RADIATIVE CAPTURE REACTIONS AT INTERMEDIATE ENERGIES

S.L. Blatt, H.J. Hausman, D. Marchlenski, T.R. Donoghue, T. Rackers, and M. Wiescher
Ohio State University, Columbus, Ohio 43212

M.A. Kovash
University of Kentucky, Lexington, Kentucky 40506 and
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

A.D. Bacher and C.C. Foster
Indiana University Cyclotron Facility, Bloomington, Indiana 47405

For the past four years, members of the Ohio State University Van de Graaff group, in collaboration with researchers from the University of Kentucky and Indiana University, have been carrying out a program of studies of radiative capture reactions at IUCF. Starting with the dual motivations of investigating the systematics of such reactions in the intermediate energy region and looking for captures to more highly-excited states than had been possible to observe earlier, we have made several discoveries of unexpected phenomena which are providing important insights into the nuclear configurations.

Our findings have included the discovery that proton capture to certain highly excited states, in light nuclei dominates the observed gamma-ray spectra;[1] our follow-up experiments, based on ideas generated by our initial observations,[2] showed that giant resonances at 2hω excitation exist, built on states at lhω (see Fig. 1).[3] A very recent result, being readied for submission, now shows that even "higher harmonic" giant resonances exist (see Fig. 2).[4] In a somewhat different direction, we have also found strong similariites in angular distributions and analyzing powers between capture transitions in closed-subshell nuclei and their neighbors with an additional proton.[5] Most recently, we have begun studying radiative capture of projectiles heavier than protons; preliminary data,[6] now reinforced with measurements recently completed, show significantly different final-state populations by ^{3}He capture than those seen in the same nuclei when produced by proton capture. Such studies, we expect, will lead to a better knowledge of configurations more complex than those seen in proton capture; 3-particle — 3-hole states, thought to be important in the region of the orignal giant dipole resonance,[7] should be more predominant in ^{3}He capture than in most other reactions, for example.

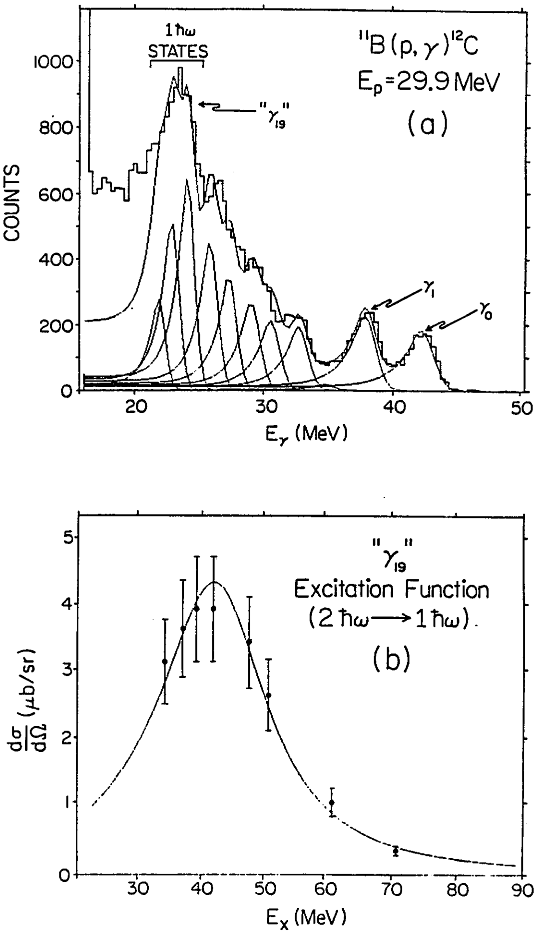

Figure 1. The "Second Harmonic" giant resonance in $^{11}B(p,\gamma)^{12}C$.

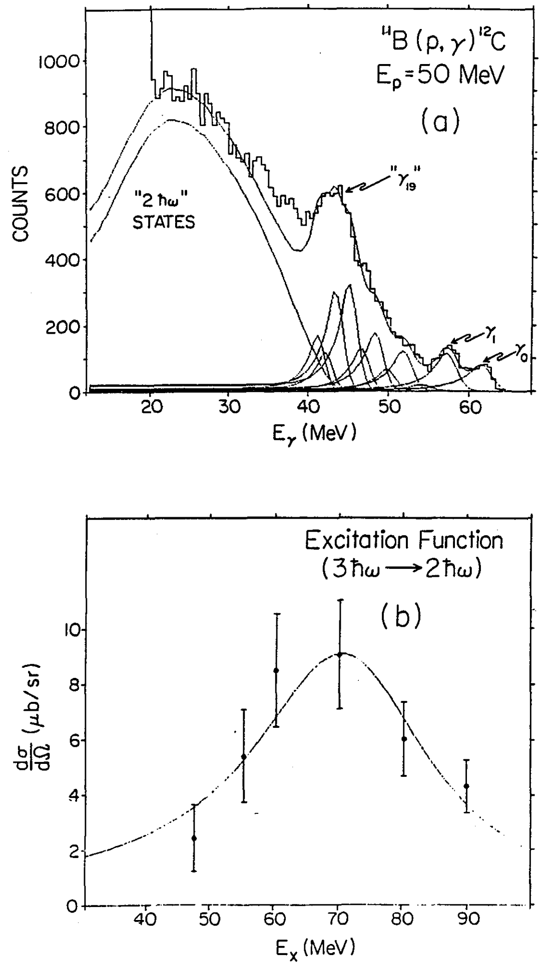

Figure 2. Evidence for a Third Harmonic giant resonance.

The work we have done thus far has raised a host of new questions which require investigation in several different directions: Higher-energy proton capture work is needed to continue the studies of giant resonances built on excited states, as well as to resume the originally proposed studies of the capture mechanism over an extended energy range to determine the relative importance of exchange currents,[8] and the influence, if any, of the Δ resonance[9] on radiative capture. Additional nuclei must be studied to test our findings on the related transitions in neighboring nuclei, and the predictions of the generalized direct-semidirect capture picture developed[5] to understand the original data. Coincidence experiments, designed to study the particle and gamma decays of the states strongly populated in identification and nature of the final state configurations. Finally, the studies of complex-projectile capture (previously studied by our group at lower energies[10] but never attempted in the intermediate energy region until now) should be continued, adding some measurements of deuteron capture, for 2-particle — 2-hole information, into the same final nuclei as studied in proton- and ^{3}He-capture.

First priority is being given to higher-energy proton capture measurements, with ^{3}He capture studies also of major interest. Apparatus is also being designed to prepare for more complex measurements, such as the coincidence experiments, for the near future. In nearly all aspects of the program outlined here, improved gamma-ray energy resolution would allow more definitive measurements to be accomplished; the acquisition of a second detector is also an absolute requirement for some of the proposed work. A proposal for the acquisition of such a detector has been submitted to the National Science Foundation by the Ohio State group. Additionally, an enlarged space in the gamma cave, or an alternative target area, will be an absolute necessity for the two-detector experiments proposed here.

A new detector for gamma rays in the 20 to 150 MeV range is needed both as a stand-alone device — taking advantage of its higher resolution — and, in conjunction with the present O.S.U. detector, as part of two-arm experiments. In the former case, we note that we already have experienced a gain of nearly a factor of two (from 4.3% FWHM to 2.4% at 40 MeV) through installation of a better NaI crystal in our original system last year; that improvement has enabled us to begin studies in the silicon-phosphorous region with nearly the experimental success we obtained earlier with carbon and nitrogen. Moving higher in the periodic table, however, is not the primary goal here. Rather, there continue to be uncertainties over exactly which states, in close-lying groups, are actually excited in the capture reactions we have already looked at. In particular, the cluster of states in ^{12}C near ^{19}MeV, which includes the 4^- "stretched" states, has been of great interest to us; resolution at the level better than 2%, while still not capable of clearly resolving every component of that cluster if it were present in the capture reaction, should be capable of verifying or rejecting our present spectrum-stripping results with substantially smaller uncertainties.

Even more important to our program will be the capability of using two detectors at once. One of the important tools we have used in our neighboring-nuclei studies is the measurement of analyzing powers. Both for the extensions of these studies and for our higher-energy proton capture measurements analyzing-power determinations will play a crucial role. Differences in predictions of cross sections and angular distributions from various proposed intermediate-energy photonuclear reaction mechanisms do exist,[8] but they are not large. Analyzing powers, however, are expected to be clearly different when calculated using different formalisms.[9] The measurements we have already made over the past few years have been limited, by the small cross sections of the reactions under study, to fewer data points and less statistical accuracy than would be desirable. The use of a second detector, in left-right geometry, will double the data acquired in a given time, while also cancelling out some of the possible experimental asymmetries one-arm analyzing power measurements cannot account for.

The coincidence measurements noted above will entail a more ambitious undertaking for our group, but they may be the only way to settle some of the questions about the states participating in the reactions we have measured. The recent experiments at IUCF led by M.A. Kovash[11], a former O.S.U. student, in measuring spin-flip probabilities in inelastic scattering of protons by ^{12}C, have demonstrated the feasibility of coincidence measurements with our detector in the IUCF environment. The use of two such detectors, for gamma-gamma coincidence measurements, would be a major addition to our capabilities in getting out the details we need.

Our group has been active for many years in developing and improving NaI-based detector systems for measuring capture-gamma spectra.[12] Our present system, built around a 10-inch diameter by 12-inch long crystal, utilizes a plastic anticoincidence shield, pileup-rejection electronics, gain stabilization, and neutron-background reduction by time-of-flight. Our data-acquisition methods, as well as data-reduction techniques, are designed to extract maximum information from the detector. The new crystal will have the same dimensions as our present detector (for symmetry in the analyzing power experiments), manufactured to the tolerances and utilizing the production and testing techniques reported in Ref. 13. A crystal so produced should have non-uniformities small enough that the energy resolution will have a substantial contribution from photoelectron production statistics in the system's photomultiplier tubes. If a crystal with the lower-energy performance of Ref. 13 (2.1% at 40 MeV, with substantially better uniformity than our present crystal) can be obtained, resolution near 100 MeV could approach 1.4%! The use of a split annulus for the shield[13], for better light collection and therefore better anticoincidence efficiency, will also be a part of the new detector design.

The richness of new phenomena we have already found in these measurements suggests that experiments of an exploratory nature, utilizing carefully selected reactions and appropriate experimental parameters, will be the most fruitful way in which our program can be run. For example, in our early studies, we found that the energy dependence of these reactions was very interesting.[3] But measuring detailed excitation curves, to get out the details (which also proved to be very interesting) was better carried out by other groups with more appropriate facilities.[14] We therefore expect to carry out experiments in each of the areas we described above (higher-energy proton capture, deuteron and ^{3}He captures, and coincidence measurements) on well-chosen examples, hoping to get a broad overview of the phenomena rather than a complete picture of a very narrow portion of the information accessible to us through radiative capture studies in this energy range.

1) M.A. Kovash et al., Phys. Rev. Lett. 42, 700 (1979).

2) L.G. Arnold, Phys. Rev. Lett. 42, 1253 (1979); S.L. Blatt, in Nuclear Structure with Intermediate Energy Probes, LA-89303-C (Los Alamos, 1980) p. 90.

3) S.L. Blatt et al., in Giant Multipole Resonances (Harwood, Chur, 1980) p. 435; H.R. Weller et al., Phys. Rev. C 25, 2921 (1982).

4) S.L. Blatt et al., submitted for publication (1984).

5) S.L. Blatt et al., Phys. Rev. C, in press (1984).

6) D. Marchlenski et al., Bull. Am. Phys. Soc. 28, 650 (1983).

7) C.M. Shakin and W.L. Wang, Phys. Rev. Letters 26, 902 (1971); H.D. Shay et al., Phys. Rev. C 9, 74 (1974).

8) M. Gari and H. Hebach, Phys. Rev. C 18, 1071 (1978); J.T. Londergan et al., Phys. Lett. 65B, 427 (1976).

9) J.T. Londergan, private communication.

10) A review of the field, with many references and figures from our group's work is found in: M. Suffert, in Charged Particle-Induced Radiative Capture (Vienna, 1972) IAEA Proceedings.

11) M.A. Kovash et al., this report, p. 1.

12) S.C. Ling et al., Nucl. Phys. A108, 221 (1968); S.L. Blatt et al., Nucl. Instr. & Meth. 60, 221 (1968); E.M. Diener et al., Nucl. Instr. & Meth. 83, 115 (1970); M.A. Kovash and S.L. Blatt, Nucl. Instr. & Meth. 163, 113 (1979).

13) A.M. Sandorfi and M.T. Collins, submitted to Nucl. Instr. & Meth. (1983).

14) D.H. Dowell et al., Phys. Rev. Lett. 50, 1191 (1983); M. Anghinolfi et al., Nucl. Phys. A399, 66 (1983).