MESON FACTORIES?

The most recent of several conferences on sector-focusing accelerators was the Gatlinburg meeting on advances in meson and nuclear research below 1 BeV, which was held last November. The matters discussed are reviewed here by A. Zucker, associate director of the Electronuclear Division of the Oak Ridge National Laboratory, and A. H. Snell, assistant director of ORNL.

By ***Alexander Zucker*** *and* ***Arthur H. Snell***

IN February 1959, a conference on sector-focusing cyclotrons was held at Sea Island, Ga., under the joint sponsorship of the National Academy of Sciences–National Research Council and the American Physical Society.[1] Eighty-six specialists attended from six countries and thirty-nine institutions in Europe and America. Theory, orbit computation, and tentative designs were discussed, and the participants parted with a general feeling of both the feasibility and the desirability of accelerators of this kind.

In April 1962, a second conference on the same topic was held at Los Angeles under the sponsorship of the Physics Department of the University of California at Los Angeles.[2] There were now several cyclotrons coming into operation that were based completely upon the sector-focusing principle; notable among them were the Berkeley 88-inch, the Oak Ridge ORIC, the University of Colorado cyclotron, and the UCLA cyclotron. Initial operation of these accelerators was found to justify the optimism that had been generated and felt at Sea Island. They are clearly good machines.

Inevitably, the UCLA conference was also forward-looking. One session was entitled "Meson Factories"; here the feasibility was discussed of using the sector-focusing principle to carry particles into the energy range of hundreds of MeV—an acreage heretofore sacred to synchrocyclotrons. Indeed, several years ago T. A. Welton had surmised that sector focusing could keep particles under control until they had kinetic energy equal to their rest mass—and maybe more. At the UCLA conference, participants from Oak Ridge described an operating model that accelerates electrons to 500 keV (i.e., mc^2) with dee voltages appropriately scaled down; its success in leading the beam through orbital resonances while still maintaining synchronism with constant-frequency accelerating voltage had actively encouraged thoughts about a proton accelerator, which the Oak Ridge people had started to call the Mc^2 cyclotron. Such a machine, by avoiding the duty cycle inherent in frequency modulation, might be expected to yield a proton beam about a hundred times stronger than that of synchrocyclotrons, so that in addition to bringing within reach certain elementary-particle experiments and new kinds of studies of nuclear structure, it would be truly a factory for pions and muons.

The term "Meson Factory" has a happy broadness that permits generalization to accelerators other than cyclotrons. It includes the proton linac that physicists at Yale University have had under

[1] *Sector-Focused Cyclotrons*, Proc. Informal Conf., Sea Island, Ga., Feb. 2–4, 1959, Publication 656, NAS-NRC (1959).
[2] *Physics Today*, Aug. 1962, p. 32.

consideration since 1959, independently of the cyclotron activities outlined above. In fact, Yale has contributed the following definition of a meson factory: "a complete research installation consisting of a high-intensity proton accelerator of maximum energy below 1 BeV, suitable targets and target areas for producing beams of mesons and other particles, devices for disposing of the spent primary beam, systems for handling secondary beams, adequate areas for performing experiments, the requisite shielding, and all necessary support facilities". Clearly, a meson factory is a major installation, comparable in size and expense to the last generation of high-energy accelerators, although minor compared with accelerators now a-building and contemplated. Where the performance of meson factories stands in relation to existing machines is illustrated in Fig. 1, in which the beam intensity is plotted against energy. Here it is apparent that the more modern accelerators fall into a kind of "main sequence"; the meson factories would have a performance range at the upper left, removed from the main sequence by two or three decades. The location suggests that they will have a field of usefulness all of their own.

The technical feasibility of realizing such machines is now beyond question; accelerator technology has advanced to such an extent that the plums are ripe for picking, whether one talks of linacs or cyclotrons. The more profound and difficult question has therefore to be considered: will meson factories bring within reach a deep enough, significant enough field of research physics to merit the very considerable expense of their construction and maintenance?

The only way to assess an unopened field of research is to discuss it with people who are on the fringe. Hence—a third conference, held on November 12 and 13, 1962, at Gatlinburg, Tenn. This time, the conference was organized within the framework of the Oak Ridge Nuclear Facilities Group. The members of the program committee were V. W. Hughes of Yale University, J. R. Richardson of UCLA, and R. S. Livingston and A. Zucker of the Oak Ridge National Laboratory. The Gatlinburg conference attracted 135 participants from forty institutions, and had the title "Advances in Meson and Nuclear Research Below One BeV". The topics ranged widely; meson physics dominated one session, while nucleons and nuclear structure dominated a second, but other subjects also were examined, such as neutrino beams, radiation effects in manned space flight, and cancer therapy using negative pions.

Elementary Particles and Their Interactions

Below one BeV there are seven elementary particles, n, p, β, π, μ, ν_e, ν_μ, and often their antiparticles, available for investigation. Weak- and strong-interaction experiments abound. Rare decay modes are being pursued with the expertise and tenacity of a woodsman following a barely discernible spoor. Pion-reaction ratios, exotic offspring of the Panofsky ratio, are measured with increasing precision. Theorists are, as usual, interested in only the most difficult measurements, and until these are made to the required precision they continue to erect lovely theories full of symmetries, conserving everything in sight, and denying with a vehemence unusual for them, any rights to neutral lepton currents. Some of the elementary-particle work is done so far below one BeV that it is practically out of sight: μ-hydrogen atoms and molecules, and a totally new breed of atom, μ^+e^-, called muonium.

We turn our attention first to strong interactions. The nucleon-nucleon phase-shift analysis is being pursued with vigor and a good measure of success

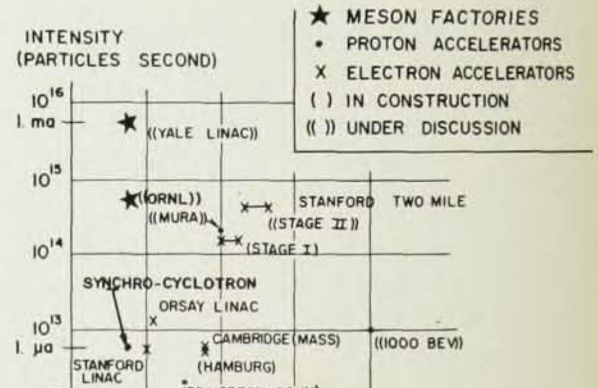

Fig. 1. This graph (allegedly attributable to J. P. Blewett of Brookhaven) shows the performance of proposed meson factories in comparison with other high-energy accelerators. Emphasis on meson factories is discernible at upper left. (Revised 12-12-62.)

The organizing committee of the Gatlinburg conference: A. Zucker (ORNL), J. R. Richardson (UCLA), R. S. Livingston (ORNL), and V. W. Hughes (Yale).

by the Yale group (Breit and collaborators). We quote from Breit's contribution to the conference:

"Through a comparison of theoretical expectation with experimental scattering data it has proved possible to make approximate determinations of phase parameters in the energy region 0–340 MeV. In these determinations the validity of theoretical expectation for the one-pion exchange (OPE) interaction is assumed for the higher values of L. On comparing the value of the pion-nucleon coupling constant derivable from p-p scattering with that from n-p data a test of charge independence of nuclear forces relevant to interactions at large distances is obtained supplementing earlier information based on the comparison of $^1S_0$ interactions. By varying the proportions of the spin-spin and tensor-force parts of the OPE interaction and adding a central-force part, the theoretical form of the OPE has received a partial test. Qualitative evidence for the correctness of the *PSps* nucleon-pion interaction theory has been obtained. The belief in the essential correctness of the general phase-parameter representation of n-p scattering receives partial support from the improvement which results through the inclusion in the analysis of nuclear magnetic moment effects."

There is, however, a great need for more measurements at various energies, for greater precision of scattering and polarization measurements, and for the accurate determination of the various double- and triple-scattering parameters. A better understanding of the pion behavior in the open channels is of obvious help in inferring the nature of their interactions in the closed channels.

Obviously p-p scattering is in far better shape than n-p scattering or the π-nucleon interaction. This latter subject is worthy of much more extensive exploration than it has hitherto received. What is needed is precise information on π-nucleon scattering, including the polarization of the recoiling nucleon. The theoretical importance of this measurement was pointed out by Hull (Yale), and experimental results were presented by Crowe (Berkeley). In particular, the polarization of the recoil proton in π-p scattering is now being measured at Berkeley, but the results are not yet conclusive. This is a difficult and important field of research. After all, the pion-nucleon interaction must somehow lie at the root of nuclear matter, and any deep theoretical understanding of nuclei will perforce have to include it. The spirit of the conference was to point to the future rather than to examine the present or exhume the past, and it was suggested that precise and exhaustive work in this field will probably benefit greatly from the high-intensity accelerators now in the planning stage.

Weak interactions are the fashion of the moment. They are likely to remain so for the following reasons: our understanding of them is tantalizingly complete; seemingly we need only a few crucial and excruciatingly difficult experiments (e.g., neutrino-electron scattering) to nail it down. In the absence of these experiments, there is still enough room for conjecture and creative thought, for theorists and experimenters alike, to keep the pot boiling.

In his review, Primakoff (Pennsylvania) posed the problem: to construct a weak-interaction Hamiltonian, analogous to the electromagnetic case, and to get the form factors of the matrix elements. In this formal framework many concrete questions appear:

What is the rest mass of the μ neutrino?

Is there an intermediate boson?

Are total lepton, muon, and electron numbers conserved?

Are neutral lepton currents strictly prohibited?

Is the vector current conserved, and what about tensor currents?

Some of the answers may be near at hand, and may be the ones we might guess from our present knowledge; others, contrariwise, may upset a cherished notion about physics, but in the end provide a more natural and broader basis for our understanding. It certainly seems worth finding out.

Two particular questions were examined in more detail at the conference. One is the μ-p weak-interaction experiment of the Columbia group, reported by Rosen, and the other is the validity of the laws of electrodynamics, at short distances, from the spectrum of the muonium atom, as discussed by Hughes (Yale). In neither case were the results astonishing: the weak-interaction constant has not changed, and electrodynamics appears safely correct at least to the order α. Both questions remain, however, under close observation.

Atomic and molecular phenomena pose some of the most troublesome problems in the μ-p experiment, and muonium is, after all, only an atom: it seems that atomic physics just will not yield its place at the forefront of physics. In yet another form this was brought out by Anderson in his review of μ-mesonic atom research at Chicago. New techniques in γ-ray scintillation spectrometry reveal interesting new information about the nuclear charge distribution in heavier elements. In some cases, notably around $A = 30$ and $A = 70$, there are some tantalizing differences in the nuclear radius parameter obtained from μ-mesonic x rays and from electron scattering. Everything points to a very rich field of research, especially if one could manage to improve the resolution, say by a crystal spectrometer.

Nuclear Structure

Turning next to the discussion on nuclear structure, it was abundantly clear that nuclear physics is taking on a new and sharpened interest in the range "Below one BeV".

It was pointed out by Glassgold (Berkeley) that at high energies, 500–1000 MeV, one really has an ideal situation because of the short de Broglie wave length: Δx of the wave packet is much smaller than the mean free path in nuclear matter. One can assume that the optical model potential $V_{OM} = A\langle\tau\rangle$, where τ is the nucleon-nucleon scattering matrix in nuclear matter. Furthermore, at high energies $\tau \rightarrow t$, t being the free scattering matrix. Experiments must be performed to verify that $V_{OM} = A\langle t\rangle$, and for example, the variation of V_{OM} with N and Z can provide such a check. Furthermore, there are corrections to this formula which are of great interest. Large-angle scattering data can provide information on the effective nucleon-nucleon interaction off the energy shell. To do this one would first have to ascertain the nuclear-structure contribution by small-angle scattering. It is also clear that nucleon-nucleon correlations would constitute a correction to the first-order formula, and these may perhaps be extracted from scattering experiments. Certainly one would expect to see the effect of the hard core.

Quasi-free collisions between the incident proton and nucleons in the target nucleus lead to the momentum distribution of bound nucleons and in such experiments as $(p, 2p)$ show clearly the existence of s and p-nucleons, and the energy difference between them. Igo (Berkeley) reported on the results of an $(\alpha, 2\alpha)$ experiment at 900 MeV. He concludes that the nucleons on the nuclear periphery are clustered into alpha particles. It is clear that high-energy nuclear physics imposes stringent requirements on the energy definition of the incident beam, and the resolution of the detectors.

Satchler (ORNL) discussed inelastic proton scattering at high energy. He pointed out that in a nuclear reaction one deals with two parts: (1) the interaction, and (2) the wave function of the nucleus. At high energy there is every reason to believe that one really knows the basic interaction, and can thus explore the structure of the nucleus much more effectively. The complicated spin relations in proton-nucleon scattering "provide one with a many-pronged tool for investigating nuclear structure". The student of nuclei might here be in the position to make use of the extensive knowledge of nucleon-nucleon interactions to explore the nucleus itself. To be sure, "many-pronged" experiments, such as correlation measurements, polarization, and total as well as differential cross sections, will be required.

The accent in the nuclear-physics papers, which was echoed by Wolfenstein (Carnegie Tech) in his summary, was on promise rather than on accomplishment. For many reasons, the study of nuclear structure at high energies has been a neglected subject. For a long while the primary concern was production of mesons, and the properties of these new particles. Then, the synchrocyclotrons with very weak and pulsed external beams were just not natural tools for nuclear physics. Much of this is changing now; we are, in fact, witnessing the formation of a high-energy salient on the nuclear-structure front.

Biology, Medicine, and Space

At first glance it would be hard to think of a field of physics with less chance of application than that "Below one BeV". There is one particle, however, in this region which is of great interest to the biologists: the negative pion.

Radiobiologists have long been concerned with the problem of relative biological effectiveness (RBE) of high linear energy transfer (LET) radiation. (The physicist will notice the transition to biology by the reluctance to use differentials, LET is equivalent to $-dE/dx$; and the use of first-letter abbreviations (RBE) where one would usually find an E^* or ϵ in physics.) High LET radiation is difficult to come by, and by its nature is difficult either to distribute uniformly throughout an organism larger than a few millimeters in size, or to deposit selectively in a particular organ. The negative pion is useful in both ways. First of all, it is always present in a broad energy band (100 to 400 MeV from 800-MeV protons); second, it produces a large amount of ionization in the star at the end of its range, accompanied with a low entrance dose. Thus by exposing an organism whose characteristic dimension is of the order of the range distribution of the π^- beam, reasonably uniform star formation in the body can be achieved. On the other hand, the use of a very homogeneous beam of π^- enables one to expose certain organs of larger animals selectively to high LET radiation. Thus one can study both the whole-body RBE and the RBE for any particular organ with stopping pion beams.

This naturally excites the biologists to a high state of interest (HSI), since, except for small organisms, the RBE vs LET curve is very poorly known (VPK) at LET higher than about 100 keV/μ. All this was brought out by Randolph (ORNL) and Comas (ORINS) in their papers.

The biological program has a further possible application of great importance: human cancer therapy. Comas discussed the use of intense π^- beams of well-defined energy such that the end of their range is placed at the tumor site. Intense doses can be delivered to the tumor while the entrance dose remains tolerable. Figure *2* shows the dose distribution according to Fowler and Perkins for Co^{60} γ-rays, 110-MeV protons and 50 MeV π^-, the last two ending at a depth of about 10 cm in tissue. The issue between pions and γ-rays is clear-cut, in favor of pions, but the merit of protons vs pions is not so easy to evaluate. Here extensive research into the RBE of π^- stars is necessary, and better data of depth dose vs entrance dose must be obtained. At

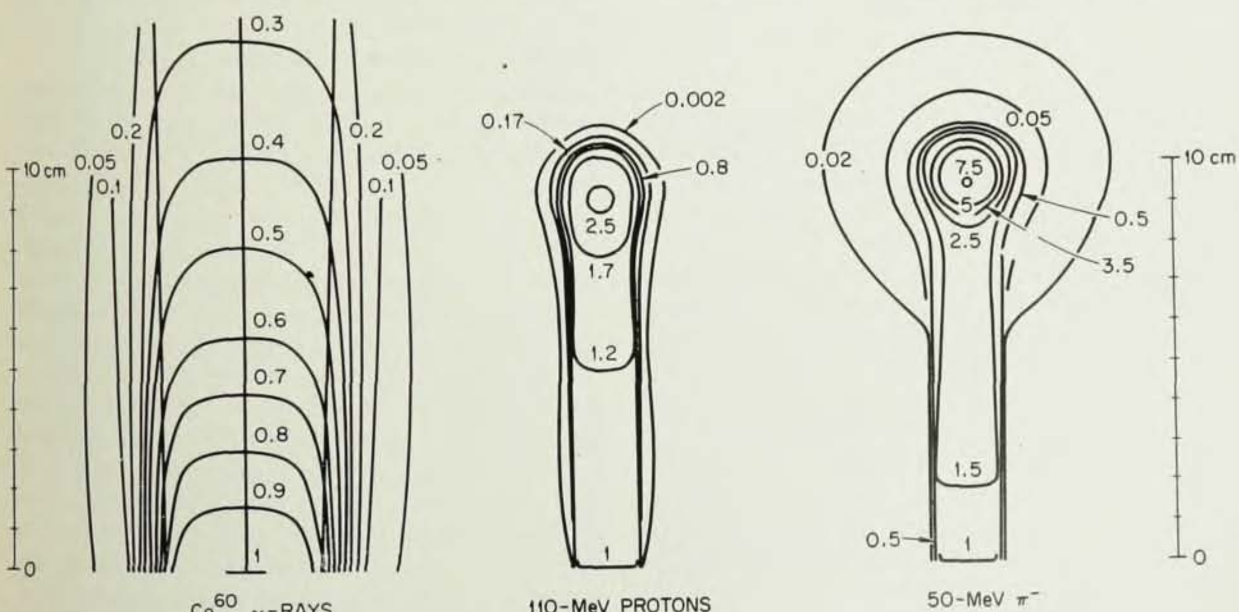

Fig. 2. Isodose distributions around beams of gamma rays, protons, and negative pions in tissue, showing the greater localization in depth of dose produced around the stopped negative pions.

present it looks as if pion entrance doses are less than one-half the proton dose for the same energy delivered at the tumor. A factor of two is by no means trivial in this kind of problem, and may in fact be just the margin by which the success or failure of practical treatment is determined.

Once again it was obvious how the most abstract theorist and the empirical experimenter take pleasure at the notion that their science may contribute concretely and directly to human welfare. And it would truly be a triumph for physics and medicine if an ephemeral particle, first discovered in cosmic rays, could be produced in copious enough quantities by modern accelerator technology to combat one of man's most unrelenting foes, cancer.

Most people, physicists not excepted, are vicarious astronauts. Peelle (ORNL) described the vicissitudes of space travel due to radiation. There are three sources: intergalactic radiation ($\sim$ 50 rem/year), the Van Allen belts ($\sim$ 100 rem/day, but quickly traversed), and solar flares. Of these the last is really the only serious one; the most intense flare observed since 1956 would give a moon-bound astronaut a dose of 200 rem with 5g/cm^2 of shielding. Requirements for shielding this radiation are now known to about a factor of two. Experiments are needed (and this is where the conference comes in) to understand the energy and spatial distributions of secondary particles in a high-energy nucleon cascade. A factor of two is very important, when one considers the stringent weight limitations in our primitive space vessels.

Conclusions

As the meeting progressed it became increasingly clear that "physics below one BeV" is a rich field, good for many years of significant and productive research even with the tools now available. Still, the most repeated phrase, "if we had a hundred times the intensity . . ." gave an indication of what was, so to speak, the leitmotif of the conference. More intensity, purer beams, better accuracy, thinner targets, higher resolution, more restrictive coincidence sorting—all these would result from one of the new accelerators now in the planning stage in the United States and abroad.

In almost every paper it was obvious that increased beams by factors from 10^2 to 10^4 would be of the greatest value to the physicist. Wolfenstein, in his summary, put it this way: ". . . the people here are concerned with what can be done in the energy region below one BeV with high-intensity accelerators. Most of us have been told that the real frontier in elementary particle physics is at high energies; that the advances are to be made by increasing machines from 3 BeV to 300 BeV. However, there does exist a real frontier in the direction of high intensity."

Another important aspect of the region "below one BeV" was brought out by Wolfenstein.

"There is a strong interaction, that was not mentioned [in the conference], between what goes on at higher energies and what we look for at more moderate energies.

"Let me just mention two examples of that kind of interaction which I think is bound to occur. One example comes in the theory of weak interactions. The weak interactions of strange particles have really hardly been understood. As we gain some understanding in strange-particle weak interactions, there undoubtedly are going to be new questions raised for the nonstrange-particle weak interaction, questions that are very hard to ask now, questions for which it will be necessary to find answers.

"The second example lies in the great interest that now obtains at very high energies in interpreting total cross-section measurements in terms of the exchanges of single rho mesons, single omega mesons, single eta mesons, and in knowing something about the coupling, say the nucleon-nucleon coupling to the rho meson.

"This is being explored at high energies, but it is something which we hope would also come out from analysis of such things as s-wave pion-nucleon scattering, or a more detailed analysis of nucleon-nucleon scattering when we can see the contribution of, say, a one rho meson exchange."

Research "below one BeV" on one hand extends nuclear-structure studies into a region where some simplifying assumptions can be made with confidence, and on the other provides a kind of precision for elementary-particle interactions that is unobtainable at higher energies. Several leading directions emerged at the Gatlinburg conference, indicating the presence of a field for investigation that will not be easily or quickly exhausted, and one that contains aspects of deep theoretical interest as seen from the apparently shallow entry that has been made so far. As for the meson factories: with their beams of protons powerful enough to be used either directly or for extraction of a polarized fraction of useful intensity, their beams of positive and negative pions, of positive and negative muons, and of neutrons and neutrinos—they would seem to constitute research centers of lasting value. All this and a source of a new radiation for cancer research!