio indicates that this transition decays predominately by M1 transition. The lifetime of this level was found to be 220^{+79}_{-48} fs.

4.2. The 2181.3 keV level

From the angular distributions of the 2181.3 keV gamma-ray from this state to the ground state we have assigned $3/2^+$ as the probable spin for this level (Fig. 4(b) and (b')) while Mitarai and Minehara [9] have reported $1/2^+$, $3/2^+$ as two probable spins for this level.

4.3. The 2247.3 keV level

This level has been reported [9] to decay via two branches to the 1363.1 keV and 1477.3 keV states with branching ratios as 3.3% and 96.7%, respectively. We have measured the respective branching ratios as 3.1% and 96.9%. Mitarai and Minehara [9] have assigned $9/2^+$, $11/2^+$ as the probable spins for this level by analysing the neutron yield excitation functions in the vicinity of the isobaric analogue resonances of odd-odd parent ^{94}Nb nucleus. Rutledge *et al.* [14] have also reported the $9/2^+$ and $11/2^+$ spins for this level. The angular distributions of the 770 keV transition de-exciting the 2247.3 keV level to 1477.3 keV ($9/2^+$) level in Fig. 4(c) suggest $11/2^+$ spin to this level with mixing ratio of -0.1 in Fig. 4(c'). The lifetime measured for this level by us is in agreement with the value available in literature [14].

4.4. The 2356.1 keV level

This level was reported to have three branches one to the ground state and other two to the 1492.3 keV and 1520.3 keV states. In the present experiment the respective branching ratios are measured as 33.2%, 15.2% and 51.2% which are in good agreement with the values reported earlier [9,14]. Rutledge *et al.* [14] have assigned $3/2^+$, $5/2^+$, $7/2^+$ spins for this level. As evident from the Fig. 4(d) the angular distributions of the 835.8 keV transition de-exciting 2356.1 keV level to 1520.3 keV ($7/2^+$) level, assigns spin as $5/2^-$ to this level. This assignment is in good agreement with Mitarai and Minehara assignment as compared to Rutledge *et al.* [14]. The mixing ratios of 0.05 in Fig. 4(d') indicates the transition to be purely E1 with very small mixing, if any, of M2 component.

4.5. The 2431.0 keV level

This level was reported to have two branches, one to the ground state and othe to the 1363.1 keV state with branching ratios of 97.3% and 2.7%, respectively [14]. Our experimental values of branching ratios are also the same. The angular distribution of 1067.9 keV transition de-exciting this level to the 1363.1 keV level suggests $7/2^-$ as the spin for this level in Fig. 5(a) with multipole mixing ratio as 1.2 Fig. 5(a').

4.6. The 2440.6 keV level

This level decays to 1363.1 and 1520.3 keV levels via 1077.5 and 920.3 keV γ-rays. The branching ratios measured in this experiment are 76.7% and 23.3%, respectively. These values are in good agreement to the values reported by Mitarai and Minehara [9]. As in evedent from Fig. 5(b), the angular distributions of 1077.5 keV transition propose the spin value as $9/2^-$ to this level with mixing ratio of 0.05 as shown in Fig. 5(b') indicating it to be pure M1 transition.

4.7. The 2479.0 keV level

This level is reported to have three branches, one to the ground state and others to the 1363.1 keV and 1477.3 keV states with branching ratios of 14.7%, 49.4% and 35.8%, respectively. In our experiment the respective branching ratios are found as 7.9%, 53.5% and 38.5%. Rutledge *et al.* were not able to assign any spin to this level. The angular distributions of 1115.9 keV transition in Fig. 5(c) assign the $7/2^-$ spin value to this level with 0.98 or -0.04 as a mixing ratio Fig. 5(c'). The measured lifetime for this level is 56^{+9}_{-6} fs which is in good agreement with the value 49^{+6}_{-5} fs reported by Rutledge *et al.* [14].

4.8. The 2539.3 keV level

This level was seen only in 43.5 min electron capture decay of ^{93}Tc by Podkopaev *et al.* [22], but was not reported in (p,nγ) work [9,14]. However in the present experiment at 4.0 and 4.3 MeV proton energy we could clearly see the 1047.0 keV γ-ray de-exciting this level to 1492.3 keV level. The angular distributions of 1047.0 keV γ-ray assign $3/2^-$ as possible spin to this level Figs. 5(d) and (d') with mixing ratio of 1.28(15). The spin assignment is in good agreement with the assigned values $(1/2, 3/2)^-$ in literature [22]. The lifetime of this level deduced from the present data is 88^{+12}_{-10} fs Fig. 3(c).

4.9. The 2642.0 keV level

This level decays to 2161.9 and 2430.0 keV levels via the 480.1 and 212.0 keV γ-rays with branching ratio of 70.8% and 29.2%, respectively. The branching ratios measured and the spin assignment of this level are in good agreement with the values quoted in the literature [9,14]. We could measure a unique value for the lifetime for this level as 290^{+50}_{-40} fs while Rutledge *et al.* [14] could place only a lower limit of 260 fs.

5. Summary

The purpose of the present study was to provide additional experimental information on the existing level structure of ^{93}Mo through $(p, n\gamma)$ reaction. We have measured the γ-ray energies, branching ratios, lifetimes of the excited levels and multipole mixing ratios of various transitions in ^{93}Mo. We have also deduced the reduced transition probabilities *i.e.* B(E2) and B(M1) values for some of the transitions observed in the present experiment.

The level structure of ^{93}Mo has been predicted on the basis of the shell model calculations by Bhatt and Ball [2] and Vervier [3] using the $(\pi g_{9/2}^2; \nu d_{5/2})$ configuration. Auerbach and Talmi [1] also made shell model calculations considering the $(\pi p_{1/2}^2, \pi g_{9/2}^2; \nu d_{5/2})$ and $(\pi g_{9/2}^4; \nu d_{5/2})$ configurations. All these calculations failed to reproduce the experimental level structure in the energy range 2–3 MeV. Chuu *et al.* [4] used the configuration $(2p_{1/2}^2, 1g_{9/2})$ for four protons and $(2d_{5/2}, 3s_{1/2}, 2d_{3/2}, 1g_{7/2})$ for an active neutron outside the ^{88}Sr core. This model predicts reasonable agreement with the observed energy levels in the low-energy region but fails to reproduce the experimental observations in the energy range 2-3 MeV. The calculations of Kumar *et al.* [23] based on weak coupling approximation within the frame work of nuclear shell theory and exact shell model calculations in a model space consisting of $2p_{1/2}, 1g_{9/2}$ proton orbits and $2d_{5/2}, 3s_{1/2}$ neutron orbits outside the ^{88}Sr core, are in reasonable good agreement with the experimental observations. The calculations of Choudhury and Clemens [6]

TABLE IV

Summary of reduced transition probabilities B(E2) and B(M1) values for a few transitions in ^{93}Mo calculated with the predicted δ-values.

Level (keV)	γ-ray (keV)	Multipole mixing ratios	Reduced transition probabilities (w.u.)			
			Present work		Ref. [14]	
			B(E2)	B(M1) $\times 10^{-3}$	B(E2)	B(M1) $\times 10^{-3}$
943.2	943.2	E2	21.8 ± 10.9	—	< 38	—
1363.1	1363.1	0.5 ± 0.8	10.8 ± 3	85 ± 12	—	83 ± 5
1477.3	114.2	$0.05^{+0.03}_{-0.02}$	—	150 ± 25	—	170 ± 85
	1477.3	E2	4.6 ± 3.5	—	4.2 ± 2.0	—
1492.3	1492.3	M1	—	380^{+70}_{-10}	—	480 ± 70
1520.3	1520.3	$1.2^{+0.5}_{-0.3}$	1.2 ± 0.7	1.7 ± 1.2	—	6.3 ± 2.4
1695.0	331.9	M1	—	810 ± 110	—	590 ± 85
	1695.0	M1	—	56 ± 5	—	59 ± 7
2142.0	778.9	$-0.04^{+0.01}_{-0.02}$	0.13 ± 0.2	83 ± 27	—	—
2161.9	684.6	$-0.15^{+0.04}_{-0.02}$	2.4 ± 1.5	48 ± 24	< 93	—
2181.3	2181.3	M1	—	56 ± 21	—	60 ± 20
2247.3	770.0	$-0.1^{+0.02}_{-0.03}$	3.0 ± 1.9	180^{+80}_{-40}	10 ± 5	160 ± 40
2304.4	827.1	$-0.2^{+0.12}_{-0.17}$	$7.0^{+1.7}_{-4.8}$	1.3 ± 0.1	—	1.5 ± 0.3
2356.1	835.8	$0.05^{+0.05}_{-0.03}$	$84.3^{+11.1}_{-8.6}$	0.56 ± 0.06	—	—
2398.1	905.8	M1	—	980 ± 320	—	220 ± 55
	2398.1	M1	—	36 ± 9	—	65 ± 11
2409.1	161.8	M1	—	580 ± 35	—	630 ± 115
	931.8	M1	—	33 ± 5	—	20 ± 3
	2409.1	E2	0.23 ± 0.03	—	0.35 ± 0.06	—
2430.0	268.1	E2	6.4 ± 0.33	—	—	—
2431.0	1067.9	1.2 ± 0.01	12.9 ± 3.5	0.28 ± 0.1	—	—
	2431.0	$6.5^{+0.14}_{-0.11}$	2.0 ± 0.5	0.27 ± 0.06	2.2 ± 0.03	—
2440.6	1077.5	$-9.7^{+0.12}_{-0.13}$	$5.7^{+0.6}_{-1.9}$	$0.046^{+0.005}_{-0.002}$	—	—
2450.2	202.9	E1	—	0.037 ± 0.002	—	—
2479.0	1115.9	-0.04 ± 0.04	—	200 ± 30	—	—
2534.5	1057.2	M1	—	150 ± 20	—	150 ± 15
2539.3	1047.0	$1.28^{+0.15}_{-0.14}$	$45.14^{+17.1}_{-10.5}$	29^{+13}_{-8}	—	—
2642.0	212.0	M1	—	910 ± 355	—	—
	480.1	0.05 ± 0.07	10.1 ± 2.8	910 ± 260	—	—

within the frame work of intermediate coupling model are in better agreement with our results up to 2 MeV excitation. However, in the excitation range of 2–3 MeV our results seem to be in better agreement with Kumar *et al.* [23] calculations.

The Table IV shows the reduced transition probabilities B(E2) and B(M1) for the transitions observed in the present work along with the results of Rutledge *et al.* [14]. From these results, it is evident that the states at 2356.1 and 2539.3 keV are collective in nature while 943.2, 1363.1, 2431.0 and 2642.0 keV states have mixed structure and the rest of the states have single particle character.

The authors thank the Cyclotron crew for providing an excellent proton beam for the experiment. One of us (TK) also thanks the Ministry of Culture and Higher Education, Iran for financial support in the form of research fellowship.

REFERENCES

[1] N. Auerbach, I. Talmi, *Nucl. Phys.* **64**, 458 (1965).
[2] J.B. Ball, K.H. Bhatt, *Nucl. Phys.* **63**, 286 (1965).
[3] J. Vervier, *Nucl. Phys.* **75**, 17 (1966).
[4] D.S. Chuu *et al.*, *Nucl. Phys.* **A321**, 415 (1979).
[5] M. Itaya, private communication.
[6] D.C. Choudhury, J.T. Clemens, *Nucl. Phys.* **A125**, 140 (1969).
[7] P. Alexander, G. Scharff-Goldhaber, *Phys. Rev.* **151**, 964 (1966).
[8] R.A. Meyer, Y.P. Yaffe, *Phys. Rev.* **C15**, 390 (1977).
[9] S. Mitarai, Minehara, *Nucl. Phys.* **A406**, 55 (1983).
[10] T. Ishimatsu *et al.*, *Nucl. Phys.* **A185**, 273 (1972).
[11] G.A. Gill, G.A. Jones, *Nucl. Phys.* **A224**, 152 (1974).
[12] M.S. Zisman *et al.*, *Phys. Rev.* **C8**, 1866 (1973).
[13] E. Finckh, U. Jahnke, *Nucl. Phys.* **A111**, 338 (1968).
[14] L.L. Rutledge *et al.*, *Phys. Rev.* **C13**, 2166 (1976).
[15] Coral M. Baglin, *Nuclear Data Sheets* **80**, No. 1, 1 (1997).
[16] J. Singh *et al.*, *Proc. DAE Symp. Nucl. Phys.* **B37**, 455 (1994).
[17] J. Lindhard *et al.*, *Mat. Fys. Medd. Dan. Vidensk. Selsk.* **33**, No. 14 (1963).
[18] A.E. Blaugrund, *Nucl. Phys.* **88**, 501 (1966).
[19] V.K. Mittal, D.K. Avasthi, I.M. Govil, *Phys. Rev.* **C26**, 1310 (1982).
[20] V.K. Mittal, D.K. Avasthi, I.M. Govil, *J. Phys. G* **9**, 91 (1983).
[21] E. Sheldon, V.C. Rogers, *Comput. Phys. Commun.* **6**, 99 (1973).
[22] Y.N. Padkopaev *et al.*, *Izv. Akad. Nauk SSSR,Ser. Fiz.* **41**, 1217 (1977); *Bull. Acad Sci. USSR, Phys. Ser.* **41**, No.6, 93 (1977).
[23] Ashwani Kumar, R.K. Bansal, *J. Phys.* **G5**, No.2, 2 (1979).