Quadrupole Radiation in Fast-Neutron Capture on ^{40}Ca

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Differential cross sections have been measured for the reaction $^{40}\mathrm{Ca}(n,\gamma_0)^{41}\mathrm{Ca}$ at seven angles in 1-MeV steps and at $\theta_{\mathrm{lab}} = 90°$ in 200-keV steps for incident neutron energies of 6–13 MeV. The extracted a_2 coefficients and the fore-aft asymmetry are in good agreement with a direct-semidirect model calculation if the isoscalar giant quadrupole resonance is included.

The well-known nature of the electromagnetic interaction operator increases the attractiveness of using radiative capture as a means of studying nuclear structure. The case of fast-neutron capture is especially interesting. One reason is that the effective charges for electric multipoles higher than $E1$ are strongly suppressed.[1] Therefore, the contributions of collective nuclear-capture amplitudes should not be obscured by direct-capture contributions as can happen in the case of proton capture.[2,3] A previous report of a similar experiment[4] has indicated the possibility of observing the effects of the quadrupole state in fast-neutron–capture experiments. In the present work we will demonstrate that improved experimental techniques make it possible to measure fast-neutron–capture cross sections with a quality and quantity comparable to that obtained in proton-capture studies. Furthermore, the effects which we observe are in agreement with those predicted by a direct-semidirect model if an isoscalar quadrupole resonance is included in the calculation. The present calculations indicate that approximately $(0.5 \pm 0.3)\%$ of the isoscalar EWSR (energy-weighted sum rule) is exhausted in the ground-state neutron channel of ^{41}Ca.

The neutron source used in this work was obtained via the reaction $^{2}\mathrm{H}(d,n)^{3}\mathrm{He}$ with a pulsed beam incident upon a gas cell. The natural calcium target was a cylindrical, 3.8×3.8-cm^2 ingot suspended 9 cm behind the deuterium gas cell. The isotopic impurities in the target (~3%) were neglected. The γ-ray spectrometer consists of a 25.4×25.4-cm^2 NaI scintillator which is mounted in a plastic anticoincidence shield in the shape of a well.[5] This detector is shielded by lead, cadmium, and paraffin doped with $\mathrm{Li_2CO_3}$ when used in charged-particle–capture experiments. Additional shielding of copper and tungsten, including a 30-cm tungsten shadow bar, was added for the present experiment. The on-line computer recorded the γ-ray energy signal and the time-of-flight signal. Only those events with the proper time of flight were accepted, and an overall time resolution of 3.5 nsec provided effective discrimination against neutron-induced background. This system achieved an energy resolution [full width at half maximum (FWHM)] of 3.1% for 16-MeV γ rays. A high-energy portion of a typical spectrum is presented in Fig. 1. The area of the peak corresponding to the ground-state transition was obtained by fitting to a standard line shape.

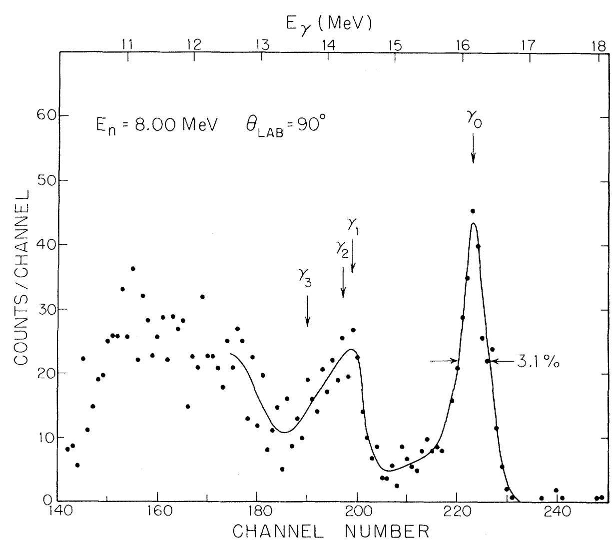

FIG. 1. Typical γ-ray spectrum obtained with the NaI spectrometer.

Angular distributions were measured at seven angles (45°–140°) for eight incident neutron energies (6–13 MeV). A sample of the data is shown in Fig. 2 where we have presented $\sigma(\theta)/A_0$ for three energies. Each datum point corresponds to approximately 2.5 h of running time. The data were corrected for finite geometry, the energy and angular dependence of the reaction ^{2}H(d,n), neutron and γ absorption, and neutron multiple scattering. The angular distributions (see Fig. 2) were fitted by an expansion in terms of Legendre polynomials using a least-squares criterion:

$$\sigma(\theta) = A_0\{1 + \sum_{k=1}^{n} P_k(\cos\theta)\},$$

with $n = 2$ and 3. The a_2 coefficients shown in Fig. 3 do not depend on whether or not the fits included a $P_3(\cos\theta)$ term. The values at 8 and 12 MeV are weighted averages of those obtained in this experiment and in an earlier work.[6]

The 90° yield curve, measured in 200-keV steps and corrected as described above, is shown at the top of Fig. 3. The absolute cross section, based on the integrated beam current, the known ^{2}H$(d,n)^3$He cross section,[7] and our γ-ray spectrometer efficiency,[8] has a total uncertainty of 20%, and agrees within errors with the results of Bergqvist, Drake, and McDaniels.[9] The high-energy portion of the data from Ref. 9 is shown as the normalized open circles.

If we assume that the interfering radiation is $E2$ and neglect the a_4 coefficient which can arise only from terms involving the $E2$ intensity, we can write the fore-aft symmetry as

$$a_s = \frac{\sigma(55°) - \sigma(125°)}{\sigma(55°) + \sigma(125°)} = 0.57a_1 - 0.39a_3.$$

The asymmetries obtained by fitting through second-order Legendre polynomials (solid circles) and through third-order Legendre poly-

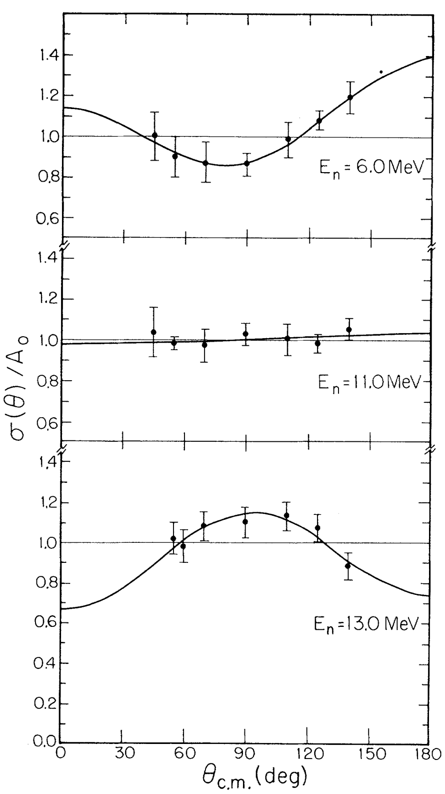

FIG. 2. Typical data at three energies for the quantity $\sigma(\theta)/A_0$. The solid curves are the results of fitting the data by Legendre polynomials to second order.

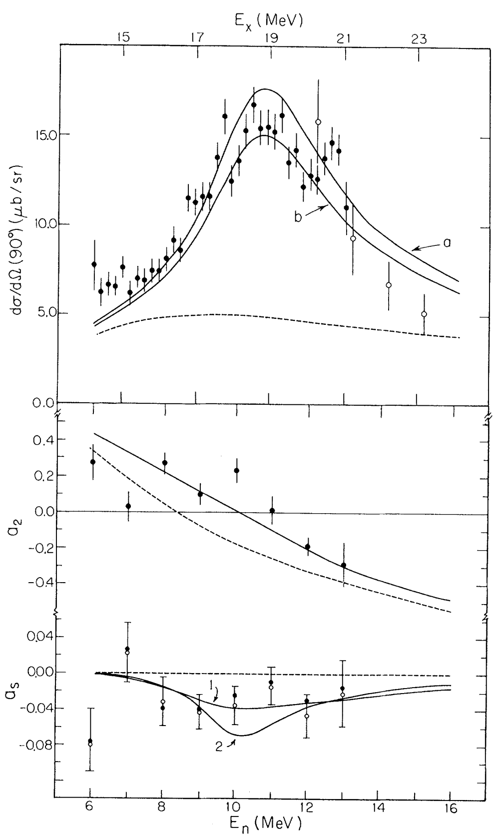

FIG. 3. Comparison of the a_2 coefficients, a_s coefficients, and 90° yield curve with a DSD reaction model calculation as described in the text. For a_s, the solid circles are from second-order fits while the open circles are from third-order fits. The dashed curves for the yield curve and a_2 coefficients are from a pure direct dipole calculation, while the dashed curve for the a_s coefficients is from a calculation that assumes DSD dipole terms but only a direct quadrupole term.

nomials (open circles) are shown in Fig. 3. We also obtained the asymmetry directly from the yields at 55° and 125°. The excellent agreement found between these values supports our assumption that a_4 is small.

The symmetry of the experimental geometry was tested by means of the reaction $^{12}C(n,n',\gamma)^{12}C$ at $E_n = 7$ MeV. The angular distribution of the γ rays from the first excited state (a pure $E2$ transition which must be symmetric about 90° in this experiment) gave $a_s = +0.004 \pm 0.010$.

A direct-semidirect (DSD) reaction model[10] calculation for the case of (the dominant) electric dipole radiation has been successful in describing the results of earlier measurements of the reaction $^{40}Ca(n,\gamma_0)^{41}Ca$.[6,10] Therefore, it seemed reasonable to expect that an extended DSD model[11] which includes quadrupole processes might be useful in interpreting the results of the present experiment. For the case of a zero-spin target nucleus we can write the $E1$ transition matrix element in the form

$$t^\nu(E1, n\rightarrow\gamma) = \langle \varphi_{nljm}(x) | d^\nu(x) | \chi_i^{(+)}(x)\rangle + \langle \varphi_{nljm}(x) | \frac{V_{1,\tau=1}{}^\nu(x)}{E - E_1 + \frac{1}{2}i\Gamma_1} | \chi_i^{(+)}(x)\rangle.$$

Here $|\chi_i^{(+)}\rangle$ is the scattering state, $|\varphi_{nljm}(x)\rangle$ is the single-particle bound state, $d^\nu(x) = e_{\text{eff}} r Y_{1\nu}(\hat{\Omega})$ is the single-particle dipole operator, and $V_{1,\tau=1}{}^\nu(x)$ represents the form factor. This latter quantity is a product of the particle-vibration coupling, responsible for the inelastic excitation of the collective state, and the electric-dipole matrix element of the target nucleus which describes the γ decay of the collective dipole state.

The calculation was performed with $\Gamma_1 = 4.0$ MeV,[12] $E_1 = 18.4$ MeV (fitted to the excitation function), and the value of the matrix element estimated from the experimental value of the energy-weighted integrated dipole cross section σ_{-1} of ^{40}Ca corrected for isospin splitting effects.[13] This latter value corresponds to 39% of the dipole EWSR. The coupling interaction of Ref. 14 was used and is proportional to $rU_1(r)$, where $U_1(r)$ is the complex optical-model symmetry potential. The real part, V_1, and the imaginary part, W_1, were treated as free parameters. However, the final values which were used are in agreement with the results from other studies.[15] The optical-model parameters were taken from Rosen *et al.*[16]

The model was extended by first including a direct quadrupole transition amplitude and then by adding a collective quadrupole one. The transition operator of the latter was of the form $V_{2,\tau=0}{}^\nu/(E - E_{20} + \frac{1}{2}i\Gamma_{20})$. The particle-vibration coupling $V_{2,\tau=0}{}^\nu$, based on the (generalized) Goldhaber-Teller model,[17] was used. It has a surface-peaked shape proportional to $-r dU_0(r)/dr$, where $U_0(r)$ is the real central potential. The values for E_{20}/Γ_{20} were obtained from inelastic α scattering[18] (case 1) and from inelastic ^3He scattering[19] (case 2) and are 18.0/4.0 and 18.2/2.2, respectively.

The results of the calculations are shown in Fig. 3 as solid lines and are in good agreement with the experimental results. The two curves labeled a and b correspond to the two parameter sets $V_1/W_1 = 90.0/45.0$ and 75.0/37.5, respectively, with both curves using $V_0 = 50$ MeV in the quadrupole coupling strength. The differences in a_2 and a_s for these two sets are less than the width of the lines. Calculations of the yield curve and the a_2 coefficients, assuming only a direct dipole term, are shown as dotted lines.

The results of a calculation of the asymmetry, a_s, which includes the DSD dipole terms and only a direct quadrupole term are shown as dased line in Fig. 3. The small values of the calculated a_s coefficients result from the small neutron quadrupole effective charge. General agreement with the experiment is obtained when the collective quadrupole resonance is included using either set of quadrupole resonance parameters (cases 1 and 2). However, it was necessary to decrease the value of the collective quadrupole matrix element for case 1 (see Ref. 18) from 43% to 30% of the EWSR. The reported value of 26% was used for case 2.[19] One exception to the good agreement is the large negative value of a_s at 6 MeV. This may indicate some fragmentation of the collective quadrupole resonance similar to that observed in ^{40}Ca by Youngblood *et al.*[20] where a narrow 2^+ state was observed approximately 4 MeV below the main giant quadrupole resonance.

It can be seen in Fig. 3 that the 90° cross sections are larger than the calculated values at low excitation energies. This may indicate the presence of compound-nucleus contributions. Although the inclusion of this effect in the present calculation should improve the agreement with the yield curve at low energies, it is not expected to be a major component above $E_x = 17$ MeV (Ref. 21) and should not alter our conclusions.

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^{48}Ca-^{40}Ca Radius Difference from Elastic Scattering of 104-MeV α Particles

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Elastic scattering of 104-MeV α particles from ^{48,40}Ca was measured between 3° and 110°. Optical-model fits were made using a Fourier-Bessel description of the real potential and also using density-dependent folding models. The average result for the difference between nuclear-matter rms radii is $r_m(^{48}\mathrm{Ca}) - r_m(^{40}\mathrm{Ca}) = 0.12 \pm 0.06$ fm. Comparisons are made with results obtained by other methods.

The density distribution of neutrons in nuclei has been a topic of considerable interest in recent years. Whereas density distributions of protons in nuclei are now known to an impressive accuracy,[1] there are somewhat conflicting results concerning neutron distributions. The latter are inevitably obtained using strongly interacting particles and therefore depend on some

