Fore-Aft Anisotropy in the Radiative Capture of 14-MeV Neutrons*

E. D. Arthur and D. M. Drake
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545

and

I. Halpern
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545, and University of Washington, Seattle, Washington 98195
(Received 15 October 1974)

Relative yields of capture photons have been observed for four nuclei at angles of 55°, 90°, and 125° in bombardments with 14-MeV neutrons. The yields from ^{10}B, ^{29}Si, and ^{40}Ca show smaller fore-aft anisotropies than those observed in corresponding proton captures. This suggests that the forward peaking in (p,γ) reactions is due mainly to direct rather than collective capture amplitudes. Photons from $^{12}C(n,\gamma_0)^{13}C$ peak backward, but this peaking cannot be straightforwardly accounted for in terms of the interference between the collective excitations dominant in this energy region.

A great variety of measurements reported in recent years have examined nuclear excitations from about 10 to 30 MeV in order to locate and characterize the collective excitations which lie in this energy region.[1] These measurements mainly involved inelastic scatterings (of electrons,[2] protons,[3] and helions[4]) and radiative captures (of protons[5] and α particles[6]). We report here a related study of the angular distributions observed in the radiative capture of fast neutrons. Although measurements with neutrons lack the precision available with charged particles, they happen to be particularly sensitive (as we argue below) to the collective character of higher multipole excitations.

The spectra observed in inelastic scatterings tend to involve many multipoles and their analysis into multipole components is generally not very straightforward.[7] On the other hand, nuclear-capture spectra for excitations between 10 and 30 MeV can be assumed to be limited solely to $E1$ and $E2$ excitations.[8] Thus the radiative-capture amplitude to a given state can be written as the sum, $A_D^{\text{sp}}+A_D^c+A_Q^{\text{sp}}+A_Q^c$, where D and Q stand for electric dipole and quadrupole and where sp and c stand for single particle and collective. "Single particle" refers to radiative transitions of the incident nucleon in the potential provided by the target, while "collective" refers to radiation from excitations induced in the target through its residual interactions with the incident nucleon.

In the energy range of interest the dipole terms are larger than the quadrupole terms and are therefore better known and better understood. At the giant dipole resonance (GDR), for example, the magnitude of the collective dipole amplitude is about 3 times the magnitude of the single-particle or direct dipole amplitude.[9] Because the quadrupole terms tend to be small they are best investigated through their interference with the dipole terms. Through the study of such interference as a function of the spin orientation of the incident nucleon, it is possible to determine the sum $A_Q^{\text{sp}}+A_Q^c$, uniquely,[10] but one cannot distinguish between A_Q^{sp} and A_Q^c. In the capture of protons one expects the amplitude of primary interest in these experiments, A_Q^c, to be dominated by the direct quadrupole amplitude, A_Q^{sp}.[11] The advantage of using neutrons rather than protons in capture studies is that A_Q^{sp} is a factor $Z/$

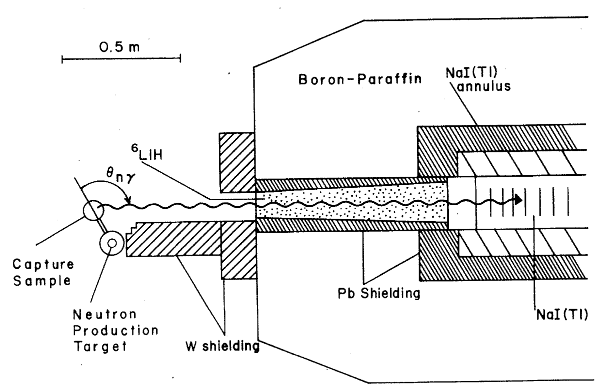

FIG. 1. A section through the apparatus taken in the plane perpendicular to the triton beam. The angle $\theta_{n\gamma}$ is varied by displacing the capture target left or right in this plane.

A^2 smaller for neutrons incident on a target (Z,A) than it is for protons. For neutrons, a determination of the quadrupole amplitude, $A_Q^{sp}+A_Q^c$, is consequently a determination of the collective amplitude alone. In particular, a finding that A_Q for neutrons is very small at an energy where A_Q for protons is large implies that the $E2$ strength observed in the proton capture does not involve appreciable collective excitation.

With these considerations in mind, we have studied the angular distributions of photons from several targets bombarded with 14-MeV neutrons produced by stopping a pulsed triton beam in a deuterium-gas target at the Los Alamos Laboratory's Van de Graaff accelerator. The capture target was placed in the plane perpendicular to the triton beam and the angle, $\theta_{n\gamma}$, between neutrons and photons was varied by displacing this target along the line of sight of the photon detector,[12] a 150-mm× 250-mm NaI crystal surrounded by an anti-Compton annulus (see Fig. 1). With this experimental arrangement it was not necessary to move the shielding that was placed between the neutron source and detector and therefore the background was nearly the same for all angles. In Fig. 2 we show the high-energy portions of pulse-height spectra for each of the targets studied (^{10}B, ^{12}C, ^{29}Si, and ^{40}Ca). The data have been averaged over three adjacent channels to reduce statistical fluctuations. For all but the ^{29}Si spectra, it was possible to identify and isolate the peak corresponding to the ground-state transition. For ^{29}Si, it was easier to study the transition to the first excited state which was more intense than that to the ground state.

Photon spectra from each target were observed at 55°, 90°, and 125° to the neutron beam and the relative yields for the transitions of interest are shown in Fig. 3. The angular distributions for these transitions were fitted with the customary expression

$$W(\theta_{n\gamma}) \sim 1 + \sum_{n=1} a_n P_n.$$

The interference of any quadrupole radiation which may be present with the dominant dipole radiation leads to nonzero values for the odd-n coefficients in $W(\theta_{n\gamma})$, i.e., to a fore-aft asymmetry. In terms of the data this asymmetry is

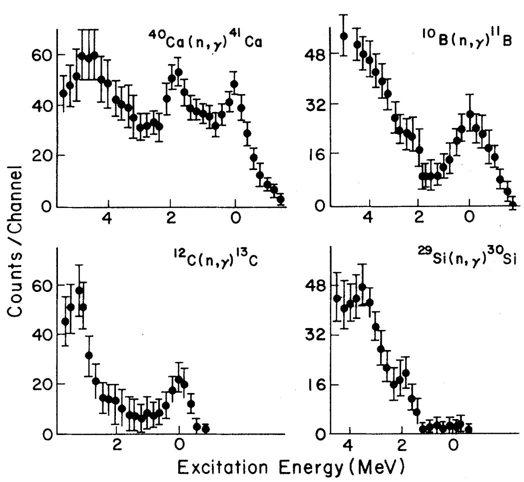

FIG. 2. Typical pulse-height spectra observed for the four targets that were studied. The energy scales are given in terms of the excitations reached in the residual nucleus as a result of the photon emission.

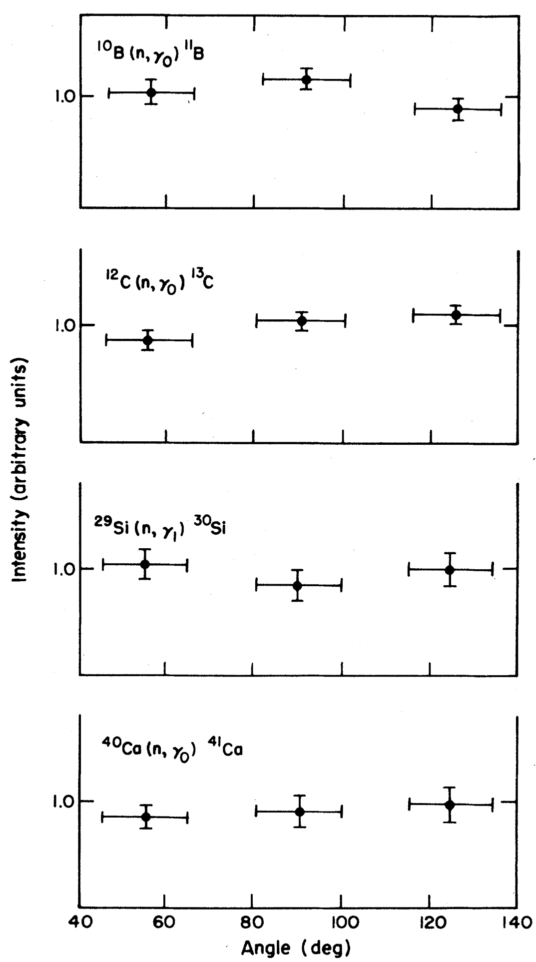

FIG. 3. Angular distributions obtained for 14-MeV neutron capture leading to the designated final states. The horizontal bars show the angular widths subtended by the capture targets.

TABLE I. Angular distribution coefficients.

Reaction	E^* (MeV)	a_2	$R_n = 0.57a_1 - 0.39a_3$	R_p
$^{10}B(n,\gamma_0)^{11}B$	25	-0.44 ± 0.28	0.05 ± 0.08	$^{10}B(p,\gamma_0)^{11}C \sim 0.3$[a]
$^{12}C(n,\gamma_0)^{13}C$	18	-0.08 ± 0.18	-0.15 ± 0.06	$^{12}C(p,\gamma_0)^{13}N \sim 0.3$[b]
$^{29}Si(n,\gamma_1)^{30}Si$	24	0.2 ± 0.24	0.02 ± 0.1	
$^{40}Ca(n,\gamma_0)^{41}Ca$	22	0.03 ± 0.20	-0.06 ± 0.08	$^{39}K(p,\gamma_0)^{40}Ca \sim 0.2$[c]

[a]Ref. 13. [b]Ref. 14. [c]Ref. 15.

most simply expressed as the ratio between the difference and the sum of the yields measured at 55° and 125°, i.e., in terms of $R = (Y_{55} - Y_{125})/(Y_{55} + Y_{125})$. Since $P_2 \approx 0$ at both these angles and since a_4P_4 at 55° can be assumed to be small compared with unity (as it is in proton captures) R is very nearly $0.57a_1 - 0.39a_3$.

In Table I we have listed the values of R and of a_2 determined from the data of Fig. 3. Also listed are typical values, R_p, observed in proton-capture studies on comparable targets at comparable excitation energies. The proton entries have been smoothed over incident-energy intervals of about 0.5 MeV in order to remove effects of fluctuations. Similar smoothing occurs automatically in the case of the neutron data because of the kinematic energy spread of the incident neutrons over the area subtended by the capture target. Proton-capture angular distribution coefficients, smoothed as described, are generally found[5,13,16] to change very slowly with bombarding energy. Thus, although our measurements are limited to the single incident energy, 14 MeV, one can meaningfully compare them with proton measurements at nearby energies.

It is seen from Table I that, with the exception of the entry for ^{12}C (to which we shall return below), the fore-aft asymmetry ratios are about 2 to 4 times smaller for neutrons than they are for the corresponding proton bombardments. We interpret this fact and the observation[16] that proton ratios, R_p, increase gradually with energy above the GDR to values much larger than those in the table to mean that the $E2$ radiation amplitudes in (p,γ) reactions come mainly from direct capture and not from induced collective excitations. A large direct $E2$ component which gives a forward asymmetry that grows with energy is expected on elementary kinematic grounds.[11] In order to discern any collective $E2$ radiation in (p,γ) studies above the GDR, it is necessary to develop a way to subtract this sizable direct $E2$ contribution.[5]

The remaining entry in Table I, $^{12}C(n,\gamma_0)^{13}C$, shows definite backward peaking in its angular distribution, and it is of interest to see whether such peaking can be accounted for in terms of the interference between the collective dipole and quadrupole amplitudes since these two amplitudes are expected to dominate at the excitation energies involved here. If one assumes that each of these collective amplitudes is associated with a single broad resonance, it is easy to show that their sum can be written as

$$\frac{a_D}{E - E_D + i\Gamma_D/2}\sin\theta_{n\gamma} + \frac{ia_Q}{E - E_Q + i\Gamma_Q/2}\sin\theta_{n\gamma}\cos\theta_{n\gamma},$$

where a_D is positive and a_Q is positive for isovector (and negative for isoscalar) neutron capture.

The quantity that corresponds most directly to the fore-aft ratio R is the crossterm of the capture intensity,

$$2\sin^2\theta_{n\gamma}\cos\theta_{n\gamma}\mathrm{Re}\left(\frac{ia_Da_Q}{(E - E_D - i\Gamma_D/2)(E - E_Q + i\Gamma_Q/2)}\right). \quad (1)$$

Now one would expect the isoscalar quadrupole resonance (which generally lies slightly below the GDR) to be the quadrupole resonance involved here. The sign of the last factor at the right of Eq. (1) leads, however, to forward rather than the observed backward peaking, if one assumes a reasonable value, $\Gamma_Q \gtrsim \Gamma_D$, for the width of the quadrupole resonance. In short, one cannot account for the $^{12}C(n,\gamma)$ angular distribution in terms of an interference between single dipole and quadrupole isoscalar resonances. But it may be unreasonable to expect the collectivity, in a nucleus as light as ^{13}C, to be represented by single broad resonances. The isoscalar and isovector quadrupole strengths are very likely spread broadly and unevenly enough, in excitation energy, to produce considerable fluctuation in the sign of the interference term.

On the basis of the foregoing discussion one would expect forward enhancement in (n,γ) as well as in (p,γ) reactions in the region of the isovector quadrupole resonance, which presumably lies about half again as high as the GDR. In this higher energy region, especially for heavier nuclei, the model of two broad interfering resonances might be expected to be reasonably valid. There is, in fact, some evidence[5] for the expected forward enhancement in the reaction $^{208}Pb(p,\gamma)$ and in preliminary studies[17] with neutrons of targets heavier than those of Table I. Hopefully it will be possible to continue to improve the precision of the (n,γ) measurements in this energy region, since neutrons appear to provide a unique tool for characterizing higher-lying collective excitations of nuclei.

*Work supported by the U. S. Energy Research and Development Administration.

[1]A. Bohr and B. R. Mottelson, "Nuclear Structure" (Benjamin, Reading, Mass., to be published), Vol. 2.

[2]M. Nagao and Y. Torizuka, Phys. Rev. Lett. 30, 1068 (1973); S. Fukuda and Y. Torizuka, Phys. Rev. Lett. 29, 1109 (1972).

[3]M. B. Lewis, F. E. Bertrand, and D. J. Horen, Phys. Rev. C 8, 398 (1973).

[4]G. M. Chenevert, N. S. Chant, I. Halpern, C. Glashausser, and D. L. Hendried, Phys. Rev. Lett. 27, 434 (1971); G. M. Chenevert, Ph.D. thesis, University of Washington, 1969 (unpublished); A. Moalem, W. Benenson, and G. M. Crawley, Phys. Rev. Lett. 31, 482 (1973); J. M. Moss, C. M. Rozsa, J. D. Bronson, and D. H. Youngblood, Phys. Lett. 53B, 51 (1974).

[5]K. A. Snover, K. Ebisawa, D. R. Brown, and P. Paul, Phys. Rev. Lett. 32, 317 (1974).

[6]R. B. Watson, D. Branford, J. L. Black, and W. J. Caelli, Nucl. Phys. A203, 209 (1973); K. A. Snover, E. G. Adelberger, and D. R. Brown, Phys. Rev. Lett. 32, 1061 (1974).

[7]M. B. Lewis, Phys. Rev. C 9, 1878 (1974).

[8]$M1$ matrix elements in the GDR region are expected to be small. See, e.g., S. Fujii and O. Sugimoto, Nuovo Cimento 12, 513 (1959).

[9]G. E. Brown, Nucl. Phys. 57, 339 (1964).

[10]S. S. Hanna, H. F. Glavish, R. Avida, J. R. Calarco, E. Kuhlmann, and R. LaCanna, Phys. Rev. Lett. 32, 114 (1974).

[11]I. Halpern, in *Proceedings of the International Conference on Photonuclear Reactions and Applications, Pacific Grove, California, 1973*, edited by B. L. Berman, CONF 730301 (Lawrence Livermore Laboratory, Livermore, Calif., 1973), p. 909.

[12]Further details in D. M. Drake, E. D. Arthur, and M. G. Silbert, LASL Report No. LA-5662-MS, 1974 (unpublished).

[13]H. M. Kuan, M. Hasinoff, W. J. O'Connell, and S. S. Hanna, Nucl. Phys. A151, 129 (1970).

[14]M. Hasinoff, private communication.

[15]E. M. Diener, J. F. Amann, and P. Paul, Phys. Rev. C 7, 695 (1973); E. M. Diener, J. F. Amann, P. Paul, and J. D. Vergados, Phys. Rev. C 7, 705 (1973).

[16]R. E. Segel, Z. Vager, L. Meyer-Schützmeister, P. P. Singh, and R. G. Allas, Nucl. Phys. A93, 31 (1967); W. E. Meyerhof, M. Suffert, and W. Feldman, Nucl. Phys. A148, 211 (1970); E. D. Earle and N. W. Tanner, Nucl. Phys. A95, 241 (1967); J. W. Jury, J. S. Hewitt, and K. G. McNeill, Can. J. Phys. 48, 1635 (1970).

[17]E. D. Arthur, D. M. Drake, and I. Halpern, Bull. Am. Phys. Soc. 10, 497 (1974).

Measurement of the $^2H(p,n)pp$ Transverse Polarization Transfer Coefficient at 20.4 MeV*

R. G. Graves, Mahavir Jain, † H. D. Knox, ‡ E. P. Chamberlin, and L. C. Northcliffe
Cyclotron Institute, Texas A&M University, College Station, Texas 77843
(Received 23 June 1975)

The transverse polarization transfer coefficient, $K_y^{y'}$, has been measured for the reaction $^2H(p,n)pp$ at 18° for E_p = 20.4 MeV as a function of neutron energy. Although predictions based on a three-body separable-potential model with S-wave N-N interactions are in reasonable agreement with the data, the need for a three-body theory with more realistic N-N forces is indicated.

Recently there has been extensive interest in the calculation and measurement of medium-energy three-body polarization observables, particularly for elastic N-d scattering.[1-3] Calculations based on increasingly realistic N-N forces now give predictions which are in fairly good quantita-