

PHYSICS AND OUR WORLD

Reissue of the Proceedings of a Symposium in Honor of Victor F Weisskopf

Editor

Kerson Huang



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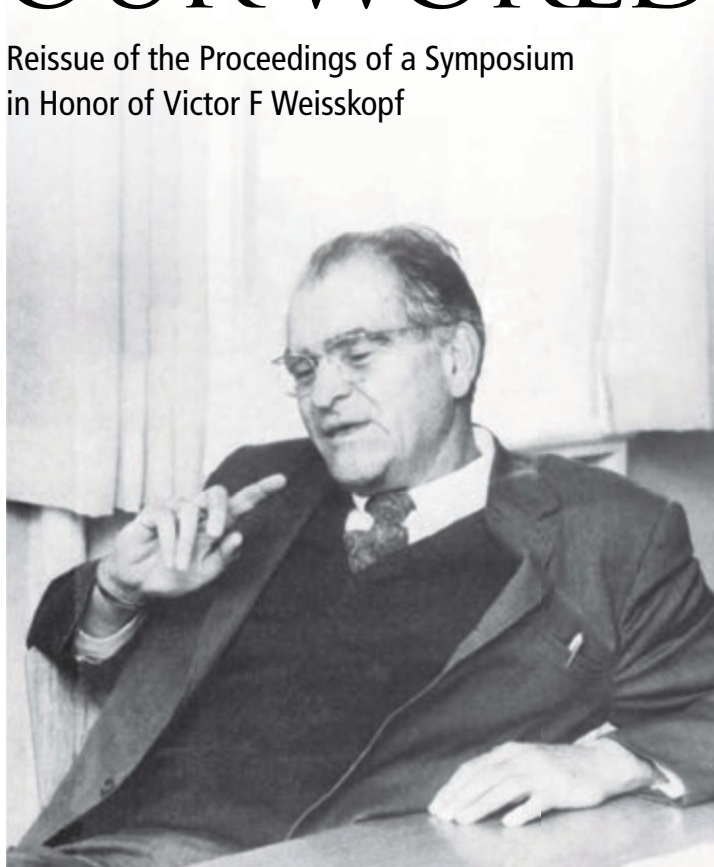
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Kerson Huang

Massachusetts Institute of Technology, USA

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PHYSICS AND OUR WORLD

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Foreword

This is a reissue of *Physics and Our World: A Symposium in Honor of Victor F. Weisskopf*, MIT, 17–18 October, 1974, ed. K. Huang (American Institute of Physics, New York, 1976), originally published as *AIP Conference Proceedings* No. 28. We thank the American Institute of Physics for permission to reset and reprint this volume. The figures, the speakers' original sketches, have been preserved.

Victor Weisskopf (1908–2002), professor of physics at MIT, known to his friends as “Viki”, was an influential figure in physics, both for his work as a theoretical physicist, and science statesman. The prominence of the symposium speakers, and the thoughtfulness of their speeches, testify to the high regard and great affection in which he was held in the physics community.

Many contributions are a delight to read. Hans Bethe's analysis of the energy problem could be written today, but for the giveaway: “Last year, the cost of a barrel of oil in the Middle East was about \$3. Now, it is \$10 or more.” And: “With great difficulty one can find out that one barrel of oil is 42 gallons.” Today, of course, oil is around \$100 a barrel, and you can instantly find out how many gallons are in a barrel from Google.

Edward Purcell's piece on how one should swim in a viscous fluid — by turning anything, as long as it isn't perfectly symmetrical — tells bacteria to develop flagella.

Stanley Ulam pointed out that mathematicians deduce theorems from axioms, but physicists go the other way — try to find the axioms (natural laws) that lead to given theorems (observations). He also recounted his experience with Enrico Fermi on computer simulations of anharmonic oscillators (which led to an astounding non-ergodic result later attributed

to solitons), and Fermi was quoted as saying, “Well, it does not say in the Bible that the fundamental equations of physics must be linear.”

Max Delbruck said that Aristotle’s physics was “pretty much a catastrophe”, but his biological thinking pointed to DNA, for he had the idea that what one generation passes to the next is a blueprint. “Aristotle considered it remarkable that human beings beget human beings, and not rabbits or an ear of corn.”

The historical significance of this Symposium is that it occurred during a paradigm change in theoretical physics, because of quarks. Here, Julian Schwinger’s talk “Model-free views of deep inelastic scattering” echoed the “old school”, while Murray Gell-Mann’s “The world as quarks, leptons, and bosons” was precursor to the new.

After the great breakthrough that was renormalized QED in 1947, there followed a long period of disenchantment with quantum field theory, because the expected quick conquest of the strong interactions did not occur. On the one hand, Lev Landau declared that the renormalized charge of the electron is zero according to quantum field theory (a problem known as “triviality”), which should therefore be buried, “with honors”. On the other hand, Geoffrey Chew and his school hold that the basic entities of quantum field theory, elementary particles, do not exist; the hadrons are “bound states of one another”. In this view of “nuclear democracy”, these particles are resonances in some kind of primordial goo that “bootstraps” itself into existence. Even Gell-Mann, who coined the name “quark”, had to tiptoe around with the so-called “current algebra”, a somewhat messy scheme which might be characterized as “quarks without quarks”.

The first break came with the deep inelastic scattering experiment at SLAC, carried out by Taylor, Friedman, and Kendall in 1968. Richard Feynman interpreted the result in terms of “partons” — point-like “parts” of the nucleon that produce back-scattering, much like Rutherford’s atomic nuclei. The clincher came in 1974, just after this Symposium, with the discovery of the J/Ψ particle by the group of Samuel Ting at the Brookhaven National Laboratory, and that of Burton Richter at SLAC. This extremely long-lived particle is a non-relativistic bound state of the heavy charmed quark and its antiquark — a veritable “hydrogen atom” whose energy levels unmistakably identify its underlying structure. This left no doubt that quarks do exist, and soon led to the standard model, a renormalizable

quantum field theory involving Yang–Mills gauge fields with spontaneous symmetry breaking.

As a historical note, Samuel Ting was present at this Symposium, and his group had already found an extremely narrow resonance peak. In Ting's words, "It was like stumbling into a village in which the average age of the inhabitants was ten thousand years." He had considered announcing the result at the Symposium, but did not, out of carefulness.

With the standard model, quantum field theory again reigns supreme. The bootstrap theory strikes back, however. It morphs into string theory, and challenges quantum field theory when the distance scale shrinks to the Planck scale, by some eighteen orders of magnitude.

Kerson Huang
Naples, Florida
June, 2013

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Acknowledgments

We are happy to acknowledge the encouragement and help which we received from President Jerome B. Wiesner, Provost Walter A. Rosenblith, and Head of the Physics Department, Professor Herman Feshbach, of the Massachusetts Institute of Technology.

We also wish to thank all of the speakers at this Symposium for their graciousness in granting permission to publish their talks, and in many cases, reading and editing transcriptions of their taped presentation.

Thanks are due to Mr. Barry Friedman and Mr. Patrick Hayes for editorial help.

Special thanks are due to Mr. Daniel H. Gould, Executive Officer of the M.I.T. Physics Department, for his help and cooperation.

Last but not least, thanks must go to Miss Diane Eulian for her conscientious, excellent, and indispensable effort in the preparation of the manuscript.

The Editor

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Preface

The essays contained in this volume are a partial record of the celebration in honor of Victor Weisskopf held at the Massachusetts Institute of Technology, October 17 and 18, 1974. No attempt was made to organize these presentations about a particular area of physics but rather the speakers were asked to select a topic which, in their opinion, would be of great interest to Viki.

The illustrious list of contributors is an indication of the high regard in which he is held by the scientific community. This is in part a consequence of his impact on the development of modern physics through many seminal contributions: the theory of line breadth; the quantizations of the scalar field; quantum electrodynamics, including a first calculation of the Lamb shift; nuclear reactions, including the optical model; the foundations of the shell model; and the structure of hadrons. It is also a consequence of his actions as a statesman of science in his roles as Director-General of CERN, as head of the M.I.T. physics department, as chairman of the High Energy Physics Advisory Committee (HEPAP) and as spokesman for basic science in the public arena, of his efforts on behalf of international cooperation and of his deep appreciation of the human aspects and human qualities of scientific research and education. But of equal importance is his style and spirit so beautifully captured by his own phrase “the joy of insight”. There is an unquenchable desire to understand the essential physical elements involved in phenomena, to strip away the complexities of a detailed explanation and to make visible the underlying ideas and concepts. It is an attitude which we at M.I.T. particularly have come to appreciate, and emulate.

He more than satisfied Milton's definition of a great man: "He alone is worthy of the appellation who either does great things or teaches how they may be done, or describes them with a suitable majesty when they have been done."

Herman Feshbach

October, 1975

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Introductory Remarks

James Killian

Massachusetts Institute of Technology

Honored guest, ladies and gentlemen. We at M.I.T. rejoice that so many of you from near and far are with us these two days in honoring our cherished colleague, Victor Weisskopf. I say Victor but that does not carry the appropriate ring — the appropriate ring of affection. I am reminded of a story about the late Charles Evans Hughes, once the Chief Justice of the U.S. Supreme Court and candidate for President, a man of formidable accomplishments in his profession and in public life. One day his young granddaughter boldly asked him what she should call him, and the Chief Justice replied: “Those who love me call me Charlie”. And so, despite his formidable array of titles, responsibilities, accomplishments, honors, and accolades, we all feel more comfortable in addressing Victor as “Viki”.

In the Gilbert and Sullivan operetta *Iolanthe*, there is a line which says: “All questions of party are merged in a frenzy of love and devotion,” and so it is today for Viki. I am not one competent to speak of Viki’s scientific accomplishments — they are amply known and appreciated by this gallery. Here at MIT he is Mr. Science. One of his colleagues has spoken of him as possessing the Copenhagen spirit, the Niels Bohr-like capacity so thoroughly to understand a complex scientific problem, that he could achieve an illuminating simplicity in presenting it or discussing it with all of us. Without yielding any of the rigor and imagination of his scientific work, he has also given meaning both to the scientific and humanistic values of science for his student and colleagues. By his largeness and liberality of spirit he has drawn about him a constellation of scholars both scientist and non-scientist who

have found in his values and his clarity of mind sustenance and reassurance in these days when science has come under attack from so many different directions. In the spirit of Copenhagen he has spoken eloquently to the layman about the role of science and, to use the title of one of his books, about knowledge and wonder and the natural world as man knows it.

In 1963 at the centennial of the National Academy of Science, Robert Oppenheimer spoke of the need to help non-scientists understand science. He said: "We the scientists have a modest part to play in history, and the barriers between us and the man of affairs — the statesman, the artist, the lawyer with whom we should be talking — could perhaps be markedly reduced if some of them knew a little more of what we were up to, knew it with some pleasure and some confidence." Despite Viki's heavy burdens of teaching, researching and administering, he is doing precisely this in many different ways. His concern about the role of science and society leads me today to give a brief report on some recent efforts in the United States to regain for science its proper place in our national policymaking.

As you know, the last administration dismantled the President's Science Advisory Committee (some of the former members of that Committee are here today), and the Office of Science and Technology. As a substitute, he has asked the Director of the National Science Foundation to serve as Science Advisor to the President, reporting not directly to the President but to an intermediary. These arrangements, in the judgement of a Committee of the National Academy of Science that was appointed to examine into the possibilities of improving scientific advice to the President, are not adequate to deal with the problems that face the people who have to make top policy in our Government today. We feel, in this Committee of which I have the honor to be Chairman, that we need some new arrangement — not the old arrangement we had, not a repetition of PSAC, but some new arrangement that can make available adequate scientific and technological advice to the President and his immediate associates in the Executive Office of the President. The advice called for is not merely the exercise of judgement in the White House, the exercise of judgement of choice among well-defined choices of alternatives. Rather the best scientific and technological talent must be immediately involved in identifying new alternatives for the President. These judgements in turn require an understanding of prospective developments at the frontier of science and technology. This is even more true now than it was after Sputnik. I think the need is much greater than it

was in 1957 when Eisenhower established PSAC as his immediate scientific advisory committee. The fundamental thesis of the NAS committee, in its report, is that the process of summation and policy-making that takes place at the level of the Presidency requires the accessibility of scientific, technological and engineering counsel — immediate accessibility. Some people in Government today say this is no longer necessary because science is present in all of the departments and agencies of the Government, but this is not an adequate substitute for having available at the top policy level adequate scientific counsel and advice and analysis. There should be means included in the staff structure of the Executive Office of the President to provide a source of scientific and technological analysis and judgement directly to the President, but also to the immediate agencies that he turns to within his family of advisors in the White House.

The first recommendation of the Committee, therefore, was that a council for science and technology be created within the Executive Office of the President and that this Council be composed of at least three full-time members drawn from the science, engineering and related fields. Now, this was not the first time that a recommendation for such a council has been made. I think Lee Dubridge was the first person that I know who proposed that there be the creation of a Council somewhat analogous to the Council of Economic Advisors. These three or more scientists and engineers would be appointed by the President with the advice and consent of the Senate and would serve at the pleasure of the President. One member would be designated by the President to be Chairman and would bear the responsibility to report to the President. In effect, he would be the President's Science Advisor.

Our Committee proposed that this Council be created by legislation, although it made this quite tentative, because I think it is very important, if such an agency is created, that the President feel it is his own mechanism to serve his own needs. The Committee further recommended that the Council for Science and Technology be empowered and able to draw from the best talent within the nation's scientific and technological and engineering communities, both from within and without the Government. It should be able to appoint panels of specialists, and to draw heavily on departments and agencies of Government themselves, as well as on the resources of industry, the universities, non-profit centers, the National Academy of Sciences and of Engineering, and the Institute of Medicine. The Committee felt that

this Council should have strong working relationships (and this we felt to be very important) with the agencies and other offices of the Executive Office, notably the Domestic Council and the National Security Council. The Chairman of the Council, we recommended, should be a member of the domestic council and should have an active role in the work of the National Security Council as PSAC did at one time. It is particularly important as we look at the role of the domestic council that it has better scientific inputs than it is getting at the present time. The National Security Council must organize its work in a fashion that will best serve the President in accord with his preferred manner of dealing with National Security Affairs.

Consistent with that requirement, there should be a provision for systematically introducing into the work of the NSC the judgement of a scientist and technologist. The Committee hoped that the Council, if proposed, would be looked to, as was PSAC, for provisions of the nation's best scientific and technical knowledge and judgement — particularly in those matters that involve advanced technology of the insights and early warnings — that the scientists working at the frontiers of their specialties would be qualified to transmit. In this fashion the NSC can benefit from highly professional judgements on military technology and arms control as undistorted by jurisdictional lines of thought as they can be. I can't help but recall that it was by virtue of the fact that the President's Science Advisor under Eisenhower was sitting in on a meeting of the National Security Council, when discussions came up about the problem of fallout; and it was possible to report on that occasion that PSAC had reached the conclusion that progress had been made in one routine test, and that it might be desirable to re-examine this. As a result of this, a committee was promptly appointed by the President, of which Hans Bethe was chairman, that made a report to the National Security Council. This started down the long road that ultimately led to the treaty of limitation of nuclear tests. That sort of thing is exceedingly important today, no less than it was at that time. I also think it important to note that, at the present time, the President does not have available to him critical analysis of military proposals that come up from the Department of Defense, and that this is something that is badly needed and that I suspect that the President is going to find he badly needs it.

In a speech to the United Nations on April 14 of this year, Henry Kissinger said, "In a global economy of physical scarcity, science and technology are becoming our most precious resource; no human activity is

less national in character than the field of science; no development effort offers more hope than joint scientific and technical cooperation.” That was a statement from the Secretary of State. Within this context, Dr. Kissinger directed his remarks to the needs of the developing countries. Relationship with the developed countries as well are affected deeply by the developments of science and technology as they work upon the international scene, and America’s position on that scene. International relationships and their aspects are involved in bilateral and multilateral agreements involving science and technology. This Council that has been proposed, working with the National Security Council and the Secretary of State, could help generate and respond to presidential initiatives, to attack mutual problems, through international scientific and technological cooperation. Incidentally, at the present time, unless I am not up-to-date, there is no scientific advisory mechanism available in the Department of State. Again the old PSAC essentially performed that role. It is also true that the Office of Management and Budget should have a strong scientific input in its deliberations and dealings with the budget and while it has greatly strengthened its staff to deal with scientific matters it still very much needs the objective advice that a group could bring to it, if it were properly related to a council of the kind that this Committee proposes. The NAS Committee also proposed that the Council for Science and Technology present to the Congress an annual report on major developments in science and engineering of significance for national policy. This report would be presented first to the President and through him to the Congress. The Committee also offered a corollary suggestion that there should be a capability, within the executive office of the President, for long range policy research and analysis, which would examine continuously the longer-range implications of current budget decisions and other policies, and would seek to anticipate problems that will face the President and the Congress in future years. The Executive Office of the President needs to employ many of the new techniques that have been developed through scholarly work for policy research and analysis. It needs to understand the close relationship for these new techniques through the methods and spirit of the physical, biological and behavioral sciences. And our Committee believed that a way can be found for making these techniques continuously useful to the President. This report, of which I have given a brief summary, is now under consideration by the Executive Office of the President and by appropriate committees in the Congress. Hearings have been held in both

the Senate and the House. There are some of you here who testified at those hearings. There seems to be a cordial reception to the proposal. There has been an extraordinary response across the country in the press, and there has been dozens of editorials, well-reported stories, about the recommendations of the report. There seems to be a national understanding of the need.

I summarize the NAS Committee report by way of pointing to the need today for better ways for the scientific and engineering communities of the nation to make their talents and insights available. Both of the plans which I have reported on, involving both scientific advice and analysis, focus on service to the Government, rather than arrangements to seek more support for the Government for science and technology, however important that may be. If there can be adequate policy inputs and adequate analysis made available to the Government, I think the chances are that science itself will be well-served, and that the relationship between Government and science will be on a sounder basis, with the result that science itself will benefit in the long run. Just by way of comment indicating the interest that this problem is currently evoking, let me read the lead paragraph from a recent column by Scottie Reston in the New York Times:

(this was on October 10)

If ever there was a time when the President of the United States needed the help of the best objective scientific minds to help him grapple with the problems of food, fuel, transportation, housing and many other things, it is now. But he is a little shorthanded at the present time.

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The Energy Problem

Hans Bethe

Cornell University, Ithaca, New York

When I was preparing my lecture, I thought there was something wrong with it, namely, that it had very little to do with Viki. However, Dr. Killian, fortunately, gave a lecture with which mine has a lot to do, namely, it points out the great need for science in our present energy situation.

Last year, the cost of a barrel of oil in the Mid-East was about \$3.00. Now, it is \$10.00 or more. Now, that may seem rather trivial. Very few of us want to buy a barrel of oil, but it is not at all trivial for the balance of payments of nations, of all western nations, of all the industrialized nations, and even more, of the underdeveloped nations. The World Bank has estimated that we shall have to pay — we meaning the oil importing nations — have to pay something like a hundred billion dollars a year to the oil exporting countries. This amount of money is enormous if it is in international trade. It would not be very much inside the United States. But to see its importance in international trade, just compare it with the gold reserve of this country which is something over ten billion dollars. There will, un-doubtedly, be a great shift of wealth from the countries which are now rich to the oil exporting countries. Now, such shifts of riches have taken place before. There was a shift from Spain to England in the sixteenth and seventeenth century, from England to America in the first half of the twentieth century, from America to Japan and Germany in the last decade or two. But the shift that is impending is of a very different nature. In all previous shifts of wealth, the country that was now getting rich wanted

something from the country that was previously rich. They wanted services and goods. We are now faced with the problem that the countries which will acquire this enormous amount of money do not really have any demand for goods which is commensurate with the amount of riches they will acquire.

What will the oil exporting countries do with their wealth? The best, for all purposes, will be if they use their money to acquire industries and perhaps real estate in the western countries and, in particular, in the United States. While this may lead to foreign domination of our industry in a rather short time, a much worse possibility is that they may leave their money as a short-time deposit in international banks, and in national banks, shifting it from one country to another, mostly to get maximum interest, but in some cases, to cause mischief. It is very much to be hoped that the oil exporting countries see their great interest in preserving the structure of the industrial world which is really the structure in which they themselves enjoy their wealth and in which they themselves can prosper. But, there is no guarantee at all that this will be so. So far, the oil exporting countries have played their advantage to the hilt. There are some slight signs of a change. It may very well be that this tremendous indebtedness, amounting to a trillion dollars ten years from now, of the western countries to the oil exporting countries may lead to a complete breakdown of the industrial and economic system of the west. In my opinion, there has only been one situation in my lifetime which was equally serious as the present one and that was the Second World War. In the Second World War, scientists, and particularly the scientists at this institution, M.I.T., came to the rescue and helped the nation and the western world to survive the crisis. This we need again.

We must find other sources of energy other than oil and natural gas. Natural gas, as you know, is already in very scarce supply and has been for some time. Not only for ourselves must we do this, but even more for Europe, Japan and still more for the underdeveloped nations. Now, to look at the dimensions of the problem, look at Table 1. This table gives information I found most difficult to obtain and most important, namely, a comparison between the various units that people use. People, unfortunately, use a Btu which doesn't mean anything to me. But, fortunately, it is very close to a kilojoule which does mean something to me. A million Btu makes about a hundred kilowatt hours of electricity at a normal efficiency of a generating plant. In global projections, people like to use the *Q as a unit*

Table 1.

1 Btu	= 1.05 kj	
1 MBtu	= 117 kwh (40% eff.)	
1 quad	= 10^{15} Btu	
1 barrel oil	= 42 gallons	= 150 kg
1 barrel oil	= 6 MBtu	
1 Mbbbl/day	= 2.10 mQ/yr.	
1 k cu. ft. nat. gas	= 1 MBtu	
1 ton coal	= 24 MBtu	

Table 2. 1973 net oil exports and imports (MB/d). Also balance of payment at \$10/barrel (billions of \$).

	Net export	Income		Net import	Cost
Mid-East	20.0	73	West. Europe	14.0	51
Africa	4.8	17	U.S.	6.3	23
Carribean	3.2	12	Japan	5.2	19
		102			93

of energy, or the milli-Q or quad which is 10^{15} (a quadrillion) Btu and that's the unit I'm going to use. With great difficulty one can find out that one barrel of oil is 42 gallons. It is in no dictionary and it corresponds to about six million Btu. One million barrels per day, we use about 17, corresponds to about two quad per year. One thousand cubic feet of natural gas is about one million Btu. To confuse the issue further, people who sell natural gas use the letter "M" for a thousand which we use for a million. One ton of coal is about 24 million Btu.

Table 2 lists the sources of oil.

The production of oil in the United States in 1972 was 26 quad, and the petroleum council projects that with great effort and with using all possible new sources we might get to 28 in 1985. The imports were 12 in 1972; they are rather more now. In 1985, a certain paper wanted to reduce this to eight. I would hope we can reduce it to zero and leave the oil which is available on the world market to those countries which cannot produce any oil themselves, namely, Western Europe, Japan and the underdeveloped countries. Arab exports were 32q. This might be raised by about 25 percent according to statements of the Arab countries. The world consumption was about 87; if it continues the way it has been going, it will be 175 in 1985.

barrel of oil was \$4.00 and the present cost is \$10.00. The cost of American imports will increase even if we decrease the imports, and would increase to sixty billion dollars if we were to continue to cover all the deficit in energy by oil which is clearly intolerable. The price of world consumption will go up from sixty to about three hundred billion dollars.

Table 3* gives the U.S. consumption of various sources of energy. The total in 1972 was 72 quads, and in 1985 I am sure it will be more than 85 quads. Of this, there was only one quad nuclear, two hydro which is a source which cannot be increased much, so the rest was all fossil fuel of which the majority was made up by oil.

Gas, I think, is a wasting asset. The second column of the Table "1985 High Estimate", is from a Cornell report which was put together last fall. This projection assumed that the oil consumption would stay about the same. The gas consumption, they assumed, might increase more, that is, we might discover more gas. I consider this very doubtful. The rest would have to be covered by coal. I made a lower estimate for 1985 in which I assumed that energy consumption will increase only 2% per year. The high estimate assumes the same increase which has prevailed, 4%. My 2% includes 1% increase in population so there is only 1% per year increase in per capita consumption. Whether we can keep down to such a small increase is very doubtful to me. In this case, I also assume that nuclear power will contribute less than the Cornell report assumed optimistically, simply because the plants will be built more slowly. And still, we need a coal production which is more than twice what we had in 1972.

Table 4 gives the available resources in the world, now in Q, i.e. in thousands of quads. Two geologists are quoted here, McKelvey who is an

Table 4. Available resources (thousands of Q).

	McKelvey	Hubbert	U.S.
Coal	320	190	23.0
Oil	23	15	1.5
Gas	20	10	1.0
Shale oil	80	10	6.0
Total	450	220	30.0

*Table 3 does not appear in this text.

optimist and Hubbert who is a pessimist. The difference in numbers is a factor of two, and one might hope that perhaps the world will settle down at a population of ten billion people — now it is four — and that they will each consume about as much energy as we consume now. In that case, the yearly consumption will be three Q, and that means that on the optimist's assumption all the available fossil fuel will be good for a little over one hundred years. On the pessimist's assumption, for seventy years.

Figure 1 gives the distribution of sources of energy and of uses of energy. This comes from a book by Hottel and Howard here at M.I.T.[†] which is a very important book. It shows that coal, in 1970, gave us only 20% of our energy, oil gave nearly half, gas most of the rest. Most of the oil goes for transportation, as you can imagine. Most of the coal goes for electricity generation. Much of the gas goes for heating of houses and of so-called commercial buildings. Transportation is the one area in which

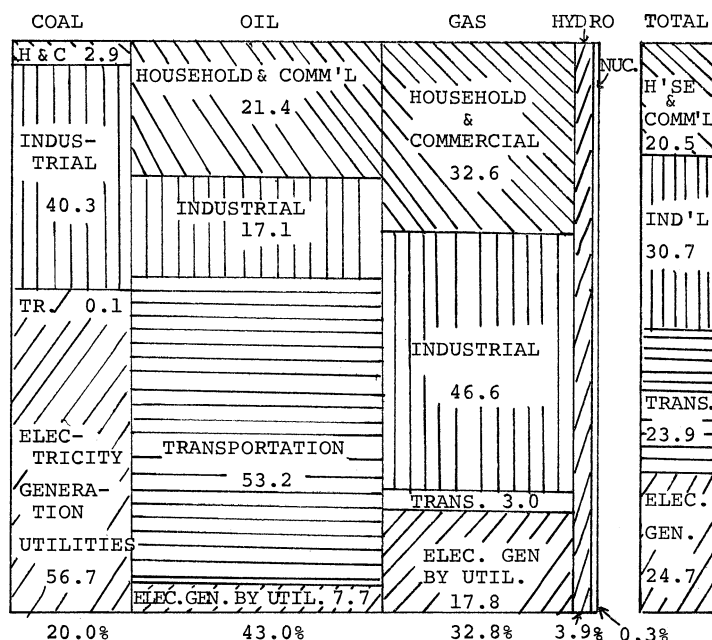


Figure 1. Distribution of U.S. energy consumption, 1970 (Preliminary estimates by U.S. Department of the Interior).

[†]From New Energy Technology.

oil is practically indispensable. So I think the endeavor must be to shift all the other uses, industrial and especially generation of electricity to other sources of energy.

The report of the Cornell workshop concluded that it is possible to double or even triple coal production in ten or fifteen years. This will be a very major effort. It will obviously mean mostly strip mining, and we have to see to it that after strip mining the land is restored to real fertility and to its previous state, not necessarily in contour but at least in fertility. This is certainly possible and the cost of it is a fraction of the value of the coal that can be obtained from western mines.

Now what do you do with the coal? One possibility is conversion into other substances which are easier to use and to transport. One of them is gas and the other oil. It seems that this is possible. The Germans did it during the Second World War but the cost of their process is high. Table 5 gives the cost of making a million Btu of energy. By the German process it is about \$2.00 and with learning it might be reduced a little bit. The present cost of a million Btu of gas, delivered to one of the transcontinental gas pipelines, is \$.43. From this you can see that it would pay us very handsomely to permit higher cost of the gas delivered to the pipelines if this gives an incentive to the producers to look for a better solution, maybe

Table 5.

Natural fuels		
Cost per MBtu (dollars) — Dec. 1974		
	1972	1974
Coal	0.20	0.40–0.80
Oil, Import	0.50	1.80
Oil, Texas	0.65	1.20
Gas	0.20	0.50–1.50
Synthetic fuels		
1985 (1974 dollars)		
Oil shale		1.30
Oil from coal		2.50
High Btu gas		2.00
Low Btu gas		1.20
Electric heating		3.50

not to make coal into gas but to transport the energy as electricity. This requires work on better ways to transmit electric power. There is one way I know about, namely super-conducting DC transmission lines. These have been worked on at the Los Alamos Scientific Laboratory for several years. I think they have great promise for the future, and perhaps the most costly thing in this connection is the conversion of AC to DC and vice versa. This problem, as well as the transmission lines, I present as a challenge to this engineering institution. Now, as I showed you, even coal will not last forever. And coal is, in addition to being a source of energy, an increasingly important source of materials. If we run out of oil, we need the coal to make plastics and all sorts of other things which are now called petrochemicals. Therefore, we'd better save some for that purpose and don't use it all up for energy.

The other main source for energy we have is nuclear energy. At present it is a small contribution. In time, I hope, it will be a great deal more. There are clearly three advantages of nuclear energy apart from its availability. The first is, you have minimum environmental trouble. In contrast to coal, the mining of uranium involves small amounts of material and strip mining will not make a major upheaval in the environment. Secondly, nuclear energy is essentially free of pollution in contrast to coal. There are ways to make coal freer of pollution than it is now, but it would be very difficult to make the pollution as small as it would be from a nuclear plant. The third is that even at present the price of nuclear energy is lower than any other energy, and this in spite of the fact that the cost of building a nuclear plant has risen from about \$100 per kilowatt installed to about \$600.

Now there are many objections to nuclear energy and you hear far more about the objections than about the advantages. One of the objections is that nuclear plants may emit radioactive rays. This, I think, has been solved. The prescription of the Atomic Energy Commission today is that the amount of radiation at the fence posts of the nuclear plant must be less than five millirem per year. Never mind what a millirem is. You are exposed in your ordinary life to about a hundred millirem per year, part of which comes from cosmic rays, part from the radioactivity in the walls of every building, and a large part from yourself, from the potassium that is inside you. Compared to this hundred, the five millirem is a very small amount, and this only occurs at the fence posts — if you live ten miles away from the plant,

there will be nothing. The second objection is the high price, which I have already mentioned.

The third is the possibility of an uncontainable accident. Nobody can deny that such a possibility exists. There has been a very intensive study going on over two years led by Professor Rasmussen of this institution which has gone into the probability and the effects of a nuclear accident more carefully than any other study that has previously been made. They come out with the result that the probability is extremely low. If we have a hundred reactors going, the probability of a major release of radioactivity is less than one in a thousand years. Also, if there were an uncontainable accident, they have investigated the possible effects and come to the conclusion that since such an accident is a rather slow affair — release of radioactivity takes a considerable time — it is likely that the number of people who will be in danger, the number of deaths, will be relatively small, in most accidents, something like two, and even in the very rare, major accident, of the order of a hundred. The material damage may be very considerable and in this very rare major accident, it may be as much as several billion dollars, clearly an amount that calls for insurance from the Government rather than for payment from the utility involved. But money is recoverable. They compare the probability of nuclear accidents with that of other catastrophes, natural and manmade, and nuclear accidents come out very well.

Now the opponents of nuclear power must have their day in court and will undoubtedly attack this report. However, if the report is anywhere near right and the care with which it was made, I think, encourages me, then we do not have to fear very much.

The next point is waste disposal. The AEC is now prescribing that all the radioactive waste has to be made into solid material, glassy substances, in contrast to liquid storage, which in the past has given rise to some troubles. Even if the solid were to be destroyed, it is most unlikely that it would get dispersed in a way to make it dangerous. The solid would be stored in strong containers, in an engineered facility, far away from human habitation, let us say in the Nevada desert, and must, of course, be well-guarded so that no fool goes there and gets himself exposed. I don't think that the waste disposal is really a major problem.

The one major problem which I see is the possibility of diversion, the possibility of theft of nuclear materials and use of these materials for bombs, either by some countries or by terrorists or criminals of other kinds. This

I think, is the most serious problem. This is a problem to which we have to apply all our ingenuity. As far as terrorists and individuals are concerned, I think it can be solved. As far as countries are concerned, I think we have to have administrative ways to minimize the problem.

Clearly, there are problems with fission energy, so let us have a look at other possible sources of energy. The one that is most talked about is fusion. Fusion research started about in 1951 with the highest hopes. Such high hopes that Admiral Strauss who was soon afterwards Chairman of the Atomic Energy Commission admonished scientists working on fusion to have it all finished by the end of the first Eisenhower administration in 1956. You all know that this didn't happen. I won three bets on this. The problem turned out to be far more difficult than anybody envisaged. The plasma which people wanted to use to confine deuterium and tritium to produce fusion simply wouldn't stay confined. It had instabilities far beyond anything that anybody had dreamed of.

What are the conditions necessary for fusion? Well, first you have to have something like one hundred million degrees temperature equivalent to ten thousand electron volts; second you have to have a sufficiently high density; and third the plasma has to stay together a sufficiently long time that the product of the particle density and the time of confinement is at least 10^{14} (e.g., 10^{14} particles in a cubic centimeter has to stay together for one second). At that point, you can get net energy gain from a deuterium–tritium mixture. When theorists saw the instabilities, they first investigated the problem theoretically and found, yes, indeed, these instabilities should be there. Then they sat down a few more years and said well, there are some ways to cure the instabilities. They found one way, and on this basis Artsimovitch in Russia invented a device known as TOKAMAK which uses the theoretical method to reduce instabilities.

Indeed, this device worked to the amazement of everybody who had worked in the field. It is now being used in this country and it still works. The TOKAMAK is a device for magnetic confinement of high temperature, moderately high density plasma so that deuterium and tritium can react with each other. The process looks better than it ever has before. It has been possible to compress that plasma by the magnetic field, and it has been possible to heat it by injection of much higher energy, two to five hundred keV natural deuterium atoms. It has been possible to get fair agreement between theoretical confinement times and experimental ones.

The disagreement is only a factor of ten now, it used to be a factor of a million or more. Partly this is due to the theorists becoming more modest, namely, they have discovered that there are certain instabilities which are unavoidable. Now, the theorists predict that if you make the device much bigger, like ten meters instead of one meter, then it will work. Maybe they are right. Anyway, the AEC has made the money available for constructing a much bigger device, and maybe in 1982 it will be possible to prove that fusion is scientifically feasible. At that time, fusion will be in the state that fission was in 1942 when Fermi proved the first chain reaction. Today, we are not yet in 1942 as far as fusion is concerned. It took twenty years, beginning in 1942, before fission energy became industrially useful.

In fusion energy, we know a great deal beforehand, but it is a much more difficult problem. Radiation damage is relatively minor in the case of fission because you mostly deal with slow neutrons which cause very little damage. In the breeder it is somewhat more. In fusion it will be enormously more because the neutrons have an energy of 14 MeV when they come out. Damage is done by high energy neutrons which propel atoms from any material to God knows where and thereby disintegrate the material which is used for the structure of the device. Furthermore, any fusion device which uses magnetic confinement uses magnetic coils which have to be especially carefully protected. This means you have to locate them far away from the fusion; therefore the magnetic field will extend over an enormous volume which is very expensive. So, I think if we estimate the time from feasibility to industrial usefulness as twenty years this is very modest; from there it will be another twenty years before fusion contributes an appreciable amount to the energy supply of this and other countries. In other words, you get to the year 2020. So it would be entirely irresponsible to rely on fusion as satisfying our energy needs for the twentieth century.

On the other hand, I think research on fusion has to be pursued with great vigor. It may be an important way of getting energy. It would give us an inexhaustible source of energy from the deuterium in the sea and would get us away from *some* of the problems I mentioned. Don't believe, however, that you will get away from the problems of storing radioactive wastes. Wherever there are neutrons there is radioactivity. The radioactivity from fusion may be smaller than it is from fission, and we may be able, to some extent, to choose the radioactive species that we deal with, but there will still be radioactivity also from fusion.

Another kind of fusion has been more fashionable in recent times, namely laser fusion. Lasers are very sexy, fusion is very sexy and so the combination is most sexy. However, laser fusion, I think, in time scale is related to magnetic confinement fusion almost the same way as that is related to fission. It's a very young subject and, while some successes have been achieved, it is not likely to lead to complete success in any short time. What is needed in this case is to take a small pellet of solid deuterium-tritium (that's not very hard to get, you only need a low temperature of some ten degrees Kelvin) and you drop that little pellet into a place where it is exposed to maybe twelve laser beams of very high intensity coming at it from all directions. And then, these laser beams are supposed to compress this pellet to a density between three and ten thousand times its normal density. This I think will be very difficult to realize, the problem is to get enough symmetry, enough freedom from instabilities, enough push in a short enough time. We don't have the lasers to do it. We need much higher power lasers, releasing their energy in a much shorter time, and we need powerful lasers somewhere in the visible which we do not now have at all. Once you have succeeded, your little pellet will give you an energy of about one kilowatt-hour which has a value of about two cents. I do not believe this is a practical device for the foreseeable future. Fifteen years from now we may talk differently, but it will not be the solution of our short-range energy problems.

Well, then there is solar power. Solar power is everywhere and it is a very big power source. In fact, it is many, many times the power which the world may consume in the twenty-first century. However, it is very diffuse and you have to catch it, and catch it reliably. So, in the first place, you have to go to a state where the sun shines most of the time, such as Arizona, maybe New Mexico, maybe western Texas. You have to go to a place where the difference between winter and summer is not too great, so you have to go to the southern states. This gets you back to the problem of transmission of electric power over large distances, but that we have to solve anyway. In addition you have the problem of storage of energy which is much more difficult, from day to night, from sunny to cloudy days which occur even in New Mexico. This is a major problem in which technical development is extremely important.

How can we catch the solar power? From a square kilometer of area, on an average sunny winter day in a southern state, you may get something

like 200 megawatts solar heat, which will give perhaps 50 megawatts electric power.

Many fancy ways have been suggested to utilize the solar power. The only way which I think has a good chance of working is a brute force, elementary way, as follows: You build a field of mirrors, each mirror perhaps a square meter, with the field maybe two kilometers on the side. There is a computer drive on the mirrors which directs the sun at any one moment to a central tower, maybe a hundred meters high, on which you have an ordinary boiler, which drives a conventional electric generator. This scheme I think has worked in Southern France. The computer drive should not be very difficult to make. The mirrors are arranged in such a way that they don't shade each other. From your four square kilometers you might then get something like 200 megawatts electric power, average. One of the troubles is that at noon you need an electric plant which is able to generate 800, so that you have 200 in the average. This is one of the reasons why this device will be very expensive. The number that has been mentioned by a fairly responsible engineering source is \$2,500 per installed kilowatt, which is about five times the cost of nuclear power at present.

Now, you say what's money? Money means labor and materials, so we cannot afford these large amounts of money even if money seems to be unimportant. For instance, the estimate is that by the year 2000 we need an installed power of a thousand gigawatts, a trillion watts. This would cost over two trillion dollars to install. Therefore, I do not believe that solar power at the cost that we can now foresee is a real solution.

Some people, even the President, have mentioned the winds. I think the winds are for the birds. There is not enough power in the winds. Then there is geothermal power. This, I think, is for real. You can tap hot water reservoirs in the West and possibly even hot rocks, so I think research on geothermal is useful and may even lead to some contribution in the twentieth century.

Having now excluded most of the alternatives, I come back to nuclear power. In my opinion, we have no choice whatever. We must use nuclear fission power; we have to make it as safe as we can, which includes safety against diversion.

Now we come to the question, do we have enough uranium? Table 6 gives the requirements of uranium for several kinds of reactors. The present reactors are light water reactors, first column, and the high temperature gas cooled reactors, second column. Future reactors are the liquid metal

Table 6. Short-term U_3O_8 required to inventory and operate 1,000-MWe reactors for 40 years.

	Inventory (tons)	40-year operation (tons)
PWR	548	5,000
BWR	580	5,000
HTGR	456	2,400
HWR	350	700

fast breeder reactor which requires more inventory for each reactor, and the Canadian-sponsored heavy water reactor which has the nice name “Can-du”. Deuterium–Uranium is the meaning of the last two letters. The consumption per year in short tons of uranium ore is very high for the light water reactor, considerably better for the high temperature gas cooled. The fast breeder makes additional fuel and the Candu consumes very little. If you use the light water reactor, exclusively, and that is what we now have, we need about seven and a half million tons of uranium ore by the year 2020 according to projections. If we use a minimum of light water reactors as has been here assumed, namely, until 1990, and afterwards use either the fast breeder or the Candu then we may get away with from three to four million tons of uranium ore.

Figure 2 gives the projected need for power and the projection of the reactors to satisfy it. This Figure I made in connection with a study last year in which the extra need was to be satisfied by fast breeders.

Estimated future nuclear generating capacity, in *millions* of megawatts (electric). AEC figures until 2000; after this, the total electric generating capacity is assumed to double every 25 years. All new capacity is assumed to be nuclear after 2010. Contribution of various types of reactors is shown separately. For detailed assumptions, see Table G2.

Table 7 is the counterpart to Table 6; it gives uranium reserves as presently projected. At present, we use very rich uranium ore which costs only about \$10.00 a pound. Of this, there are available about one million tons. Remember, seven million tons is needed if we continue to use light water reactors. Going down to \$30.00 uranium doesn’t really make the cost of nuclear power much higher but makes the environmental cost considerably higher because you have to dig about eight times more rock than you have to do at the present time. And that about doubles the amount of

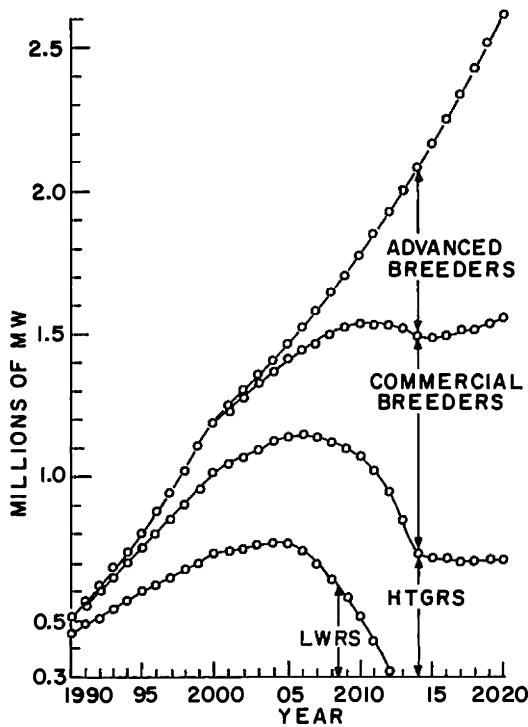


Figure 2.

Table 7. United States uranium reserves.^a

		1,000 tons U ₃ O ₈		
Ore concentration ppm U ₃ O ₈	S/lb U ₃ O ₈	Reasonably assured	Estimated additional	Total
1600	Up to \$10 ^b	427	700	1,127
1000	Up to \$15 ^b	630	1,000	1,630
200	Up to \$30 ^c	800	1,600	2,400
60	Up to \$50 ^c	4,800	3,600	17,400

^a Source: WASH-1242, 1243.^b Includes copper leach residues and phosphates.^c Includes Chattanooga shale.

available uranium. You have to get down to the uranium listed at \$50 in the Table, but this should really be priced at about \$100.00 because of the need for restoring the environment. At this level, we have enough uranium ore in this country to satisfy the needs for light water reactors up to the year 2020 and, of course, we have plenty if we go to the more uranium conserving reactors like the Candu or the fast breeder.

I conclude from this that not only do we have to have nuclear energy but we have to find nuclear reactors which are more conservative in the use of uranium. The one that is most talked about is, of course, the breeder, cooled by liquid metal. This has been under development for a long time. An existence proof has been given by the French who have built a fast breeder which works smoothly and reliably and isn't even terribly expensive. Our fast breeder, unfortunately, gets more and more expensive and has now arrived at a cost equal to even solar power, something like \$3,000 per kilowatt for the first fast breeder. But this will come down with time, while in the case of solar power no similar decrease of price is in sight.

The reactor which I like best is the heavy water reactor which has been developed by the Canadians. It has been developed with the view of using natural uranium and avoiding the isotope separation. This, I believe, is not the important point for the future. Isotope separation will probably get cheaper than it is now, for instance, by the centrifuge method of separation. But it is important that Candu reactor in Toronto has been available more than ninety percent of the time for electricity generation which is very much better than the average power plant whether nuclear or fossil fired. The other important point is that Candu can be modified to conserve uranium. The modification consists of putting in thorium as a fertile material from which can be bred uranium-233. This advanced Candu can easily be arranged in such a way that you only use ten percent of the fuel you put in. Thus it has a conversion ratio of 90 percent, and, thereby, you get the good performance that showed in Table 7. With ten percent fuel used, our uranium will last a long time. And once uranium ore gets more expensive, Candu will be as economical as our present light water reactors. It costs a little more to build because the heavy water is an expensive substance, but this will easily be repaid in the uranium economy. It

is believed, in addition, that it is even safer than our present light water reactors.

The Canadian project, I think, is inviting the United States to participate in the further development of the Thorium thermal breeder with heavy water moderation. I believe that this is the best source of energy that we can think of for the next 50 years.

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3

Model-Free Views of Deep Inelastic Scattering

Julian Schwinger

U.C.L.A.

Perhaps I should point out first that my choice of topic was dictated by the injunction that the nature of this symposium should revolve around subjects that might be conceivably of interest to Viki. Viki has, along with most high energy physicists been very interested in the subject of deep inelastic electron scattering. With his characteristic attention to directly visualizable approaches to physical phenomena, he has dealt with this in terms of rather specific models, attempting then to give very elementary explanations of these fascinating phenomena. I thought he might be interested to see the other side of the coin, namely, the extent to which one can correlate and comprehend these physical effects without the use of specific models. I think this may lend a certain useful balance to the way things are looked at these days. So my remarks are directed to Viki but you're all welcome to eavesdrop.

You must forgive me for this somewhat technical subject, and, in fact, I was rather disconcerted to listen to the first two speakers and realize the level at which they had pitched their remarks. So, again, please forgive me, but let's see what we can get out of it. The subject then is inelastic electron scattering with unpolarized particles. These, of course, were the experiments that were first performed in the famous MIT-SLAC collaborations now several years old. The experimental idea is very crudely symbolized in Fig. 1.

This is an experiment in which an electron is scattered under conditions where the properties of the incident and the scattered electron are determined. That is, the energies and angles are known. As a result, an



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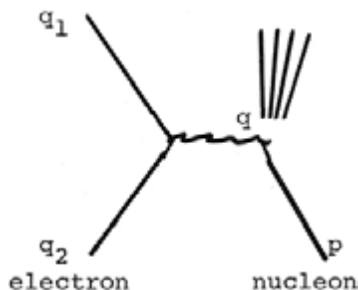


Figure 1.



Figure 2.

electromagnetic field in the form of a virtual photon is set up, and through the control of the electron one specifies the energy and the momentum of this virtual photon. Virtual because the energy-momentum relations are not at all that of a real photon. The photon then interacts with a nucleon (experiments have been performed on both neutron and proton) as a result of which, at very high energies, large numbers of particles are emitted. The experiments I'm going to deal with here exert no control over which particles appear in the final state, so these are total cross sections in a certain sense. In fact, as I indicate in Fig. 1, the electrons are there simply to create the "photon", the virtual photon. The physical process then is one of absorption of the photon by the nucleon to produce all possible multi-nucleon states (Fig. 2).

Now, since I'm not going to use models, obviously I have to replace them with something else, and a certain amount of formalism, which is of a rather elementary nature, is required. It is the mathematical expression of quite simple physical ideas, but may be rather strange at first encounter. I can only apologize for that. But the idea is that this picture (Fig. 2), if it represents

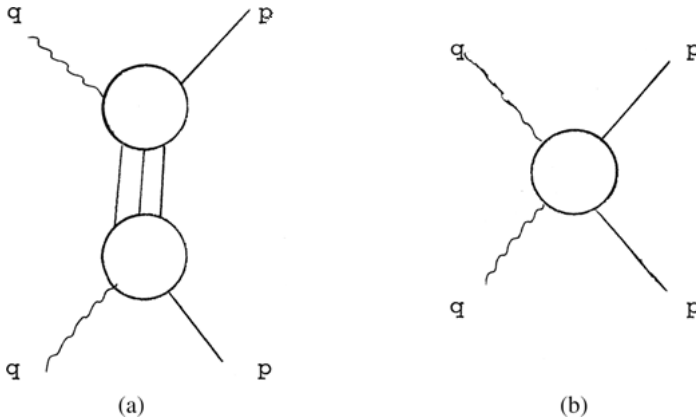


Figure 3.

anything, is a sort of shorthand for the quantum mechanical description of the process in terms of a probability amplitude — the amplitude for photon absorption by the nucleon to produce some multi-nucleon state. However, what one is really interested in is the total probability, the absolute square of that amplitude summed over all possible things that can happen. Think of the probability amplitude for the emission process multiplied by its complex conjugate. In quantum mechanics taking the complex conjugate is to some extent running things backward.

Therefore, this is the picture (Figure 3(a)) for the process of computing not the amplitude but the probability, in which we have the particles coming together to form the general multi-particle state and then coming back out again to reform the initial state. And one can also recognize this process as Compton scattering — photon plus nucleon combining to again form a photon and a nucleon (Figure 3(b)). It is forward Compton scattering because the final state is the same as the initial state, that is, the final-photon is identical with the initial photon.

What I'm saying here is perfectly standard in all ways of doing this. I am however, removing the operator language that is customarily used to express it. So we are interested in forward Compton scattering, and, through its description, we will have an account of the virtual photon absorption that occurs in our original problem. Let's then begin to see how we can quantitatively characterize this forward Compton scattering. We are dealing with photons or electromagnetic excitations and the important physical

Table 1. Gauge invariant combinations.

$$\begin{aligned}
 (1) \quad & -\frac{1}{2} F^{\mu\nu}(-q) F_{\mu\nu}(q) \equiv |E|^2 - |H|^2. \\
 (2) \quad & -\frac{1}{2} F^{\mu\nu}(-q) \underbrace{\left(g_{\nu\lambda} + \frac{P_\nu P_\lambda}{M^2} \right)}_{\text{projects } \perp \text{ to } p} F^{\lambda\kappa}(q) \left(g_{\kappa\mu} + \frac{P_\kappa P_\mu}{M^2} \right) \equiv |H|^2 \quad (\text{in the } p \text{ rest frame}).
 \end{aligned}$$

requirements is that of gauge invariance. And so you will see that I list various gauge invariant combinations of electromagnetic fields in Table 1. The emphasis is on the electromagnetic fields, because since the nucleons are unpolarized, they carry no kinematically important properties except their momentum. No further reference to their characteristics is involved. So here I've listed particular ways, the ways I consider especially significant, of constructing gauge invariant combinations:

Again, forgive me for the technical notation, but $F_{\mu\nu}(q)$ is the electromagnetic tensor that is associated with the incoming electromagnetic field of associated momentum q . In $F_{\mu\nu}(-q)$ we have something similar for the outgoing electromagnetic field. It takes away momentum instead of supplying it. And in (1) of Table 1 we see the very familiar gauge invariant scalar combination of electromagnetic fields which I've also written out in ordinary three-dimensional notation. That's not the only way of forming such combinations, however, it makes no reference to the nucleon — the proton, for example. But the momentum of the proton may figure as well and in fact there is just one other combination; it is (2). I've written out this elaborate thing but it has a very simple meaning. Namely, the proton momentum is being used here through the particular combination which projects perpendicularly to the momentum. If, in fact, you think of things in the laboratory system where the nucleon is at rest, where the nucleon momentum has only a time component — its energy, then this is simply the tensor to pick out the spatial components. And so this elaborate structure evaluated in this natural coordinate system, the p rest frame, is simply the absolute square of the magnetic field. Between these two, then, we have the square of the magnetic field and the square of the electric field, the two independent measures of the character of the electromagnetic field. We are free to control them to a large extent because of the fact that, through

Table 2. Kinematical scalar variable.

- (1) $p^2 = -m^2$, m is nucleon mass.
- (2) $q^2 > 0$, (space-like) momentum transfer.
- (3) $\nu = \frac{-qp}{m}$, energy loss of electron in p rest frame.

electron scattering, the energy and the momentum of the virtual photon are, to some degree, independently variable.

Now I also remind you of the fact that in any description of such a quantum mechanical process, a fundamental role is played by the various kinematical variables: the four-dimensional momenta and in particular the scalar combinations that can be made from them. And here they are.

Of course, the square of the nucleon momentum is not a variable quantity since it is determined by the mass of the nucleon. The minus sign here is simply my convention that time-like quantities are of negative square and space-like quantities are positive square. In this particular arrangement in which the electron is deflected, the momentum that it transfers, that it creates, is in fact space-like. Accordingly, q , the squared momentum associated with the virtual photon, is positive. This is the invariant measure of the momentum transfer from the electrons to the nucleons. Then, the third combination is the product of the two vectors, the photon momentum and the nucleon momentum. This, when evaluated in the p rest frame, is the nucleon mass multiplied by the same component of q , and therefore, proportional to the energy loss of the electron — one of the experimentally controllable variables.

I now write down the forward Compton scattering amplitude, putting together these various ingredients:

$$1 + iV d\omega_p 4e^2 A^\mu(-q) \left[\sum_{a=1}^2 T_{a\mu\nu} H_a(q^2, pq) \right] A^\nu(q)$$

where

$$d\omega_p = (2\pi)^{-3} d\vec{p}/2p^\circ, \quad p^\circ = (\vec{p}^2 + m^2)^{1/2}. \quad (1)$$

Unity refers to the situation holding almost everywhere in which the particles simply miss each other, and the probability amplitude for that is just

one. The second term describes what happens when the particles do interact. It has the following ingredients: (1) i is there because a scattering amplitude tends typically to be out of phase with non-scattering amplitudes. (2) V is the four-dimensional interaction volume. The two beams of particles, the photons and the nucleons, are focused on each other. They interact for a certain volume of space and for a certain time and, there is a four-dimensional interaction volume to represent that. (3) $d\omega_p$ refers to the nucleon, namely, it is an invariant measure of the small range of momentum space in which the nucleon is to be found. (4) e is the electron charge in rationalized units, where $e^2/4\pi$ is the fine structure constant, e^2 is therefore present because the electromagnetic field is going to act twice. (5) There are two electromagnetic fields. The field of the photon that comes in, and the field of the photon that goes out. You recall I wrote gauge invariant forms explicitly in terms of the field strengths. Now I make it a little more explicit in terms of the vector potentials from which those field strengths are derived, and so, correspondingly there are two tensor structures which contain the photon momentum and the nucleon momentum. Here they are:

$$T_{1\mu\nu} = m^2(g_{\mu\nu}q^2 - q_\mu q_\nu), \quad q_\mu T_{1\mu\nu} = 0; \quad (2a)$$

$$T_{2\mu\nu} = q^2 p_\mu p_\nu - qp(q_\mu p_\nu + p_\mu p_\nu) \\ + (qp)^2 g_{\mu\nu} + m^2(q^2 g_{\mu\nu} - q_\mu q_\nu);$$

$$q_\mu T_{2\mu\nu} = p_\nu T_{2\mu\nu} = 0. \quad (2b)$$

I trust that you still carry enough of the field strength idea with you to realize that $T_{1\mu\nu}$ is related to the product of the field strengths. The q 's are the derivatives that act upon the vector potentials to make the field strengths, and a factor of m^2 is inserted to give this a convenient set of dimensions. These things have the dimension of the fourth power in momentum. And the fact that this all came from a gauge invariant combination is verified by multiplying the photon momentum into this tensor, yielding zero. The second one looks much more complicated. But it is just that elaborate combination of projection tensors and field strengths designed to pick out the square of the magnetic field in the laboratory system. Its intrinsic meaning is very elementary indeed. As you see, it expresses a gauge invariant combination since it is zero when multiplied by the photon momentum. It also satisfied the second requirement to pick out things that are or

the particle momentum. These are the basic ingredients, with each tensor multiplied by an arbitrary function $H_{1,2}$ of the scalar variables.

These tensors have two general properties. They are both symmetrical in the vector indices of the electromagnetic fields. Secondly, they are both even functions in q . This is related to a property which is generally called crossing. You notice that a particular momentum q appears in the forward scattering amplitude. But actually this is just a shorthand, because if we wrote down the forward scattering amplitude for an arbitrary electromagnetic field we would really be summing over all possible momentum transfers. In particular, along with q , $-q$ would occur everywhere. As an expression of what is basically Bose–Einstein statistics, there must be a symmetry between these. In other words, if you replace q with $-q$, everything must look the same. Replacing q by $-q$ interchanges these two vector potentials. You should also interchange their indices but that's not necessary here because everything is symmetrical. The whole structure must have a crossing symmetry, which is to say that it must be even under the replacement of q by $-q$. That's true of the tensors. It must, therefore, be true equally well of the functions H_1 and H_2 . So the H 's must be even functions in qp . That's just something to keep in mind.

Now this is a very general description. Actually its much simpler to consider, not the general electromagnetic field, but specific polarizations. The possibility of varying the polarization depends on the freedom to vary the electromagnetic field which in turn is tied to the possibility of choosing different angles of deflection and different energy losses in the actual electron scattering. There are in fact just two kinds of polarizations in this situation.

Polarization

$$L : A_\mu(q) = n_\mu \quad (\text{unit time-like vector in } q-p \text{ plane}) \quad (3a)$$

where

$$n_\mu = \frac{q^2 p_\mu - (q \cdot p) q_\mu}{\sqrt{m^2 q^2 + (qp)^2 q^2}}$$

$$T : A_\mu(q) = m_\mu \quad (\text{unit space-like vector } \perp \text{ to } q \text{ and } p)$$

The one that I've called longitudinal is often called scalar. For that situation the vector potential is a unit time-like vector multiplied by a scalar measure

of the field strength. The unit time-like vector is in the $q-p$ plane and I have written its actual construction. The second kind of polarization is called transverse. It is constructed from any unit space-like vector. This is a space-like vector perpendicular to q and perpendicular to p . The details don't matter. These properties characterize it, together with a measure of the strength of the electromagnetic field. And now I write the amplitudes, namely the forward scattering amplitudes, specialized to longitudinal polarization and transverse polarization.

$$L : 1 + iV d\omega_p 4e^2 A(-q)A(q) m^2 q^2 H_1 \quad (4a)$$

$$T : 1 + iV d\omega_p 4e^2 A(-q)A(q) m^2 [-q^2 H_1 + (q^2 + v^2)H_2] \quad (4b)$$

where

$$v = qp/m.$$

We note that for longitudinal polarization only the function of H_1 is picked out because the tensor associated with H_2 is perpendicular to p . When we look at transverse polarizations, both H_1 and H_2 enter in a particular combination. You see that the scattering amplitudes involve the following general elements: interaction volume, density of the nucleon, e^2 as an intrinsic measure of the strength of electromagnetism, measure of the intensity of the electromagnetic field and then two functions of the independently variable quantities characterizing the experiment, q^2 and qp .

Now, what we're interested in, of course, is not probability amplitudes but probabilities. And so those two probability amplitudes that I just wrote down are to be squared to give the probability of forward scattering. However, from the fact that the total probability of something happening is one, we get as the complement of the probability of nothing happening (namely, forward scattering) the total probability of something happening. The probability of scattering forward is one minus the probability of some deflection, of any kind whatever. So when we take the absolute square of the forward scattering amplitude, we can infer the total transition probability. All of this is standard optics, and such reasoning is called the Optical Theorem. The interference between the scattering amplitude of unity and the scattering amplitude that starts out of phase, with an i in front, gives the transition probabilities in terms of the imaginary parts of those two H functions. Now what we are interested in, and in fact what is physically measured, is

sections. So I want to go directly to the cross sections and work with the cross sections as the quantities of physical interest. Most of the literature of this subject is expressed in terms of other quantities, of so-called structure functions. If you look at the experimental literature, you will find that the cross sections are measured first and then the structure functions are computed from them. The cross section is generally defined in the following way: The total transition probability per unit interaction volume, per unit flux. I call it invariant flux, because it is an invariant measure of the densities and the relative velocities of the two beams of particles with respect to each other. Here are the explicit expressions for the cross sections — longitudinal cross section, transverse cross section.

Cross sections

$$\sigma(\text{total cross section}) = \frac{\text{Total transition probability}}{V(\text{invariant volume}) F(\text{invariant flux})}$$

$$F = d\omega_p A(-q) A(q) 4\sqrt{m^2 q^2 + (qp)^2},$$

$$\sigma_L = \frac{8\pi\alpha}{mv} \frac{1}{\sqrt{1 + (q/v)^2}} m^2 q^2 \text{Im } H_1, \quad (5a)$$

$$\sigma_T = \frac{8\pi\alpha}{mv} \frac{1}{\sqrt{1 + (q/v)^2}} m^2 \times [(q^2 + v^2) \text{Im } H_2 - q^2 \text{Im } H_1], \quad (5b)$$

$$\sigma = \sigma_L + \sigma_T = \frac{8\pi\alpha}{m_v} \frac{1}{\sqrt{1 + (q/v)^2}} m^2 (q^2 + v^2) \text{Im } H_2, \quad (5c)$$

$$\sigma_L/\sigma = (q^2/q^2 + v^2) \text{Im } H_1/\text{Im } H_2.$$

They involve kinematical factors and the imaginary parts of the two basic invariant functions, H_1 and H_2 . By the way, I also note what the “total” cross section is, that is to say, the sum of longitudinal and transverse cross section. And you will notice the simplifying feature that while the longitudinal cross section involves only H_1 , the total cross section involves only H_2 . So each of these functions plays a determining role with regard to a particular kind of physical process as characterized by a certain cross section. Also, if you look at these expressions and recall the dimensions of the various quantities in

m and v are both masses or energies, you see the factor $(mv)^{-1}$ is designed to produce the dimensions of cross sections. Since you will also find four powers of momenta in front of the H functions, both of these must be inverse fourth powers of momenta, which is something to keep in mind. Finally, I've written a useful thing for comparison with experiments, the ratio of the longitudinal cross section to the total cross section, which you see involves a kinematical factor and the ratio of the imaginary parts of H_1 to H_2 . Instead of this, the longitudinal/transverse is often used. But since the ratio in practice is small, σ_L/σ is just as good a measure and I prefer to use it because it is simpler.

Now let me point out to you what happens in a related but independent physical situation in which we deal with real photons. The physical process then is just photo-absorption, in which a photon beam falls on a nucleon and we measure the total cross section.

Real photon cross section ($q^2 = 0$)

$$\sigma_L(q^2) = 0 \quad (6a)$$

$$\sigma_\gamma = \sigma_T = \frac{8\pi\alpha}{m^2} m^3 v \operatorname{Im} H_2(q^2 = 0, qp = -mv) \quad (6b)$$

$$\text{Experiment: } \begin{cases} (v/m \gg 1) \sigma_\gamma(n) \sigma_\gamma(p) \rightarrow 1 \\ m^3 v \operatorname{Im} H_2(q^2 = 0) \cong 1 \end{cases}$$

$$\text{Approx. description: } \sigma_\gamma(n)/\sigma_\gamma(p) \cong 1 - \frac{1}{4} \sqrt{\frac{m}{v}}. \quad (6c)$$

Of course, a real photon possesses only transverse polarization, and so one would expect that the longitudinal cross section disappears. I denote the total cross section, which is the only thing of interest, by σ_γ . I have written it in terms of a unit, $8\pi\alpha/m^2$ which is $\simeq 80$ micorbarns. Multiplying this unit is the invariant function H_2 (its imaginary part) evaluated for the photon situation. So of the two variables in general, q^2 is zero here and there is only one variable, which is v . Now let me remind you of some experimental facts, because, if I am not to use models, I must, of course, put in something. That something consists of utilizing other experimental bits of information which border on but are not themselves deep inelastic scattering. Of course, all workers in this field make use of related experimental facts. The only question is whether you can handle the facts directly, or whether you always

have to go through the intermediary of a model. I simply want to cut out the middle man, the model, and work directly with the experimental facts. At large photon energies compared to the nucleon rest mass, the proton and neutron cross sections seem to approach a common limit. They are slowly, asymptotically, approaching a constant at the energies available. A reasonable extrapolation gives a value of $m^3 \nu \text{Im} H_2$ or about one, which is why I've written it as I have. Actually, it's 1.2, but we will round it off to 1. Secondly, we are going to be interested in the manner in which the neutron and the proton cross sections approach equality. An approximate fit to the data is given by Eq. (6c). I'll remind you of this again. I want to use this as a basic experimental input.

So far we have had just general formalism and a few experimental facts upon which to draw. Now, we need a little more than that, and here is where we get rather more specific. Namely, under the heading of double spectral forms, I will describe to you the general theoretical framework in which all of this is going to be imbedded. In order to appreciate what I am going to say, think, not of the actual experimental arrangement, but a special space-time arrangement.

Double spectral forms

Here, in other words, are momenta not necessarily having the values that are of physical interest. We will get to that later by a process of extrapolation. Think of two nucleon fields and two electromagnetic fields in a particular arrangement. The nucleon field injects some momentum not necessarily

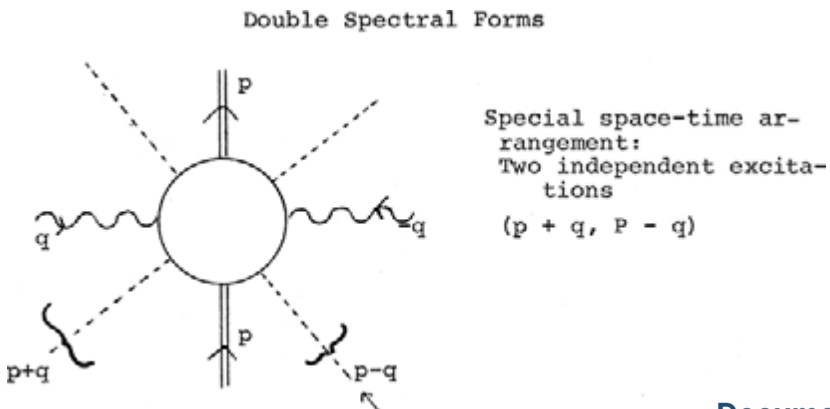


Figure 4.

related to the nucleon mass. Then, in addition, there are, from the sides, spacelike insertions of photon momentum q , and photon momentum $-q$. The net result, for the total momentum injected is p , and that goes out in the form of the nucleon. A nucleon in the general sense, that is, a virtual nucleon. So here we have a coupling of four fields, the same four fields we're interested in but under more general space-time or kinematical conditions. The main point of thinking of it this way is that we can usefully view it in another manner which I have already suggested here. Namely, by thinking of these things as being somewhat variable in their space-time arrangements, you can regard the momentum p and the momentum q , combined together as a total excitation of momentum $p + q$, running through the system in a time-like direction. And then quite independently of that, we can alternatively think of p and the other electromagnetic field with momentum $-q$ producing an excitation of momentum $p - q$. Our ability, to move these around in various ways, to control the space-time arrangement, gives us the possibility of considering these two independent excitations of momenta $p + q$, $p - q$. Well, p and q or their various squares are the basic independent variables. I am just directing your attention here through a particular space-time arrangement, and a certain way of thinking of things, to the importance of the particular combinations $p + q$, $p - q$. The result is to consider an excitation with total momentum $p + q$ running through the system and setting up states of various masses, which I will call M_+ . Independently a momentum $p - q$ sets up states of various masses, which I will call M_- . One is lead to superimpose the two and construct the two functions of the variables q^2 and qp in terms of $p + q$ and $p - q$:

$$H_a(q^2, qp) = \int \frac{dM_+^2}{M_+^2} \int \frac{dM_-^2}{M_-^2} \frac{2h_a(M_+^2, M_-^2)}{[(p+q)^2 + M_+^2 - i0][(p-q)^2 + M_-^2 - i0]}. \quad (7)$$

The denominators are standard propagation functions of these particular momentum excitations. Multiplying these are arbitrary spectral weight functions that measure the probability of exciting the general spectrum. They are dimensionless (recall the inverse fourth power of momentum for the dimensions of H_a). I also point out to you the requirement of crossing symmetry. That is, Eq. (7) should be symmetrical between q and $-q$ or symmetrical between M_+ and M_- . So here is the general idea of considering

related physical situations, insisting on their generality, and then extrapolating to the situation of interest.

It's always possible to add single spectral forms, things that depend upon only one of these variables at a time. But I will use the assumption that there are no single spectral forms, and I merely point to the fact there seems to be no need for them. There are no contradictions, no difficulties, and there are comparisons with experiment and rather special situations that motivate us to exclude single spectral forms for this particular situation. Now what we are interested in, is the imaginary part, and here I've indicated to you the possibility of picking it out:

$$\begin{aligned} \frac{1}{\pi} \text{Im } H_a &= \int \frac{dM_+^2}{M_+^2} \int \frac{dM_-^2}{M_-^2} \frac{\delta[(p+q)^2 + M_+^2] 2h_a}{(p-q)^2 + M_-^2} \\ &= \int \frac{dM_+^2}{M_+^2} \int \frac{dM_-^2}{M_-^2} \frac{\delta(q^2 - 2Mv - m^2 + M_+^2)h_a}{q^2 + \frac{1}{2}(M_-^2 + M_+^2) - m^2}, \end{aligned} \quad (8a)$$

since

$$\text{Im} \frac{1}{x - i0} = \pi \delta(x). \quad (8b)$$

Notice that in Eq. (7) both denominators possess an $i0$, which is the characteristic reference to propagation. So it is this imaginary part that contributes, that produces a delta function describing the fact that an injection of momentum $p + q$ produces a certain mass, M_+ . Now forgive me if I ask you to take on faith quite elementary manipulations which the running clock prevents me from doing for you. It's all quite direct. I've rewritten the delta function in terms of the variables q^2 and v ; the denominator is also written conveniently in terms of q^2 . So we isolate in the numerator to some extent the energy input and in the denominator the momentum transfer. Then, just as a mathematical device to separate even further the interesting variable, which is q^2 , from the details of the spectrum, I take this denominator and I put it in an exponential by introducing a new integration variable:

$$\begin{aligned} &\frac{1}{q^2 + \frac{1}{2}(M_- + M_+)^2 - m^2} \\ &= \int_0^\infty \frac{d\zeta}{M_+^2} e^{-(q^2/M_+^2)\zeta} e^{-[(M_+^2 + M_-^2 - 2m^2)/2M_+^2]\zeta}, \end{aligned} \quad (9a)$$

$$h_a\left(\zeta, \frac{m^2}{M_-^2}\right) \equiv \pi \int \frac{dM_-^2}{M_-^2} e^{\frac{-(M_+^2 + M_-^2 - 2m^2)\zeta}{2M_+^2}} h_a(M_+^2, M_-^2) \quad (9b)$$