Chadwick and the Discovery of the Neutron

FEATURE

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INTRODUCTION

February 2007 marks the 75th anniversary of James Chadwick's discovery of the neutron at the Cavendish Laboratory of Cambridge University. That discovery was a critical turning point in the development of nuclear physics and would affect the history of the last half of the twentieth century in ways Chadwick could not have imagined at the time. Just over two years later Enrico Fermi would artificially induce radioactivity by neutron bombardment, work which would lead to the discovery of neutron moderation and the development of nuclear reactors. Within seven years of Chadwick's discovery Hahn and Strassmann would discover neutron-induced uranium fission. It has rightly been said that there are two eras in the history of nuclear physics: that before the discovery of the neutron and that following.

It seems appropriate to honor this anniversary by reviewing the experiments and analysis that lead Chadwick to his discovery. The relevant physics involves no more than classical and special-relativistic energy and momentum conservation concepts well within the grasp of a sophomore-level student who has completed a standard "Modern Physics" course. This story not only illustrates how basic physical concepts underlay an important discovery but also how some of the leading nuclear researchers of the time put forth breathtakingly incorrect interpretations of their own experiments before the truth was finally sorted out.

This article is divided into three sections. First, the relevant experiments and how they were initially interpreted is described. Second, the physics of the experiments is set up and analyzed. Then we follow the steps of Chadwick's analysis as he showed how the initial interpretation was both inconsistent with the experimental evidence and incompatible with the conservation laws, following which he put forth a new hypothesis—the existence of the neutron - that fit the facts.

Chadwick's analysis appeared in two papers. The first, titled "Possible Existence of a Neutron," is a brief (just over half a printed page) paper dated February 17, 1932, and published in the February 27 edition of *Nature* [1]. A more extensive follow-up paper dated May 10, 1932, was published in the June 1 edition of *Proceedings of the Royal Society of London* [2]. The *Nature* paper is reproduced in Andrew Brown's excellent biography of Chadwick [3]; if your school library subscribes to the JSTOR journal retrieval system the *Proceedings* paper can be downloaded at no cost. As we work through Chadwick's analysis these will be referred to as Papers 1 and 2, respectively.

THE EXPERIMENTS: BERYLLIUM, GAMMA-RAYS, AND PROTONS

A complete description of the experiments which resulted in the discovery of the neutron would be quite extensive, so only a brief description of the essentials is given here. A more thorough discussion appears in Chapter 6 of reference [3]; see also chapter 6 of Richard Rhodes' *The Making of the Atomic Bomb* [4].

The experiments which lead to the discovery of the neutron were first reported in 1930 by Walther Bothe and his student Herbert Becker, working in Germany. Their research involved studying gamma radiation which is produced when light elements such as magnesium and aluminum are bombarded by energetic alpha-particles emitted in the radioactive decay of elements such as radium or polonium. In such reactions, the alpha particles often interact with a target nucleus to yield a proton (hydrogen nucleus) and a gamma-ray, both of which can be detected in Geiger counters. A good example of such a reaction is the one used by Chadwick's mentor, Ernest Rutherford, to produce the first artificially-induced nuclear transmutation in 1919. Rutherford used alpha-particles emitted in the natural decay of radium to bombard nitrogen atoms, inducing the reaction

$$ {}^{4}_{2}\mathrm{He} + {}^{14}_{7}\mathrm{N} \rightarrow {}^{1}_{1}\mathrm{H} + {}^{17}_{8}\mathrm{O} + \gamma \,. \qquad (1)$$

The mystery began when Bothe and Becker found that boron, lithium, and particularly beryllium gave evidence of gamma emission under alpha bombardment *but with no accompanying protons being emitted*. A key point here is that they were certain that some sort of energetic but electrically neutral "penetrating beryllium radiation" was being emitted: it could penetrate foils of metal (even inches of lead) but could not be deflected by a magnetic field as electrically charged particles would be. Gamma rays—that is, high-energy photons—were the only electrically neutral form of penetrating radiation known at the time, so it would have seemed natural to interpret their results as evidence of gamma-ray emission despite the anomalous lack of protons.

Bothe & Becker's unusual beryllium result was picked up by the Paris-based husband-and-wife team of Frédéric Joliot and Irène Curie, hereafter referred to as the Joliot-Curies. In January 1932, they reported that the (presumed gamma-ray) beryllium radiation was capable of knocking protons out of a layer of paraffin wax that had been put in its path. The situation is shown schematically in Figure 1, where the supposed gamma-rays are

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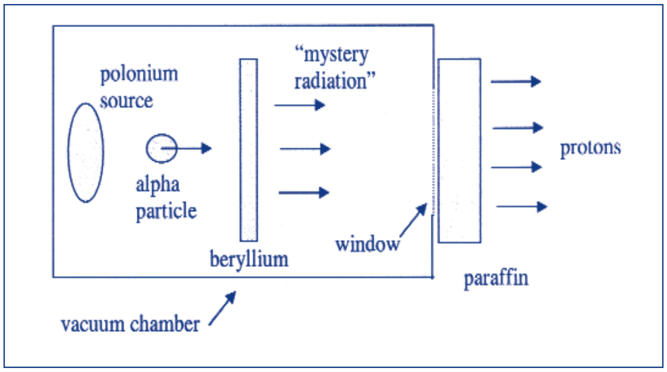

Figure 1
The "beryllium radiation" experiment of Becker, Bothe, the Joliot-Curies and Chadwick.

labeled as "mystery radiation." The energy (hence speed) of the protons could be deduced by such means as determining what thickness of metal foil they could penetrate before being slowed down or by measuring how many ion pairs they created in a Geiger counter; such measurements were well-calibrated by this time. In comparison to the gargantuan particle accelerators of today these experiments were literally "table-top" nuclear physics: in his recreation of the Joliot-Curies' work, Chadwick's experimental setup involved polonium deposited on a silver disk 1 cm in diameter placed close to a disk of pure beryllium 2 cm in diameter, with both enclosed in a small vessel which could be evacuated (a photograph appears in reference [3]).

In reactions like that appearing in equation (1) the sum of the masses of the products on the output (right) side of the arrow is often less than that of the input reactants on the left side, with the difference appearing in the form of kinetic energy of the products via $E = mc^2$. Such energies, known as "Q-values," are usually of the order of a few millions of electron-volts (MeV) and can be written on the output side of the reaction equation. For example, the alpha-producing polonium decay in Figure 1 can be written

$$ {}^{210}_{84}\text{Po} \rightarrow {}^{206}_{82}\text{Pb} + {}^{4}_{2}\text{He} + 5.41 \text{ MeV}, \quad (2)$$

that is, this spontaneous decay liberates 5.41 MeV of energy to be shared between the product lead and alpha nuclei. While this is a lot of energy, the masses of the products involved in such reactions are typically such that their speeds are non-relativistic; we can usually write their kinetic energies and momenta classically as $mv^2/2$ and mv. Even if mass is created or lost in a reaction momentum must always be conserved; if the polonium nucleus is initially stationary then the lead and alpha nuclei must recoil in opposite directions. One can easily show from classical momentum conservation that if the total kinetic energy of the two product nuclei is Q, then the kinetic energy of the lighter product nucleus must be

$$K_m = Q/(1 + m/M) \quad (3)$$

where m and M are respectively the masses of the light and heavy product nuclei. For lead and alpha nuclei $m/M \sim 4/206$, so the alpha-particle carries off the lion's share (about 5.3 MeV) of the liberated energy. The speed of such an alpha-particle is about 0.05c, justifying the non-relativistic assumption.

The Physics

We now set up some expressions that will be useful for dissecting Chadwick's neutron discovery analysis.

First, let us assume that Bothe & Becker and the Joliot-Curies were correct in their interpretation that α-bombardment of Be creates gamma-rays. To conserve the number of protons involved, they hypothesized that the relevant reaction is

$$ {}^{4}_{2}\text{He} + {}^{9}_{4}\text{Be} \rightarrow {}^{13}_{6}\text{C} + \gamma . \quad (4)$$

Strictly speaking, we are cheating here in writing the reaction in modern notation that presumes knowledge of both neutrons and protons, but this has no effect on the argument. Now, it happens that this reaction has a Q-value of 10.65 MeV; this energy when added to the ~ 5.3 MeV kinetic energy of the incoming alpha means that the γ-ray can have an energy of at most about 16 MeV. More precisely, the energy of the gamma-ray works out to about 14.6 MeV if the recoil motion of the carbon nucleus is accounted for. The gamma-rays then strike protons, setting them in motion. See Figure 2. Such a collision is a problem that requires both relativistic and classical dynamics: a γ-ray is relativistic, whereas the protons can be treated classically (this is justified under "Analysis" below.)

Suppose the gamma-ray strikes an initially stationary particle of mass m. In what follows, the symbol E_m is used to represent the Einsteinian rest energy mc^2 of the struck particle while K_m is used to designate its classical kinetic energy $mv^2/2$; E_γ is used to designate the energy of the gamma-ray. Maximum possible forward momentum will be imparted to the struck particle if the gamma-ray recoils backwards after the collision; we assume that this is the case. If the energy of the gamma-ray after the collision is E_γ*, then conservation of relativistic mass-energy demands

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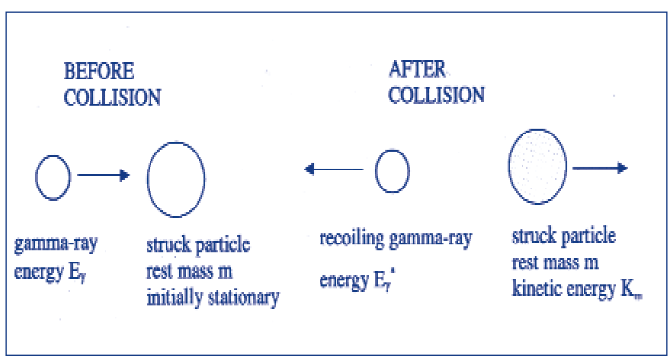

Figure 2
A gamma-ray strikes a stationary massive particle, setting it in motion. The gamma-ray is assumed to recoil backwards.

$$E_\gamma + E_m = E_\gamma^* + E_m + K_m \ . \quad (5)$$

In writing Equation (5) we are assuming that the struck particle does not change its identity, so the E_m terms can in fact be cancelled. Since the momentum of a photon of energy E is given by E/c, conservation of momentum for this collision can be written as

$$E_\gamma/c = -E_\gamma^*/c + mv \ , \quad (6)$$

where v is the post-collision speed of the struck particle. The negative sign on the right side of equation (6) means that the γ-ray recoils backwards. It will prove handy to also have on hand expressions for the classical momentum and kinetic energy of the struck particle in terms of its rest energy:

$$mv = \sqrt{(2mK_m)} = \sqrt{(2mc^2K_m)}/c = \sqrt{(2E_mK_m)}/c \quad (7)$$

and

$$K_m = 1/2\ mv^2 = ((mc^2)v^2)/2c^2 = 1/2\ E_m\ (v/c)^2 \ . \quad (8)$$

With equation (7) a factor of "c" can be cancelled in equation (6); then, on eliminating E_γ^* between equations (5) and (6) we can solve for E_γ:

$$E_\gamma = 1/2\ [(K_m + \sqrt{(2E_mK_m)})] \ . \quad (9)$$

If the kinetic energy of the struck particle (proton) can be measured, we can use equation (9) to figure out what energy the gamma-ray must have had to set it into such motion. On the other hand, if we desire to solve for K_m presuming that E_γ is known the situation is slightly messier as equations (5) and (6) combine to give a quadratic in $\sqrt{(K_m)}$ that has no neat solution. But if we assume that the rest energy E_m of the struck particle is large compared to E_γ the resulting quadratic can be solved approximately as [5]

$$K_m \sim (2E_\gamma^2)/E_m\ [1 - (2E_\gamma)/E_m + \dots\ ] \ . \quad (10)$$

This approximation is quite reasonable: the gamma-rays have $E_\gamma \sim 14.6$ MeV (see following Equation 4) while a proton has a rest energy of about 938 MeV.

Chadwick's analysis also involves examining the possibility that instead of a gamma-ray being created in the α-Be collision a neutral material particle of mass μ is created (the neutron!) which subsequently collides with an initially stationary particle of mass m as illustrated in Figure 3. This collision can be analyzed with the familiar head-on elastic-collision formulae of freshman-level physics; if the neutron has speed v_μ and kinetic energy K_μ, then the post-collision speed and kinetic energy of the struck mass will be

$$v_m = [2\mu/(\mu + m)\ v_\mu\ ] \text{ and } K_m = [4\mu m/(m+\mu)^2]\ K_\mu \ . \quad (11)$$

The Analysis

Upon reading the Joliot-Curies' paper, Chadwick immediately plunged into an intense three-week period of work during February 1932 to reproduce, extend, and finally radically reinterpret their findings. With the expressions developed in the preceding section we are ready to follow the steps of his analysis.

Upon reproducing the experiments Chadwick found that the protons emerge from the paraffin with speeds of up to about 3.3 x 10^7 m/s [Paper 2, page 695; quoted in Paper 1 as 3.2 x 10^7 m/sec]. This corresponds to (v/c) = 0.11, so our assumption that the protons can be treated classically is reasonable. The modern value for the rest mass of a proton is 938.27 MeV. From equation (8) these figures give the kinetic energy of the ejected protons as 5.7 MeV, exactly the value quoted by Chadwick on p. 695 of Paper 2. Equation (9) then tells us that if a proton is to acquire this amount of kinetic energy by being struck by a gamma-ray, then the gamma-ray must have an energy of about 54.4 MeV [Chadwick quotes 52 MeV in Paper 1 and 55 MeV on p. 696 of Paper 2.] *But we saw just after Equation (4) that a gamma-ray arising from the Joliot-Curie's proposed* $\alpha + Be \rightarrow {}^{13}C$ *reaction has an energy of only about 14.6 MeV—a factor of nearly four too small! This is the first difficulty with the gamma-ray proposal.*

To be historically correct, the mass of beryllium atoms had not yet been accurately established in 1932, so Chadwick did not know the 14.6 MeV figure for certain. However, he was able to sensibly estimate it as no more than about 14 MeV unless the beryllium nucleus lost an unexpectedly great amount of mass in the reaction, so, as he remarks in Paper 2 (p. 693), "... is difficult to account for the production of a quantum of 50 MeV from the interaction of a beryllium nucleus and an α-particle of kinetic energy of 5 MeV." But Chadwick was not satisfied with only this argument: he was a careful, meticulous experimenter, and so devised a further test to investigate the remote possibility that 55-MeV gamma-rays might somehow be being created in the α-Be collision. In addition to having the "beryllium radiation" strike protons, he also directed it to strike a sample of nitrogen gas. The mass of a nitrogen nucleus is about 14 mass units; at a conversion factor of 931.49 MeV per mass unit the rest energy of a ^{14}N nucleus is about 13,040 MeV. If such a nucleus is struck

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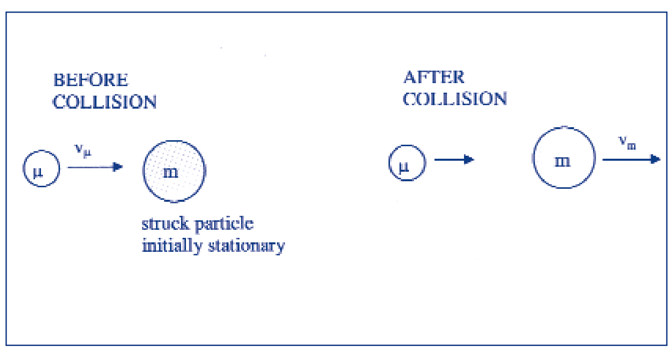

Figure 3
A particle of mass μ strikes a stationary particle of mass m, setting it in motion with speed v_m.

by a 54.4-MeV gamma-ray, Equation (10) indicates that it should acquire a kinetic energy of about 450 keV. From prior experience [Paper 2, p. 696] Chadwick knew that when an energetic particle travels through air it produces ions, with about 35 eV required to produce a single ionization (hence yielding "one pair" of ions). A 450 keV nitrogen nucleus should thus generate some 13,000 ion pairs. Upon performing this experiment, however, he found that some 30,000 to 40,000 ion pairs would typically be produced. These figures imply a kinetic energy of ~ 1.1 – 1.4 MeV for the recoiling nitrogen nuclei, which in turn (equation 10) would require gamma-rays of energy up to ~ 90 MeV, *completely inconsistent with the ~ 55 MeV indicated by the proton experiment.* Indeed, upon letting the supposed gamma-rays strike heavier and heavier target nuclei, Chadwick found that "... if the recoil atoms are to be explained by collision with a quantum, we must assume a larger and larger energy for the quantum as the mass of the struck atom increases." The absurdity of this situation is the second problem with the gamma-ray hypothesis, and led him to write [Paper 2, p. 697] that, "It is evident that we must either relinquish the application of conservation of energy and momentum in these collisions or adopt another hypothesis about the nature of the radiation." One cannot but stand in awe of what Hans Bethe has described as a beautiful example of systematic experimentation [6] as well as smile inwardly at the dry British understatement with which Chadwick demolished the gamma-ray hypothesis.

The fundamental problem with the gamma-ray hypothesis is that for the amount of energy liberated in the α-Be reaction any resulting gamma-ray will possess much less momentum than a classical particle of the same kinetic energy; the ratio is $p_\gamma/p_m = \sqrt{(E/2E_m)}$ where E is the energy involved and E_m the rest energy of the massive particle. Only an incredibly energetic gamma-ray could kick a proton to a kinetic energy of several MeV. *Chadwick's key insight was to realize that if the protons were in reality being struck billiard-ball style by neutral material particles of mass equal or closely similar to themselves then the striking energy need only be on the order of the kinetic energy that the protons acquired in the collision.* In a later recollection (ref. [3], p.104) Chadwick remarked that when he informed Rutherford of the Joliot-Curie's gamma-ray interpretation, he (Rutherford) had exclaimed, "I don't believe it."

This is the point at which the neutron makes it's debut. Chadwick hypothesized that instead of the Joliot-Curie reaction (4), the α-Be collision leads to the production of a carbon-12 atom and a neutron via the reaction

$$ {}^{4}_{2}\mathrm{He} + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n}\,. \qquad (12)$$

Note that in this case a C-12 atom is produced as opposed to the Joliot-Curies' proposed C-13. Since the "beryllium radiation" was known to be electrically neutral, Chadwick could not invoke a charged particle such as a proton or electron here. The C-12 nucleus, incidentally, will likely remain trapped in the Be target and hence undetected since it is not radioactive. If the neutron is assumed to have a mass similar to that of a proton (a presumption Chadwick was able to verify experimentally—see below), the Q-value of this reaction is 6.48 MeV. With the addition of the 5.3 MeV kinetic energy of the alpha we can expect the kinetic energy of the neutron to be at most about 11.8 MeV; the actual figure is about 10.9 MeV if the neutron's true mass and the momentum acquired by the C-12 nucleus are accounted for. A subsequent neutron/proton collision will be like a collision between equal-mass billiard balls, so it is entirely plausible that a neutron that begins with about 11 MeV of energy will be sufficiently energetic to accelerate a proton to a kinetic energy of ~ 5.7 MeV even after it (the neutron) batters its way out of the beryllium target and through the window of the vacuum vessel on its way to the paraffin.

Recall Chadwick's nitrogen experiment described above. Suppose that neutrons emerging from the vacuum vessel do indeed have energies of 5.7 MeV. With neutrons of mass 1 and nitrogen nuclei of mass 14, Equation (11) indicates that a nitrogen nucleus should be set into motion with a kinetic energy (56/225) that of the incoming neutron, about 1.4 MeV. *This figure is in excellent agreement with the energy indicated by the observed number of ion pairs created by the recoiling nitrogen nuclei!*

As Chadwick related in Paper 2 (p. 698), independent cloud-chamber measurements of the recoiling nitrogen atoms indicated that they acquired speeds of ~ 4.7×10^6 m/s as a result of being struck by neutrons. Knowing this and the fact that neutron-bombarded protons are set into motion with a speed of about 3.3×10^7 m/s he was able to estimate the mass of the neutron by a simple classical argument. If the mass of a proton is 1 unit and that of a nitrogen 14 units, Equation (11) indicates that the ratio of the speed of a recoiling proton to that of a recoiling nitrogen would be $(\mu+14)/(\mu+1)$ where μ is the mass of the neutron; the measured speeds lead him to conclude μ ~ 1.15 with an estimated error of 10 percent. The important point here is that this result is independent of any presumed knowledge of the neutron's kinetic energy. Further experiments with boron targets led Chadwick to report a final estimate of the neutron mass as between 1.005 and 1.008 mass units. The modern figure is about 1.00866; the accuracy he achieved with equipment which would now be regarded as hopelessly primitive is nothing short of awe-inspiring.

In summary, Chadwick's analysis consists of four main points: (1) If the "beryllium radiation" comprises gamma-rays then they must be of energy ~ 55 MeV to set protons in motion as observed. (2) Such a high energy is unlikely from an α-Be collision, although not inconceivable if the reaction happens in some unusual way involving considerable mass loss. (3) Letting the same "gamma-rays" strike nitrogen nuclei causes the latter to recoil with energies indicating that the gamma-rays must have energies of ~ 90 MeV, utterly inconsistent with point (1). (4) If instead the "beryllium radiation" is assumed to be a neutral particle of mass close to that of a proton, consistent results emerge for the proton and particularly the nitrogen recoil energies.

The tightness of Chadwick's experiments and logic is compelling. The neutron hypothesis also quickly proved to resolve longstanding issues concerning the spin properties of nuclei, and Chadwick was awarded the 1935 Nobel Prize in Physics for his discovery. He further speculated in Paper 2 that neutrons might

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represent a complex particle consisting of a proton and an electron, but this proved not to be the case: Heisenberg's uncertainty principle was to rule against the possibility of containing electrons within such a small space. Subsequent experiments by Chadwick himself (see reference [6]) showed that the neutron is a fundamental particle in its own right.

Chadwick left Cambridge in 1935 to accept the chair of physics at the University of Liverpool. During World War II he headed the British Mission attached to the Manhattan Project and witnessed the Trinity atomic-bomb test in July 1945. Curiously, the "initiators" in those weapons designed to provide a flux of neutrons at just the right time to trigger the nuclear explosion utilized a polonium-beryllium mixture, the same materials Chadwick had used in his historic 1932 experiments.

Like many other pioneers of nuclear physics, Chadwick struggled with the implications of his work. In a 1969 interview ([4], p. 356) he related that, "I remember the spring of 1941 to this day. I realized then that a nuclear bomb was not only possible—it was inevitable.... And I had nobody to talk to.... But I did realize how very very serious it could be. And I had then to start taking sleeping pills. It was the only remedy. I've never stopped since then. It's 28 years, and I don't think I've missed a single night in all those 28 years." After the war he returned to England to become Master of Gonville and Caius College at Cambridge until his retirement at the end of 1958. He passed away at the age of 82 on July 24, 1974, survived by his wife Aileen and twin daughters Joanna and Judy.

Chadwick had begun his career as a student of Rutherford about 1911; by 1932 he had the combination of experimental experience, theoretical knowledge, preparedness of mind and just plain good luck of being in the right place at the right time to recognize the neutron when it made its presence known. Rutherford had invented the concept of the "nuclear" atom and had begun seriously speculating on the possibility of neutrons about 1920; the concept must have been pervasive at the Cavendish Laboratory. [7] But the play of history is not preordained: had the Joliot-Curies not committed such incredible errors of fundamental physics and experimental misinterpretation our textbooks might relate a very different story. As it happened, for a few intense weeks in early 1932 James Chadwick enjoyed the rare experience of making a fundamental discovery about the nature of the physical universe.

References

[1] J. Chadwick, "Possible Existence of a Neutron," *Nature* **129**, 312 (1932).

[2] J. Chadwick, "The Existence of a Neutron," *Proceedings of the Royal Society of London* **A136**, 692-708 (1932).

[3] A. Brown, *The Neutron and the Bomb: A Biography of Sir James Chadwick*, Oxford University Press, Oxford, 1997.

[4] R. Rhodes, *The Making of the Atomic Bomb*, Simon and Schuster, New York, 1986.

[5] If the momentum of the struck particle is treated relativistically the exact expression is $K_m = 2E_\gamma/(2+E_m/E_\gamma)$, a first-order expansion of which gives our equation (10). In the fully relativistic treatment Equation (9) becomes modified by the addition of a factor of K^2 under the radical, but this will be small in comparison with $2E_mK$ for the energies involved here.

[6] H. A. Bethe, "Nuclear physics," *Rev. Mod. Phys.* **71**, S6-S15 (1999—Centenary edition).

[7] Emilio Segré recalls that "James Chadwick reported to Rutherford the Curie-Joliet publication of January 18 [1932], and when his Lordship heard of the proposed explanation, it seems that he said with unusual vehemence, 'I do not believe it.' On reading the same paper, Ettore Majorana, a young physicist in Rome,...said...'They have discovered the neutral proton and they do not recognize it.' Chadwick at the Cavendish did more..." E. Segré, *From X-Rays to Quarks* (Freeman, 1980), pp. 183-184.

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