Brief Reports

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Excitation of $E2$ transitions in ^{40}Ca by 334-MeV protons

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Measurements have been made of the inelastic cross sections and analyzing powers between 2° and 9° for nine 2^+ states in ^{40}Ca with excitation energies below 10.0 MeV excited by 334-MeV protons. The data can be well described by macroscopic distorted-wave Born approximation calculations. In general the βR values deduced from the analysis are in agreement with those obtained by other means. We do not observe a 2^+ state at 6.422 MeV recently reported in a study of the (γ,γ') reaction. A peak at 9.868 MeV is observed which can be described by an $L=(0 \text{ or } 1)+2$ admixture. For the $L=2$ component (i.e., 2^+ state), we deduce $B(E2)\downarrow = 2.0 \pm 0.4\ e^2\,\text{fm}^4$.

In the course of a study of spin flip transitions in ^{40}Ca(p,p′), we have obtained partial angular distributions for the inelastic cross section and analyzing powers for excitation of nine 2^+ states. Our angular distributions cover the angular interval 2.17–8.78° in the center of mass. Since the maximum of an $L=2$ transfer for protons of 334 MeV occurs at about 9.5°, we feel the data are sufficient to extract βR values for comparison with other works. Recently Moreh *et al.*[1] have reported on a study of $E2$ transitions using the ^{40}Ca(γ,γ') reaction and give $B(E2)$ values for these same levels.

The experiment was performed at the Clinton P. Anderson Meson Physics Facility (LAMPF) utilizing the high resolution spectrograph (HRS) with protons of 334 MeV polarized perpendicular to the reaction plane. The beam polarization was monitored periodically by measuring the

TABLE I. Deformation parameters deduced from DWBA fits to data for excitation of 2^+ states in ^{40}Ca by 334-MeV protons. Optical model parameters are given in Table II.

E_x (Mev)	$(\beta R)^2$ (fm)	βR (fm)	$(\beta R)_{\text{EM}}$[a] (fm)	βR[b] (fm)	βR[c] (fm)
3.904	0.181(16)	0.43	0.49	0.43	0.52
5.249	0.0114(13)	0.11	0.13	0.12	
5.630	0.0181(21)	0.13	0.14		0.15
6.422	< 0.0018	< 0.04	0.27		
6.909	0.174(22)	0.42	0.44	0.44	0.49
7.467	< 0.005	< 0.07	0.21[d]		
7.873	0.078(10)	0.28	0.32	0.23	
8.091	0.044(5)	0.21	0.26	0.16	
8.580	0.026(4)	0.16	0.18	0.17	
8.748	0.015(2)	0.12	0.14	0.14	
9.868[e]	0.020(3)	0.14	0.25[f]		

[a]From Ref. 1 except as noted with $R=1.2A^{1/3}$ fm.
[b]From 25–40 MeV (p,p′) of Ref. 3.
[c]From 800 MeV (p,p′) of Ref. 4.
[d]From Ref. 5. Using the maximum uncertainty would give $\beta R = 0.14$.
[e]This is a doublet with other component $L=0$ or 1.
[f]Based on a resonance strength $S=(2J+l)\Gamma_p\Gamma_\gamma/\Gamma$ of 2.1 ±0.4 eV from Ref. 6; $\Gamma_{\gamma_0}/\Gamma = 0.85$ from Ref. 7.

$^1H(\vec{p},p)$ analyzing power with a thin CH_2 target located upstream from the scattering chamber. The beam polarization was found to be 84% for both spin up and spin down orientations.

The detector system and ray-tracing techniques used in the analysis allowed us to make measurements into 2.11° in the laboratory system. Most of the data were taken with the elastic scattering peak off of the focal plane where the elastic protons may scatter from various structures of the spectrograph into the detectors. At small angles, such scattering can produce large backgrounds. Fortunately, the ray-tracing techniques for the HRS provide the capability to distinguish between the inelastic scattering events from the target and the background counts originating from the elastic proton rescattering.

The spectrometer was set to accept an angular interval of 1.8°, and the beam current was monitored with ionization chambers. The data were binned in the off-line analysis into 0.4° segments. The angular resolution was $< 0.1°$. Absolute cross sections were determined by normalization to measurements of proton-proton scattering at 7.75° and 9.75° from a CH_2 target using accepted cross section values.[2] The uncertainty in this normalization is $\pm 8\%$. The parameters used in the analysis programs to define the solid angle acceptance of the spectrograph for the ^{40}Ca were also used for the CH_2.

Since the main goal of the experiment was to study $M1$ transitions, data were taken only for small laboratory angles of 2.75°, 3.75°, 5.75°, and 7.75° which spanned an angular interval of 2.17–8.78° in the center of mass for ^{40}Ca. The target was an isotopically enriched ^{40}Ca ($> 99\%$) foil of thickness 46.9 mg/cm^2.

The overall energy resolution for these data was ~ 80 keV full width at half maximum (FWHM). A summary of the 2^+ states observed in this work is given in Table I. In particular, we do not observe a new level at 6.422 MeV which was recently reported by Moreh *et al.*[1] Angular distributions for the nine 2^+ states observed in this work are shown in Fig. 1 and their corresponding analyzing powers, $A_y(\theta)$, in Fig. 2. As can be seen from these figures the shapes of the differential cross sections and analyzing powers are very similar for these nine states.

Cross sections and asymmetries were calculated with a macroscopic distorted-wave born approximation (DWBA) model including spin-orbit terms using the coupled-channels code ECIS[8] with relativistic kinematics. We used ECIS to determine optical-model potential (OMP) parameters by

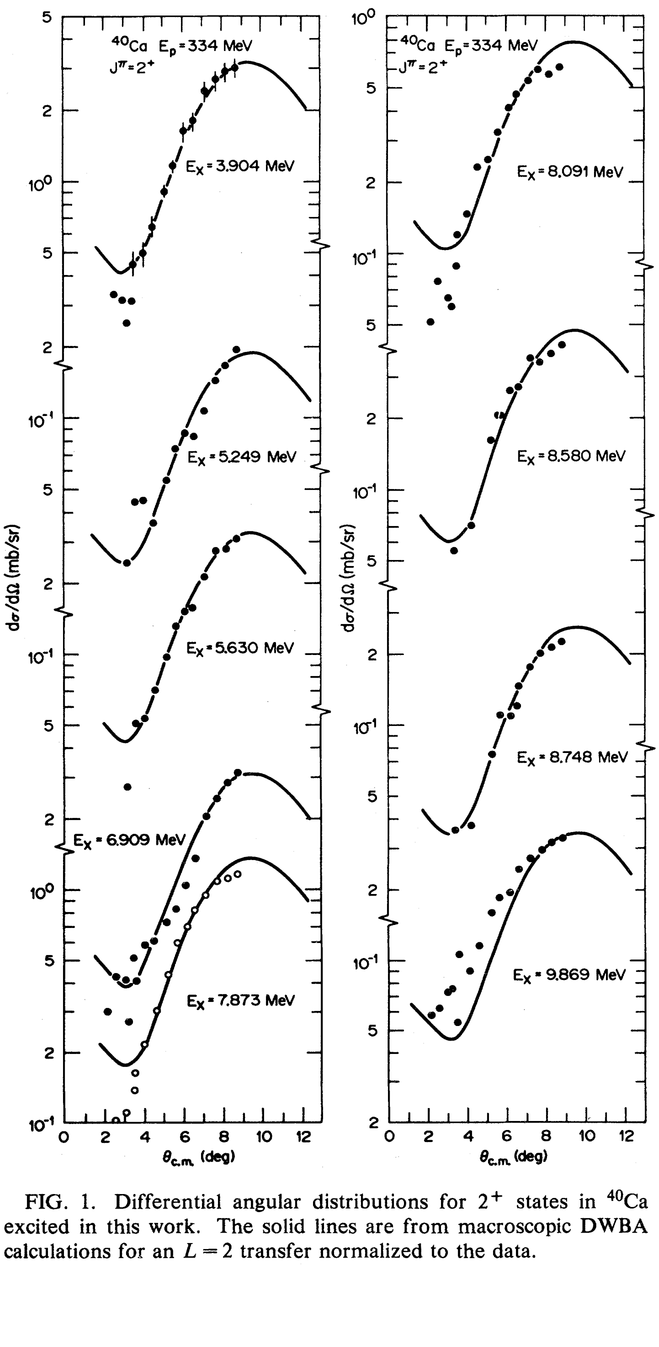

FIG. 1. Differential angular distributions for 2^+ states in ^{40}Ca excited in this work. The solid lines are from macroscopic DWBA calculations for an $L = 2$ transfer normalized to the data.

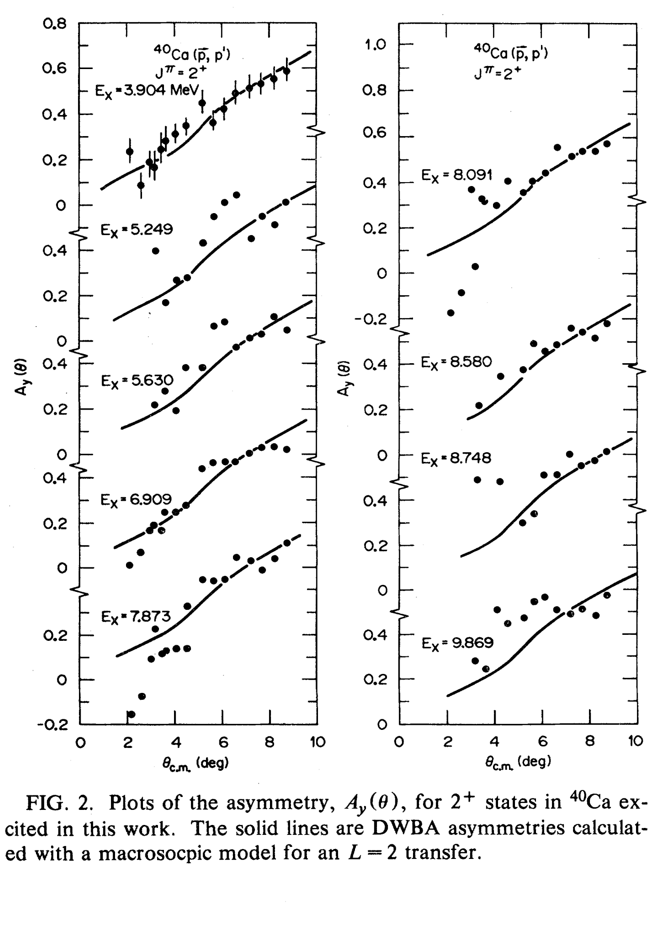

FIG. 2. Plots of the asymmetry, $A_y(\theta)$, for 2^+ states in ^{40}Ca excited in this work. The solid lines are DWBA asymmetries calculated with a macrosocpic model for an $L = 2$ transfer.

searching on ^{40}Ca elastic cross section and asymmetry data[9] taken at TRIUMF. These data extend out to $\theta_{cm}=50°$ for proton energies of 200, 300, 400, and 500 MeV. These were then used as starting parameters for a search on our 334-MeV elastic cross section and asymmetry data which extend only to $\theta_{cm}=14°$. The resultant OMP parameters are listed in Table II. The latter were used to calculate the inelastic cross sections and asymmetries for an $L=2$ transfer shown as solid curves in Figs. 1 and 2. In these calculations the value of β was adjusted so that the deformation length βR was identical for all components of the optical model potential. The value of βR was set equal to $(\beta R)_{EM}$ calculated from the $B(E2)$ for the 3.904-MeV level. The calculated differential cross sections and asymmetries are seen to reproduce the data for the 2^+ levels fairly well.

For each level, a value of $(\beta R)^2$ was deduced by scaling the calculated cross section to fit the data. These are given in Table I where we also compare with βR determined from other studies. Our quoted uncertainties include contributions from all sources, i.e., statistical, cross section normalization, and scaling to the calculated cross sections. For most of the states, our βR are slightly smaller than the corresponding $(\beta R)_{EM}$. However, in most cases when normalized to the 3.904-MeV state, our relative values of $(\beta R)^2/(\beta R)^2_{3.904}$ agree to better than 10% with the corresponding ratios $B(E2)/B(E2)_{3.904}$ obtained from Ref. 1. We can use this result to deduce $B(E2)\downarrow = 2.0 \pm 0.4\ e^2\ \mathrm{fm}^4$ for the 9.868 (2^+) state. Rangan *et al.*[10] in a study of the ^{39}K(p,γ)^{40}Ca reaction reported levels at 9.865 (1^+) and 9.868 (2^+) MeV. The $(\beta R)_{EM}$ listed in Table I for the 9.868-MeV level is derived from the proton resonance capture works of Cheng *et al.*[6] and Leenhouts and Endt[7] which would give $B(E2)\downarrow \sim 4.7\ e^2\ \mathrm{fm}^4$. We believe our quoted value which is deduced from a more direct measurement to be the more reliable. These levels are observed as an unresolved doublet in ^{40}Ca(e,e') measurements.[11]

The values of βR reported from low energy proton scattering agree very well with our values. Adams *et al.*[4] have studied the ^{40}Ca(p,p′) reaction at 800 MeV and using a macroscopic analysis obtained βR values $\sim$10% greater than the corresponding $(\beta R)_{EM}$ for the 3.904-, 5.630-, and 6.909-MeV levels. Miskimen *et al.*[12] also find $\beta R \sim 10\%$ greater than $(\beta R)_{EM}$ for the 3.904-MeV level in a measurement at $E_p = 650$ MeV and a microscopic distorted-wave impulse approximation (DWIA) analysis. It is not clear at this time whether the consistent differences in the βR reported here and from the higher energy proton scattering works are significant or whether they are related to the data reduction and/or analysis.

TABLE II. Optical model parameters for 334-MeV protons on ^{40}Ca.

	Depth (Mev)	r (fm)	a (fm)
V	10.194	1.272	0.833
W	31.212	1.025	0.699
V_{SO}	1.160	1.07	0.634
W_{SO}	−2.817	0.97	0.658
Coulomb		1.20	

As reported earlier, we do not observe a level at 6.422 MeV reported by Moreh *et al.*[1] Neither do we see a level at 7.467 MeV which is reported[5] to be 2^+ with a mean life of 0.01 ± 0.006 psec and 100% branching to the ground state. This level was not observed by Moreh *et al.*[1] These results would suggest that if the assigned J^π is correct, then the partial mean lifetime for ground state radiation is larger than has been assumed.

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[1]R. Moreh *et al.*, Phys. Rev. C **25**, 1824 (1982).
[2]R. A. Arndt, R. H. Hackman, and L. D. Roper, Phys. Rev. C **9**, 555 (1974); R. A. Arndt, Scattering Analysis Interactive Dial-In Program (unpublished).
[3]C. R. Gruhn *et al.*, Phys. Rev. C **6**, 915 (1972).
[4]G. S. Adams *et al.*, Phys. Rev. C **21**, 2485 (1980).
[5]P. M. Endt and C. Van der Leun, Nucl. Phys. **A310**, 1 (1978).
[6]C.-W. Cheng, S. K. Saha, J. Keinonen, H.-B. Mak, and W. McLatchie, Can. J. Phys. **59**, 238 (1981).
[7]H. P. Leenhouts and P. M. Endt, Physica (The Hague) **32**, 322 (1966).
[8]J. Raynal (unpublished).
[9]D. A. Hutcheon and P. Schwandt (private communication).
[10]L. K. Rangan, G. I. Harris, and L. W. Seagondollar, Phys. Rev. **127**, 2180 (1962).
[11]W. Stefen *et al.*, Phys. Lett. **95B**, 23 (1980); P. E. Burt *et al.*, Phys. Rev. C **25**, 2805 (1982).
[12]R. A. Miskimen *et al.*, Phys. Lett. **131B**, 26 (1983).