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Excitation of the 10.212 MeV 1^+ state in $^{48}Ca(p,p')$ at $E_p = 44.4$ MeV

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Differential cross sections of the $^{48}Ca(p,p')$ (1^+, 10.212 MeV) transition have been measured at $E_p = 44.4$ MeV using an isochronous cyclotron and a high resolution magnetic spectrometer. The data are compared to microscopic distorted-wave Born approximation calculations with wave functions taken from random phase approximation calculations.

[NUCLEAR REACTIONS $^{48}Ca(p,p')$, $E = 44.4$ MeV; measured $\sigma(E;\theta)$; microscopic DWBA analysis, resolution $7-10$ keV; $\theta = 7.3-80.0°$, $\Delta\theta = 4-5°$.]

Investigation of magnetic $M1$ transitions to unnatural parity 1^+ states provides an ideal means to study the distribution of spin excitation strength in nuclei and, directly related to it, the spin and isospin dependent parts of the particle-hole residual interaction. Furthermore, it provides indirect information on the admixture of Δ isobar-nucleon hole excitations in the low-lying excitation spectrum.[1–5] These Δ admixtures manifest themselves in the so-called quenching of the $M1$ and Gamow-Teller transition strength which has now been observed in many nuclei.[5–8] Another interest in the 1^+ states is caused by the possible occurrence of precritical phenomena in finite nuclei related to pion condensation.[9–11] Experimental difficulties in studying 1^+ states arise from the high level density at excitation energies around $E_x = 10$ MeV, where these states are expected, and the fact that two particle two hole contributions may split the strength into several weakly populated levels.

In a recent high resolution electron scattering experiment,[12] the highly selective excitation of magnetic transitions at backward angles has been used to excite 1^+ states in the Ca isotopes. In these experiments, strong excitation of a 1^+ state in ^{48}Ca has been identified at $E_x = (10.227 \pm 0.005)$ MeV, but a number of more weakly excited 1^+ states have also been observed in the vicinity of this strong 1^+ state.[13]

Another important method to investigate unnatural parity 1^+ states is the spin-flip excitation by inelastic hadron scattering. These processes are preferably studied at high incident energies where two step contributions to the direct reaction mechanism are expected to be small. In fact, a strong spin flip transition to a state at about 10.2 MeV in ^{48}Ca has been observed in inelastic 160 MeV proton scattering at the Indiana cyclotron with an energy resolution of about 70 keV.[14]

In this paper we report on a high resolution inelastic proton scattering experiment at $E_p = 44.4$ MeV, in which the excitation spectrum of ^{48}Ca around 10.2 MeV has been investigated in detail. An incident proton beam provided by the isochronous cyclotron JULIC was analyzed by a double analyzing magnet system setup for the high resolution dispersive mode. The target consisted of a 27 $\mu g/cm^2$ thick ^{48}Ca layer (isotopic enrichment: 98.0%, ^{40}Ca: 1.5%) evaporated on a 100 $\mu g/cm^2$ thick carbon backing. Reaction products were momentum analyzed in the $Q_1Q_2D_1D_2Q_3$ high resolution spectrometer BIG KARL. The variable momentum dispersion was set to $D = 15.4$ cm/% momentum and the dispersion of the incoming beam was matched to the dispersion of the spectrometer. An energy resolution of $\Delta E/E$

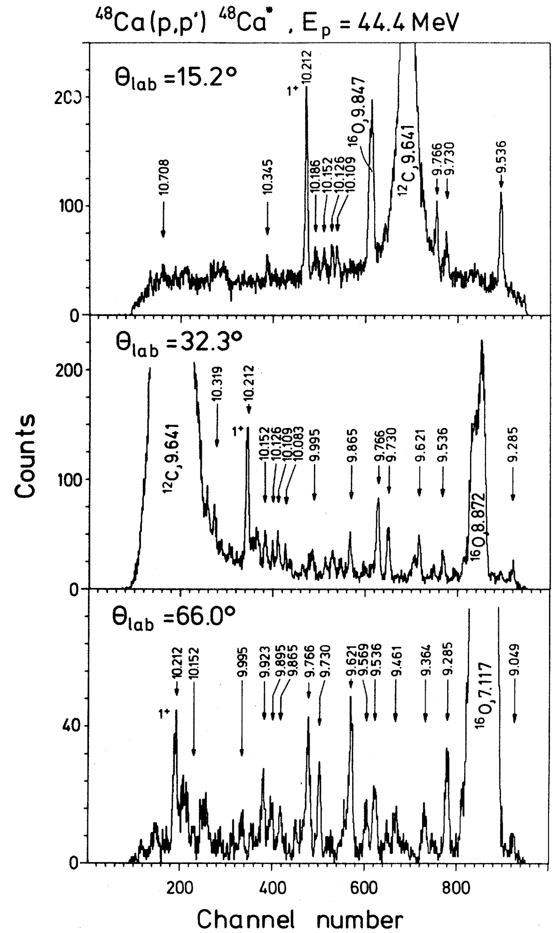

FIG. 1. Measured momentum spectra for three different scattering angles. The energy resolution is 7–10 keV. The large broad peaks arise from kinematically mismatched scattering from carbon and oxygen contaminants. Relative errors of excitation energies are 2–3 keV, but the absolute error is about 10 keV, as explained in the text.

$<2\times10^{-4}$ has been obtained in the position spectrum using a 30 cm long multiwire proportional chamber[15] in the detector plane. Particle identification was achieved by additional plastic scintillation counters. A ray tracing procedure was employed to optimize the quadrupoles Q_1Q_2 and the multipole components of the dipole magnets (using H_t correction coils) for a solid angle of $d\Omega=2.5$ msr. Sample spectra for three scattering angles are shown in Fig. 1. The energy resolution was typically 7–10 keV, and allowed for the identification of about 50 energy levels in the range of $E_x=9.2-10.7$ Mev.

By using the ^{12}C (9.641 and 7.654 MeV) and the ^{16}O (8.872 MeV) states as a natural calibration, the energy of the strong state around $E_x=10$ MeV was determined to be 10.212 ± 0.009 MeV, the error being mainly due to the uncertainty of the incident energy and the scattering angle. The relative errors for the excitation energies shown in Fig. 1 are 2–3 keV. Absolute normalization of the inelastic cross section was achieved by adjusting the measured elastic cross section to optical model calculations.[16] For different optical model potentials (Refs. 17 and 18 and variations of these parameters) this normalization yielded the same value within 8%.

In the following, we concentrate our discussion on the states around $E_x=10.2$ MeV. (The results for the other states identified in the present experiment will be presented in a forthcoming publication.) Within the error limits the strongest peak in the energy region discussed above is located at $E_x=(10.212\pm0.009)$ MeV (see Fig. 1), very close to the position of the strong 1^+ state observed in inelastic electron scattering.[12,13] A recent $^{48}Ca(p,n)$ experiment[8] at Indiana University confirms this assignment by the observation of the strongly excited isobaric analog state of this level. Since the energy resolution of our experiment was appreciably better than that of the existing (e,e') and (p,p') measurements, we were able to study the vicinity of the 1^+ level in much more detail. It turns out that a number of additional states close to the 1^+ level are excited with appreciable strength. The identification of these states is important with respect to the angular distribution as well as the absolute 1^+ strength. It has been argued[11] that precritical effects should enhance the cross sections at large momentum transfer ($q\sim1-2$ fm^{-1}) corresponding to $\theta\sim42°-84°$ at our energy. Unresolved peaks of transitions with large orbital angular momentum transfer ($l>2$) would simulate a similar enhancement. Therefore we carefully analyzed the spectra from $E_x=10.212$ to 10.152 MeV by a peak fitting procedure. Apart from the strong 1^+ state we were able to identify five peaks at $E_x=10.198$, 10.186, 10.177, 10.166, and 10.152 MeV, which all have angular distributions different from the 1^+ state. Since these states have been identified in this experiment for the first time, the spin-parities are not known (DWBA analysis of our data does not allow unambiguous multipolarity assignments). It should be mentioned that the angular distributions of these states resemble the strong states at $E_x=9.730$, 9.766, and 10.345 MeV. These states and all other strongly excited states in the measured energy range (Fig. 1) have angular distributions different from the 1^+ state. It cannot be excluded, however, that some of the weaker states carry some 1^+ strength. Actually, some additional 1^+ strength has been

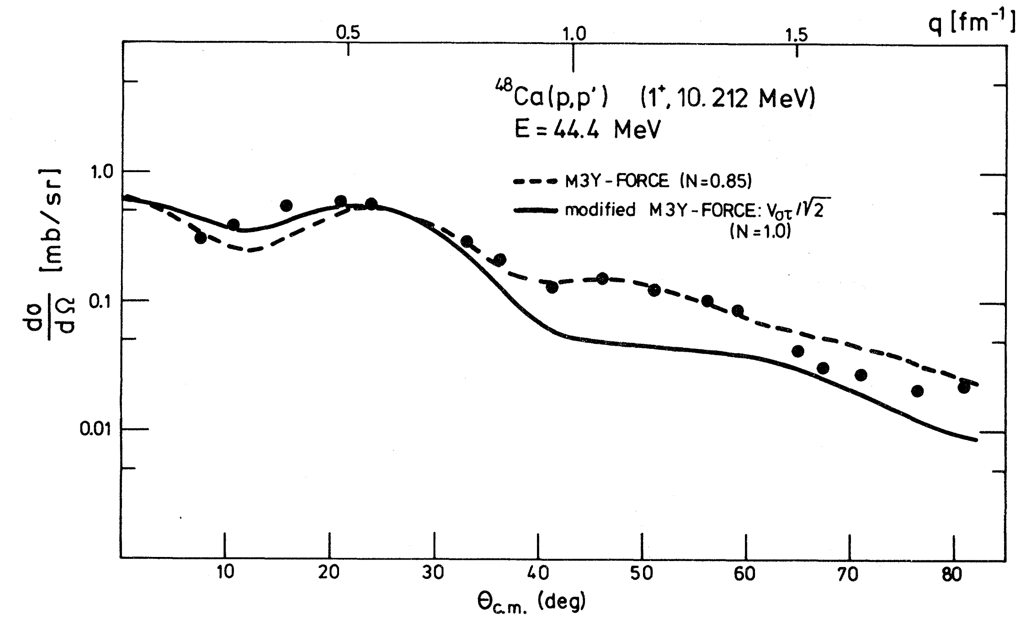

FIG. 2. Experimental angular distribution of the ^{48}Ca(p,p') (1^+, 10.212 MeV) reaction at E_p=44.4 MeV. Theoretical cross sections have been calculated with optical potential parameters of Ref. 25 and with the $M3Y$ interaction of Bertsch *et al.* (Ref. 19) (dashed line). The solid line corresponds to a calculation with a modified $M3Y$ interaction (Ref. 22). The theoretical cross sections were renormalized by the factor N in order to match the data at forward angles.

found in recent improved ^{48}Ca(e,e') experiments.[13]

The experimental data have been analyzed by microscopic DWBA calculations using the $M3Y$ interaction of Bertsch *et al.*[19] for the projectile-target nucleon interaction, and the random phase approximation (RPA) wave functions of Ref. 20 for the nuclear structure description of the 1^+ state. The calculations have been performed with the fast speed DWBA code FROST–MARS,[21] which includes knockout exchange amplitudes exactly. In Fig. 2 two DWBA calculations are compared with the experimental data. The dotted curve has been obtained with the "original" $M3Y$ interaction while the solid line results from a calculation where the spin-isospin flip part $V_{\sigma\tau}$ of the $M3Y$ interaction has been reduced by a factor of $\sqrt{2}$.[22] The dashed curve reproduces the shape of the angular distributions fairly well except for some deviations at forward angles. These deviations are smaller for the case where the modified $M3Y$ interaction[22] has been used, although the description of the data becomes worse at larger scattering angles in this case. Both calculations, however, reproduce the absolute magnitude of the cross section rather well (the full curve was renormalized by a factor of $N=0.85$ only and the dashed curve not at all). This is surprising, since the RPA calculations do not contain the important coupling to the Δ resonance, which would lead to a quenching of the strength by an estimated factor of 2–3 as has been clearly observed in the analysis of (p,n) reactions[20,23,24] and of electron scattering experiments.[12]

On the other hand, two step processes which are not included in our analysis of the data cannot completely be disregarded in low energy hadron scattering and may lead to an enhancement of the calculated cross section. To arrive at definite conclusions on the amount of $M1$ strength located at around 10 MeV excitation energy, it is therefore necessary to study the energy dependence of the 1^+ excitation in detail. As demonstrated by the present experiment such investigations with hadrons have to be performed with extremely good energy resolution in order to isolate possibly weak 1^+ states from other levels which are present at the excitation energy relevant to 1^+ excitations.

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