J. H. D. Jensen (Heidelberg University) and G. Brown (Institute for Theoretical Physics, Copenhagen) discuss theories of the giant dipole resonance during the photonuclear conference held at the National Bureau of Standards in Washington, D. C. The conference coincided with the 1958 spring meeting in Washington of the American Physical Society.

Conference on Photonuclear Reactions

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Informal "box lunch" discussion on giant resonance width. *Photos by Hank Walker, courtesy* Life.

SCIENTISTS from ten countries, representing leading centers for the study of photon-induced nuclear reactions, met at the National Bureau of Standards in Washington, D. C., on April 30 and May 1, 1958, for the Sixth Conference on Photonuclear Reactions. Previous conferences have been held at the Massachusetts Institute of Technology, the University of Pennsylvania, Case Institute of Technology, and the University of Chicago. Cosponsors of the meeting were the US Atomic Energy Commission, the Office of Naval Research, the Air Force Office of Scientific Research, and the National Bureau of Standards.

Photonuclear research is interested in essentially the same problems of nuclear structure as other areas of low-energy (i.e., below 100 Mev or so) nuclear physics. However, the study of photonuclear reactions is characterized by a special set of experimental difficulties. Since sources of monoenergetic photons are difficult to obtain, it has usually been necessary to work with continuous (bremsstrahlung) spectra whose shape and absolute normalization are not too accurately known. As a result, for most experiments it is necessary to make measurements at many different peak bremsstrahlung energies; and from these measurements to deduce a cross section. For this reason, much interest centers on the monitoring of bremsstrahlung beams and calibration of the accelerators—betatrons and synchrotrons, for example—that produce the photons by bombarding a high-Z target with an electron beam.

It was to discuss such problems and to compare experimental methods and results that the first photonuclear conference was held several years ago, and its success in promoting the solution of experimental problems has led to its repetition every year or two since.

However, as the techniques and experimental results become more reliable, there is a growing tendency for the conferences to include discussions of related fields.

An extensive survey of the current experimental activity was given on the first day of the present conference, when twenty-one laboratories reported on their general programs and recent experimental results. The second day of the conference was held in conjunction with the Washington Meeting of the American Physical Society. The morning session was devoted to invited papers by G. E. Brown (Institute of Theoretical Physics, Copenhagen), J. H. D. Jensen (University of Heidelberg), R. E. Marshak (University of Rochester), and J. H. Smith (University of Illinois). In the afternoon session, contributed papers to the Physical Society on photonuclear reactions and bremsstrahlung spectra were read.

In attempting to summarize some of the highlights and major trends of the conference discussions, it is convenient to group them under four headings: fundamental reactions, reactions in light nuclei, reactions in heavy nuclei, and experimental techniques.

Fundamental Reactions

THE photon-induced reactions which might be classified as fundamental reactions (exclusive of meson production) are the elastic scattering of photons from hydrogen and deuterium and the photodisintegration of deuterium and helium. Significant theoretical advances in the understanding of the photodisintegration of the deuteron were presented by R. E. Marshak in his invited paper which represented a summary of calculations underway by a group at the University of Rochester. Previously only partial calculations of the electric and magnetic dipole contributions to this reaction as carried out by Marshall and Guth or by Schiff have been available. These calculations have been reasonably successful in explaining the deuteron photodisintegration up to about 20 Mev but have failed quite markedly at higher energies. However, such calculations have generally neglected one or more of the terms entering into a complete calculation of the dipole contributions, such as outgoing *F* waves, and any contributions from noncentral forces. By including all of these terms, using the Signell-Marshak potential which has been quite successful in explaining *pp* scattering up to about 150 Mev, Marshak and his group have carried the agreement between theory and experiment for the photodisintegration of deuterium up to about 75 Mev or so. At higher energies the need for additional theoretical terms, probably including specific mesonic effects, is quite evident.

The apparent success of these calculations should act as a powerful stimulus to the experimentalists. Particularly interesting but most difficult would be experiments with polarized photon beams. Measurements of the polarization in the bremsstrahlung beam from accelerators reported by R. W. Kenney (University of California) and P. Axel (University of Illinois) should encourage such polarization studies.

Reactions in Light Nuclei

ONE of the more interesting points of discussion in recent years in the light nuclei is the observation of sharp breaks or near discontinuities in bremsstrahlung activation curves for reactions in light nuclei. These have been observed by many laboratories and are by now quite well confirmed. The clear implication of these "breaks" is that some or all of the photon absorption in these elements takes place through well-defined excited states of the parent nucleus. From the shapes of the activation curves near these breaks, estimates of level widths and peak cross sections have been made. Several experiments were reported which attempted to confirm the existence of absorption in levels. These experiments included measurements of total absorption coefficients (University of Pennsylvania), high-resolution measurements of the energy spectrum of protons from (γ, p) reactions (Stanford University), and high-resolution measurements of the cross section for the inverse (p, γ) reactions (Australian National University). At present very little indication is observed for level structure in these measurements, although it is probable that in most of these experiments the experimental resolution is just marginal for observing the structure in the energy regions studied, particularly if not all of the breaks in the (γ, n) activation curves were found as yet.

The Stanford University and National Bureau of Standards reports given by W. C. Barber and H. W. Koch, respectively, showed that measurements of (γ, p) reactions by counter techniques have improved considerably in ease and accuracy. In those elements where the levels of the residual nucleus are widely spaced it is possible to measure the partial (γ, p) cross section to the ground state of the residual nucleus in considerable detail over large energy regions. The strong influence at higher energies of quadrupole and higher modes of photon absorption is quite evident from the asymmetry of the observed angular distributions. Some semiquantitative information on (γ, p) transitions to specific excited states of the residual nucleus was reported. For example, in $C^{12}(\gamma, p)B^{11}$ about 50% of the cross section above 30 Mev goes to the 4.46- or 5.03-Mev states of B^{11}. Data of this kind are available from many laboratories, particularly for carbon-12; the data are in fair agreement, except perhaps for absolute scale, and the disagreements here will probably be reduced as analysis of the experimental data is refined. The abundant information on these reactions should provide theoreticians with an opportunity for rather detailed tests of shell-model wave functions.

The high-energy photoeffect was very well summarized by J. H. Smith (University of Illinois) in his paper on the "pseudo-deuteron" model. This model is based essentially upon the assumption that for energies at which the single-particle momentum distribution in nuclei is exhausted, the primary source of high-momentum components is in the collisions of two nucleons inside the nucleus. Since the photon carries very little momentum, the only source of high-momentum components will be from such collisions. One should therefore see correlated emission of neutrons and protons. Such correlations are observed and have been studied extensively by the groups at MIT and Illinois.

Smith's talk dealt primarily with the Illinois work. The results of this work indicate, if one includes scattering of the neutrons and protons in leaving the nucleus, that above 100 Mev essentially all of the nuclear photoeffect can be explained in terms of the cross section for photodisintegration of the deuteron. By examining the angular correlation between the neutrons and protons one obtains a measure of the momentum distributions within the nucleus. It would be interesting to look in more detail at how this reaction merges into the (supposedly) "single-particle" absorption just above the giant dipole resonance.

Reactions in Heavier Nuclei

THE work on photonuclear reactions in heavier elements was almost completely dominated by studies of the influence of nuclear deformation on the dipole absorption cross section. Considerable progress both experimentally and theoretically has been made in these studies. The prediction that the giant resonance absorption should be split into two peaks by the nuclear deformation was first made independently by Okomoto and by Danos. At the conference Wilkinson presented calculations starting from a single-particle model which also predict such a splitting of the giant resonance. Probably the easiest model to visualize is that of Danos based on the hydrodynamic model of Goldhaber and Teller. In this model the frequency of nuclear oscillation is determined by the nuclear size. For a spherical nucleus, one resonance should be observed, corresponding to the nuclear diameter. For a deformed nucleus, the cross section should be split into two resonances corresponding to the major and minor axes; and one should observe a broadening of the resonance, with the two resonances actually resolved by about 3 Mev in a highly deformed nucleus like Ta.

Attempts to measure the giant resonance splitting in deformed nuclei were presented by laboratories at the University of Melbourne, University of Pennsylvania, University of Saskatchewan, Australian National University, and the National Bureau of Standards. While most of the experimental results presented were not of sufficient statistical accuracy to resolve the splitting into two levels, the correlation between the over-all width of the giant resonance and the nuclear deformation seemed quite definite. Experimental results presented by H. W. Koch (NBS), which were taken with extremely good statistical accuracy, showed a pronounced splitting for Ta with virtually no splitting for Au. The values for the quadrupole moment of deformed nuclei deduced from these experiments are in excellent agreement with values measured by Coulomb excitation experiments. These new experiments would seem to be a valuable means of measuring quadrupole moments; for spin-0 nuclei it is perhaps the only way.

The invited papers of G. Brown (Institute for Theoretical Physics, Copenhagen) and J. H. D. Jensen (Heidelberg University) presented theories of the giant resonance applicable primarily to the heavier nuclei. Jensen discussed the semiclassical description of the giant resonance. The emphasis was on those general results given by this theory, and which must be contained in any proper theory.

The theory presented by Brown was concerned primarily with explaining the anomalously large photoproduction of fast particles from the heavier nuclei. These large yields of fast particles have been explained by Wilkinson using a modified shell model. Using nuclear dispersion theory, Brown has attempted to formulate this model more properly. The results are in general agreement with experiment and with the results of the Wilkinson calculations.

Developments in Experimental Techniques

STUDIES of the reliability of betatron energy control systems were reported by J. Halpern (University of Pennsylvania), L. Katz (University of Saskatchewan), J. McElhinney (NRL), and A. S. Penfold (University of Chicago). Tests described by J. Halpern indicate that, with the usual means of energy control, the betatron at the University of Pennsylvania becomes nonlinear above 20 Mev. This is probably due to saturation effects in the magnet-core iron. It would be expected that this is a difficulty common to all betatrons of this type. New energy control systems which sample the magnetic field at the x-ray target were described by Halpern and by Penfold. If the electrons are not expanded too rapidly into the x-ray target, this should permit improved measurement of the betatron energy.

Efforts to develop an electron-spin resonance device for absolute calibration of accelerator energy at the National Bureau of Standards were reported; this should be particularly useful for circular accelerators. A new radiation monitor for the NBS Betatron Laboratory was also discussed. Calibrated over a fairly large energy region with an accuracy of two or three percent, this will increase the reliability of cross-section measurements—especially on the high-energy side of the giant resonance where the usual thimble-in-lucite ionization chambers become quite inaccurate.

Exciting experimental possibilities were opened by the account given of a 32.5-Mev, 4-kw linear accelerator soon to be installed at General Atomics Laboratory. Described by C. Oxley (General Atomics), the new machine is designed to produce x-ray and electron beam intensities several orders of magnitude larger than those of existing accelerators.

Photonuclear research has for several years consisted largely of what might be called "survey experiments"—where the main concern is with the systematics of nuclear reactions and measurements are made of total cross sections, location of the giant resonance peak, etc. The conference showed that this survey period is nearly over, and that the emphasis is shifting toward more accurate investigation of the giant resonance shape and of detailed features of the partial cross sections.