Nuclear sizes and density distributions

Kamal K. Seth

a conference report

By Kamal K. Seth

NUCLEAR SIZES and DENSITY DISTRIBUTIONS

IN recent years a large number of conferences somewhat vaguely devoted to nuclear structure have been held both within and without the United States. While conferences, especially those abroad, are more than welcome, quite often such conferences tend to be too diffuse in their objective and more or less repetitive in their subject matter. The International Conference on Nuclear Sizes and Density Distributions held at Stanford University, Stanford, Calif., on December 17, 18, and 19 was, by definition, above this criticism. It concerned itself with a topic which had never before been the exclusive subject of any conference, and the manner in which it was organized by Dr. Hofstadter and his colleagues on the steering committee left no room for vagueness or confusion.

The conference was jointly sponsored by the National Science Foundation and Stanford University, with the cooperation of the Office of Naval Research and the US Air Force Office of Scientific Research. It met each day for morning and afternoon sessions, each of three hours duration, thus allowing ample time for the presentation and discussion of twenty-two invited papers and about ten short contributions. The precise definition of the domain of the conference allowed a systematic development of its deliberations. The subject of nuclear sizes was vigorously examined from all possible angles. The variety of these approaches, which ranged from the classic atomic to those "a week old", might at first suggest unending confusion; however, it can be safely said that the conference succeeded in resolving quite a few discrepancies, and reconciling many more differences. Of course no conference could be of lasting value if it did not pose twice as many questions as it answered. The Stanford meeting was no exception in this respect.

It is extremely difficult to summarize a good conference; it is impossible to summarize Bethe's summary of the conference. Yet this is exactly what I must try to do here.

Currently engaged in neutron physics research at Duke University, Kamal Kishore Seth was born in 1933 in Lucknow, India. He received his bachelor's degree (1951) and his master's degree in physics (1954) from Lucknow University. He came to the US in 1954 and was awarded the PhD in physics by the University of Pittsburgh in 1957.

The problem of nuclear sizes has been defined in terms of three fundamental properties of all nuclei—they all have a mass, a charge, and a field of specifically nuclear force. The determination of the radial and angular variations in the distributions of these three quantities provide one of the most reliable ways of understanding nuclear structure as well as some insight into the structure of nucleons. Only the nuclei which correspond to closed shell numbers of protons and/or neutrons are known to be spherical, others are more or less deformed. In the first approximation, however, we may consider a typical nucleus as spherical. The simplest conjecture about its size, on assuming a uniform density, is that the nuclear volume is proportional to the total number of nucleons (A) contained, i.e., the radius $R_0 = r_0 A^{1/3}$. But uniform density is quantum mechanically impossible; the nuclei must have a surface region over which the density falls slowly from its central value to zero. Accurate experiments have, as a matter of fact, shown that this is the case. Most of the data is now analyzed in terms of such a distribution (Fig. 1), which is characterized by a parameter $r_1 = R_1 A^{-1/3}$ where R_1 is the "halfway radius", i.e., the radius at which the density reaches half its central value, and t, a parameter specifying the "surface thickness", i.e., the distance in which density falls from 90 percent to 10 percent of its value at the center. The questions that now arise are:

(a) Is such a picture of nuclear density borne out by all experiments? If so, what are the values of r_1 and t?

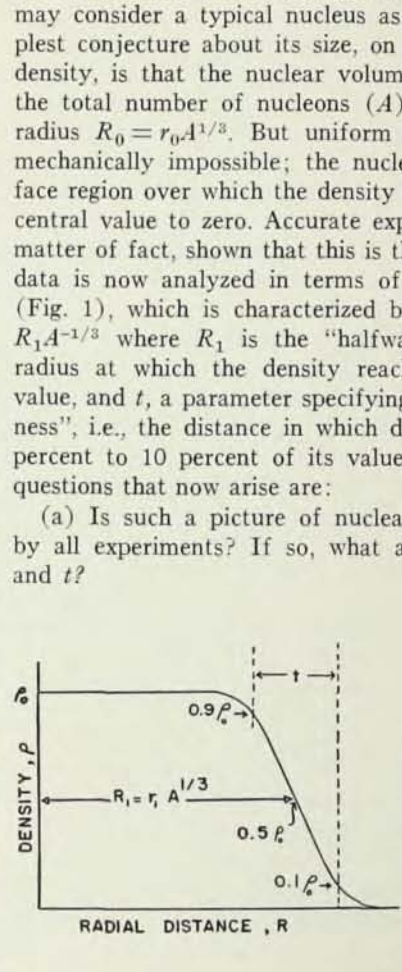


Fig. 1. One of the commonly used rounded edge distributions, $\rho = \rho_0/[1 + \exp\{(R - R_1)/a\}]$. Variously called Saxon or Fermi distribution, its equivalent square well radius R_0 is larger than the half-density radius R_1.

(b) Are the values of these parameters different for the three distributions (matter, charge, and potential) that one can measure?

(c) Are neutrons and protons point particles, or do they have a structure also?

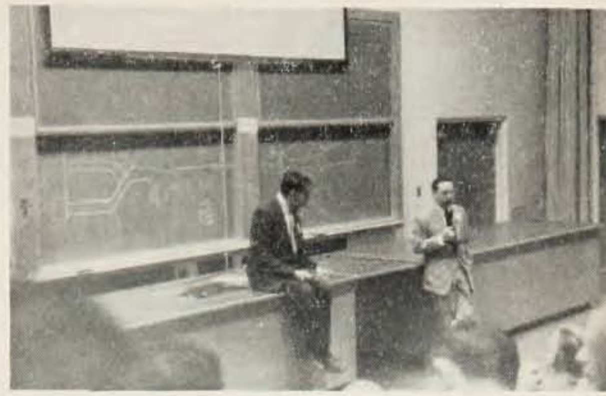
The theoretician has his share of questions too:

(a) Is nuclear radius just an "operational concept" or does it have a physical meaning—how can it be explained in terms of the general problem of nuclear saturation, compressibility, etc.?

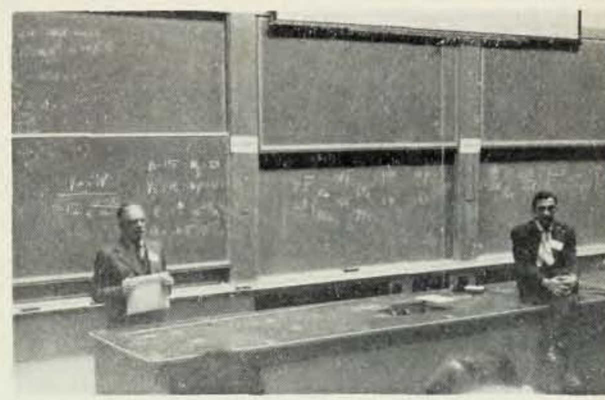
(b) How and why are the different values of r_1 and t for the three distributions related?

(c) How does nucleon structure arise—can it be explained with the help of meson theory?

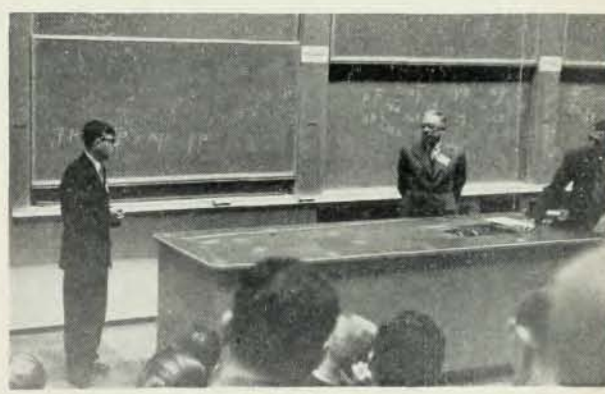
The purpose of the Stanford Conference was to bring together the latest experimental information on the subject and the most recent developments in the theoretical understanding of nuclear structure in order to answer these questions.



Session on nuclear surface; E. Teller of Berkeley (presiding) and L. Wilets of the Institute for Advanced Study.



E. Segrè (Berkeley) . . . an interpretation of large proton-antiproton cross sections . . .



A question from the floor by L. B. Okun (USSR)

WHEN a projectile which interacts strongly with all the nucleons in a nucleus is employed, the interaction can always be described in terms of the optical model, in which a complex average potential replaces the actual nucleus. Such projectiles are neutrons, protons, alpha particles, and π mesons, and the optical model analysis of experiments with them was reviewed in detail by Fernbach, Glassgold, Rasmussen, Seth, and Cool.

Fernbach and Glassgold reviewed the data on the total and differential cross section of neutrons and protons, respectively, and concluded that a diffuse edge potential with a halfway radius parameter $r_1 = 1.25 \pm 0.05$ fermis (1 fermi $= 10^{-13}$ cm) fits all the existing data up to 1.3 Bev. Fernbach, in a historical development of the optical model, emphasized the importance of spin-orbit potential being included in the interpretation of high-energy data. Glassgold discussed the energy dependence of the optical model parameters, which is very clearly brought out by proton elastic scattering experiments, and stressed the basic difficulty of optical model analyses. Such analyses always tend to yield the value of a combination of potential depth with the radius (V_0R^n, $n = 2$ at low energy, $2 \leqslant n \leqslant 4$ at higher energy). Thus it is difficult to arrive at a unique value of the radius parameter.

Rasmussen surveyed the alpha-particle scattering as well as alpha-decay experiments. The interpretation of these experiments is particularly difficult because of the relative insensitivity of the α particle to the potential value in the inside of the nucleus. However, recent analyses yield results in essential agreement with neutron and proton experiments. Seth pointed out the rather pronounced effect of nuclear deformations in the very low-energy (1 ev to 100 kev) neutron experiments, and presented experimental evidence for deformation of medium heavy and heavy nuclei. No theoretical justification was forthcoming for the very large (~ 35 times the value estimated by the conventional theory) value of the spin-orbit potential required by the experimental data at high energy. Only direct polarization experiments can be expected to settle this question. Similarly, though theoretical considerations favor the idea that absorption should take place predominantly on the nuclear surface (where the Pauli principle inhibits capture less than it does deep inside the nucleus), the experimental data which has been suc-

Delegation from the USSR: Dzhelepov, Blokhintsev, Okun, Nikitin.

Conversation with F. Bloch.

A. de-Shalit (Weizmann Institute) and F. Villars (MIT).

cessfully analyzed in terms of an imaginary potential confined to the nuclear surface is still too meager for one to say how successful this interpretation is. However, it appears that the optical model is undergoing sophistication at such a rapid rate that before long it will qualify as a full-fledged theory.

Cool presented the results of optical model analysis of $\pi^{\pm}$ absorption cross sections at energies near 1 Bev. At these energies the π meson wavelength is so small compared to the nuclear size that it essentially sees the nuclear matter distribution as modified by the range of pion-nucleon interaction. Cool's results agree with a rounded-edge optical potential with $r_1 = 1.14$ fermis. When the effect of the finite range of interaction is unfolded Cool essentially gets the measure of nuclear matter distribution. However, a more direct measure of matter radius can only be obtained when a very weakly interacting projectile is used. Leiss reported on the coherent photoproduction of neutral pions in carbon. These experiments were done at energies 0–70 Mev above the π^0 production threshold so that elastic production was the major contribution. Since the π^0 production cross section is almost the same for protons and neutrons, these experiments essentially measure average nuclear matter distribution. Mention was also made of Jones' suggestion that the K^- meson capture by heavy nuclei in the nuclear emulsions, giving Σ^- mesons and $\pi^{\pm}$ mesons, might be used not only to determine matter radius but also to look into the question of neutron excess on the nuclear surface where the absorption occurs. The analyses of Cool, Leiss, and Jones essentially bear out the hypothesis that, within the limits of experimental error, the nuclear matter distribution has the same extent as nuclear charge distribution. Can this be interpreted to mean that neutron and proton distributions in a nucleus have the same extent? Opinion on this question was divided and nobody was prepared to commit himself. For the difference $r_n - r_p$ numbers like $-(0.3 \pm 0.3)$ and $+(0.8 \pm 0.8)$ fermi were quoted and it is not surprising that few attached any real significance to them.

A rather interesting report came from Segrè and Chew on the interpretation of abnormally large proton-antiproton cross sections. A few months back the only way of interpreting these results seemed to be in terms of an interaction radius which was disconcertingly large. Using a model in which the strong repulsive core of the phenomenological two-nucleon potential was replaced by an infinite sink (in which every antiproton was annihilated) Chew has been able to account for the large experimental cross sections at an antiproton energy of 140 Mev in a simple manner. The application of the optical model by Glassgold to antiproton interaction with heavy nuclei leads to $r_0 = 1.3$ fermis.

SO far I have dwelt only on the potential and matter distributions in the nucleus. There are numerous ways of looking at the nuclear charge distribution, but the field is unquestionably dominated by the high-energy electron scattering experiments. Though Hofstadter likes to call them "nonprecision experiments", these are probably the most definitive experiments in the whole field of nuclear sizes. These experiments are too well known to require any elaboration here. However, the final results of experiments with a large number of elements may be mentioned. Ravenhall summarized the up-to-date situation on the interpretation of these experiments. It is found that the nuclear charge distribution is not uniform throughout. In the central region it is more or less uniform (the accuracy of the present experiments cannot distinguish between slight modifications in the central charge density), but on the surface it gradually tapers off. The half-density radius is $R_1 = 1.07A^{1/3}$ fermis and the surface thickness is $t \simeq 2.5$ fermis. Alternatively the radius of the equivalent uniform model is $R_0 \simeq 1.07A^{1/3} + 0.7$ fermis, which gives $R_0 = 1.35A^{1/3}$ for the very light nuclei and $R_0 = 1.18$ for the very heavy nuclei.*

Amongst other methods of determining nuclear charge distribution, Henley discussed results obtained by studying the transitions between levels of μ-mesic atoms. The energies of these transitions are very strongly dependent on the finite nuclear charge distribution, the μ-meson orbits being very close to the nucleus because of the meson's heavier mass. These experiments yield values of r_0 in excellent agreement with those obtained by electron scattering. Kofoed-Hansen discussed the coulomb energy difference between mirror nuclei. Hitherto these measurements led to values of r_0 as large as 1.45 fermis. However, when one takes into account the fact that the mirror nuclei differ in the single nucleon which is one of the outermost, it is found that $r_0 = 1.28 \pm 0.05$ fermis. It may be noted that electron scattering gives almost the same value of

* Elton reported on more accurate semiempirical formulae for both R_1 and R_0, and they might be mentioned here as an illustration of the complicated nature of seemingly simple things.

$$R_1 = 1.121A^{1/3} - 0.970A^{-1/3} \text{ fermis},$$
$$t = 2.53 \pm 0.06 \text{ fermis, or}$$
$$R_0 = 1.121A^{1/3} + 2.426A^{-1/3} - 6.614A^{-1} \text{ fermis}.$$

Of course these describe the experimental results better.

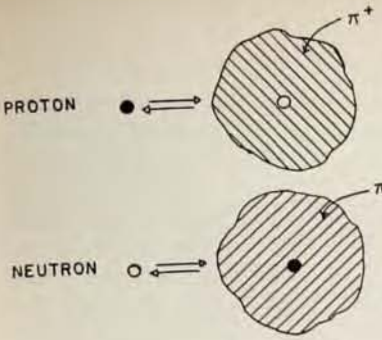


Fig. 2. Two of the various possible states of neutrons and protons. The "bare" proton is denoted by the filled circle and the "bare" neutron by the open circle.

r_0 in this region of atomic weights. Similar improvements in agreement with the results of the electron scattering experiments were reported by Breit and Brix, who discussed isotope shifts, Shacklett, who discussed x-ray fine structure, and Jaccarino, who reported on magnetic hyperfine splitting. These experiments are not easy to interpret but it is encouraging to note that as knowledge of the corrections that must be applied in interpreting the data is increasing, the results are tending to be in better and better agreement with electron scattering experiments. The subject of nuclear shapes was excellently reviewed by Temmer, who described the complementary nature of the experiments based on the effects of nuclear deformations on the electron cloud around the nucleus, and experiments which determine nuclear deformations by observing the effects they give rise to in the nucleus itself, e.g., the rotational spectra.

The major triumph, upset, or sensation (it depends on whether you are an experimentalist, theorist, or a newspaperman) of the electron scattering experiments is provided by the results for the proton and the neutron. Experiments done over a large range of energies and for a number of different angles of scattering lead Hofstadter and his co-workers (Yearian and Bumiller) to the conclusion that both the charge and the magnetic moment scattering of the electrons by protons is very different from what would be predicted on assuming that the proton is a point particle. Stated in the physicist's jargon, the *form factor* for both charge and magnetic moment scattering by a proton has a value different from unity (< 1). This implies that the proton charge and magnetic moment are both distributed over a finite volume. Hofstadter, in fact, finds the root-mean-square radii $r_{\text{charge}} = r_{\text{mag. mom.}} = 0.8$ fermi for the proton. Moreover, the magnetic moment distribution of the neutron is found to have the same radius. Since the net charge of a neutron is zero, the determination of the charge distribution of a neutron is much more difficult. However, whether it turns out to be concentrated positive in the center and diffuse negative on the outside, or identically zero everywhere, it poses problems. In order to appreciate this and the consequent distress of Goldberger, Chew, and other theorists present at the conference, let us look into what structure theory would expect protons and neutrons to have.

The suggestion of a structure of the nucleons comes directly from the fact that they have magnetic moments ($\mu_p = +2.79$ nm, $\mu_n = -1.91$ nm) which cannot be explained in terms of their over-all charge alone. The charge of the proton accounts only for one unit of its magnetic moment, so that we are left with an anomalous magnetic moment which is equal and opposite for the proton and the neutron ($\sim \pm 1.85$ nm). The explanation for this is traditionally given in terms of the weak coupling meson theory. Here one postulates that part of the time a physical nucleon is made of a "bare nucleon" core with a meson cloud enveloping it (Fig. 2). The nucleon core is by definition without extension, while the meson cloud has a finite size (of the order of $\hbar/\mu c = 1.4$ fermis). The motion of the charged meson cloud gives rise to the anomalous magnetic moments.

The electron-neutron interaction, which was discussed in detail by Foldy, provides the main principal evidence for the idea that the charge core of the neutron is almost a point. However, Hofstadter's experiments claim that the proton core is 0.8 fermi in radius. If there is a charge symmetry, the "bare neutron" should have the same extension also. This would mean that somehow the picture of nuclear structure drawn from the electron-neutron interaction experiments is fallacious. One hates to say so, because that is the picture the theory also predicts, and that is the picture which explains anomalous magnetic moments rather well. If, however, both Hofstadter's and the electron-neutron interaction experiments are being correctly interpreted, one would have to re-examine one of the long cherished ideas of physics, namely, charge symmetry. On the other hand there is always the possibility that we are not interpreting the electron scattering experiments correctly. The present interpretation, however, is based on the fundamentals of electrodynamics. A modification would have to be basic in nature, and rather sensational, like postulating that the electron has a finite size, or that electrodynamics breaks down at small distances (~ 1 fermi).

In this connection it was pointed out by Blokhintsev (USSR) that Tamm has recently postulated that one need not be so radical as to revise these basic concepts. If only one considers that the π-meson cloud around the core dissociates continuously into nucleon-antinucleon pairs, and the antinucleons annihilate with the bare nucleon in the center, then the net result is a core which is extended as far as the meson cloud (Fig. 3). This viewpoint would not require that there be a mirror symmetry between the charge distributions of the proton and the neutron and would therefore preserve the result of the electron-neutron interaction as well as electron scattering experiments.

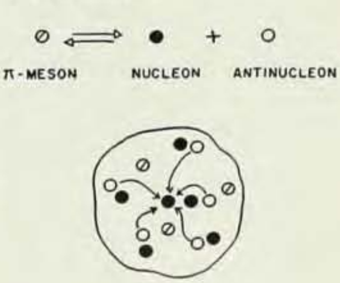


Fig. 3. Illustrating Tamm hypothesis: annihilation of antinucleon $\bar{N}$ (of each $N + \bar{N}$ pair produced) with the central "bare" nucleon is denoted by arrows, with distribution of bare nucleons left behind throughout the volume.

There are objections to this explanation and it appears that more elaborate and accurate experiments on the electron scattering by neutrons will have to be done in order to determine higher moments of the neutron's charge distribution. At the moment, a phenomenological model like Schiff's is the best one can do. As to the validity of the electrodynamics at small distances, Okun pointed out that it has been proposed by Pomeranchuk that scattering of polarized electrons from polarized protons be studied. This must be considered a rather distant prospect.

The theoretical aspects of nuclear matter, the surface, saturation, and compressibility problems were the subject of papers presented by Wilets, Brueckner, and Watson. Wilets reported on the phenomenological self-consistent statistical considerations developed by himself, Swiatecki, Brueckner, and others. According to this treatment there is a fundamental nonlinear relationship between nuclear matter density and the average potential to which it gives rise. This causes a relative extension of the potential distribution beyond the matter distribution, and, when the "finite range of nuclear force" effect is folded in, completely accounts for the difference between the potential radius ($r_1 = 1.25$ fermis) and charge radius ($r_1 = 1.07$ fermis). Since the nonlinearity does not exist for the potential as seen by a meson, this also explains the lower radius obtained by Cool ($r_1 = 1.14$ fermis). Wilets' theory also shows how coulomb repulsion, which tries to push protons on towards the nuclear surface, and the symmetry energy, which tries to push neutrons to the surface, balance each other, so that there is hardly any net excess of neutrons over the protons on the surface. This explains the experimental results for $r_n - r_p$ already mentioned. Brueckner and Watson took up the subject of nuclear saturation from the point of view of the many-body problem. The numerical results of these theories as applied to finite size nuclei are so far not available. Green discussed the information about nuclear structure that one obtains from the study of nuclear masses. His revised mass formula yields results in good agreement with electron scattering experiments and Wilets' theory.

THE conference concluded in a joint session with the American Physical Society, presided over by Dr. K. K. Darrow, in the music auditorium of Stanford University. A capacity crowd heard Bethe deliver the closing talk, a masterly summary of the deliberations of the conference—the excellence of which can be savored only by listening to him or reading the transcript which is to be published along with other contributions made at the conference in the *Reviews of Modern Physics*. (We wish to take this opportunity to thank Dr. E. U. Condon for this new trend in *RMP* which enables those who cannot attend such conferences to keep from falling behind the latest developments in physics.)

It is a pity that in any attempt at reporting on such a conference, one of the best parts invariably remains unreported. These are the discussions across the dinner table, in bathrooms and lounges, and in private sessions between little groups of two or three during coffee breaks. It is impossible to report on these because sometimes they consist of frank opinions and projected thoughts on which people would rather remain unquoted, and sometimes detailed discussions of minutiae, which are out of place in such a report. However, I feel that it would not be out of place if I took this opportunity of stating how stimulating and refreshing these personal contacts are.

It would be unjust if I gave an exclusively academic picture of the conference, for it had its social highlights too. The traditional banquet was held on the 17th at Rickey's Studio Inn, after a cocktail party. The banquet itself was much more relaxed and informal than any I have attended in a long time. Much of the credit for this must be given to the dozen foreign speakers who tried to outperform each other in saying thank you to America and thank you to Hofstadter and his colleagues. In his after-dinner talk, Condon reminisced aloud about the good old days of physics, when quantum mechanics was embryonic, and nuclear physics only a young upstart. The best physicists of today were only graduate students, or fresh PhD's, and tended to congregate at the universities of Munich and Göttingen. Condon gave a picturesque description of the plight of these young men (which included Condon, Bethe, Oppenheimer, Rabi, and others), as they labored to keep pace with physics which was entering the awkward age of adolescence, an age when it grew very fast, and was most difficult to understand. The uninhibited laughter which greeted Condon's jokes made one of the foreign physicists comment that he had "never seen physicists who looked and acted more unlike physicists than those present that evening!" On the 19th the Blochs, Chodorows, Schiffs, and Hofstadters said thank you to the participants of the conference by being hosts at another cocktail party at Hofstadter's home.

If you are impressed by statistics, here are some: Registration showed two hundred and thirty-seven physicists in attendance, but a conservative estimate of the over-all number is about four hundred. This included delegates from Australia, Canada, Denmark, England, France, Germany, Holland, Israel, Italy, Switzerland, and the USSR. (The Russian delegation was headed by Dr. D. I. Blokhintsev and comprised of Drs. D. I. Blokhintsev, V. P. Dzhelepov, S. Nikitin, and L. B. Okun.)

The delegates were lodged mostly in the Stern Hall Dormitory where the arrangements were perfect. The travel arrangements and other personal conveniences were expertly taken care of by the Physics Department, and tours of the high-energy and microwave laboratories were conducted a number of times.

After this conference it can hardly be said that "nuclear radius" is merely an operational definition. It is beginning to have a rather well-defined physical meaning now. The nucleons; well, they are still a different story.