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THE PHOTON AS HADRON*

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Gothic cathedrals were dimensioned by enormous panels of stained glass, framed in high bays with narrow buttresses, so that, in the words of Hugues de St. Victor, "the splendor of the True Light might pass into the church and enlighten those inside." If such a Gestalt relates to the nature of light, specifically to its spiritual essence, then it also suggests the nature of medieval man — homo spiritualis. Similarly, the physiological properties of light involve not only light itself, but also a sensitive receptor, for example, the human eye and nervous system with which light can interact. It is not surprising, therefore, that the physical nature of light should manifest itself through a variety of physical processes which depend not only upon the characteristics of the interacting photons — light quanta, but also upon the particular interaction taking place. Thus light may act as a wave in propagating through a lens and as a particle when colliding with an atomic electron. Although in each process the interplay between observer and light has a completely different mechanism, they all remind us that the study of light and the study of its interactions are inseparable.

During the last several years, a new "hadronic" character of light has been found: photons of extremely high energy behave as hadrons when interacting with other hadrons — those subatomic particles, including mesons and nucleons, that are associated with nuclei and with nuclear forces. This behavior appears only when photons have a billion times as much energy as photons of visible light. To understand the significance of this "hadronic" aspect of light, we should first recall how its wave and corpuscular aspects were formulated and reconciled by studying the interactions of light at lower energies. This early knowledge has helped physicists to generate and study photons of higher and higher energies until, at the highest energies, the photons behave much as nucleons, mesons, and other hadrons. The appearance of a new, somewhat paradoxical, but fundamentally important behavior of photons should not surprise anyone aware of how fertile the study of light has been throughout the history of physics.

Prior to the 17th century, most people believed that light consisted of a stream of particles emitted radially from light sources such as the sun and the stars. Certain materials were transparent to light, while others were opaque or translucent and tended to reflect or absorb light in varying degrees. In 1678 Christian Huygens showed that if light consisted of successive waves rather than of independent corpuscles, the laws of reflection and refraction could be simply explained. Early in the 19th century, Thomas Young and Augustin Fresnel independently carried out experiments on the phenomena of interference and diffraction which were consistent with wave motion and which even measured the wavelength of light.

In the later half of the 19th century, James Clerk Maxwell succeeded in summarizing the entire field of electricity and magnetism — the work of Coulomb, Gauss, Ampere, Faraday, and many others — with four equations which still serve as the fundamental operating principles of all large-scale electromagnetic devices, from magnets, motors, and computers to particle accelerators. Maxwell's equations predict that an oscillating electrical circuit will radiate electromagnetic waves whose velocity can be computed from purely electrical and magnetic measurements. The astonishing result — that such waves must travel at precisely the velocity already determined experimentally for light — convinced physicists that light consists not only of waves, but more explicitly, of those same electromagnetic waves predicted by the electromagnetic equations. Thus Maxwell's equations led to the concept of a broad electromagnetic spectrum including visible light as well as the radio waves discovered by Heinrich Hertz in 1900.

The discrete nature of light was reintroduced by Albert Einstein in 1905 to explain how light, shining on a metal, ejects electrons from its surface. The light energy, instead of being distributed in a wave, is concentrated in packets called photons. When a single photon strikes a surface electron in the metal, the photon is completely absorbed and imparts to the electron all of its energy. Ironically, Einstein predicted, and Robert A. Millikan experimentally proved, that the energy of the photon, and thus of the ejected electron, depends only upon the frequency of the light — as if each photon were simultaneously a wave! Another example of the corpuscular behavior of light was discovered by Arthur H. Compton in 1921 when he observed that photons also scatter on electrons: the photons behave as material bodies having energy and momentum that are conserved in such collisions. The wave-particle duality of light is reconciled in Quantum Electrodynamics, perhaps the most elegant and successful theory in physics. Quantum Electrodynamics predicts the electromagnetic interactions of photons with such great precision, and over such a wide range of energies (more than 10^{18} to one), that many rigorous tests are possible. Since physics so often advances from broken theories, the latest successes of Quantum Electrodynamics have been greeted almost with dismay.

Until quite recently, the interaction of photons with matter was believed to be entirely electromagnetic, that is, it appeared to involve only the charges and magnetic fields of the target particles but did not appear to involve their possible nuclear ("hadronic", "strong") interactions. Furthermore, photons serve as the sole mediators of all other electromagnetic interactions: two electrons repel each other by firing photons back and forth. The exchanged photons exist for exceedingly short times and cannot be directly detected. For this reason they are called "virtual".

When an electron is scattered by another electron or by any charged particle, it is sharply accelerated and may radiate additional photons that are not reabsorbed. This process, called bremsstrahlung, is analogous to the emission of radio waves by an oscillating electrical circuit. Like radio waves, bremsstrahlung photons can be detected and are therefore called "real".

Physicists apply their knowledge of electromagnetic interactions to produce large numbers of real or virtual photons of known energies under controlled conditions, i.e., to make photon "beams". The availability of such high-energy photon beams was the key to discovering the "hadronic" behavior of photons.

Generally, when an electron radiates a real high-energy photon during a collision with a massive atomic nucleus, the energy given to virtual photons is small, and the nucleus remains almost at rest. The energy of the real photon is then equal simply to the difference in the electron energies before and after collision. These energies can easily be measured by bending the incident and scattered electrons in strong magnetic fields. In this way a beam of "tagged" real photons is produced in which each photon in the beam has a known energy.

Physicists are also interested in processes involving virtual photons and nuclei. If no real photons are radiated during an electron-nucleus collision, the energy of the virtual photon is equal to the difference in the electron energies before and after collision. When some portion of the virtual-photon energy is used to break up the nucleus or to create new particles, such as pions, the process is called inelastic. Inelastic electron scattering is thus analogous to tagging real photons and permits experiments to be carried out with undetected virtual photons similar to those done with real photons.

A second method for producing a beam of real high-energy photons is to scatter visible light 180° on a beam of high-energy electrons, just as a thrown baseball is scattered 180° by a moving bat. This is Compton scattering again except that the target electrons are now moving at nearly the speed of light when the head-on collision occurs. As in Compton's original experiment, the scattered photons behave like material bodies having a definite kinetic energy and momentum that can be calculated from the experimental conditions. And whereas the baseball struck by the bat may have its energy increased tenfold, the energy of the scattered photon may be increased by a factor of ten billion. A beam of this type, using a high-power pulsed laser as the primary light source, demonstrates the direct correspondence between photons in widely different regions of the electromagnetic spectrum. Let there be no doubt that radio waves, visible light, x-rays, and gamma rays are all manifestations of the same basic phenomenon!

Another method for producing real or virtual photons is particle-antiparticle annihilation. When a beam of positrons strikes a target, one of these antiparticles can interact with its corresponding particle, an electron, to produce two real photons — two packets of electromagnetic energy with no mass. Two photons, rather than just one, are required to balance energy and momentum. (This is the reverse of pair production in which a single real photon materializes literally by creating an electron-positron pair. A second photon is also required in pair production, a virtual photon, which balances energy and momentum by transferring these quantities to a nearby nucleus.) Positron-electron annihilation can also yield a single virtual photon which, if it has sufficient energy, may then materialize directly into another particle-antiparticle pair such as a proton-antiproton pair or a pair of positive and negative pions.

There is an apparent contradiction here. In electron-positron annihilation, one real photon is insufficient to balance energy and momentum. How, then, can annihilation into only one virtual photon be allowed? This is possible because the virtual photon, unlike a real photon, is not a final product and cannot be detected; thus it need not be massless. Since the virtual photon exists for an exceedingly short time, there is, via the Heisenberg uncertainty principle, a correspondingly large uncertainty in its energy. Within this uncertainty, momentum and energy need not balance during the short interaction period, although they are conserved for the initial and final particles which endure long enough to be detected. To say that momentum and energy do not balance is equivalent to saying that the virtual photon has non-zero mass: the shorter the lifetime, the wider is the range of masses a virtual particle can assume. Illegally parked cars seem to obey a similar principle: the owner may risk a $2 fine for several hours, but will park in a tow-away zone for only a few minutes. A real photon can also have a non-zero mass during the brief time in which it interacts, but again this momentary discrepancy cannot be directly measured. Thus two real photons are required by annihilation because these can be detected, while one virtual photon suffices because this photon materializes immediately before its mass discrepancy can be observed.

So far, the Heisenberg uncertainty principle has been applied only to electromagnetic interactions. It is even more important, however, in linking photons to hadrons. The ability of interacting high-energy photons to assume a broad range of masses is crucial in understanding the hadronic character of light since it allows interacting photons to take on the masses and attributes of certain hadrons, called vector mesons. The elementary particles can be classified by assigning to each a set of labels, like charge, called quantum numbers. Once their quantum numbers are known, the possible interactions between particles can be predicted. This simplifies an otherwise confusing web of interactions. The uncharged members of a certain class of particles called vector mesons have the same quantum numbers as the photon. However, even in their free, real state they are not massless, and they interact strongly with other mesons and with nucleons (i.e., they are hadrons). Quantum Mechanics insists that if two particles differ only in mass, then whenever they have the same apparent mass, they must have the same interactions. This greatly facilitates the photon-hadron interaction, which may then be thought of as occurring in two steps: first, the photon materializes into a vector meson in the vicinity of the interacting hadron, and second, this vector meson interacts strongly with that hadron.

At high energies this two-step process is more likely than a single direct interaction because photon materialization into vector mesons occurs more readily when the energy and the virtual-mass uncertainty are large and because the subsequent meson-hadron interaction is about 200 times more likely to occur than a direct photon-hadron interaction. Thus, while the uncertainty principle allows the photon to materialize as a vector meson, it is the nature of the photon and the nature of the photon-hadron and meson-hadron interactions that causes most photon interactions yielding hadrons to occur in this two-step process.

The vector-dominance model of photon-hadron interactions, introduced by J. J. Sakurai in 1960 and developed further by M. Gell-Mann, F. Zachariasen, Y. Nambu, L. Stodolsky, and many others, is based essentially on three relations. The first says that during a photon-hadron interaction, the incident photon is equivalent to a combination of vector mesons. The second relation says that any photon surviving such an interaction is a combination of vector mesons. The third is a venerable principle, first discovered in ordinary optics, which relates the absorption of light to the diffractive scattering of that same light. This relationship between absorption and diffraction is known as the "optical theorem", and the adjective "eikonal" is applied to models in which the theorem is important. The term "eikonal", meaning picture or image, seems particularly appropriate in that the diffracted light images the target — be it a stained-glass window or an atomic nucleus, while those photons that are absorbed account for its shadow. Essentially, then, the optical theorem is a relationship connecting image and shadow.

The application of the optical theorem to high-energy photons is elegantly shown in recent experiments on the elastic scattering (diffraction) of high-energy photons by protons. "Elastic" means that no additional particles are produced, and both the photon and the proton survive. At smaller and smaller angles, the probability of scattering approaches the optical theorem's prediction from the separately measured probability of absorption of photons by protons — in which neither the photon nor the proton survives. Thus the scattering is related to the absorption; the image is related to the shadow.

While the vector-dominance model describes a number of processes involving real or virtual photons and vector mesons, it specifically relates the following quantities: (1) the constants indicating how strongly the photon is coupled to each vector meson, (2) the probabilities that a photon striking a nucleon will yield each of the vector mesons, (3) the probabilities for each vector meson striking a nucleon to interact with that nucleon, and (4) the total probability for absorbing photons on hadrons, that is, the total probability for a photon striking a nucleon to interact strongly. The model is tested by measuring these coupling-constants and probabilities in various experiments, which we shall soon describe.

Three vector mesons are presently known: the rho, the omega, and the phi. The charge of the rho can be positive, negative, or zero, while the omega and phi exist only with zero charge. (Photons, being neutral, couple strongly only to neutral vector mesons.) The observed regularities and gaps in classifications of the elementary particles inspire attempts to explain and predict them. One such attempt is the quark model in which the elementary particles are combinations, perhaps purely mathematical, of subunits called quarks. The quark model predicts that the photon should behave as if it were 75% rho, 8% omega, and 17% phi. This really means, of course, that in a large sample of interactions the photon will behave as a rho in 75% of the interactions, as an omega in 8%, and as a phi in 17%. Thus the rho is the most important of the vector mesons in mediating photon-hadron interactions, and one sometimes speaks of rho dominance instead of vector-meson dominance. Vector mesons can be readily produced by hadrons as well as by photons so that various production mechanisms can be compared. Finally, the vector-meson lifetimes, though much longer than the lifetime of a virtual photon, are still quite short. None, for example, persists long enough to form a track in a bubble chamber or streamer chamber, and each must be observed indirectly through the long-lived particles into which it decays. Typically, the rho yields two pions, the omega yields three pions, and the phi yields two kaons.

The mass of a particular vector meson can be calculated from the measured masses, energies, and momenta of its decay products. Experimentally, even when the errors of measurement are negligible, the masses calculated from a sample of decays of the same vector meson do not coincide but instead form a "resonance" distribution, a bell-shaped curve with a certain width about some central mass value. This follows from the uncertainty principle, which requires only that the product of the average lifetime and of the width of the resonant mass distribution for a particle should be constant. Thus a broad mass distribution implies a short lifetime, and a narrow distribution implies a longer lifetime.

The first predictions that such mesons might exist were made by Y. Nambu in 1957 and by W. Frazer and J. Fulco two years later to explain the diffuse structure observed for protons and neutrons, particularly in the electron-nucleon scattering experiments carried out by R. Hofstadter and his colleagues at Stanford University. The name "vector meson" derives from the intrinsic angular momentum or spin of these particles, which is unity and which transforms from one spatial coordinate system to another as a vector quantity. The intrinsic parity is negative. The spin and parity, like all other internal quantum numbers, are the same for photons and vector mesons, as already mentioned. The vector mesons were among the first of nearly one hundred particle resonances discovered.

The most elegant method for studying the vector-meson composition of the photon is clearly the colliding electron and positron beams in which the production of the vector mesons is well isolated from other, potentially confusing, interactions. As already mentioned, the annihilation of a positron with an electron frequently yields a single <u>virtual</u> photon, which can materialize immediately into any one of its vector-meson components. As usual, the creation of a particular vector meson is signalled by its mass, as calculated from the energies and momenta of its decay products. These decay products are, in practice, detected by spark chambers and counters surrounding the interaction region.

The annihilation of a positron and electron into a single virtual photon is purely electromagnetic and can be calculated with great confidence and precision. Furthermore, all vector mesons produced by virtual photons decay immediately, so that it is necessary only to measure what fraction of these decays are detected and to calculate the efficiency of the detection apparatus in order to determine the probability for a virtual photon to materialize. The photon composition found at Orsay is $(75 \pm 2)\%$ rho, $(10 \pm 2)\%$ omega, and $(15 \pm 2)\%$ phi, in good agreement with the quark model prediction. These experiments also directly measure the central masses and the widths of the resonant mass distributions, which seem to be affected by the presence of target hadrons in other experiments. Thus, not only are the colliding-beam experiments, performed at Orsay, France and at Novosibirsk, USSR, technical tours de force, but further, they have the distinct advantage that no target hadrons are involved.

Vector-meson production by real photons has been studied in a wide variety of experiments. All of the methods described earlier for generating beams of high-energy photons have been used successfully including bremsstrahlung radiation with or without tagging, positron-electron annihilation, and backward Compton scattering of laser photons on high-energy electrons. The detectors have ranged from bubble chambers, streamer chambers, and optical spark chambers — visual devices — to massive 2000-ton magnetic spectrometers that detect single recoil particles, such as target protons, from which resonance production can be inferred.

In general, the visual devices allow a detailed analysis of both the production and decay processes, even for events in which many final particles are involved. Electronic devices, such as magnetic spectrometers with various types of counters, wire spark chambers, etc. give less detailed information on particular events and cannot readily handle complex events which produce many particles. They do, however, have an important advantage in that they can be used with highly intense beams to accumulate large numbers of events or to study processes which occur only rarely after many photons have passed through the target. In addition to studying vector-meson properties and production mechanisms, these experiments search for new vector mesons, so far without success.

Given that the path traced by a rho during its brief life is too short to be seen, shorter even than the radius of an atom, so short in fact that the rho normally decays into two pions within a few nuclear radii of its production point, how can one hope to study rho-nucleon scattering? The answer, suggested by Drell and Trefil, is that one studies rho-nucleon scattering within the very same nucleus in which the rho was produced! Rho production without subsequent rho-nucleon scattering can be studied on the simplest nucleus, hydrogen, a single nucleon. The hydrogen results can then be compared with data from nuclei of increasing diameter, such as beryllium, carbon, aluminum, copper, silver, and lead, which increasingly show the effects of rho-nucleon scattering and absorption.

In the rho-photoproduction experiments done at the Deutsches Elektronen-Synchrotron (DESY), at Cornell, and at the Stanford Linear Accelerator Center (SLAC), data were taken with as many as fourteen different target nuclei over a wide range of photon energies and rho production angles. Counters and wire spark chambers, used with magnetic spectrometers, permitted high data rates, and hundreds of thousands of rhos were recorded.

Qualitatively, at small angles, rho photoproduction per target nucleon increases with the number of nucleons in the target nucleus up to about 64 nucleons (copper) and decreases thereafter. The increase per nucleon indicates that the target nucleons work together coherently to produce rhos more efficiently than would the same number of independent nucleons. This is analogous to the constructive interference observed with light from coherent sources, such as lasers. In heavier nuclei, more and more rhos are absorbed via rho-nucleon scattering before they escape. This absorption overcomes the advantage of coherent rho production and causes the decrease seen per target nucleon for elements with more than 64 nucleons.

The experimental results indicate that the characteristic distance for a rho-nucleon interaction to occur in nuclear matter, called the mean-free-path, is about 3 fermis, roughly the radius of a carbon nucleus and about 4 times the radius of a proton. (There are about 25 million million fermis in one inch.) The corresponding experiments for pions and nucleons on nuclei, carried out with conventional particle beams instead of with the "rho beams" generated within individual nuclei, give similar results. When interacting with hadrons, therefore, the rho meson acts like a typical hadron.

Finally, vector dominance predicts the probability for a photon at high energy to interact strongly with nucleons. In such a process, all of the photon's electromagnetic energy materializes into hadrons. Again, each of the techniques described earlier for producing high-energy photons of known energy has actually been used in total-absorption experiments. Specifically, annihilation photons have been used in the 1-meter hydrogen bubble chamber at SLAC, while Compton-scattered laser photons were incident on the 2-meter chamber. Tagged-photon beams have been used in both bubble-chamber and counter experiments at DESY, as well as in a counter experiment at SLAC. Finally, inelastic electron scattering has been studied in a spectrometer experiment at SLAC to determine the rates for absorbing virtual photons on protons. These experiments, extending to 18 billion electron-volts, are in excellent agreement and show: (1) that the absorption of real and virtual photons by protons is the same, and (2) that the variation with energy of <u>photon</u> absorption by protons is the same as the variation with energy of <u>hadron</u> absorption by protons — even though the absorption of hadrons is 200 times more probable. In short, the variation with energy of real-photon or virtual-photon absorption is entirely consistent with hadronic photon character. This tends to confirm the importance of the two-step process — photon materializes to vector meson, which interacts with hadron — described earlier.

Another prediction of the vector-dominance model is that, at very high energies, the absorption of photons by neutrons and by protons should be the same. This comparison has been made up to 18 billion electron-volts at SLAC by the Santa Barbara-SLAC collaboration in a counter experiment using deuterium and hydrogen, as well as other targets. The deuterium nucleus consists of one neutron and one proton, while the hydrogen nucleus is a single proton: photon absorption by neutrons is thus nearly equal to the difference between absorption by deuterium and absorption by hydrogen. (A "Glauber correction" of about 5% must be made to this difference to account for "shadowing" of one nucleon by the other in deuterium.)

When the Santa Barbara results are extrapolated to infinite photon energy, the absorptions by neutrons and by protons are found to be identical, as expected. At lower energies the absorption on protons is about 10% larger than on neutrons suggesting that other, non-vector, mesons may participate.

It is in the total absorption of high-energy photons by large nuclei, however, that the hadronic character of light has its most startling consequences. Here, more than anywhere else, the nature of light itself depends on whether its electromagnetic or hadronic interaction is being observed.

The absolute rate for photon absorption on protons or neutrons is roughly 200 times lower than, for example, the rates for rho or pion absorption on protons. This is no surprise, since the first step — photon materializes to vector meson — of the double photon-hadron interaction process is rather improbable. On the other hand, the mean-free-path for photons, corresponding to this observed absorption rate, is about 700 fermis, over 200 times longer than the 3 fermis found for rhos. It is as if 700 layers of nuclear matter were required to absorb light in its original electromagnetic form while only 3 layers of the same material sufficed to stop hadrons. Thus photons pass easily through large nuclei, but hadrons barely scratch the surface, seldom interacting with the nucleons inside.

Since photons pass undiminished through so many nuclear volumes, we might naively expect that they would illuminate all the nucleons in a particular nucleus. Photon absorption would then be proportional to the total number of nucleons in each nucleus and thus to the nuclear volume. In contrast, hadron absorption is known to be proportional to the number of exposed surface nucleons and thus proportional to the area of the nuclear surface — as if each nucleus were a black disc. Paradoxically, the vector-dominance model and the optical theorem lead to the prediction that the ratio of photon-nucleus to hadron-nucleus absorption should depend only on the probability of a photon's materializing as a hadron and should be the same for any nucleus, both processes varying together in proportion to the surface area, not in proportion to the nuclear volume. Thus nuclei are nearly transparent to light, while at the same time, surface nucleons completely obscure those inside!

This is the kind of paradox, repugnant to common sense, that nature is continually thrusting at those who have too much confidence in their intuition. For example, in 1819, the French mathematician Poisson demolished the wave theory of light by reductio ad absurdum. He showed with impeccable mathematics that Fresnel's wave theory predicted that the shadow of a disk illuminated by a point source would have a bright spot at its center, which seemed clearly absurd. Hélas for M. Poisson: the shadow cast by such a disc, for example by a penny illuminated with a pinhole light source, does have a bright central spot.

To understand the surface paradox observed with strongly interacting photons, we must once again evoke the uncertainty principle. Specifically, the longitudinal position of the photon-hadron conversion point is uncertain by an amount proportional to the photon energy. When this uncertainty is large compared to the mean-free-path for hadrons inside nuclei — as it is for high-energy photons — then the photon must have converted to a hadron well before reaching the nuclear surface and shadowing results. The argument can be turned around. Suppose there were no shadowing. Then the photon-rho conversion must have occurred immediately in front of the absorption point. But this destroys the required uncertainty in the conversion point. Therefore there must be shadowing!

Does this mean that a large nucleus absorbs most of the light striking it? No, nearly all of the light passes through unaffected. However, the probability that a photon will show hadronic behavior and interact strongly — a small probability — is effectively blocked by the surface nucleons and does not extend to nucleons inside. The photon, after penetrating the nuclear surface, is temporarily a "bare" photon striped of its hadronic character. Suppose a photon passes through two widely separated nuclei in succession; does the first shadow the second? No, at presently attainable energies, the distance, set by the uncertainty principle, over which the photon remains "bare" is much shorter than the distance between nuclei. Thus shadowing of one atomic nucleus by another rarely occurs.

The prediction of photon shadowing by surface nucleons follows directly from the uncertainty principle argument and the hadronic character of light — independently of any details of the vector-dominance model. A sufficient test for hadronic character is therefore provided by photon total-absorption studies on nuclei of increasing size. Photons can be considered purely electromagnetic only if the nucleus remains transparent, only if all of the nucleons are illuminated, and only if the absorption is therefore proportional to the total number of nucleons.

The results obtained in the Santa Barbara experiment at SLAC on hydrogen, deuterium, carbon, copper, and lead show that photoabsorption is proportional neither to the total number of nucleons nor to the number of exposed surface nucleons; rather, the data fall somewhere between. Some degree of shadowing is certainly present so that the basic hadronic character of light is confirmed. Qualitatively, therefore, the results are consistent with vector dominance. Quantitatively, however, the amount of shadowing is less than vector dominance, together with the results of other experiments, would predict. Does this mean that there are other vector mesons besides the rho, omega, and phi? Perhaps photons become vector mesons less readily than was thought, or perhaps vector mesons are absorbed less strongly in nuclear matter than present experiments suggest. The answers to these questions, as well as the ultimate fate of the vector-dominance model, may depend on experiments already planned for the 70-billion-electron-volt accelerator now operating at Serpukhov, USSR, and for the 500-billion-electron-volt National Accelerator Laboratory nearing completion near Chicago.

FIGURE CAPTIONS

1. Photograph of the choir of La Sainte-Chapelle in Paris. In the words of Hugues de St. Victor, such structures were built so that "the splendor of the True Light might pass into the church and enlighten those inside".

2. Fresnel target used every 12.2 meters in the alignment system of the two-mile electron and positron accelerator at the Stanford Linear Accelerator Center. A laser beam passing through the large-diameter vacuum tank supporting the accelerator tube produces a characteristic diffraction pattern as each accelerator section is aligned. Laser light is also Compton-scattered 180° on high-energy electrons at SLAC to produce beams of high-energy photons that are both monochromatic and polarized.

3. Feynman diagrams are used by physicists in visualizing elementary-particle interactions. Electron-electron scattering (a) proceeds purely electromagnetically through the exchange of an energy-momentum packet, a virtual photon which, via the uncertainty principle, may assume a non-zero mass. Real, massless photons are occasionally radiated during electromagnetic interactions (b) and can be used in experiments requiring photon beams. Photon beams can also be produced by positron-electron annihilation into two real photons (c). The inverse of annihilation is pair production (d). Positron-electron annihilation can also yield a single virtual photon (e), which may then produce a pair of pions. The materialization of a virtual photon into two pions is greatly enhanced in the two-step process (f) in which the virtual photon first materializes into a rho vector meson, which then decays rapidly into two pions.

4. Yield of pion pairs versus the total energy of the annihilating electron and positron (the mass of the virtual photon). These data, obtained in the colliding beam experiment at Orsay, show that few pions are produced except through

the production and decay of the rho vector meson. The rho vector meson mass (770 ± 4 million electron-volts) and width (111 ± 6 million electron-volts) were found by fitting the data points as shown to a theoretically predicted shape. The resonance width corresponds, via the uncertainty principle, to a rho lifetime so short that most rhos decay before traveling more than a few nuclear radii. Similar, much smaller peaks are found at the omega and phi masses.

5. Elevated view of the End Station A experimental area at SLAC. A beam of electrons, positrons, or photons enters from the bottom of the figure and strikes a target located at the center of rotation of three independent magnetic spectrometers, the largest of which is 170 feet long and weighs 2000 tons. This particular spectrometer has been used to study virtual-photon absorption in inelastic electron-proton scattering, while all three spectrometers have been used in experiments investigating vector-meson photoproduction.

6. Rho photoproduction per target nucleon versus rho mass M and versus transverse momentum given to the target nucleus, $t_\perp$, which is roughly proportional to the square of the production angle. For a given value of $t_\perp$, the area under the resonant mass distribution <u>per nucleon</u> increases at first, then decreases with increasing nucleon number A. The data shown were obtained by the DESY-MIT collaboration at Deutsches Electronen-Synchrotron, Hamburg, Germany.

7. Experimental arrangement used by the Santa Barbara-SLAC collaboration at the Stanford Linear Accelerator Center to study photon absorption on a variety of nuclei. Positrons of known energy enter from the left and are bent into the tagging counters after producing photons in the radiator. The tagged-photon energy is the difference in the positron energy before and after radiation

occurs. Hadronic absorption in the target is signaled by the absence of a photon in the shower counter and by the presence of hadrons in the hadron counters. Photons that produce positron-electron pairs or that Compton-scatter on electrons in the target are not detected as hadronic events since the electromagnetic products of these interactions are moving nearly parallel with the photon beam and pass cleanly through the beam holes in the hadron counters. They are then detected in the shower counter as if no interaction had taken place.

8. Compilation of data on total photon absorption by protons via hadronic interactions. The results for virtual photons, obtained in the inelastic-electron scattering experiment at SLAC, are in good agreement with the data from other experiments using real photons. Further, the sharp peaks below two billion electron-volts, and the smooth behavior above, are also observed in pion absorption by protons. Thus the energy variation for both real-photon and virtual-photon absorption on protons is entirely consistent with hadronic photon character.

9. Comparison of total photon absorption on protons and on neutrons in the Santa Barbara-SLAC experiment. These data, when extrapolated to infinite photon energy, give the same absorption for protons and neutrons, as is expected if photons act like hadrons. The small difference seen at low energies may indicate that mesons other than the known vector mesons contribute to the absorption.

10. Shadowing of an average nucleon against high-energy photons versus nuclear size. The data, averaged between 7 and 18 billion electron-volts, are from the Santa Barbara experiment at SLAC. Purely electromagnetic photons would

give zero shadowing. Vector dominance predicts more shadowing than is seen — the lines give predictions from other experiments. The photon is certainly hadronic, but vector dominance does not fit perfectly.

11. Probability of elastic photon scattering on protons at high energy, versus scattering angle. As the scattering angle becomes smaller, the probability approaches that predicted by the optical theorem from the total absorption of photons by protons. These measurements were made at SLAC using the smallest of the three spectrometers to detect the recoiling proton and a separate counter to detect the scattered photon.

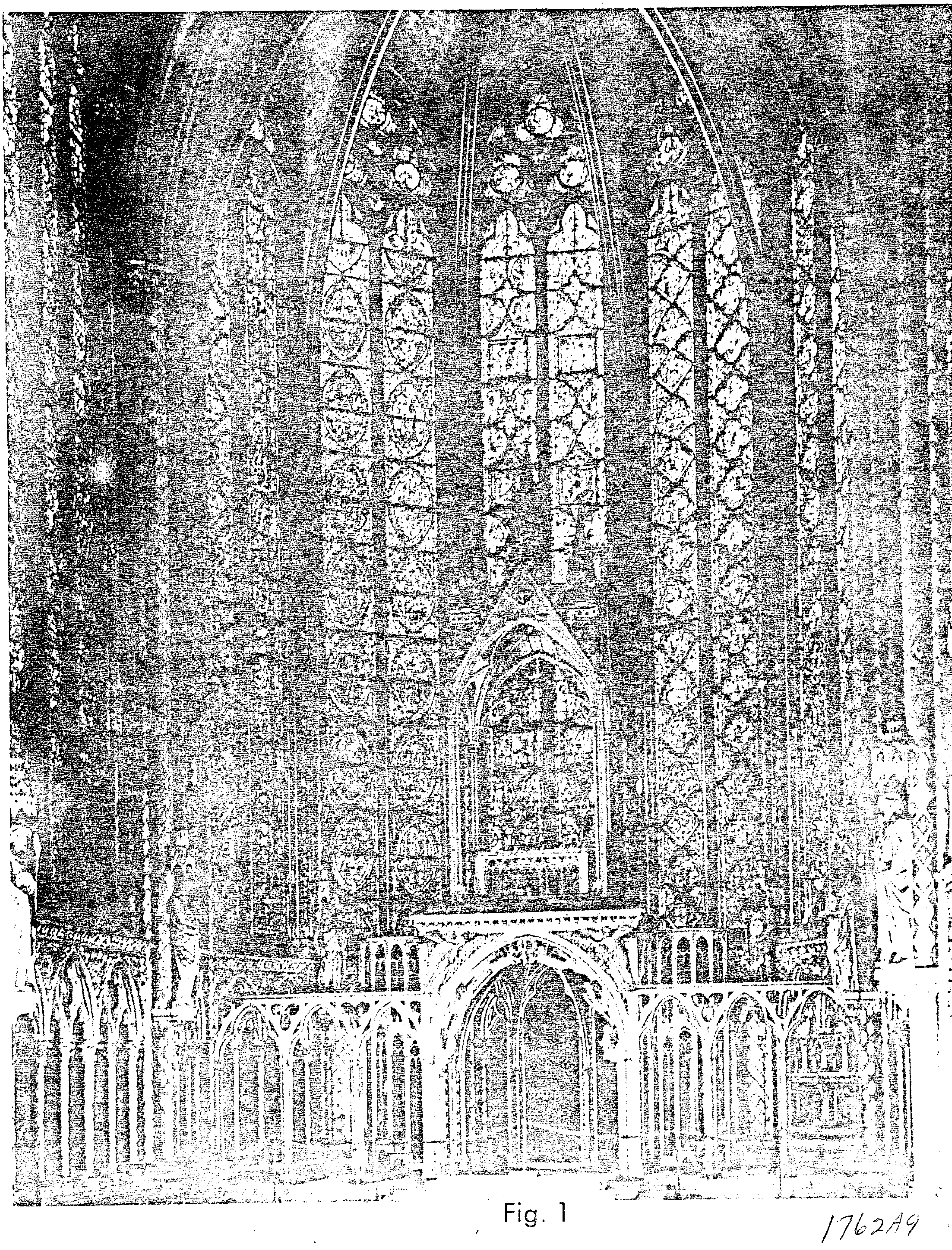

Fig. 1

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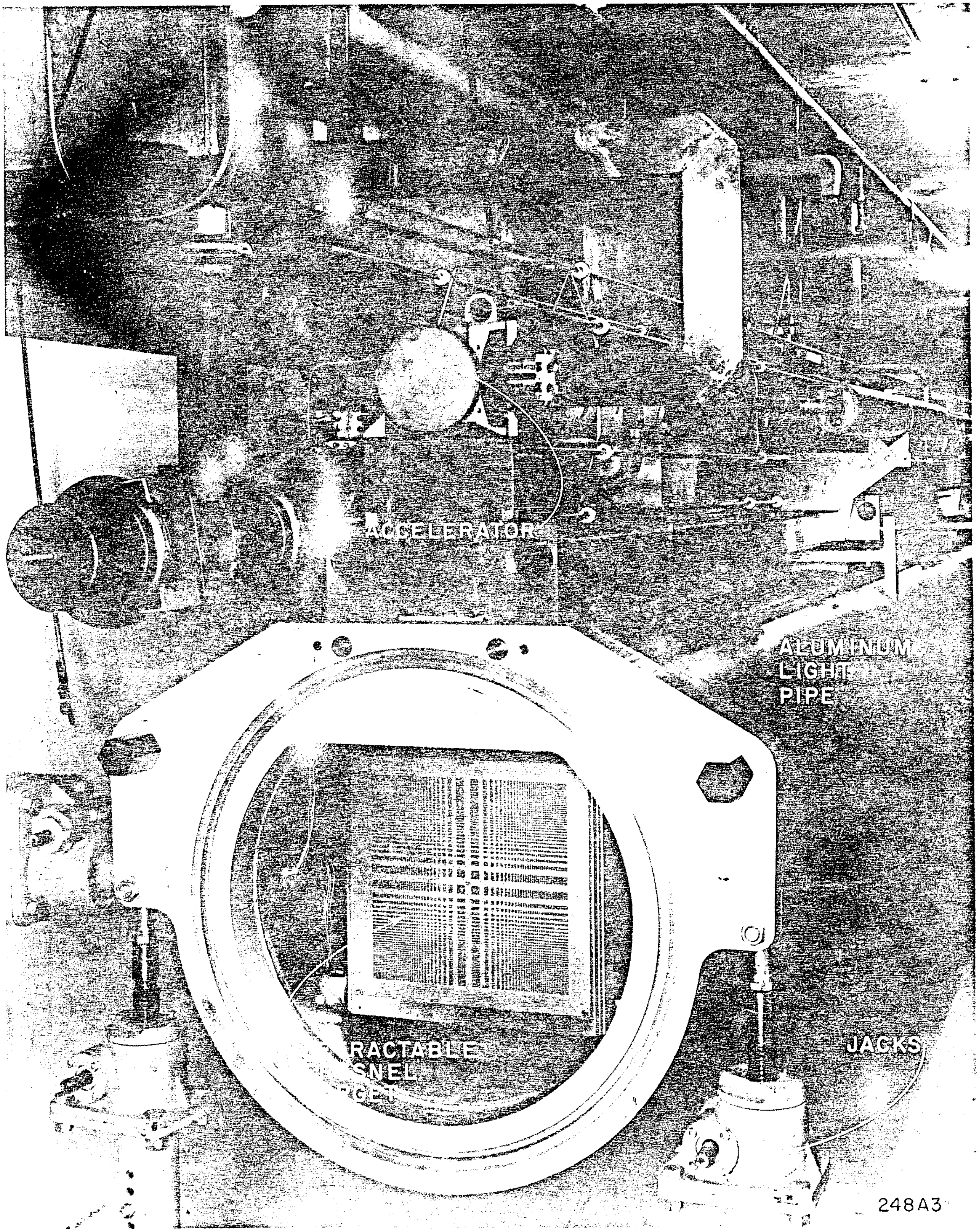
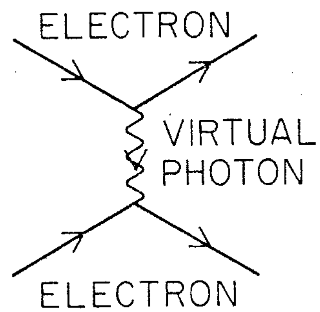
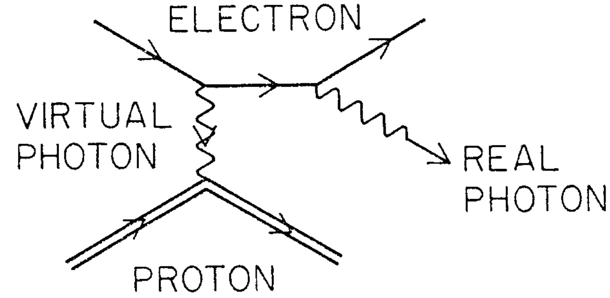


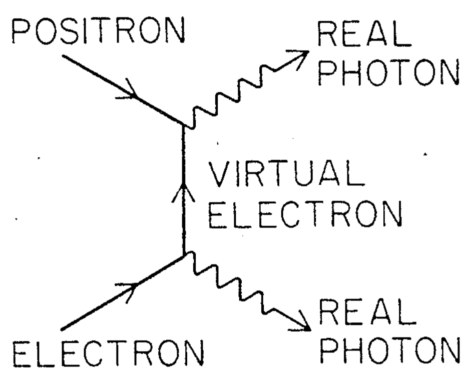
Fig. 2



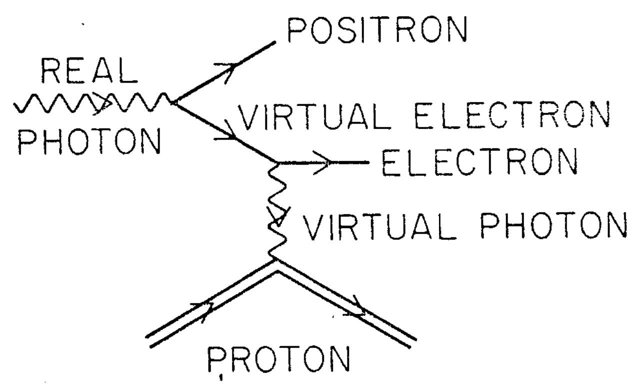
(a) SCATTERING



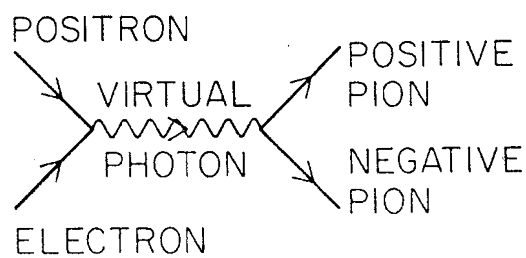
(b) RADIATION



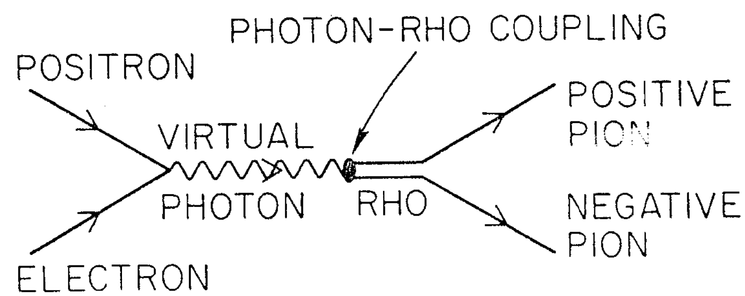
(c) REAL ANNIHILATION



(d) PAIR PRODUCTION

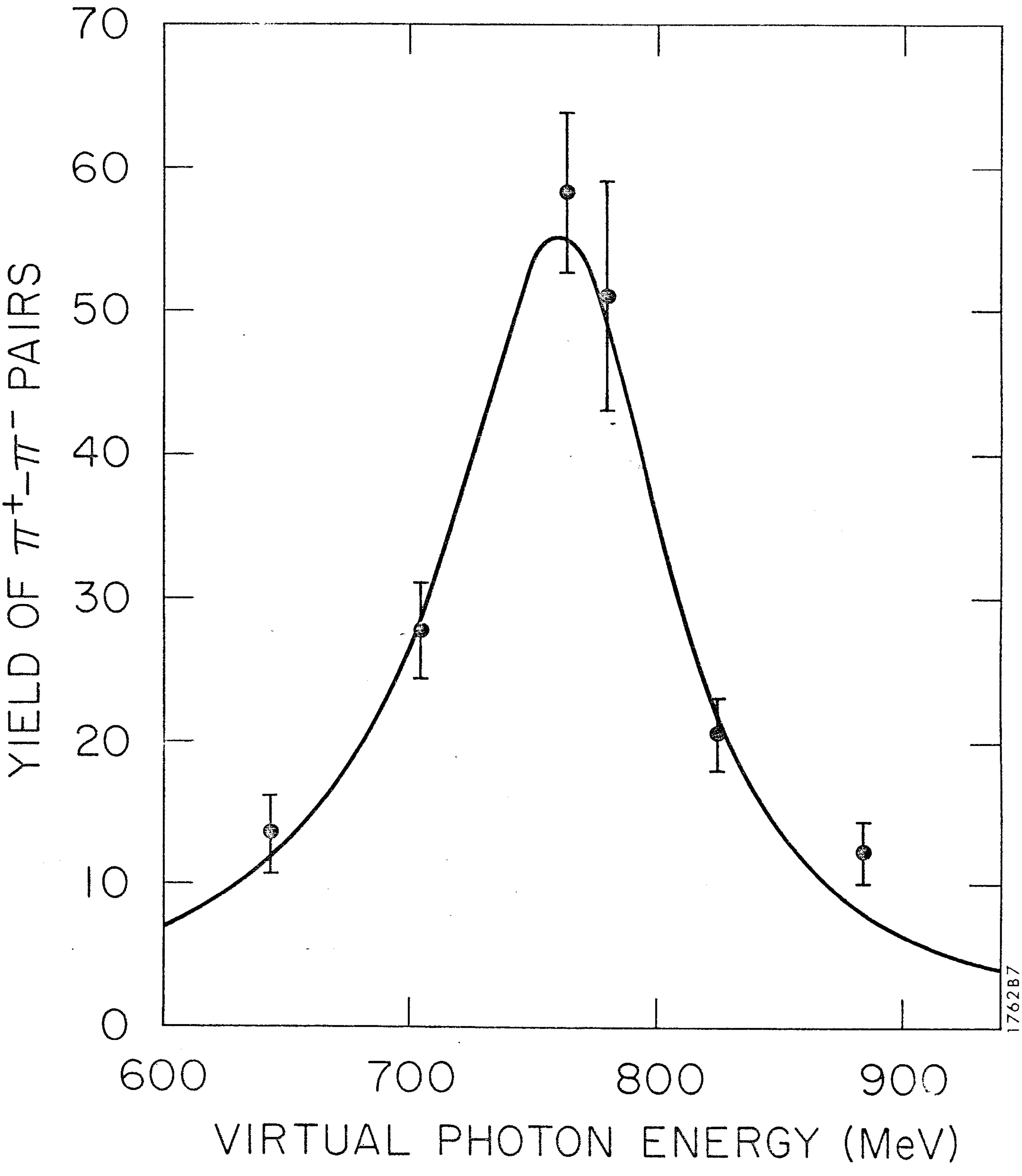


(e) VIRTUAL ANNIHILATION



(f) VIRTUAL ANNIHILATION MEDIATED BY RHO

1762B1



70
60
50
40
30
20
10
0
600
700
800
900
YIELD OF π^+–π^- PAIRS
VIRTUAL PHOTON ENERGY (MeV)
1762B7

Fig. 4

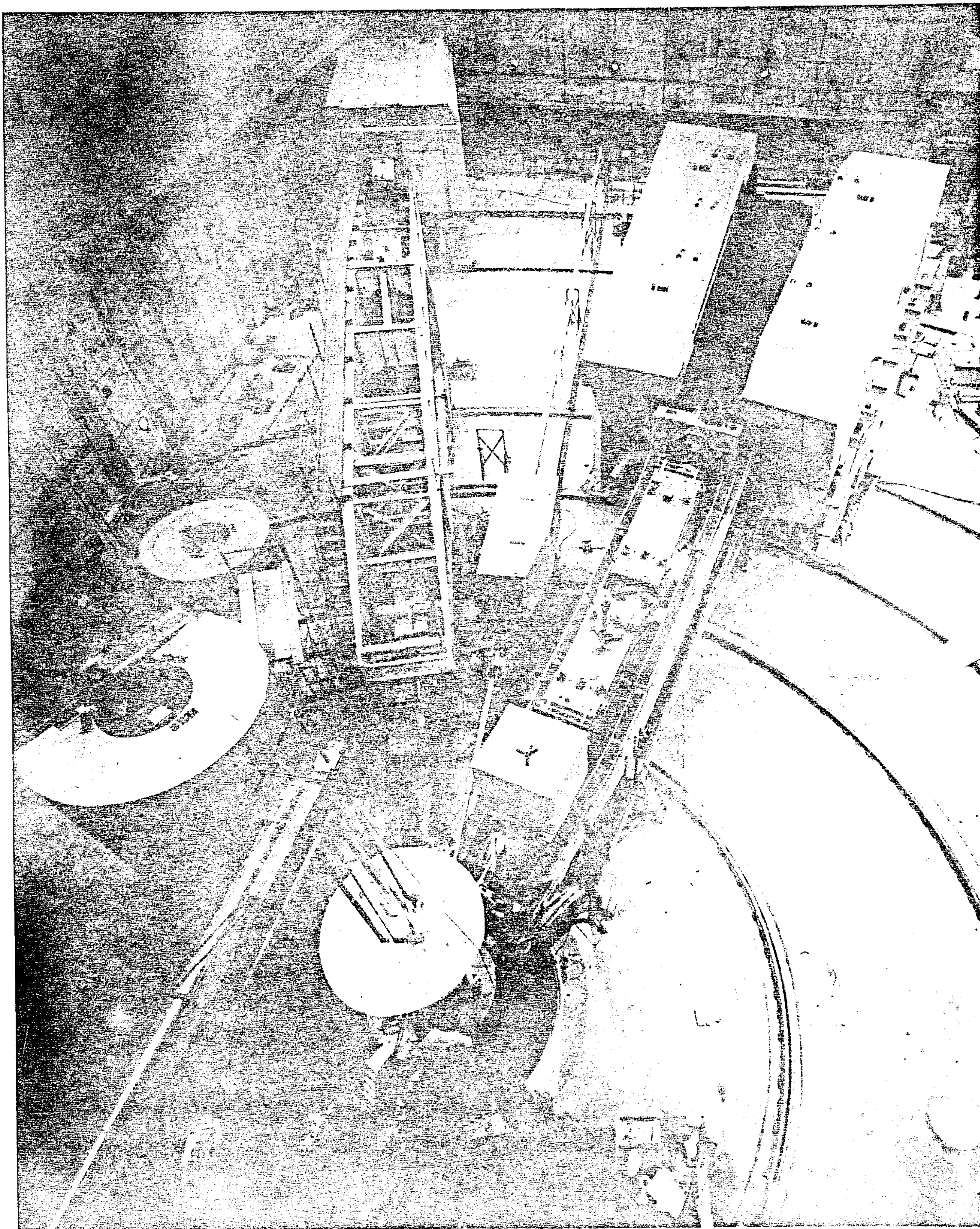


Fig. 5

1762 A2

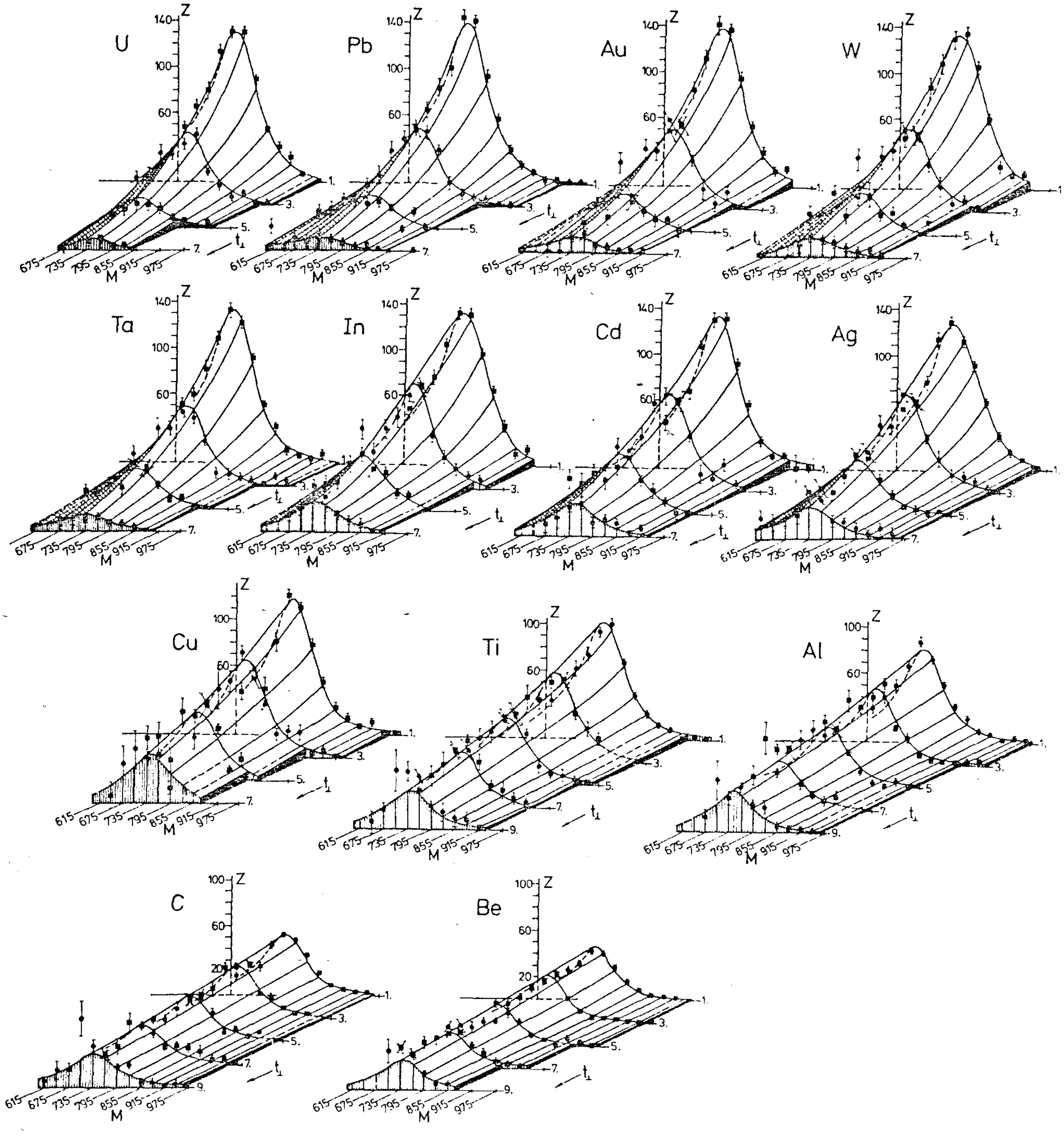
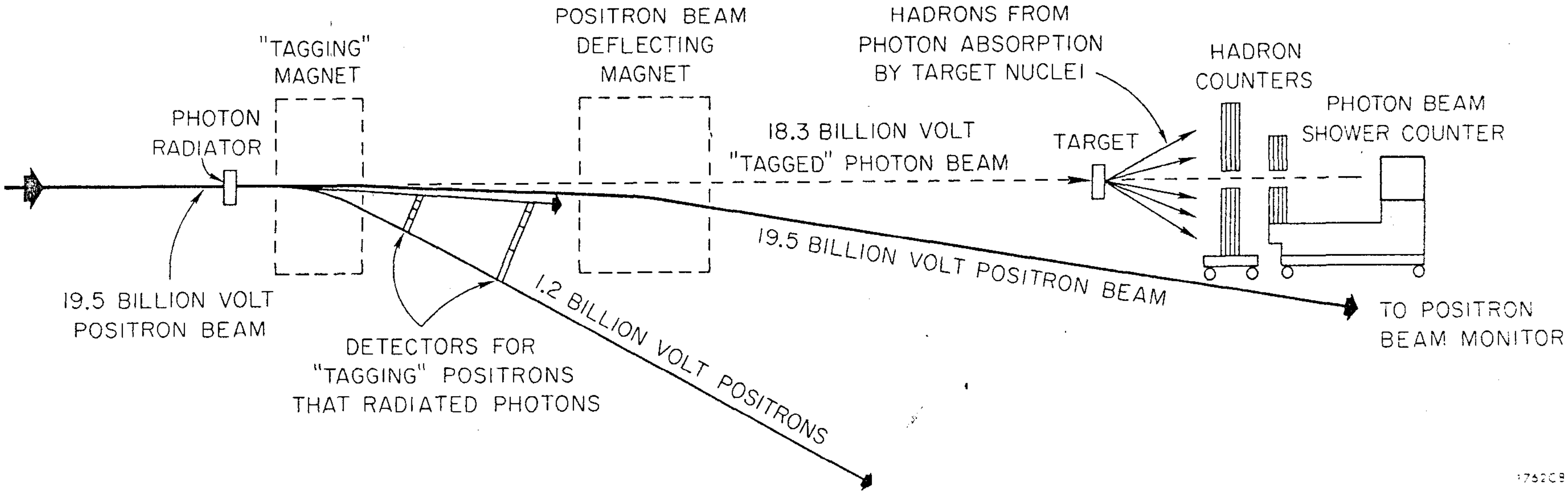


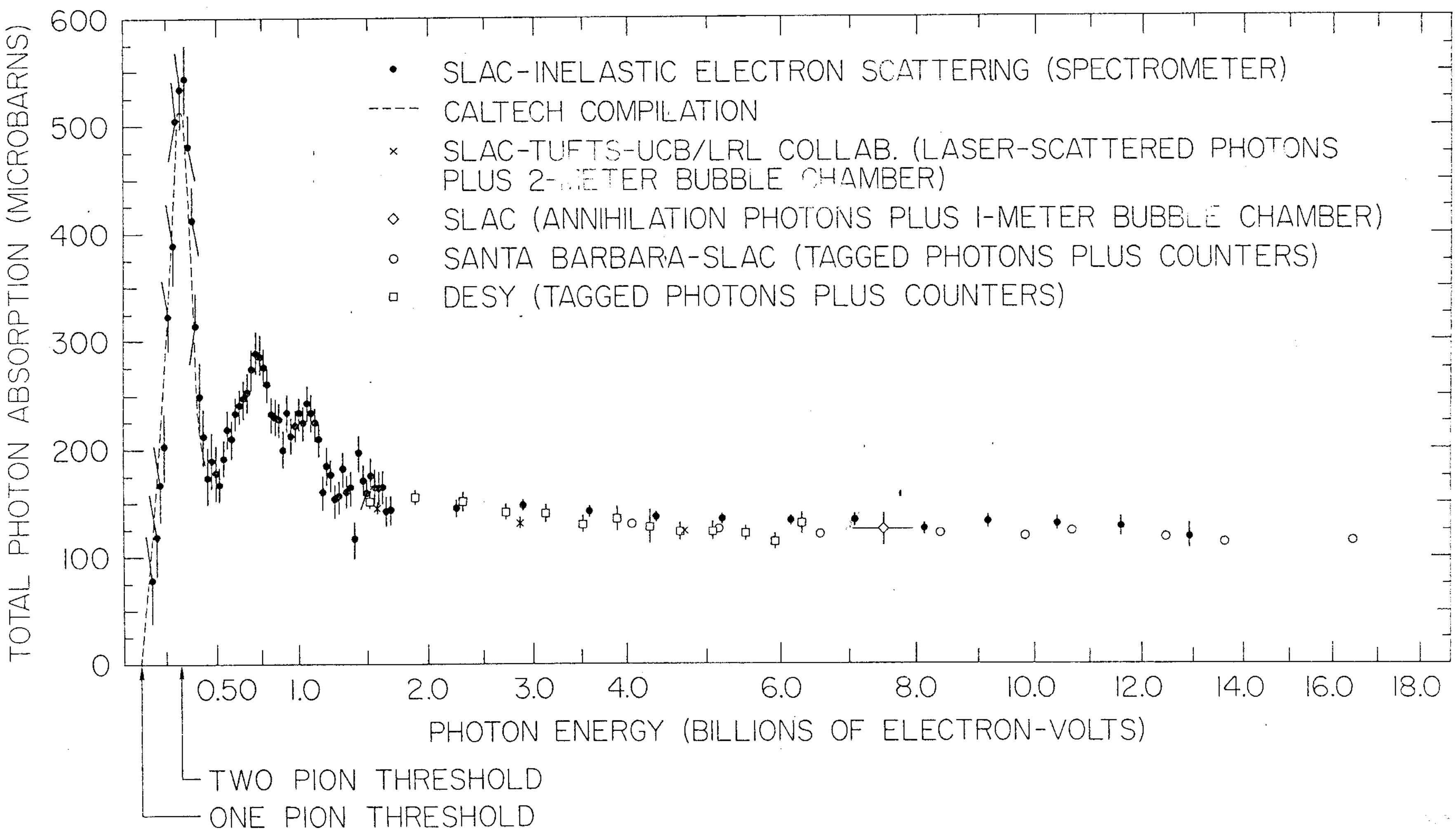
Fig. 6

1762A10



"TAGGING"
MAGNET
POSITRON BEAM
DEFLECTING
MAGNET
HADRONS FROM
PHOTON ABSORPTION
BY TARGET NUCLEI
HADRON
COUNTERS
PHOTON BEAM
SHOWER COUNTER
PHOTON
RADIATOR
18.3 BILLION VOLT
"TAGGED" PHOTON BEAM
TARGET
19.5 BILLION VOLT POSITRON BEAM
19.5 BILLION VOLT
POSITRON BEAM
1.2 BILLION VOLT POSITRONS
DETECTORS FOR
"TAGGING" POSITRONS
THAT RADIATED PHOTONS
TO POSITRON
BEAM MONITOR

Fig. 7



TOTAL PHOTON ABSORPTION (MICROBARNS)
600
500
400
300
200
100
0
SLAC-INELASTIC ELECTRON SCATTERING (SPECTROMETER)
CALTECH COMPILATION
SLAC-TUFTS-UCB/LRL COLLAB. (LASER-SCATTERED PHOTONS PLUS 2-METER BUBBLE CHAMBER)
SLAC (ANNIHILATION PHOTONS PLUS I-METER BUBBLE CHAMBER)
SANTA BARBARA-SLAC (TAGGED PHOTONS PLUS COUNTERS)
DESY (TAGGED PHOTONS PLUS COUNTERS)
0.50
1.0
2.0
3.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
PHOTON ENERGY (BILLIONS OF ELECTRON-VOLTS)
TWO PION THRESHOLD
ONE PION THRESHOLD

1762D3

Fig. 8

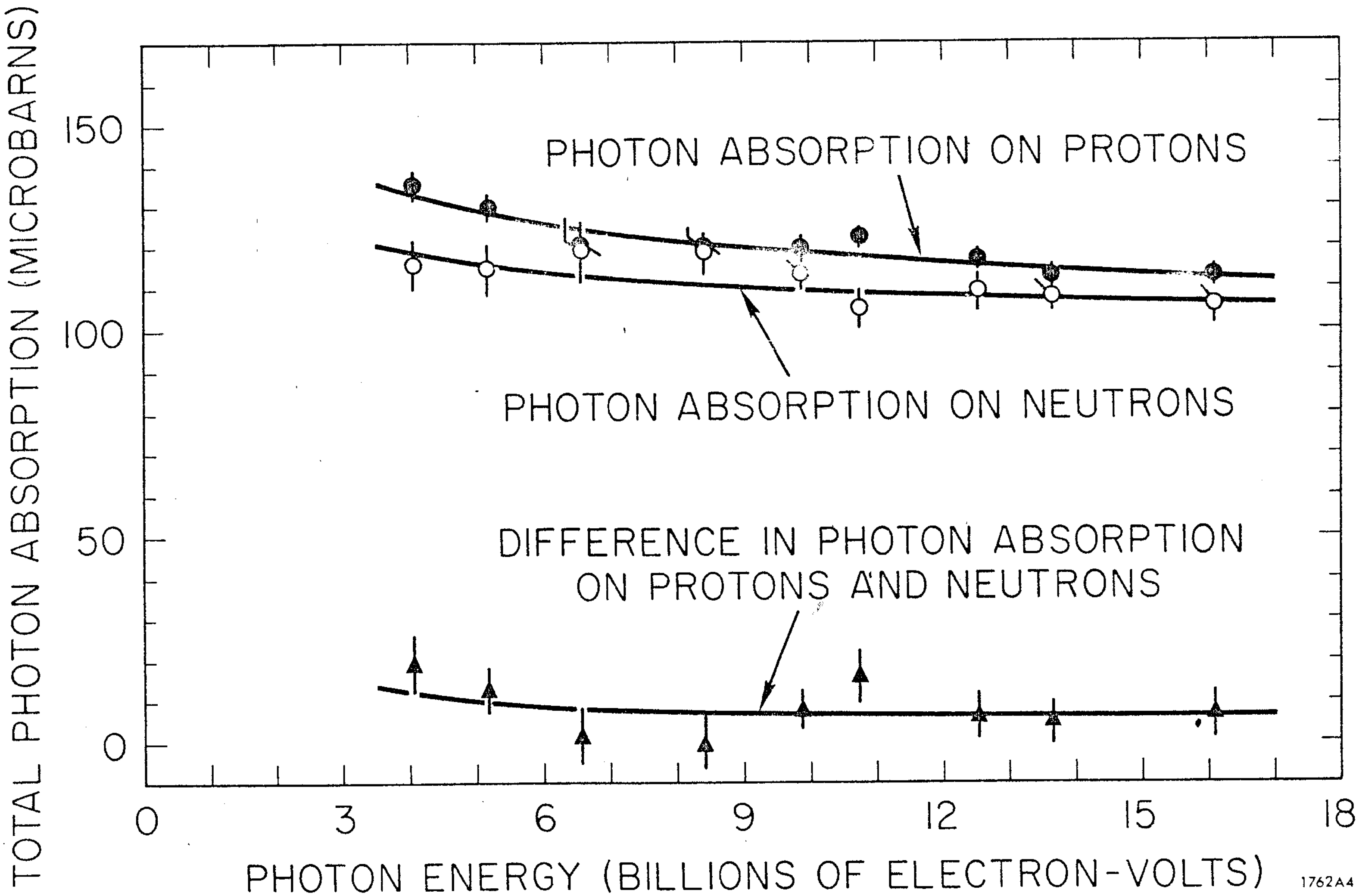

TOTAL PHOTON ABSORPTION (MICROBARNS)
150
100
50
0
PHOTON ABSORPTION ON PROTONS
PHOTON ABSORPTION ON NEUTRONS
DIFFERENCE IN PHOTON ABSORPTION ON PROTONS AND NEUTRONS
0
3
6
9
12
15
18
PHOTON ENERGY (BILLIONS OF ELECTRON-VOLTS)
1762A4

Fig. 9

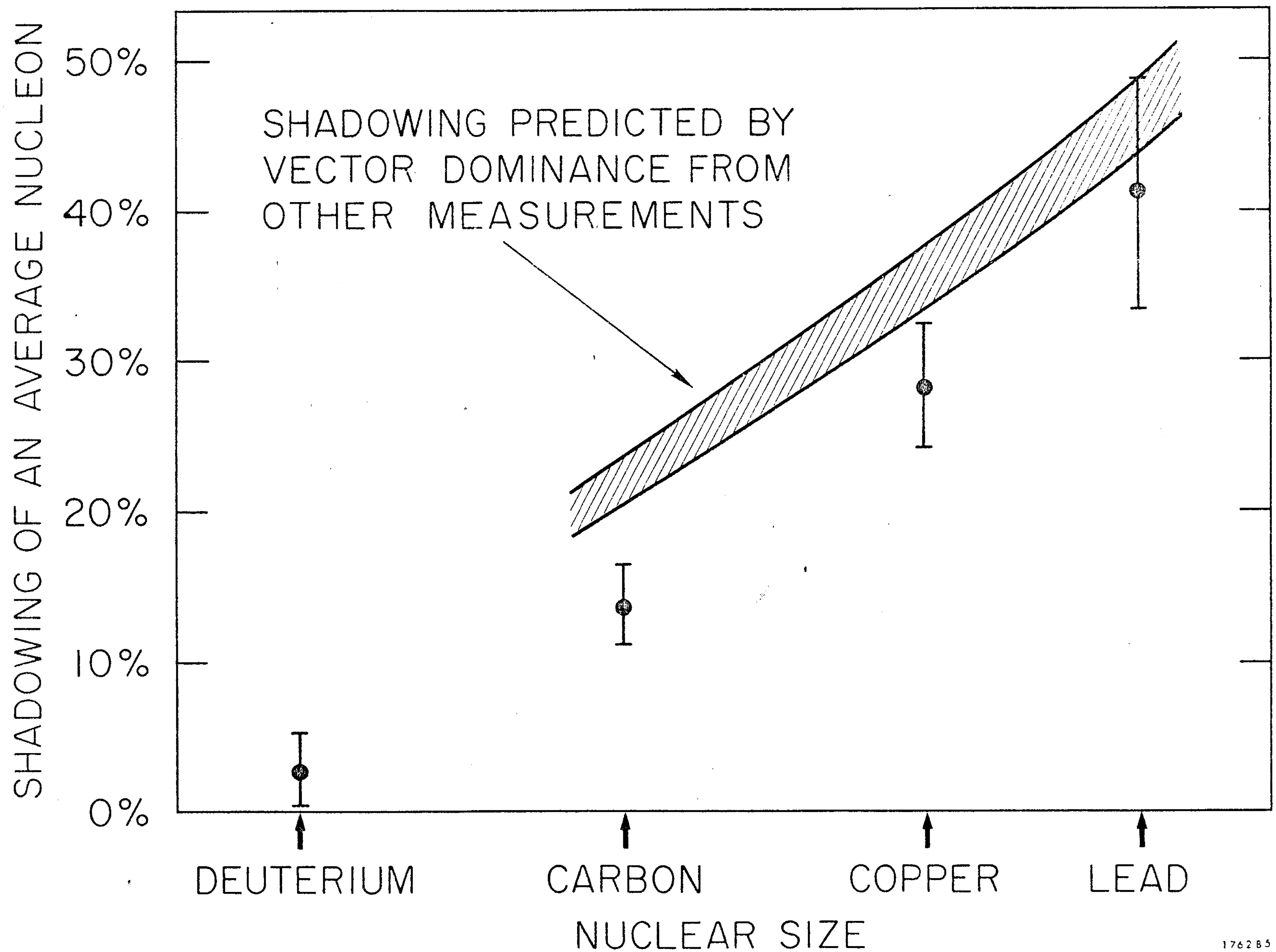

SHADOWING OF AN AVERAGE NUCLEON
50%
40%
30%
20%
10%
0%
SHADOWING PREDICTED BY
VECTOR DOMINANCE FROM
OTHER MEASUREMENTS
DEUTERIUM
CARBON
COPPER
LEAD
NUCLEAR SIZE
1762B5

Fig. 10

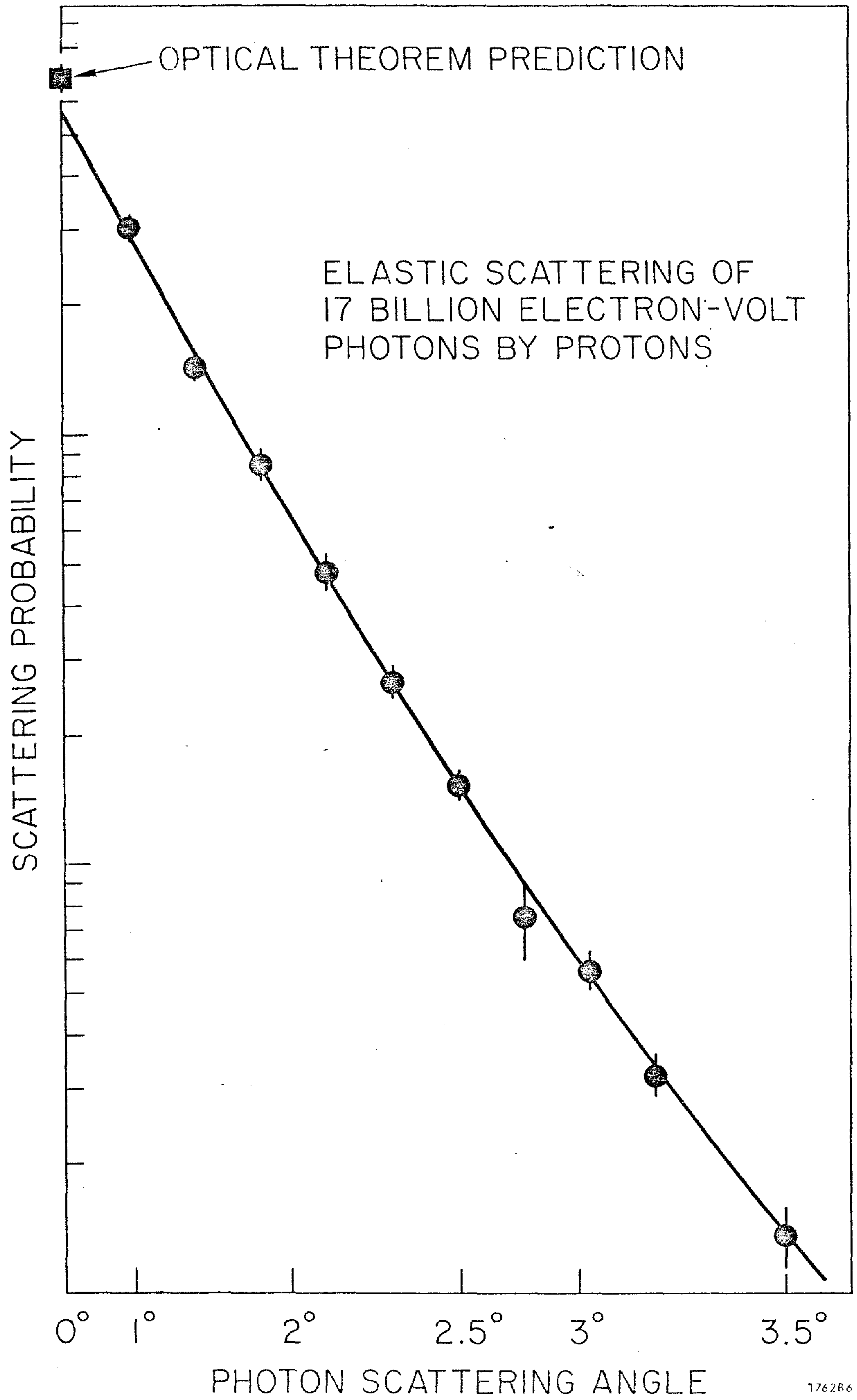

OPTICAL THEOREM PREDICTION
ELASTIC SCATTERING OF
17 BILLION ELECTRON-VOLT
PHOTONS BY PROTONS
SCATTERING PROBABILITY
0°
1°
2°
2.5°
3°
3.5°
PHOTON SCATTERING ANGLE
176286

Fig. 11