Low energy octupole resonance in ^{46}Ti studied by inelastic proton scattering at 65 MeV

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(Received 7 November 1986)

The level structure of the low-energy octupole resonance in ^{46}Ti has been studied by inelastic scattering using a 65 MeV polarized proton beam. The excitation strength and distribution of the 2^+, 3^-, and 4^+ states below $E_x \sim 8.0$ MeV have been determined. The energy weighted sum rule fractions of 10.8%, 11.7%, and 1.98% are found to be exhausted for the quadrupole, octupole, and hexadecapole transitions, respectively. No clear bump of the low-energy octupole resonance strength isolated from the first 3^- states has been observed. All the 3^- states dispersed in the region of $E_x = 3$–8 MeV seem to form one bump in ^{46}Ti. It is suggested that the fragmentation of a collective 3^- state is due to the coupling effect of the octupole excitation with the static deformation of the ^{46}Ti ground state, being in qualitative agreement with a random phase approximation calculation.

I. INTRODUCTION

Recent high resolution (p,p′) studies of the low energy octupole resonance[1,2] (LEOR) seem to have established that the LEOR, which was first observed systematically as a 1–2 MeV width bump by inelastic α scattering[3] from nuclei with $66 \leq A \leq 200$ with a resolution of about 100 keV, is composed of many discrete 3^- levels. Furthermore, the high resolution experiments also revealed that the summed strength of the discrete 3^- states in the LEOR excitation energy region ($E_x \sim 32A^{-1/3}$ MeV) was 10–20% of the energy weighted sum rule (EWSR) strength in the nuclei ^{208}Pb, ^{48}Ca, ^{50}Ti, ^{52}Cr, and ^{54}Fe. This implies that the occurrence of the LEOR strength with a fine structure, as typically illustrated in Fig. 1 for the case of the N=28 isotones, is a rather common phenomenon for all the nuclei throughout the periodic table.

In this paper, we report the results of the high resolution (p,p′) study of the low-energy octupole resonance in ^{46}Ti. The experimental situation in ^{46}Ti as regards the fragmentation of the 3^- states is of special interest. As first reported by Yntema and Satchler[4] from inelastic α scattering at 43 MeV, a small number of closely spaced strong 3^- states in ^{46}Ti have been known so far. Contrary to the expectation from the general behavior of collective first 3^- states, the first 3^- state in ^{46}Ti is not the strongest. Most of the 3^- strength is found to be exhausted by the third 3^- state. Yntema and Satchler suggested from these empirical facts that the lowest 3^- strength is fragmented among two or more levels in ^{46}Ti by some interaction. However, the explanation of this fragmentation of octupole strength is not clear as yet.

Similar observations of the fragmentation of the low-lying 3^- state have been reported in the Mg, Sm, and Er mass regions where there appear typical deformed nuclei.[5–7] Since the ground state of ^{46}Ti is considered to have a permanent quadrupole deformation, there is a possibility that the fragmentation of the strong 3^- state in ^{46}Ti might be explained in terms of the coupling effect of the octupole excitation with the deformation degree of freedom.[8] In fact, the spreading and weakening of the LEOR strength has been observed in the case of heavy deformed nuclei, in qualitative agreement with theoretical predictions.[3,8,9]

The interest in the fragmentation of the low-lying 3^- states in connection with the low-energy octupole resonance in ^{46}Ti impelled us to study the more detailed level structure of ^{46}Ti through a high resolution inelastic scattering measurement using a 65 MeV polarized proton beam. In order to get a reasonable explanation for the fragmentation of the 3^- states, the information about the strength distribution of the 3^- states, if possible, over the $1\hbar\omega$ excitation energy region seems to be indispensable. It should be noted that since the bombarding energy of 65 MeV is high to ensure the predominance of a simple direct excitation process, and since analyzing powers were measured, the present experiment provides reliable spin-parity assignments and transition strengths.

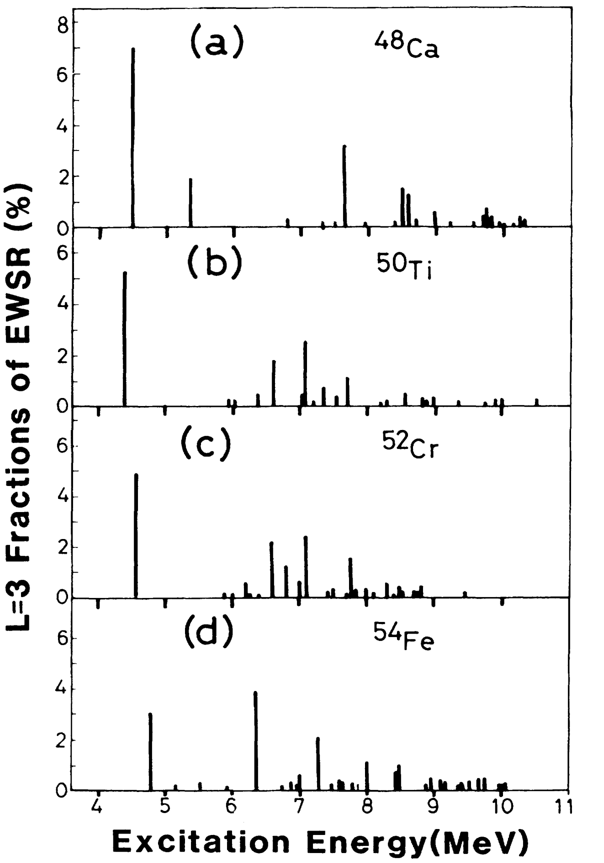

FIG. 1. The distributions of the energy-weighted sum rule (EWSR) percentages for the $L=3$ strengths found in the $N=28$ isotones of ^{48}Ca, ^{50}Ti, ^{52}Cr, and ^{54}Fe. The experimental data are taken from Refs. 1 and 2.

II. EXPERIMENTAL PROCEDURES

The experiment was carried out using a 65 MeV polarized proton beam from the azimuthally-varying-field cyclotron at the Research Center for Nuclear Physics (RCNP) at Osaka University. The data have been obtained using the magnetic spectrograph RAIDEN.[10] The polarized protons were produced by an atomic-beam-type ion source. The beam was energy analyzed by a tandem monochrometer system and deflected by a cleanup magnet before entering the scattering chamber of the spectrograph.

During the experiment, the proton beam polarization was intermittently monitored by a sampling-type beam polarimeter placed in the beam line.[11] A polyethylene (CH_2) target foil was periodically put in the beam for a few seconds with an interval of 10—100 sec. The beam polarization was checked by measuring the ^{12}C(p,p$_0$) analyzing power ($A_y=0.975$ at the scattering angle of 47.5° for elastic scattering of 65 MeV protons) in the period when the polarimeter target was in the beam. The measurement with the spectrograph was carried out only when the polyethylene target was out of the beam. A beam polarization of 85—87% was routinely obtained with beam currents of up to 30 nA on the target. The proton spin orientation was periodically reversed every second in order to minimize systematic errors.

The target used was a self-supporting metallic foil of ^{46}Ti with the measured thickness of 0.275 mg/cm^2 and isotopic enrichment of 81.2% (^{46}Ti:81.2%, ^{47}Ti:2.1%, ^{48}Ti:14.5%, ^{49}Ti:1.1%, and ^{50}Ti:1.1%).

The reaction products were momentum analyzed by the spectrograph, and subsequently detected by a counter system[12] consisting of a two-dimensional position sensitive proportional counter of 1.5 m in length, two gas proportional counters as ΔE detectors, and a plastic scintillation E counter.

The position information (x) along the focal plane was obtained by the charge-division method, and vertical positions (y) were determined by measuring the drift time of the electrons liberated in the ionization process. All data were stored on magnetic tapes in a list mode by using a computer. The final momentum spectra were obtained in an off-line analysis where particle identification and background reduction were made by requiring coincidences with the gates in the $\Delta E - E$ and $x - y$ two dimensional spectra. The detailed description of the data deduction method has already been given in Ref. 12. The typical energy resolution was 25 keV full width at half maximum (FWHM), which was dominated by the beam resolution of polarized protons. The solid angle of the spectrograph was set at 3.2 msr with the angular acceptance of $\pm 1.15°$ in the plane of reaction. The angular distributions were measured over the angular range of $\theta_{lab}=10$—47°.

The normalization factor to convert yields to cross section values was obtained by comparing the measured yields of the elastically scattered protons with the optical model calculation of Noro *et al.*[13] The absolute cross sections thus obtained were within 10% of those calculated independently from the knowledge of the target thickness, solid angle, and collected charge. Due to the limited energy range ($\Delta E_x \sim 4.5$ MeV) in one spectrum available for each setting of the spectrograph field, two series of measurements were required to cover the excitation energy up to $E_x \sim 8.5$ MeV.

The position spectra were analyzed by the automatic peak-searching and peak-fitting program "SPECFIT" (Ref. 14). Contamination peaks caused by the poor enrichment of the ^{46}Ti target were carefully checked and rejected in the analysis using the information from the ^{47}Ti, ^{48}Ti, and ^{50}Ti(p,p′) spectra at $E_p=65$ MeV, which was obtained in separate runs.

The energy calibration was obtained from the known excitation energies of some low-lying states in ^{46}Ti. The energy determinations were consistent to ± 5 keV or less for strong peaks with those quoted in the recent new level scheme.[15] We estimate the accuracy of the present excitation energy to be better than 10 keV for the states above $E_x=5$ MeV. Conversion of momentum spectra to energy spectra was accomplished via the energy calibration.

In Fig. 2, a typical proton spectrum of the inelastic proton scattering on ^{46}Ti at $E_p=65$ MeV is compared with those on ^{48}Ti and ^{50}Ti at the scattering angles where the cross sections for the 3^- states are nearly maximum. The

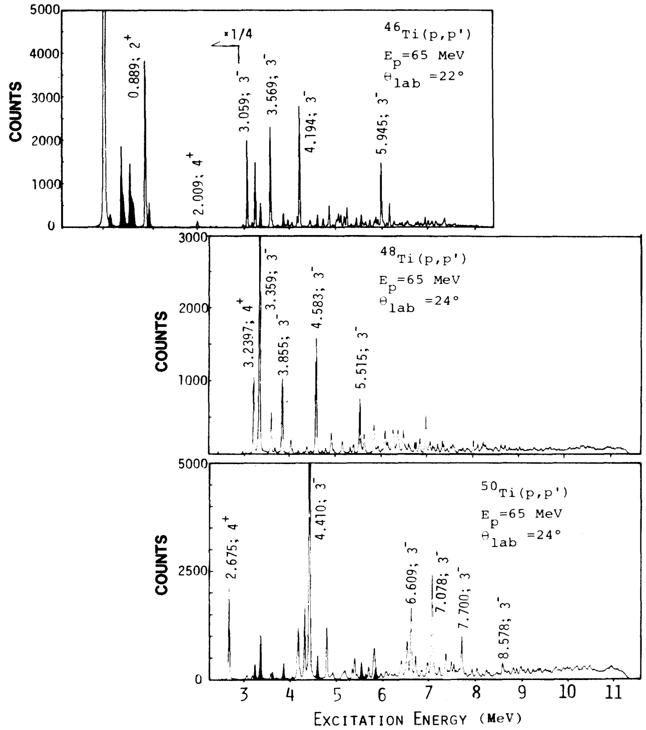

FIG. 2. Energy spectra of inelastically scattered protons on the ^{46}Ti, ^{48}Ti, and ^{50}Ti targets at $E_p = 65$ MeV. Contamination peaks due to ^{48}Ti are indicated.

first 3^- state at $E_x = 4.410$ MeV is seen to be the strongest one among many 3^- states in the ^{50}Ti(p,p′) spectrum, while the first 3^- state at $E_x = 3.059$ MeV in ^{46}Ti is not the strongest in the ^{46}Ti(p,p′) spectrum. Apparently, other two 3^- states at $E_x = 3.569$ and 4.194 MeV are more strongly excited than the first 3^- state, being consistent with the previous measurements.[4,16] Although in ^{50}Ti several strong 3^- peaks making up the LEOR bump appear at $E_x = 6$–9 MeV [see also Fig. 1(b)], there are only a few strong 3^- peaks in the LEOR region in ^{46}Ti.

III. ANALYSIS

Angular distributions were analyzed in the framework of distorted-wave Born approximation (DWBA). In order to predict the inelastic cross sections and analyzing powers, the code ECIS (Ref. 17) was employed under the condition of neglecting the channel coupling effect. The form factors used in the calculations were of conventional collective types with the full Thomas terms for the spin-orbit part.[17] The full Thomas terms were necessary to obtain good fits to the analyzing power data. A set of the best-fit optical model parameters[13] was used for the incoming and outgoing proton channels and for the calculations of transition form factors. The effect of Coulomb excitation was included in the calculations, but the results for the states with $L \geq 2$ angular momentum transfer were not sensitive to the inclusion of this process. The results of the DWBA calculations thus obtained were found to be in rather good agreement with both the cross section

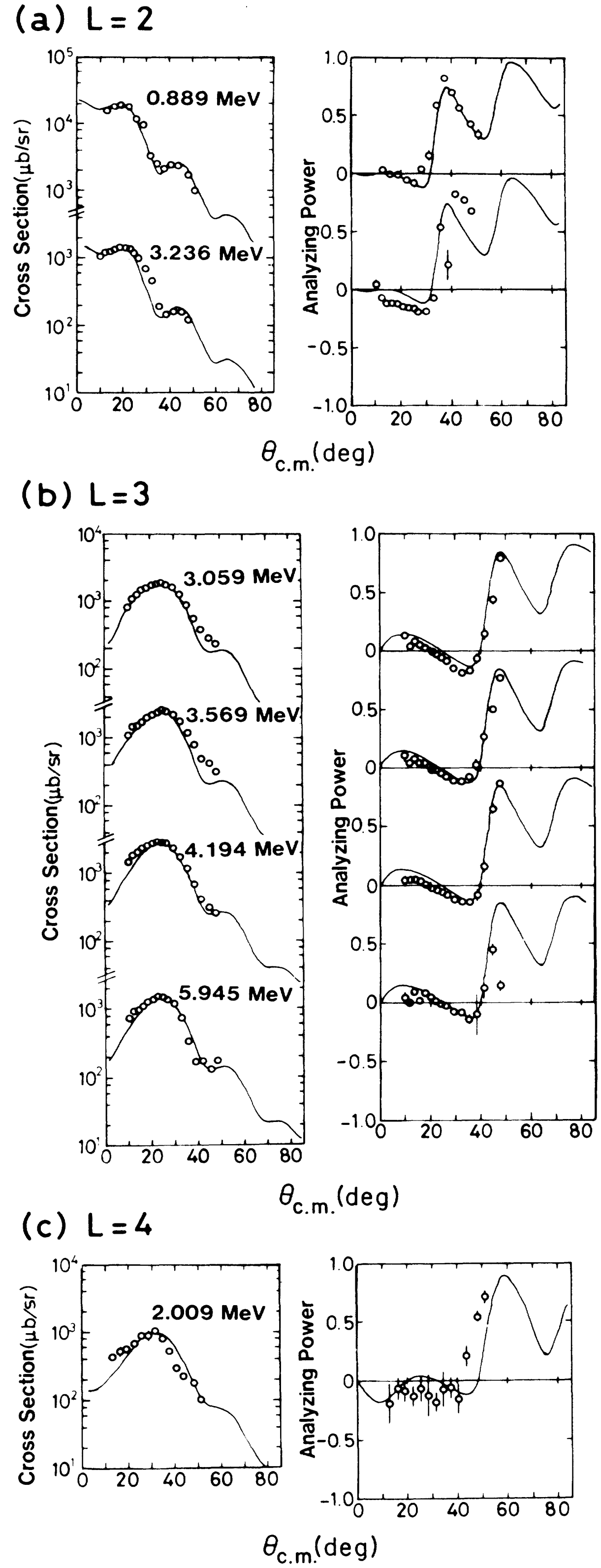

FIG. 3. The angular distributions for typical $J^\pi = 2^+$, 3^-, and 4^+ states in ^{46}Ti. The DWBA calculations shown by solid curves are normalized to the data.

TABLE I. Present inelastic proton scattering results for the excitation energies, J^π $\beta_l R$, and EWSR percentages for the levels of ^{46}Ti compared with previous results.

	Present work			(p,p′)[a]		(α,α′)[b]	
E_x (MeV)	J^π	$\beta_l R$ (fm)	EWSR (%)	J^π	$\beta_l R$ (fm)	J^π	$\beta_l R$ (fm)
0.889	2^+	1.1	5.66	2^+	1.30	2^+	1.18
2.009	4^+	0.37	0.40	4^+	0.72		
2.961	2^+	0.071	0.08	2^+	0.24		
3.059	3^-	0.423	1.38	3^-	0.70	3^-	0.36
3.168	1^-						
3.236	2^+	0.29	1.45				
3.298	6^+	0.081	0.01				
3.436							
3.569	3^-	0.459	1.90	3^-	0.77	3^-	0.41
3.607							
3.680							
3.722	$(4^+,5^-)$						
3.848	$(4^+,5^+,5^-,6^+)$			4^+	0.41		
3.893	2^+	0.060	0.07				
3.941	4^+	0.161	0.15				
4.006							
4.030							
4.143	2^+	0.133	0.39				
4.194	3^-	0.511	2.77	3^-	0.95	3^-	0.47
4.312	1^+						
4.370	3^-	0.074	0.06				
4.419	(5^-)	0.215	0.20				
4.527	(6^+)	0.168	0.09				
4.700	(2^+)	0.117	0.34				
4.788							
4.827	3^-	0.208	0.53				
4.900							
5.027	3^-	0.127	0.21				
5.080	(4^+)	0.205	0.32				
5.154							
5.207	3^-	0.200	0.52				
5.230							
5.360	$(5^-,6^+)$						
5.409	3^-	0.137	0.26				
5.515	2^+	0.142	0.59				
5.604	(2^+)	0.089	0.24				
5.697	(2^+)	0.127	0.49				
5.793	4^+	0.155	0.21				
5.828	3^-	0.142	0.30				
5.872	(2^+)	0.112	0.39				
5.945	3^-	0.367	2.03				
5.992	(4^+)	0.155	0.21				
6.118	2^+	0.185	1.11				
6.217	3^-	0.112	0.20				
6.275							
6.338	4^+	0.114	0.12				
6.389	4^+	0.134	0.17				
6.458	3^-	0.078	0.10				
6.513							
6.574							
6.685	4^+	0.142	0.20				
6.739	(4^+)	0.142	0.20				
6.794							
6.852							
6.890	$(3^-,4^+)$						
6.958	(3^-)	0.142	0.35				
7.019	$(3^-,4^+)$						

TABLE I. (*Continued*).

	Present work			(p,p')[a]		(α,α')[b]	
E_x (MeV)	J^π	$\beta_l R$ (fm)	EWSR (%)	J^π	$\beta_l R$ (fm)	J^π	$\beta_l R$ (fm)
7.120	(3^-)	0.127	0.29				
7.172							
7.238							
7.312	3^-	0.155	0.45				
7.392	(3^-)	0.088	0.15				
7.472							
7.534	(3^-)	0.088	0.15				
7.608							
7.660							
7.710							
7.735							
7.788							
7.874							
7.937							
8.013							
8.040							
8.134							
8.230							

[a]Reference 16.
[b]Reference 4.

and analyzing power data.

The L assignment through the comparison of the data with the DWBA prediction was made using the position of the first and largest maximum in the cross section, and also using the overall shapes of the analyzing power. The deformation parameter $\beta_l R$ and the fractions of the energy weighted sum rule (EWSR) for the isoscalar states were derived by using the procedure given by Satchler.[18] Proton scattering can excite unnatural parity states as well as isovector states. It is, in principle, impossible to exclude the possibility that a few states are of unnatural parity. However, most of the excited states observed in the present work correspond well to those reported in the (α,α') experiments, which may imply negligibly small contributions from the unnatural-parity states. This is also in agreement with the theoretical expectation[19] of relatively weak spin excitations around $E_p = 65$ MeV. Thus we may assume that the states whose angular distributions are well described by the collective model DWBA prediction have natural parities. The possibility of excitation of isovector states was neglected, since simple isovector states with 1p-1h character are expected to occur above the ground analog states in ^{46}Ti at $E_x = 9.156$ MeV.[20]

Figure 3 presents the experimental data of cross sections and analyzing powers for the typical natural parity states in comparison with the DWBA fits. In the energy region analyzed in the present work ($E_x < 8.2$ MeV), we found about 75 levels with different multipolarities. Among them, the angular distributions of as many as 17 levels were identified to be of $L = 3$ character from the collective DWBA prediction. In addition to the octupole states, 11 and 9 states were found to have $L = 2$ and $L = 4$ characters, respectively. There were still remaining many weakly excited states, whose spin-parity assignment was somewhat less reliable.

The observed levels are summarized in Table I and are compared with the previous results. The assignments of J^π values in Table I are based on the observed angular distributions of the cross sections and analyzing powers mentioned above, and also on the correspondence in energy with the known levels.[15]

IV. RESULTS AND DISCUSSIONS

The obtained EWSR fractions are shown in Fig. 4 for the states with $L=2$, 3, and 4 angular momentum transfers. The EWSR fractions found in the energy region below $E_x = 8.2$ MeV in ^{46}Ti are 10.8% for the 2^+ states, 11.7% for the 3^- states, and 1.98% for the 4^+ states. We cannot exclude the possibility that some weak levels might have escaped in the present analysis especially in the high excitation region where the continuum background exists.

Three 3^- states of ^{46}Ti at 3.059, 3.569, and 4.194 MeV show very similar angular distributions of cross sections and analyzing powers to each other (see Fig. 3). The sum of the EWSR fraction depleted by the three 3^- states amounts to 6.07%, which is about a half of the total EWSR fraction observed for the octupole states in the present study. The comparable EWSR value is exhausted by the first 3^- state at $E_x = 4.410$ MeV in ^{50}Ti (5.35%). These facts lead us to the conjecture that the 3^- state which appears as a single level in ^{50}Ti is fragmented in the case of ^{46}Ti, as was first suggested by Yntema and Satchler[4] with the finding of a small number of strongly excited 3^- states. However, there seems to be some problems with this rather simple conjecture for the following reasons: (a) In the present work, many additional 3^-

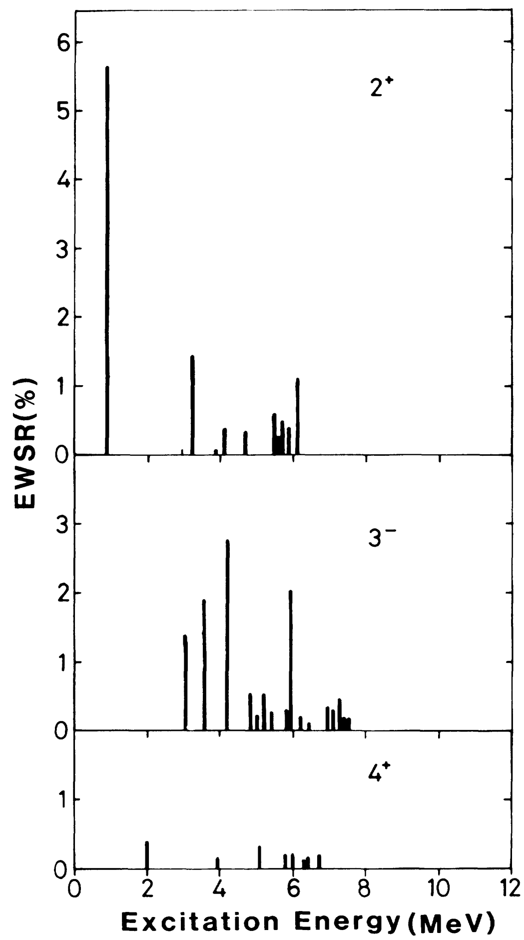

FIG. 4. The distributions of the EWSR percentages for the $L=2$, $L=3$, and $L=4$ strengths found in ^{46}Ti.

states have been observed in the vicinity of the three strong 3^- states in ^{46}Ti. (b) While in ^{50}Ti a clear separation between the first 3^- state and the 3^- states in the LEOR region is recognized [see Fig.1 (b)], no such separation and no LEOR bump exists in ^{46}Ti. (c) In contrast to the ^{50}Ti case, the first 3^- state and the LEOR in ^{46}Ti are seen to be integrated in one bump with the centroid at $E_x=4.86$ MeV. Obviously this resonance excitation energy does not follow the systematic trend of $32A^{-1/3}$ MeV which predicts the central value of $E_x=8.9$ MeV for ^{46}Ti. Thus it might be reasonable to infer that the fragmentation of the first collective 3^- state has a close relation with that of the LEOR strength.

Kishimoto et al.[8] and Malov et al.[9] have studied the effect of the quadrupole deformation on the LEOR bump in heavy deformed nuclei. They have shown that the LEOR strength splits into two or more components depending on the K quantum numbers in a permanent quadrupole deformed nucleus. Since the ground state of ^{46}Ti is known to have a large permanent deformation, similar splitting phenomena of octupole vibration to those in heavy deformed nuclei may be expected to occur also in ^{46}Ti. One of the pieces of evidence for the permanent deformation of the ^{46}Ti ground state is seen in the presence of the well developed rotational ground band of the 0^+, 2^+, 4^+, and 6^+ states. Recent observation of the isovector $M1$ collective excitation in ^{46}Ti also supports a large deformation of the ^{46}Ti nucleus.[21,22]

In the Nilsson model[23] for the deformed nuclei, the $f_{7/2}$ orbit in the spherical shell model splits into four orbits with the quantum numbers $[Nn_z\Lambda]K^\pi$ of $[330]\frac{1}{2}^-$, $[321]\frac{3}{2}^-$, $[312]\frac{5}{2}^-$, and $[303]\frac{7}{2}^-$. The one-particle one-hole excitations combining the intrinsic Nilsson orbit of $[200]\frac{1}{2}^+$, which corresponds to the $s_{1/2}$ orbit at zero deformation, with the above four orbits, are able to produce many 3^- states with different K quantum numbers, contrary to the limited number of the 3^- states in the spherical shell model base. Actually, the contributions from the other Nilsson orbits, such as $[202]\frac{3}{2}^+$ and $[211]\frac{1}{2}^+$, are

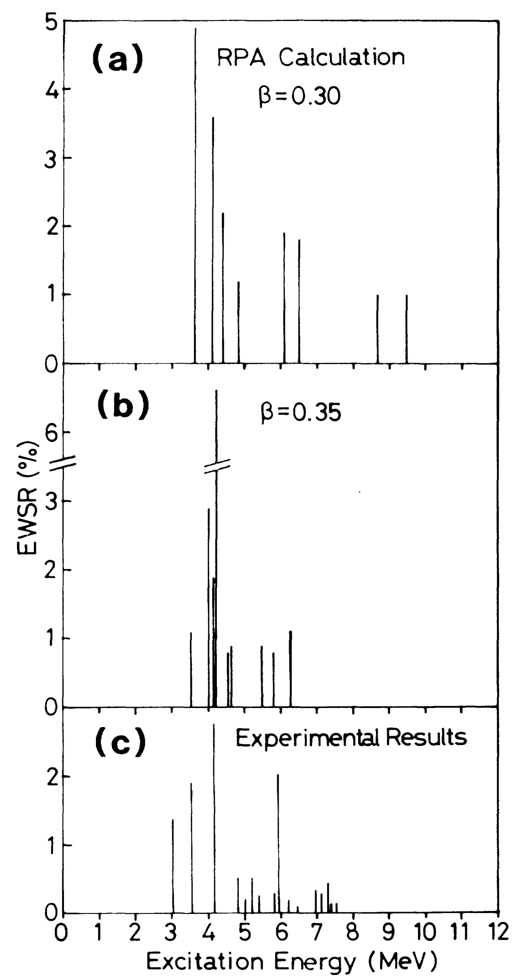

FIG. 5. Comparison of the experimental data and the theoretical calculations of Sakamoto and Kishimoto for the 3^- states in ^{46}Ti. The upper and middle parts are the results of the RPA calculation of the isoscalar EWSR strength with the deformation parameters $\beta=0.3$ and 0.35, respectively, for the ^{46}Ti ground state. The lower part shows the experimental data on the isoscalar EWSR strength distribution obtained in the present (p,p′) study.

also incorporated to form a larger number of additional 3^- states.

Recently, Sakamoto and Kishimoto[24] performed a random-phase-approximation (RPA) calculation to explain the fragmentation of the low-lying 3^- states in ^{46}Ti. This theoretical model is an extension of the work of Ref. 8 to the octupole case in the fp shell nuclei. The results of their model calculation are compared with the experimental data in Fig. 5. In the case where the ground state deformation parameter is $\beta=0.3$, the lowest 3^- state remains the strongest one [see Fig. 5(a)]. For $\beta=0.35$, the fourth 3^- state at $E_x=4.2$ MeV becomes the strongest [Fig. 5(b)], which is qualitatively in agreement with the experimental observation. Thus it appears that the large deformation possibly leads to the splitting of the 3^- state. In both the calculations, the resulting percentages of the isoscalar EWSR values are about 19%, irrespective of the deformation parameters. The experimental EWSR percentages are about 12%. It is not clear at the present time whether or not the missing part of about 7% is due to the experimental difficulties in finding weak 3^- states. On the basis of the present analysis it cannot be excluded that part of the missing strength will be observed at higher excitation energies than 8 MeV. It is noteworthy to point out here that the coupling with the underlying 2p-2h states would cause further fragmentation of the 3^- states.

V. SUMMARY AND CONCLUSION

In the present high resolution (p,p′) experiment, the fine structure of the low-energy octupole resonance (LEOR) in ^{46}Ti has been studied. A large number of new peaks have been observed in the excitation energy below $E_x=8.2$ MeV. The differential cross sections and analyzing powers were measured over the angular range of $\theta_{lab}=10$—$47°$. A collective-model DWBA analysis has been carried out to determine transferred L values and deformation parameters for the excited states in ^{46}Ti. Many states have been assigned to be natural-parity states with $L=2$, 3, and 4. The fractions of the EWSR (energy-weighted sum rule) depleted are found to be 10.8%, 11.7%, and 1.98% for the quadrupole, octupole, and hexadecapole transitions, respectively.

We have confirmed that the first 3^- state at $E_x=3.059$ MeV is not the strongest one among many low-lying 3^- states in ^{46}Ti, in contrast to the common observation for the first 3^- state in other nearby nuclei. No clear separation in energy between the LEOR bump and the lowest 3^- state has been observed. The envelope of the strength distribution of the 3^- states showed one resonance-like shape with the centroid at 4.89 MeV which is considerably lower than the empirical expectation value of $32A^{-1/3}$ MeV for the LEOR bump. The splitting of the collective 3^- state observed in ^{46}Ti has been interpreted to originate from the permanent quadrupole deformation of the ground state. On the basis of the deformed Nilsson model, it has been schematically shown that the collective 3^- state can possibly split into, at least, four components with the quantum numbers $K=0$, 1, 2, and 3 in ^{46}Ti. The experimental strength distribution of the 3^- states has been found to be in qualitative agreement with the result of the RPA calculation by Sakamoto and Kishimoto in which a large permanent deformation of $\beta=0.35$ is considered for the ^{46}Ti ground state. Generally speaking, the splitting of the collective first 3^- state into the $K=0$, 1, 2, and 3 components as discussed in the present paper seems to be a phenomenon similar to the well known splittings of the giant dipole and quadrupole resonances in deformed nuclei.[7,8,25] Thus, the present experiment, which has revealed the fragmented strength distributions for the $L=2,3,4$ states over the $1\hbar\omega$ excitation in ^{46}Ti, may provide further information in understanding the octupole-quadrupole coupling effect in nuclei.

In this connection, it would be of special importance to investigate the fine structures of the octupole strength distributions in ^{154}Sm and ^{170}Er via high resolution inelastic scattering. In these well deformed nuclei, the splitting and weakening of the low-lying 3^- states has been reported. It is hopefully with such experimental studies as reported here that the octupole-quadrupole coupling effect might be observed more clearly.

ACKNOWLEDGMENTS

The authors wish to thank RCNP staff members for generous support during the experiments. They are grateful to Prof. T. Kishimoto and Dr. H. Sakamoto (Tsukuba University) for allowing us to compare the experimental data with their results of the RPA calculations of octupole excitations in the present paper. Sincere thanks are also due Prof. H. Ohnuma for the loan of the ^{47}Ti target which was used in the ^{47}Ti(p,p′) measurement for the identification of contamination peaks. This experiment was performed at RCNP under Program No. 21A11.

[1]Y. Fujita, M. Fujiwara, S. Morinobu, I. Katayama, T. Yamazaki, T. Itahashi, H. Ikegami, and S. I. Hayakawa, Phys. Rev. C **32**, 425 (1985).
[2]M. Fujiwara, Y. Fujita, S. Imanishi, S. Morinobu, T. Yamazaki, H. Ikegami, K. Katori, and S. I. Hayakawa, Phys. Rev. C **32**, 830 (1985).
[3]J. Moss, D. R. Brown, D. H. Youngblood, C. M. Rozsa, and J. D. Bronson, Phys. Rev. C **18**, 741 (1978).
[4]J. L. Yntema and G. R. Satchler, Phys. Rev. **161**, 1137 (1967).
[5]K. van der Borg, M. N. Harakeh, and A. van der Woude, Nucl. Phys. **A365**, 243 (1981).
[6]P. O. Tjøm and B. Elbek, Nucl. Phys. **A107**, 385 (1968).
[7]A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, Reading, Mass., 1975), Vol. II, pp. 453 and 577.
[8]T. Kishimoto, J. M. Moss, D. H. Youngblood, J. D. Bronson, C. M. Rozsa, D. R. Brown, and A. D. Bacher, Phys. Rev. Lett. **35**, 552 (1975); T. Kishimoto, private communication.
[9]L. A. Malov, U. O. Nesterenko, and V. G. Soloviev, J. Phys. G **3**, L219 (1977).
[10]H. Ikegami, S. Morinobu, I. Katayama, M. Fujiwara, and S.

Yamabe, Nucl. Instrum. Methods **175**, 335 (1980).
[11]T. Ichihara, H. Sakaguchi, K. Hatanaka, M. Fujiwara, and K. Hosono, Research Center for Nuclear Physics (Osaka) Annual Report, 1981, p.194.
[12]Y. Fujita, K. Nagayama, M. Fujiwara, S. Morinobu, T. Yamazaki, and H. Ikegami, Nucl. Instrum. Methods **217**, 441 (1983).
[13]T. Noro, H. Sakaguchi, M. Nakamura, K. Hatanaka, F. Ohtani, H. Sakamoto, and S. Kobayashi, Nucl. Phys. **A366**, 189 (1981).
[14]H. P. Blok, J. C. Delange, and J. W. Schotman, Nucl. Instrum. Methods **128**, 545 (1975).
[15]R. L. Auble, Nucl. Data Sheets **24**, 1 (1976).
[16]R. J. Peterson and D. M. Perlman, Nucl. Phys. **A117**, 185 (1968).
[17]J. Raynal, code ECIS79, Saclay (unpublished); J. Raynal, International Atomic Agency Report IAEA-5MR-818, 1972, p.75.
[18]G. R. Satchler, Nucl. Phys. **A195**, 1 (1972).
[19]F. Petrovich and W. G. Love, Nucl. Phys. **A354**, 499c (1981).
[20]F. D. Becchetti, D. Dehnhard, and T. G. Dzubay, Nucl. Phys. **A168**, 151 (1971).
[21]C. Djalali, N. Marty, M. Morlet, A. Willis, J. C. Joudain, D. Bohle, U. Hartmann, G. Küchler, A. Richter, G. Caskey, G. M. Crawley, and A. Galonsky, Phys. Lett. **164B**, 269 (1985).
[22]L. Zamick, Phys. Rev. C **31**, 1955 (1985).
[23]S. G. Nilsson, Kgl. Dansk. Vidensk. Selsk., Mat.-Fys. Medd. **29**, No. 16 (1955).
[24]H. Sakamoto and T. Kishimoto, private communication.
[25]M. Danos, Nucl. Phys. **5**, 23 (1958).