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Observation of 1^+ state in ^{48}Ca by hadron inelastic scattering

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The 10.2 MeV state in ^{48}Ca has been confirmed to be $J^\pi = 1^+$ by (p,p') and (α,α') experiments. The state was strongly excited by the (p,p') reaction at $E_p = 65$ MeV. Differential cross sections of the state are compared with a microscopic distorted-wave Born approximation calculation based on a shell model. The calculation overestimates the cross sections by a factor of 4.

NUCLEAR REACTIONS ^{48}Ca(p,p'), $E = 65$ MeV, ^{48}Ca(α,α'), $E = 70$ MeV; measured $\sigma(\theta)$; $J^\pi = 1^+$ assigned for the 10.2 MeV level. Enriched target. DWBA analysis.

Among the important problems in nuclear structure are the location and the strength of spin excitation.[1] Study of $M1$ transitions by proton inelastic scatterings is indispensable in order to obtain better understanding of the spin excitation in nuclei and of the effective spin-spin interaction. In a shell model picture, $M1$ states are particle-hole states in closed shell nuclei with spin-unsaturated j-shell closure. Thus ^{48}Ca, ^{90}Zr, and ^{208}Pb seem to be the best candidates for studying spin excitation, and concentration of $M1$ strength might be expected in these nuclei. However, the $M1$ strength in these nuclei has been a long standing problem. In the case of ^{208}Pb, the strength which has been experimentally found amounts to only a quarter of a theoretical estimate.[2] Recently there were two reports about the $M1$ states in ^{90}Zr. One is by Meuer *et al.*,[3] who used high resolution inelastic electron scattering. They identified three 1^+ states at 8.233, 9.000, and 9.371 MeV of excitation and suggested seven additional states as probable 1^+ states. The upper limit of the total strength deduced was less than one-third of a theoretical prediction.[3] The other report is by Anantaraman *et al.*,[4] who observed a giant $M1$ transition in ^{90}Zr by the (p,p') reaction at 200 MeV with the energy resolution of 80 keV. The resonance was located at 8.90 ± 0.15 MeV of excitation with the width of 1.7 ± 0.2 MeV [full width at half maximum (FWHM)]. The differences in shape and yield of the 1^+ states between the two experiments seem to raise more questions about the nature of the $M1$ states in ^{90}Zr. In the case of ^{48}Ca a strong $M1$ state was recently identified at 10.227 MeV by Steffen *et al.*[5] using the (e,e') reaction. They reported no significant fragmentation of the $M1$ strength in ^{48}Ca. Another indirect evidence for the strong $M1$ resonance in ^{48}Ca was obtained from the ^{48}Ca(p,n) ^{48}Sc reaction by Anderson *et al.*[6] They found a narrow peak at 16.8 MeV in ^{48}Sc and interpreted it as the analog of the 1^+ state in ^{48}Ca. The ground state analog of ^{48}Ca is at 6.67 MeV, thus their suggestion is consistent with the ^{48}Ca(e,e') result. In view of these circumstances, the present work is devoted to the direct observation of the 1^+ state in ^{48}Ca by the (p,p') reaction. The experiment is particularly important because this mode of excitation provides complementary information about the $M1$ state to the (p,n) reaction. Furthermore, it is of our great interest to see consistency or a difference, if any, between the results from the ^{48}Ca(p,p') and the ^{48}Ca(e,e') experiment about the 1^+ state.

The ^{48}Ca(p,p') experiment was performed using a 65 MeV proton beam from the Research Center for Nuclear Physics cyclotron. The ^{48}Ca target was a 1.06 mg/cm^2 thick self-supporting foil with 97.7% isotopic enrichment. The inelastically scattered protons were

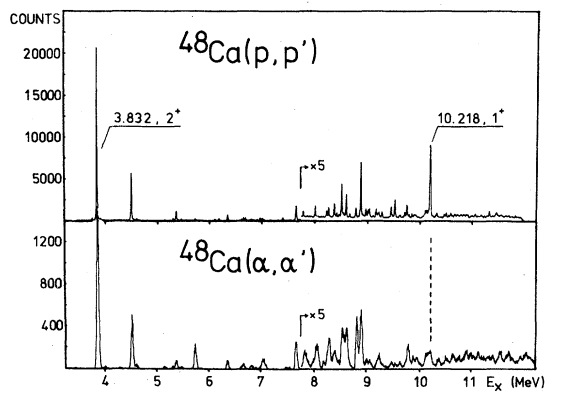

FIG. 1. Upper half: spectrum of inelastically scattered protons on ^{48}Ca at $E_p = 65$ MeV, $\theta_{lab} = 8°$. A sharp peak can be seen at 10.2 MeV. Lower half: spectrum of inelastically scattered α particles on ^{48}Ca at $E_\alpha = 70$ MeV, $\theta_{lab} = 16°$. The peak height for the 2^+ state at 3.832 MeV is normalized to that for the same state in the (p,p') spectrum.

momentum analyzed with the spectrograph RAIDEN[7] and detected with a newly developed 1.5 m long two-dimensional position-sensitive proportional counter.[8] The overall resolution of 15 keV was obtained for the acceptance solid angle of 2.4 msr. Two-dimensional position determination of the particles and the time-of-flight measurements employed in the experiment were powerful in obtaining reliable data by reducing background counts especially at forward angles.

Spectra were taken at angles from $\theta_{lab} = 6°$ to $70°$. The angular distributions for elastic protons were also measured for the calibration of the target thickness and the total efficiency of the spectrograph system. The upper half of Fig. 1 shows the spectrum at $\theta_{lab} = 8°$. A prominent peak was observed at 10.218 ± 0.007 MeV. The width of the peak was not wider than the experimental resolution of 15 keV.

The excitation energy of this peak corresponded well to the 10.227 MeV, 1^+ state observed in the (e,e') experiment.[5] In Fig. 2, the measured angular distribution for this state is presented together with that of the first 2^+ state at 3.832 MeV. A peak deconvolution program was used to obtain reliable cross sections. The absolute errors of the cross sections were estimated to be about 10%. The experimental angular distribution of the 2^+ state shows an oscillating pattern and that of the 10.218 MeV state shows a rather monotonous pattern.

For the purpose of the parity assignment for the 10.218 MeV state, the ^{48}Ca(α,α') experiment was performed at $E_\alpha = 70$ MeV with the same target. The spectra were taken at two angles of $\theta_{lab} = 13°$ and $16°$. The angles chosen corresponded to the expected local minimum and second maximum of the angular distribution for the 2^+ state. Measurements at the two an-

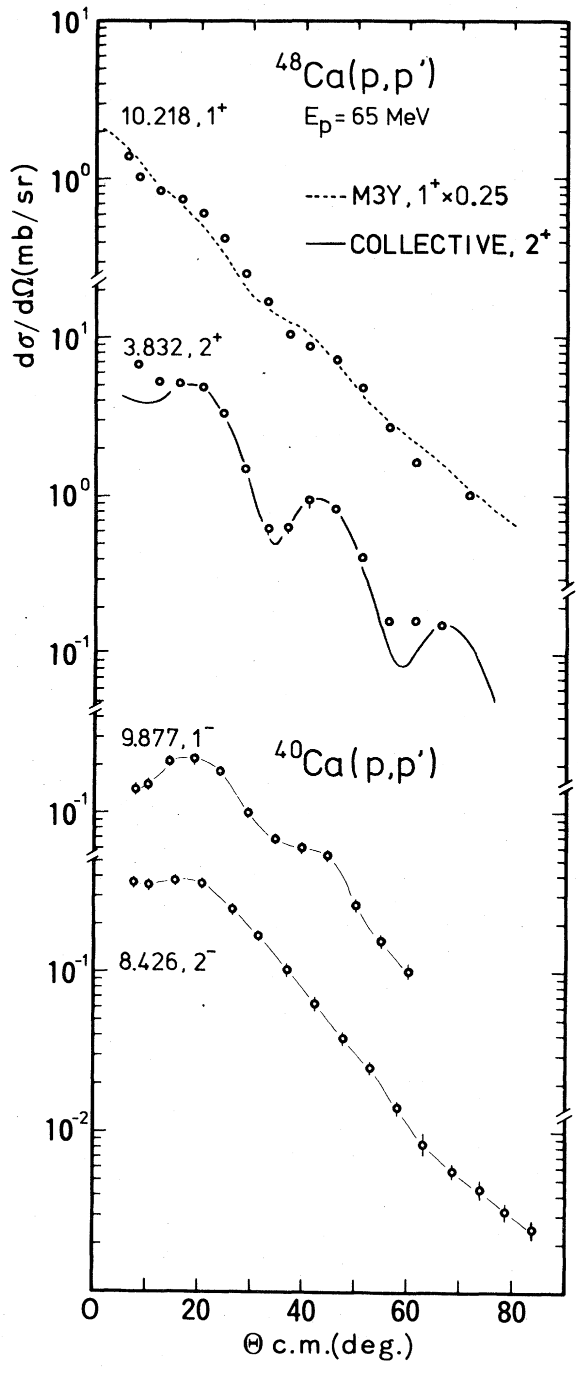

FIG. 2. Upper half: experimental angular distributions of the ^{48}Ca(p,p') reaction leading to the 1^+ and 2^+ states. The dotted line shows the results of the microscopic DWBA calculation for the $J^\pi = 1^+$ state using the M3Y interaction. The calculated absolute cross sections are reduced by a quarter to fit the experimental data. The solid line is the result of the DWBA calculation with a collective form factor. Lower half: angular distributions of the ^{40}Ca(p,p') reaction leading to the 1^- and 2^- states. The solid lines are drawn only for the guide of the eye.

gles were also important for discriminating against contaminant peaks. The spectrum obtained at 16° is shown in the lower half of Fig. 1, where the height of the 3.832 MeV peak is normalized to that of the (p,p') peak. Though the resolution was rather poor ($\sim$30 keV) in the (α,α') experiment, good overall correspondence of the peaks was observed in the two experiments.

In order to make the spin and parity assignment for the 10.218 MeV state, we first examined the result of the (p,p') reaction. Forward peaking of the angular distribution for this state as shown in Fig. 2, rules out the possibility of the 10.218 MeV state being $J \geq 3$, and the possibilities of $J^\pi = 2^+$, 2^-, and 1^- still remain. The comparison between the result of (p,p') and (α,α') experiments strongly suggests that the state is an unnatural parity state. As is seen in Fig. 1, the 2^+ state at 3.832 MeV was clearly seen in both the spectra. On the other hand, no strong peak was seen in the (α,α') experiment around 10.2 MeV of excitation. As shown in Fig. 2, a possibility of this state being 2^- can also be ruled out by comparing the present angular distribution with that of a 2^- state obtained in the $^{40}Ca(p,p')$ reaction at the same incident proton energy.[9] With the same reason $J^\pi = 1^-$ is rejected for the state. Thus we conclude that spin and parity of the 10.218 MeV state are $J^\pi = 1^+$. In our experiment no other evident peak showing the similar angular distribution to that of the 10.218 MeV state was observed in the energy region around 10.2 MeV. It is interesting to note that we obtained a good agreement between the (p,p') and (e,e') experiments in contrast to the case of ^{90}Zr. Concentration of the $M1$ strength in the 10.218 MeV state is in agreement with the calculation[10] using the random phase approximation (RPA), but not with a recent shell model calculation[11] which expects two 1^+ states.

In the distorted-wave analysis we assumed the ground state of ^{48}Ca to be a pure $\nu(f_{7/2})^8$ configuration and the 1^+ state to be a pure $\nu(f_{5/2}, f_{7/2}^{-1})$ configuration. A computer code DWBA74[12] which treats knock-on exchange processes exactly was used. Single particle wave functions were calculated in a Woods-Saxon well of radius $R = 1.25\ A^{1/3}$ fm, diffuseness $a = 0.6$ fm, and a spin-orbit force of 6 MeV. The $1f_{7/2}$ and $1f_{5/2}$ neutrons were assumed to be bound by 9.9 and 1.5 MeV, respectively. The optical-model parameters used were taken from Ref. 13, which fitted not only the elastic cross section but also the polarization data. This set of parameters reproduce well the experimental angular distribution of the 2^+ state at 3.832 MeV in the collective DWBA analysis[14] as shown in Fig. 2. The effective-two-body interaction used is the M3Y[15] which is based on G matrices constructed from realistic interaction potentials.

As shown in Fig. 2, the calculation for the 1^+ state reproduces the decreasing pattern of the angular distribution of the 10.218 MeV state quite well. But it overestimates the cross sections by a factor of 4. This factor may imply that the 10.2 MeV state exhausts about 25% of the total $M1$ strength. This is consistent with the result of the $^{48}Ca(p,n)\,^{48}Sc$ experiment at 160 MeV[6] in which they found that the corresponding $T_>$, 1^+ state in ^{48}Sc exhausted 29% of the sum rule limit. When a similar assumption of $f_{7/2} \rightarrow f_{5/2}$ transition was used in the $^{48}Ca(e,e')$ analysis,[5] they found that the 1^+ state at 10.2 MeV carried roughly one-third of the total $M1$ strength. A similar quenching factor of 2 was also reported for the $M1$ giant resonance in ^{90}Zr through $^{90}Zr(p,p')$ reaction to 200 MeV.[4] Quenching of the $M1$ strength in medium and heavy nuclei is still a big unsettled problem[16] However, recent shell model calculation of ^{48}Ca by McGrory and Wildenthal[11] seems to give better understanding of excitation strength of this 1^+ state.

In summary, we confirmed a strong 1^+ state at 10.218 MeV in ^{48}Ca by using (p,p') and (α,α') experiments. The shape of the angular distribution obtained in the (p,p') reaction was well described by the microscopic calculation using the M3Y interaction. But the experimental yield was found to be a quarter of the calculated yield. The result was consistent with the quenching factors obtained in the recent (e,e') (Ref. 5) and (p,n) (Ref. 6) experiments.

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