RADIATIVE PROTON CAPTURE STUDIES AT INTERMEDIATE ENERGIES

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The study of photonuclear reactions at intermediate energies is a field of rapidly growing interest. Recent calculations of theoretical cross sections have indicated that much can be learned about meson exchange effects[1)] and virtual excitation of nucleons[2)] in such studies. Controversy[3)] has developed concerning the possibility of using experimental data from these reactions[4)] to determine the momentum distribution of protons in target nuclei. Continued work, both experimental and theoretical, is required to sort out these questions. Measurements of radiative capture reactions, inverse to the photonuclear reactions investigated thus far, can contribute to the resolution of some of these questions; further, systematic studies of capture reactions have additional interest of their own. By investigating the radiative transitions to excited states, a far broader set of data becomes available for comparison with theoretical models, and some of the relationships between structure and reaction mechanism in these reactions may more easily be clarified.

With the completion of our initial (p,γ) measurements at IUCF last summer, we now have the first systematic information on radiative capture at intermediate energies. Measurements were made on ^{11}B and ^{12}C targets at energies from 40 to 100 MeV, at a fixed γ-ray detector angle of 60°. Less extensive measurements were made with ^{27}Al, ^{89}Y, and ^{3}H targets. In these experiments, we observed strong primary capture γ-rays not only to the ground- and low-lying excited states of the final nuclei, but to several isolated high-lying excitations as well. The latter, unexpected phenomenon is the subject of a paper we have recently submitted for publication in Physical Review Letters.[5)] The cross sections for primary transitions to the low-lying states, including ground-state capture (for direct comparison with existing calculations), are also available, in preliminary form, but additional detector efficiency tests must be completed before final values are extracted from the data. Additional experimental runs are desirable for further investigating both the newly-discovered high-lying-state captures and the low-lying transitions, which are of continuing fundamental interest.

1. Intermediate-Energy Gamma-Ray Detection System

As the result of design, construction, and testing over the past three years, we have developed a detector capable of meeting the requirements of the intermediate-energy capture program: adequate resolution (∿ 3.8%) to separate ground- and first-excited-state γ-rays for a variety of nuclei up to at least 100 MeV; high efficiency; and ability to discriminate against neutrons and cosmic rays. The high total counting rates found in the capture measurements, arising from competing reactions, necessitated a system which also drastically reduces pulse pileup and rate-dependent gain shifts. The detector is an improved version of the now standard plastic scintillator shielded NaI(Tℓ) spectrometer; the original design of Blatt and Kohler[6)] dates back to the early 60's, and many versions utilizing large crystals have since been described in the literature.[7)]

In the present system (see Fig. 1), the 25 x 30 cm NaI crystal is viewed by 5 fast phototubes, which produce a good compromise for both energy and time resolution. Neutron shielding is used both around the crystal, in the form of a thin ^{6}Li shield in a plastic envelope, and outside the entire detector, where we have boron-loaded polyester sheets. The plastic scintillator rejects cosmic ray background, and is used in a summed-coincidence technique to improve the detector

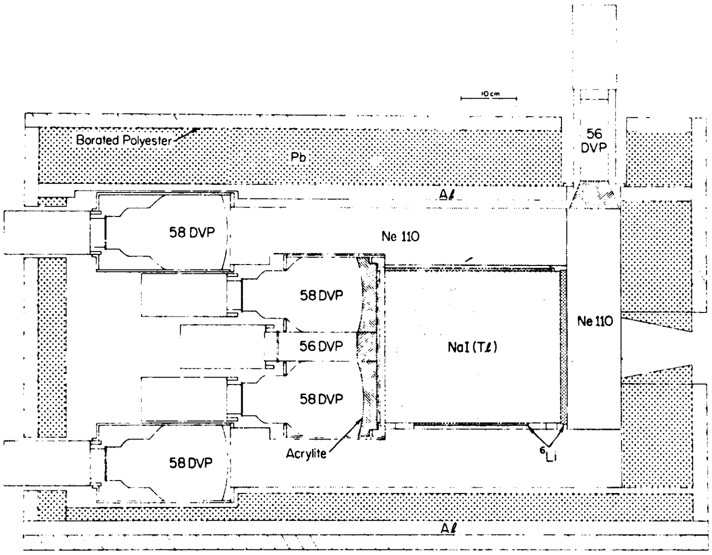

Figure 1.

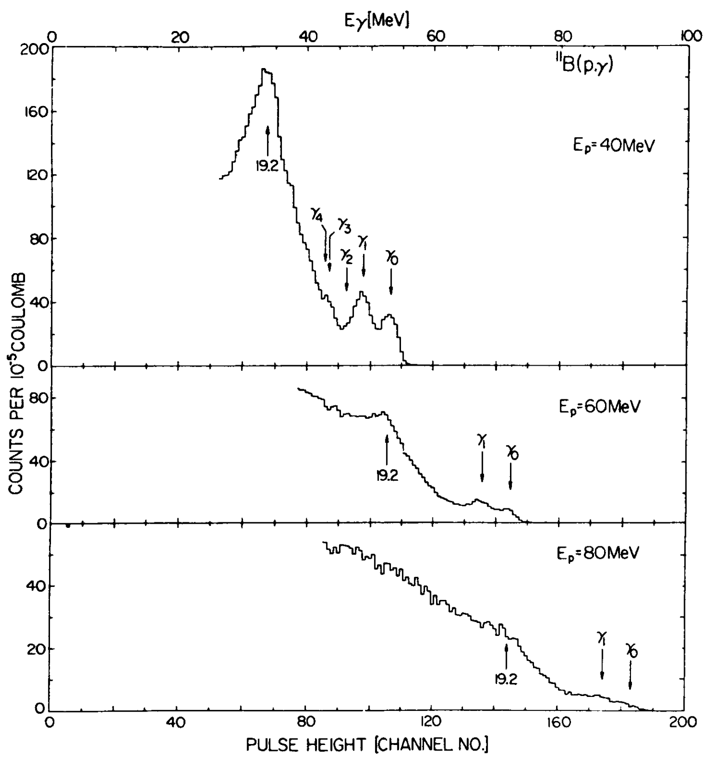

Figure 2.

resolution without the efficiency degradation of the usual anti-coincidence technique.

The electronics provide for pileup reduction by processing the fast anode pulse directly in a charge-sensitive ADC; auxiliary pileup rejection is provided to eliminate residual pileup within the 200 ns ADC gate period. Count rates up to 300,000/sec were routinely

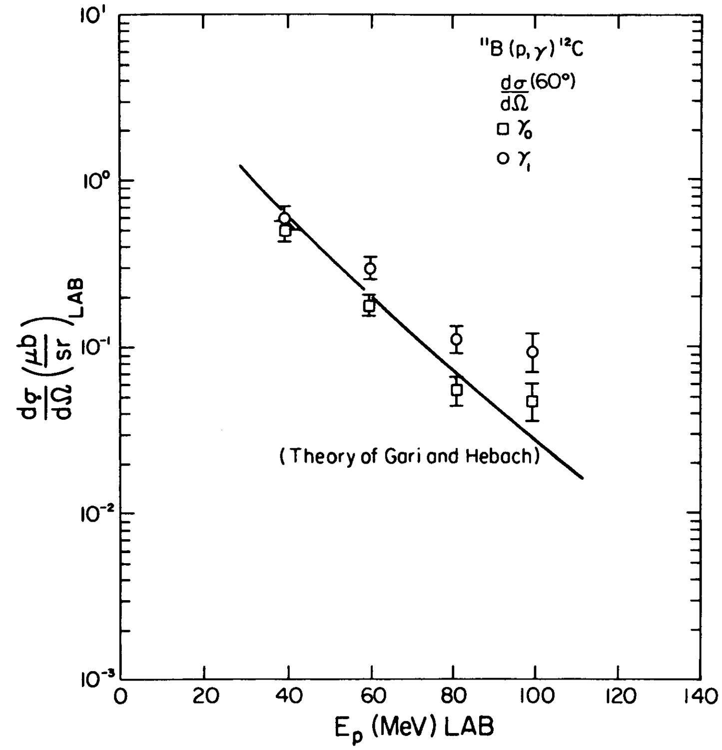

Figure 3.

handled with this scheme . At such count rates, a special gain stabilizer was also required; our circuit, utilizing a second fast gate on the anode pulse, maintained the gain constant to better than 1% for count rates from 10^3 to 3 x 10^5/sec.[8)] In addition to the NaI pulse-height spectrum, we recorded the pulse-height in the plastic scintillator for all coincident events, and the time-of-flight for each event. This 3-parameter mode was used to store data, and sorting was performed, for monitoring purposes, during each run; re-sorts were made after the runs as desired.

2. Initial Results of the Program

Figure 2 shows the γ-ray spectra obtained for ^{11}B(p,γ) at 40, 60 and 80 MeV. The ground and first excited state captures (γ_0 and γ_1, respectively) are seen clearly. A prominent bump is also visible for capture to a state (or narrow group of states) at 19.2 ± 0.6 MeV excitation in ^{12}C. The bump moves with the kinematics appropriate for a capture γ-ray; no competing reactions produce γ-rays with such an energy dependence.

Measurements were also taken on ^{27}Al targets. The ^{27}Al(p,γ) measurements do not resolve the captures to low-lying states cleanly. However, again, a prominent bump shows up at lower γ energies. The bump moves, again, exactly as expected for a capture γ-ray, and we identify it as due to a primary capture to a state or group of states at 13.8 ± 0.6 MeV excitation in ^{28}Si.

The differential cross section for the ^{11}B(p,γ)^{12}C* (19.2 MeV) peak, estimated by subtracting a smooth background from the peak, is 0.96 ± 0.3 μb/sr at 40 MeV and 0.12 ± 0.04 μb/sr at 60 MeV. The ^{27}Al(p,γ)^{28}Si* (13.8 MeV) peak is produced with a cross section of ∿ 1.0 ± 0.3 μb/sr at 40 MeV. The large uncertainties arise almost entirely from a lack of knowledge of the shape of the γ-ray continuum in the vicinity of the peaks of interest.

States most strongly populated in a (p,γ) reaction on a target with a single proton hole in its outermost shell, which is the case for both ^{11}B and ^{27}Al, would likely be ones of a simple one-particle one-hole nature, where the incoming proton simply radiates away enough energy to allow it to drop into the appropriate particle orbit. The most interesting candidates for the high-lying ^{12}C and ^{28}Si states reported here are the "stretched" configuration states described by Donnelly and Walker[9)] and experimentally observed in inelastic electron scattering,[10)] inelastic proton scattering,[11)] and the (α,t) reaction.[12)] These states are thought to have, in ^{12}C, a $(p_{3/2}^{-1},d_{5/2})$ configuration summing to J^π=4$^-$, and in ^{28}Si, $(d_{5/2}^{-1},f_{7/2})$ summing to 6$^-$. The (e,e') experiments place the 4$^-$ state in ^{12}C at 19.6 MeV, compared with our observed final state energy of 19.2 ± 0.6 MeV. In ^{28}Si the 6$^-$ state has been located at 14.3 MeV, while our peak appears to arise from captures to a state at 13.8 ± 0.6 MeV. In both cases, the inelastic scattering studies indicate states narrower than our detector resolution; in our experiment, the observed ^{28}Si transition shows a nearly unbroadened line shape, while the ^{12}C line appears to be broadened somewhat beyond the ∿ 200 keV width reported from (e,e'), although background uncertainties do not allow definite widths to be assigned in the present experiment.

If we do identify the states observed here as stretched configurations, we can expect some further interesting effects to show up in radiative proton capture experiments. Such configurations would have very little radiative strength for electric dipole decays to lower-lying states; very strong E1 transitions (essentially the entire sum-rule value) could then take place between higher-lying states and the states of interest. For example, a giant dipole resonance for $f_{7/2}$ protons could be built on the ^{12}C 4$^-$ state; likewise, $g_{9/2}$ protons could undergo resonant capture to the 6$^-$ state in ^{28}Si. Such "second harmonic" resonant capture could be sought in (p,γ) experiments in the 20-40 MeV range of bombarding energies, and, if observed, would provide strong support for the simple pictures presented here, namely, that we are seeing the first evidence for $2\hbar\omega$ to $1\hbar\omega$ radiative transitions.

The spectrum of γ-rays from ^{12}C+p is qualitatively different from the other two reactions. The dominant peak at the high-energy end of the spectra measured for 40-100 MeV protons is observed to be from ^{12}C(p,$\gamma_{2,3}$)^{13}N, where the final state is the unresolved second and/or third excited state of ^{13}N. The lower-energy portion of the 40 MeV spectrum is characterized by three broad peaks. If these peaks arise from ^{12}C(p,γ), the final state groups in ^{13}N would be centered at 16.1, 12.0, and 8.1 MeV. Unfortunately, in this case, the peaks cannot be unambiguously assigned to the capture reaction, because the structure in the spectrum becomes washed-out at the other measured energies. Measurements at smaller energy increments in the vicinity of 40 MeV should clarify this identification. As in the other two cases reported, final states seen most strongly here should be of a simple single-particle nature. The $5/2^+$ third excited state, for example, has a substantial $d_{5/2}$ spectroscopic factor, while the nearby second excited state appears to be a much less pure single-particle state.[13)] Thus, the strong peak indicated as $\gamma_{2,3}$ is likely to consist mostly of γ-rays to the $5/2^+$ state. The bumps in the spectrum appearing at lower γ-ray energies do not seem to have a one-to-one correspondence to reported levels in ^{13}N and further work is necessary to clarify matters.

Precise values for the cross sections for $^{11}B(p,\gamma_{0,1})$ and $^{12}C(p,\gamma_{0;2,3})$ can also be obtained from the data. However, extensive evaluation of the detector response, as observed in the present set of experiments, along with other line-shape information,[14)] is still in progress. When this work is completed, we hope to understand the systematic behavior of the detector as a function of γ-ray energy, and the cross sections can be presented with small uncertainties. We have extracted "preliminary" cross sections, using a consistent set of line shapes; those for $^{11}B(p,\gamma)$ are presented in Figure 3 to give some idea of the general features of the captures to low-lying states. The agreement of the γ_0 data with Gari and Hebach's calculation[15)] appears striking, but two cautions are in order: a) the experimental values, as noted, are preliminary; and b) all theories give about the same predictions at 60° for these energies. Theoretical differences show up most prominently at higher energies and at more extreme forward and backward angles.

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1) H. Hebach, A. Wortberg, and M. Gari, Nucl. Phys. A267, 425 (1976).

2) J.T. Londergan, G.D. Nixon, and G.E. Walker, Phys. Lett. 65B, 427 (1976).

3) Conference at University of Maryland, January, 1978.

4) J.L. Matthews, W. Bertozzi, M.J. Leitch, C.A. Peridier, B.L. Roberts, C.P. Sargent, W. Turchinetz, D.J.S. Findlay, and R.O. Owens, Phys. Rev. Lett. 38, 8 (1977).

5) M.A. Kovash, S.L. Blatt, R.N. Boyd, T.R. Donoghue, H.J. Hausman, and A.D. Bacher (submitted to Phys. Rev. Lett., 1978).

6) S.L. Blatt, Ph.D. Dissertation, Stanford University (1965); S.L. Blatt, J. Mahieux, and D. Kohler, Nucl. Instr. and Meth. 60, 221 (1968); P. Paul, S.L. Blatt and D. Kohler, Phys. Rev. 137, B493 (1965).

7) See, for example, E.M. Diener, J.F. Amann, S.L. Blatt, and P. Paul, Nucl. Instr. and Meth. 83, 115 (1970).

8) M.A. Kovash and S.L. Blatt, Nucl. Instr. and Meth. (in press, 1978).

9) T.W. Donnelly and G.E. Walker, Ann. Phys. (N.Y.) 60, 209 (1970).

10. R.A. Lindgren, Bull. Am. Phys. Soc. 23, 948 (1978); T.W. Donnelly, Jr., J.D. Walecka, G.E. Walker, and I. Sick, Phys. Lett. 32B, 545 (1970); T.W. Donnelly, J.D. Walecka, I. Sick, and E.B. Hughes, Phys. Rev. Lett. 21, 1196 (1968).

11. G.S. Adams, A.D. Bacher, G.T. Emery, W.P. Jones, R.T. Kouzes, D.W. Miller, A. Picklesimer, and G.E. Walker, Phys. Rev. Lett. 38, 1387 (1977).

12) C.C. Chang, J.R. Wu, T.W. Koontz, and H.D. Holmgren, Bull. Am. Phys. Soc. 23, 929 (1978).

13. D. Ajzenberg-Selove, Nucl. Phys. A268, 1 (1976), and references contained therein.

14. E. Hayward and W. Dodge (private communication, 1978); A. Nathan (private communication, 1978).

15. M. Gari and H. Hebach, Phys. Rev. C18, 1071 (1978).