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Scattering of α-Particles from Nuclei

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1. Introduction

In the history of modern physics one of the important developments was a paper published in 1911 by RUTHERFORD on *The Scattering of α- and β-Particles by Matter and the Structure of the Atom.* In this paper[1] the theory was proposed that the atom consists of «a central charge supposed concentrated at a point... surrounded by a compensating charge of electrons». More specifically, the assumption was that atoms consist of positive centers (nuclei) which contain most of the atomic mass and which have a radius of less than 3×10^{-12} cm, surrounded by a cloud of electrons of about 10^{-8} cm radius. The experiments which led RUTHERFORD to this conclusion were observations by GEIGER and MARSDEN that α-particles traversing matter are occasionally deflected ('scattered') by very large angles. These large deflections occurred too frequently to be explained as the accidental cumulative effect of many small scatterings. According to RUTHERFORD's theory α-particles are deflected by a large angle in a single collision with an atom. The source of the large force which is necessary to scatter a fast-moving α-particle was seen in the very strong electric field near the nucleus.

Assuming that the force between an α-particle and a nucleus follows Coulomb's law of electrostatic repulsion, RUTHERFORD predicted quantitatively how the number of α-particles scattered from a thin foil should depend on the atomic weight of the foil material, on the angle of scattering and on the kinetic energy of the α-particles. GEIGER and MARSDEN[2] verified these predictions for a number of foils ranging in atomic weight from that of carbon to that of gold. Their experimental arrangement is shown in Figure 1. α-particles from a radioactive source (about 100 millicuries of radium emanation) were collimated by a slit such as to produce an approximately parallel beam of particles. Foils about 0·0001 cm thick were placed in the beam. The scattered particles were counted by visual observation of the scintillations produced by the particles as they hit a small screen of ZnS-powder. The ZnS-screen and the microscope could be rotated with respect to the foil and the source to allow measurements for different scattering angles Φ. The equipment was contained in an evacuated box.

The following discussion will deal with the scattering of α-particles from nuclei. These experiments may be regarded as an extension of the work of GEIGER and MARSDEN. The principle is the same, i.e., from the deflection which α-particles undergo one draws conclusions about the force which must have acted on the particle along its path. The term «nuclear scattering» refers to a situation where during part of its path the particle gets in contact with the nucleus. This requires that the particles have sufficiently high velocity to overcome the Coulomb-repulsion of the nuclear electric field. Over the past decade many experiments of this type have been performed. Basically, the experimental arrangement of Figure 1 is still being used, except that accelerators have replaced the radioactive sources and highspeed electronic circuits are used to count the number of scattered particles. The development of modern accelerators has made it possible to use intense, well-collimated beams of protons, deuterons, α-particles and heavier ions (lithium, carbon, oxygen, etc.). Ideally the accelerator is such that the energy of the particles is sharply defined and can be varied over a wide range.

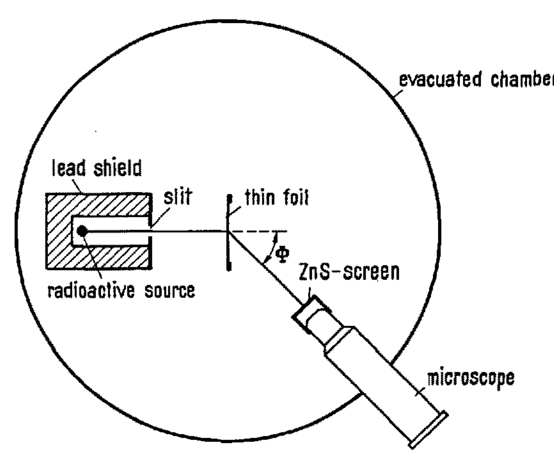

Fig. 1: Schematic diagram of the experimental arrangement used by GEIGER and MARSDEN to investigate the scattering of α-particles from thin foils

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[1] E. RUTHERFORD, Phil. Mag. *21*, 669 (1911).

[2] H. GEIGER and E. MARSDEN, Phil. Mag. *25*, 604 (1913).

Scattering experiments have been used to a large extent to investigate the force acting on a particle inside the nucleus. Perhaps the most important conclusion is that the problem is a complicated one. There is no simple force law which describes all experiments. Until now the most successful approach has been to group the experiments into certain classes and to try to invent for each class a semi-empirical theory which describes the results. In the following the scattering of α-particles from heavy nuclei and the scattering of α-particles from very light nuclei will be used as illustrations.

2. *Scattering of α-Particles from Heavy Nuclei*

To be specific in discussing the scattering of α-particles from heavy nuclei consider the case of scattering from gold. Figure 2 shows examples of trajectories which α-particles of 10 MeV energy[3] are expected to follow when they pass near a gold nucleus. The drawing is to scale. Note that on the scale of Figure 2 the next closet gold nucleus is very far away. The paths were computed on the assumption that the force between α-particle and nucleus follows Coulomb's law of electrostatic repulsion at each point along the trajectory ('Coulomb Scattering'). The computation of the trajectories is contained in the paper by RUTHERFORD quoted above. The figure shows that for large 'impact parameter' p the deflection Φ is small (trajectory 1). For smaller impact parameters the particle gets closer to the nucleus and is subject to a stronger electrostatic force which in turn causes a larger deflection (trajectories 2 and 3). Many particles are deflected by small angles, few by large angles because large impact parameters are more likely to occur than small ones. That large impact parameters are more likely than small ones simply expresses the commonly known fact that if one blindly shoots at a small object one is more likely to miss than to hit. RUTHERFORD treated the problem quantitatively and found that the scattering cross section[4] is proportional to $1/\sin^4(\Phi/2)$.

The dependence of the scattering on the energy of the incoming particles can be predicted in a similar way. Assume that only those particles are counted which are scattered through a given angle, for instance $\Phi = 60°$. Figure 3 shows trajectories for particles of different energy E. The impact parameter which is necessary for scattering through a fixed angle decreases with increasing particle-energy. Consequently the scattering cross section decreases with increasing energy. Calculation shows that the cross section is proportional to $1/E^2$.

For each trajectory one can define a 'distance of closest approach' d. With reference to Figure 3 the term is selfexplanatory. At a certain critical energy the distance of closest approach is equal to the sum $R_\alpha + R_{Au}$ of the radii of α-particle and gold nucleus. According to Figure 3 the critical energy is about 30 MeV. The value of course depends on the element being bombarded and on the angle of observation. Above the critical energy the particles will be affected by nuclear forces in addition to Coulomb forces.

Figure 4 shows the observed number of α-particles scattered by gold through $\Phi = 60°$ plotted as a function of the energy of incident α-particles between 13 and 36 MeV[5]. For low energies the points agree well with Coulomb scattering (solid line). The break at 27 MeV coincides closely with the critical energy. Above the critical energy the observed number of particles drops rapidly below that expected for Coulomb scattering. At 36 MeV the observed scattering is ten times smaller than the scattering one would expect if the nucleus were a point-charge.

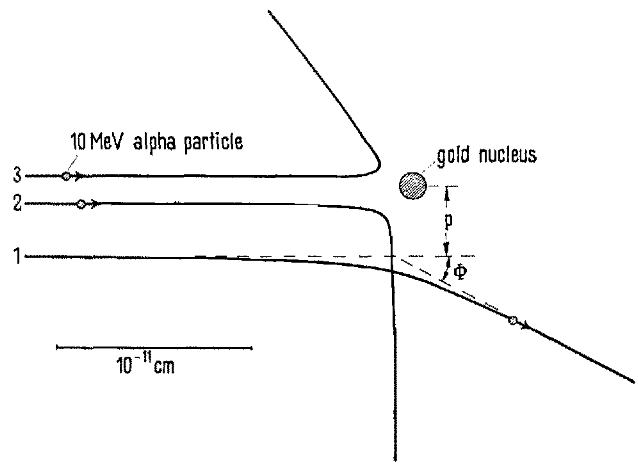

Fig. 2: Deflection of 10-MeV α-particles by the Coulomb field of the gold nucleus. For trajectory 1 the impact parameter p and the scattering angle Φ is indicated. The recoil of the gold nucleus is neglected, i.e., the nucleus is assumed to remain stationary

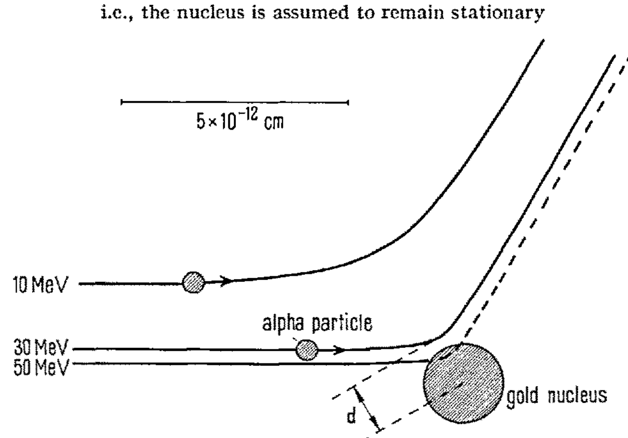

Fig. 3: α-particle trajectories of a fixed scattering angle $\Phi = 60°$. For each trajectory the energy of the α-particle is given. The distance of closest approach d is indicated for one trajectory only

[3] The kinetic energy $E = m v^2/2$ of particles is generally measured in MeV (million electron-volt). 1 MeV $= 1{\cdot}6 \cdot 10^{-13}$ joule $= 1{\cdot}6 \cdot 10^{-14}$ mkg*. The velocity of a 10 MeV α-particle is $2{\cdot}2 \cdot 10^7$ m/s.

[4] The term 'scattering cross section' is used for the number of scattered particles when foil thickness, detector size and number of incident α-particles are all normalized to unity.

[5] G. W. FARWELL and H. E. WEGNER, Phys. Rev. *93*, 356 (1954).

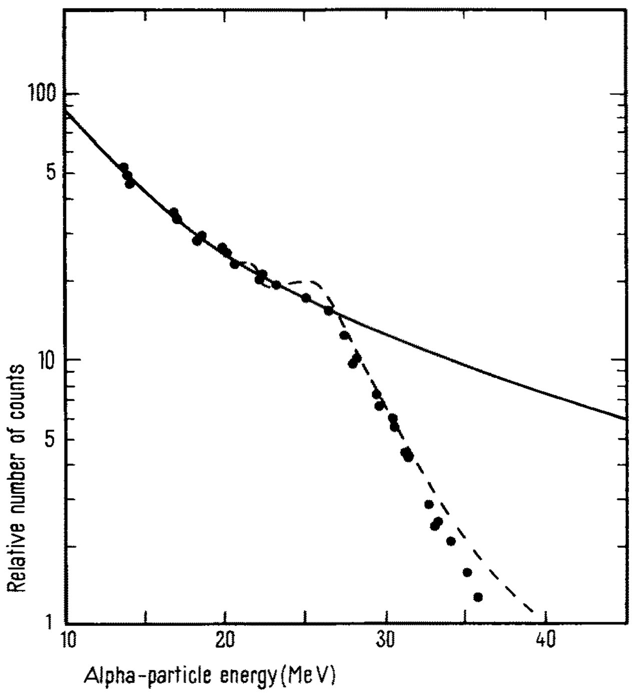

Fig. 4: The number of α-particles scattered by $\Phi = 60°$ from a gold foil is plotted as a function of the energy of the particles incident on the foil. The solid curve corresponds to Coulomb scattering from a point charge. The dotted curve was calculated assuming strong absorption of the α-particles by the nucleus. The measurements are by Farwell and Wegner[5], the calculations by Blair[6]

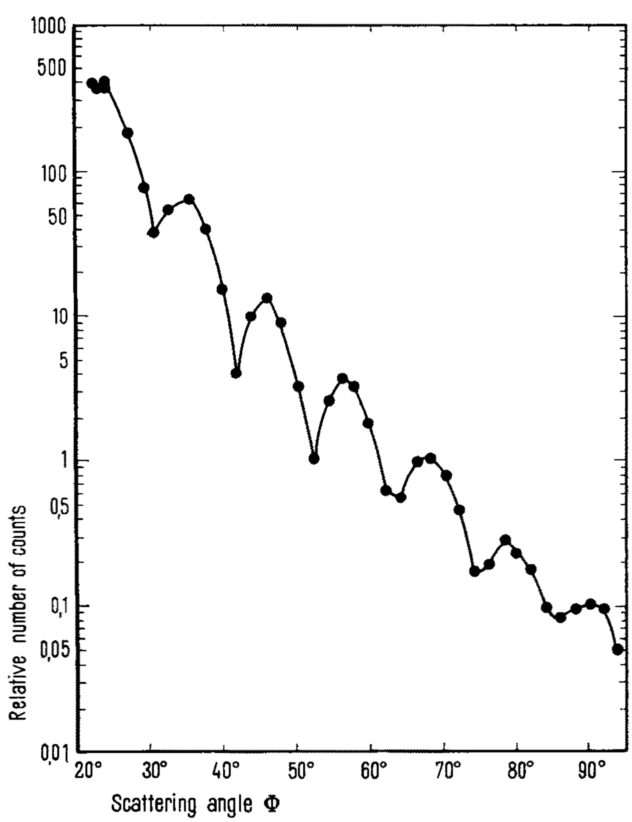

Fig. 5: The relative number of 40-MeV α-particles scattered from copper is plotted as a function of the scattering angle Φ. The measurements are by Igo *et al.*[7]. The solid line is a smooth curve drawn through the measured points

The rapid decrease of the number of scattered particles suggests that α-particles are absorbed by the nucleus. In the extreme case of the 'black nucleus model' the α-particle is assumed to be completely absorbed or broken up as soon as it gets in contact with the nucleus. If this assumption were correct one should presumably find that at the critical energy the number of scattered particles abruptly falls to zero. While this does not agree with observation, an important point was omitted in the preceding discussion. According to the theory of wave mechanics a particle of mass m moving with velocity v is to be considered a wave of wavelength $\lambda = h/mv$, where h is Planck's constant. From the study of optical phenomena it is known that geometrical optics fails when the object is small, i.e., comparable or smaller than the wavelength of light. Similarly the consideration of particle trajectories fails here, since a gold nucleus of about 9×10^{-13} cm radius is being 'looked at' with α-particles of wavelength 3×10^{-13} cm. Consequently one can understand that the drop at the critical energy is not sharp but instead smeared out over a certain energy range, much in the same way as shadows of small objects are unsharp. The dashed line of Figure 4 is the result of a calculation[6] which takes into account the wave-nature of the problem. The agreement with experiment is satisfactory. The radii of α-particle and gold nucleus which were assumed in the calculation ($R_\alpha + R_{Au} = 10{\cdot}6 \times 10^{-13}$ cm) agrees well with what is known about nuclear radii from other experiments.

Figure 5 shows how the number of scattered particles depends on scattering angle for 40 MeV α-particles scattered from copper[7]. The curve which the measured points follow is strongly reminiscent of a diffraction pattern. A quantitative comparison between these results and the 'black-nucleus model' requires the use of the mathematical methods of quantum mechanics. The calculation produces diffraction peaks at the correct angles, but their amplitude is in contradiction to the experiment. Good agreement is found, however, if the black nucleus model is modified in two ways: (i) the α-particle can travel some distance inside the nucleus before it gets absorbed, and (ii) the α-particle is subject to an attractive nuclear force when it is near the nuclear surface. The second condition causes the α-particle wavelength to become shorter as it penetrates the nuclear surface, while the first condition results in an attenuation of the wave inside nuclear matter. In the terminology of optics the α-particle wave encounters the nucleus as a ball of refractive and absorptive material. This nuclear model is frequently called the 'optical model' of the nucleus.

[6] J. S. Blair, Phys. Rev. *95*, 1218 (1954).

[7] G. Igo, H. E. Wegner and R. M. Eisberg, Phys. Rev. *101*, 1508 (1956).

The optical model has been fruitful also in describing the scattering of neutrons, protons and deuterons from nuclei. To obtain reasonable agreement with experiment, the parameters (i.e., index of refraction and transparency) must be adjusted empirically. One finds that the parameters depend on the type of projectile and to a lesser degree on their energy. The optical model is presented here only in its simplest form. One modification which has been found to be necessary is to assume that the nuclear surface is somewhat diffuse, i.e., that the index of refraction changes continuously on the nuclear surface rather than in a stepwise fashion.

3. Scattering from Light Nuclei

If very light nuclei are bombarded with particle beams of 1 to 10 MeV energy, phenomena quite different from those described in the preceding section are observed. Instead of the smooth variation exhibited in Figure 4 the number of scattered particles shows large fluctuations, called 'resonance', as the bombarding energy is varied. The term 'resonance' probably is most commonly associated with acoustics, but the phenomenon accurs quite generally in systems which can undergo oscillations. A tuning fork placed in the vicinity of a source of sound oscillates strongly when the frequency of the source is identical – or very close – to the characteristic frequency of the fork. More precisely, if the amplitude of oscillation of the tuning fork is plotted as a function of the source-frequency, one finds a narrow peak – a 'resonance' – at the characteristic frequency and possibly additional smaller peaks at multiples of the characteristic frequency (higher harmonics). With devices other than a simple tuning fork, like a taut rubber membrane or a volume of air enclosed in walls, a large number of resonances may be observed. The resonances are not necessarily sharp. The larger the damping (friction) of the oscillating system the broader the resonance peaks.

The resonance behavior of scattering cross sections is demonstrated by Figure 6, which shows the number of α-particles scattered from carbon as a function of bombarding energy for five different scattering angles[8]. Among others there occurs a resonance at 4.3 MeV. Its half-width is about 0.04 MeV. It is apparent that the resonance is superimposed on a background. The background changes slowly with energy and is caused by the tails of other, broad resonances and by Coulomb scattering. The shapes of the resonances can be explained as being caused by interference between resonance- and background-scattering. The interference can be constructive or destructive depending on the phase-relation between resonance- and background-scattering. Typically a resonance observed at a fixed angle shows both constructive and destructive interference (see Figure 6; 4.3 MeV resonance at 90°, 140.8°, 147.9°) because as the energy is varied over the resonance the phase-shift between resonance- and background-scattering changes.

Other resonances are apparent at 5.8 and 7.0 MeV. To explain the measurements one must in addition assume a very broad resonance (1.6 MeV wide) at 6 MeV. The significance of these resonances is that each indicates a mode of oscillation or an 'excited state' of the nucleus O^{16}, which is the nucleus obtained by combining C^{12} with an α-particle. The energy of a particular mode of oscillation is found from the kinetic energy of the α-particle for which resonance occurs. The width ΔE of a resonance is associated with the lifetime τ of the excited state by $\Delta E \cdot \tau \sim h/2\pi$, where h is Planck's constant. The lifetime (i.e., the time during which the O^{16} nucleus exists in a given mode of oscillation before again breaking up into a C^{12} nucleus and an α-particle) is generally very short, being about 10^{-20} s for the resonance at 4.3 MeV.

Another quantity which may be deduced from the measurements is the angular momentum of the excited states of O^{16}. Classically, the angular momentum is given by the product of the momentum mv of the relative motion of α-particle and C^{12} nucleus times the impact parameter p. According to quantum mechanics, the angular momentum has to be a multiple of $h/2\pi$

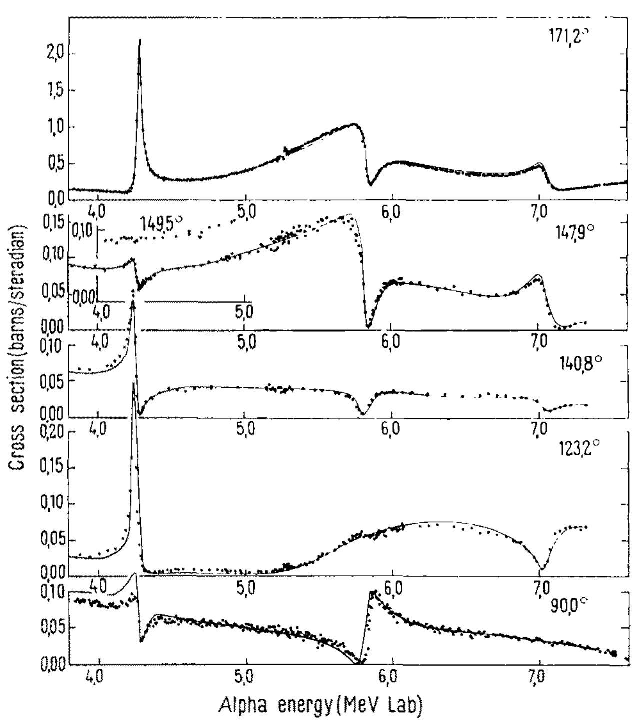

Fig. 6: The number of α-particles scattered from C^{12} is shown as a function of energy for five different scattering angles. The solid line represents calculated cross sections. The measurements are by Bittner and Moffat[8]

[8] J. W. Bittner and R. D. Moffat, Phys. Rev. *96*, 374 (1954).

where h is Planck's constant. Each resonance is characterized by one value of angular momentum. If the angular momentum is an odd multiple of $h/2\pi$, the application of quantum mechanics to the problem predicts that the resonance should be unobserved for a scattering angle of 90°. This is clearly the case for the resonance at 7.0 MeV. For each value of the angular momentum (except $J = 0$) there is a predictable scattering angle (or a set of angles) for which the resonance should not be observed. For instance the fact that the resonance at 4.3 MeV is not observed for a scattering angle of 149.5° labels it as a resonance of angular momentum $4 \cdot (h/2\pi)$. Once the angular momenta of the resonances are known, the resonance shapes and amplitudes at all other scattering angles is predictable. The solid line of Figure 6 shows that the predicted scattering agrees well with the measurements.

From experiments of this type one now has a large amount of information on the position, the lifetime and the angular momentum of excited states of nuclear. There remains the problem of explaining why the excited states of nuclei occur where they do. The treatment of this problem has met so far only with very limited success.

Zusammenfassung

Nach einem Überblick über die RUTHERFORDsche Theorie der Ablenkung von α-Teilchen im elektrostatischen Feld des Atomkernes wird auf kürzliche Streuexperimente hingewiesen. Die Streuung von α-Teilchen an schweren Kernen ist einem optischen Beugungsphänomen ähnlich. Resonanzen wie sie in der Streuung an leichten Kernen beobachtet werden, sind akustischen Resonanzen vergleichbar.

Hochenergiephysik

Von P. PREISWERK*

Einleitung

Kurz vor der letzten Jahrhundertwende wurde das erste Elementarteilchen, das Elektron entdeckt. Heute ist die Zahl der bekannten und vermuteten Elementarteilchen auf 32 angestiegen. Wesentlich für deren Entdeckung war die Entwicklung der Experimentiertechnik, die Instrumente geschaffen hat, die gestatten Elementarprozesse, Zusammenstösse zwischen Elementarteilchen und Zerfallsprozesse einzeln zu registrieren, zu beobachten und im Experiment zu untersuchen. Neben dem Auffinden dieser Teilchen selbst ist die Beobachtung, dass im Stoss zweier Teilchen neue entstehen können, dass die Elementarteilchen selbst umwandelbar sind, eine der fundamentalen Entdeckungen unseres Jahrhunderts.

Die Schwelle der Erzeugung von Teilchen ist durch die Ruhmasse der Teilchen bestimmt. Viele dieser Teilchen und Prozesse treten deshalb erst in Erscheinung, wenn die Stossenergie sehr hoch ist; auf hohe Stossenergien sind die Physiker bei der Untersuchung der kosmischen Strahlung gestossen.

Kosmische Strahlung

So kann man den Beginn der Geschichte der Hochenergiephysik willkürlich mit der Entdeckung der kosmischen Strahlung, die vor einem halben Jahrhundert gemacht worden war, gleichsetzen. VICTOR HESS schloss aus Beobachtungen der Ionen in der Luft, in verschiedenen Höhen über dem Erdboden, dass aus dem Weltraum eine ionisierende Strahlung in die Erdatmosphäre eindringe. Es dauerte Jahre ehe die Natur dieser Primärstrahlung, die wie wir heute wissen, vorwiegend aus energiereichen Protonen besteht, eindeutig erkannt worden war, da sie sich als von der komplexen, in der Atmosphäre erzeugten Sekundärstrahlung verdeckt erwies.

In dieser Sekundärstrahlung wurde erstmals das Positron beobachtet, ebenso die Mesonen – die leichten Muonen, die geladenen Pionen, die schweren K-Mesonen – und fast alle heute bekannten Hyperonen. Beobachtet wurden Entstehungs- und Zerfallsprozesse. Das Positron und der Materieerzeugungsprozess des Elektron-Positron-Paares war in der relativistischen Quantumtheorie DIRACS enthalten. Die Mesonen hatte YOUKAWA – vor ihrer Entdeckung – als die schweren Quanten des Kernfeldes zur Deutung der Kernkräfte erfunden. Die ersten entdeckten Mesonen, die Muonen, hatten allerdings keineswegs die von YOUKAWA erwarteten Eigenschaften; sie sind dem Elektron viel ähnlicher. K-Mesonen und Hyperonen zeigten Eigenschaften die zu der Bezeichnung «fremdartiger Teilchen» führte, einem Namen, der ihnen auch heute noch anhaftet. In einer ersten Periode der neuen Forschungsrichtung, der «heroischen», stiegen die Physiker mit ihren Messapparaten auf hohe Berge um «näher an die Primärstrahlung zu kommen», sie begaben sich in Tunnels, um die Absorption durchdringender Komponenten zu studieren, fuhren auf Schiffen, um die geographische Intensitätsverteilung zu registrieren und führten Dauermessungen, um Korrelationen mit der Sonnen- und Sternzeit festzustellen, die Herkunft der Strahlen zu eruieren.

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