Higgs Essay

A Review of Higgs Particle Physics

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Abstract

This paper is an overview of Higgs particle physics. This discusses the particle physics behind why the Higgs particle was presumed to exist, some aspects of its detection and how the Higgs particle might be a door into deeper foundations.

1 How the Higgs particle saved physics

The reasons for the Higgs particle are often not discussed. It is common to hear the lore that that Higgs field produces the mass of particles. While this is the case, the most important role the Higgs field plays is in rescuing quantum field theory from a complicated problem with massive vector bosons. The weak interactions at low energy are mediated by massive vector bosons. At sufficiently high energy this theory is not causally consistent. The mass is a degree of freedom, or equivalently a longitudinal mode, which is absorbed by the gauge bosons that is massless at higher energy. This means weak interactions at high energy are mediated by massless gauge bosons at high energy. This prevents the theory of weak interactions from being inconsistent. The Higgs field in the standard model which contains 3 Goldstone fields that are absorbed by the Z and $W^{\pm}$ gauge bosons and a remaining particle-field that may be detected.

This is then a brief ABC overview of Higgs theory, and the detection by the LHC. This is followed by some possible future implications of Higgs physics.

The Higgs field was proposed as a way to fix a problem with massive gauge vector bosons. A massive particle exhibits dispersion. This leads to difficulties with a vector gauge boson with a mass, for this particle has a longitudinal degree of freedom. The longitudinal mode becomes pathological for extremely large energy. A massive particle obeys the relativistic four-momentum

$$E^2 = p^2 + m^2$$

where $c = 1$. The group velocity of the particle is

$$v = \frac{\partial E}{\partial p} = \frac{p}{E}$$

which approaches unity, or the speed of light, as the spatial momentum $p \rightarrow \infty$. The phase velocity is $v_p = \frac{E}{p}$ which converges to the speed of light as $p \rightarrow \infty$, but from the other direction with $v_p > c$ for finite p. The wave equation $\Box A + mA = 0$ has

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solutions for the vector potential $A_i \simeq A_i(0)e^{i(\vec{k}\cdot\vec{r} - \omega t)}$with $\omega = \sqrt{k^2 + m^2}$. For high momenta $\omega \simeq k + m^2/2k$. If the problem is reduced to one dimensions with $x = v_g t$ for $v_g = 1 - m^2/2k^2$the vector potential is $A_i \simeq A_i(0)e^{-im^2t/k}$. The evaluation of the vector potential at $k' = m$ by the Kramers-Kronig relationship

$$A(k') = \frac{A(0)}{\pi i}\int_{-\infty}^{\infty}\frac{e^{-im^2t/k}}{k - k'} = \frac{A(0)}{\pi i}e^{-imt}\left(Ei\Big(\frac{im(k - m)}{k}\Big) - Ei\Big(\frac{im^2}{k}\Big)\right).$$

The elliptic integral $Ei\Big(\frac{im(k - m)}{k}\Big)$ diverges for $k = m$, while the rest of the domain of integration we are not as interested in. This approximate approach illustrates though the big problem with a QFT with massive bosons. There is a breakdown in establishing a causality condition for the field when the value of the momentum becomes comparable to the mass of the boson. This is a very approximate way of illustrating how something fails with quantum field theories once interaction energy or transverse momentum becomes sufficiently large. We may think of this as a case where the oscillating longitudinal field can causally influence an interaction faster than the field actually propagates. This can mean the longitudinal field can impart causal information faster than light.

In particular we are interested in the theory of weak interactions. The standard interaction is the β decay, such as $n \to p + e^+ + \bar{\nu}_e$. On the level of QCD this is a transition between quark types $d \to u + e^+ + \bar{\nu}_e$. The initial quantum field theory of β decay by Enrico Fermi invoked a quartic interaction term which describes the creation and annihilation of the appropriate particles [1]

$$\mathcal{L}_{Fermi} \simeq G_F\bar{\psi}_u\psi_d\bar{\psi}_{\nu,e}\psi_e.$$

The correct theory of course involves three vertex interactions

$$\mathcal{L}_{\bar{q}Wq} = g(\bar{\psi}_u W^+\psi_d + \bar{\psi}_{\nu,e}W^+\psi_e),$$

where now the four point vertex is "blown up" into two vertices connected by a W^+ internal edge link. This expands the theory into a theory of gauge bosons, but the mass associated with the four point interaction remains. The theory is then only acceptable if the momentum of the weak currents are less than the mass of the $W^\pm$ weak current, or the neutral weak current Z. The above argument, which is approximate but illustrates with elementary machinery the essential problem, is the theory fails for transverse momentum comparable to the mass of the boson. The oscillation of the longitudinal mode for large enough momentum becomes such that proper causality conditions do not exist.

A gauge boson with mass has a longitudinal degree of freedom, plus the two transverse degrees of freedom. The problem lies with the longitudinal mode, where that degree of freedom is then inherited from some other field at a threshold energy. Physics above that threshold energy has the gauge boson as massless with only the two degrees of freedom from the transverse field modes. In order to shift a single degree of freedom from some field into this gauge field requires this additional field be a scalar field. So enter the Higgs field [2]. This is a scalar field in the vacuum composed of two doublets

$$\begin{pmatrix} H^+ \\ H_0 \end{pmatrix}, \begin{pmatrix} H^- \\ H_0' \end{pmatrix}.$$

At very high energy the gauge particles of the electroweak theory (W^+, W^-, Z^0, γ) are not coupled to the Higgs field (or very weakly coupled) and are massless, or nearly so. The covariant differential of the Higgs field H is given by $\partial_\mu H \rightarrow (\partial_\mu + igA_\mu)H$ which results in coupling between the gauge potential and the Higgs field that increases near the Higgs potential minimum. The field then contains a term $A^*_\mu H A^\mu$, which is similar to a mass term in a Proca equation. The fields then absorb the Higgs degrees of freedom $W^+ + H^+ \rightarrow W^+$, $W^- + H^- \rightarrow W^-$ and $Z^0 + H_0 \rightarrow Z^0$, which are massive, plus a remaining H' left over. The left over H_0' is the Higgs particle. This particle is what has recently been discovered.

The Higgs field being searched for is the basic standard model Higgs particle. However, there is the minimally supersymmetric standard model, where the supersymmetric extension of the standard model means there are 4 doublets of Higgs field [3]. The reason for this number is you need to increase the number of Higgs doublets by two, for a single Higgsino will have a gauge anomaly of the form $\psi_h \rightarrow \psi_h + \gamma \cdot \partial\phi$ that contributes a gauge term of a loop. The term is integrated to be non-zero around the loop and so a gauge dependent term contributes to an amplitude. However, with two gravitinos you can cancel the two. This means there are 8 total components to the MSSM Higgs and 5 of them contribute as particles. The doublet representation of the 5 Higgs particles is

$$\begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \begin{pmatrix} \begin{Bmatrix} +1/2 \\ +1/2 \\ -1/2 \\ +1/2 \end{Bmatrix} \end{pmatrix}, \begin{pmatrix} H^- \\ H^0 \end{pmatrix} = \begin{pmatrix} \begin{Bmatrix} -1/2 \\ -1/2 \\ +1/2 \\ -1/2 \end{Bmatrix} \end{pmatrix}, H_0 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

The 5 Higgs particles left over are a light scalar Higgs, a massive Higgs field, a pseudoscalar Higgs and two charged Higgs. Of the 8 Higgs field particle states, three have their degrees of freedom absorbed by the EW field, which produces the Z and $W^\pm$ masses and the lepton or quark masses in $\mathcal{L}_{yuk} = g\bar\psi H\psi$ (again due to weak interactions that are flavor changing neutral current interacting) . The light Higgs is comparable to the simple non-supersymmetric Higgs mass of the standard model is one of them.

Supersymmetry provides a counter term to a problem that occurs with the standard model Higgs theory. The Higgs particle couples to the vacuum state of weak interactions, so that at lower energy this coupling becomes stronger. The result is that the mass of the Higgs field is not stable; the Higgs particle can have almost arbitrary mass. The negative vacuum energy of fermions provides an equal counter term to the large unstable mass of the Higgs in the standard model. This is one compelling reason for supersymmetry; now that the Higgs particle has been found the claim for supersymmetry is almost compulsory.

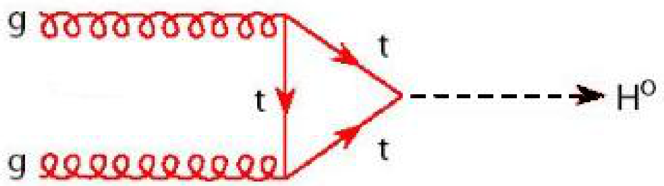
The last doublet particle corresponds to the standard Higgs particle found at 125 GeV. The other Higgs particles, which come in at up to 300 GeV have not been found. These will be the target of investigation after the LHC has been reconditioned to do experiments from 7 TeV to 14 TeV. The experimental discovery of these Higgs particles will be strong evidence for supersymmetry at higher energy.

2 Detection of the Higgs particle

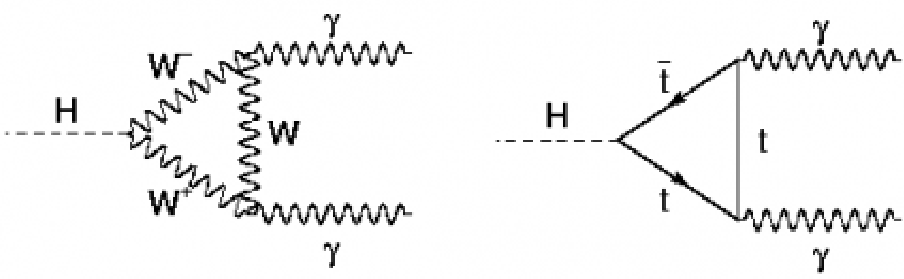
The Higgs Boson is a scalar with no spin. Other elementary particles in the standard model are either fermions with spin one-half or gauge bosons with spin one. Particles with spin that is any multiple of one half are possible and it is a quantity that needs to be checked experimentally. The channel where they are seeing the signal for the Higgs boson most strongly is through its decay into two high energy photons. The photons have spin one but spin is conserved because the two photons take away spin in opposite directions that cancel. It is not possible for fermions that have a odd-integer spin to decay without producing at least one new fermion so we know already that the particle observed is a boson. By a theoretical result known as the Landau-Yang theorem it is not possible for a spin-one particle to decay into two photons either, but it is possible for a spin-two particle to decay into two photons with spins in the same direction.

We know already that the new particle has spin zero or spin two and we could tell which one if we could detect the polarizations of the photons produced. Unfortunately this is difficult and neither ATLAS nor CMS are able to measure polarizations. The only direct and sure way to confirm that the particle is indeed a scalar is to plot the angular distribution of the photons in the rest frame of the centre of mass. A spin zero particle like the Higgs carries no directional information away from the original collision so the distribution will be even in all directions. This test will be possible when a much larger number of events have been observed. In the mean time we can settle for less certain indirect indicators.

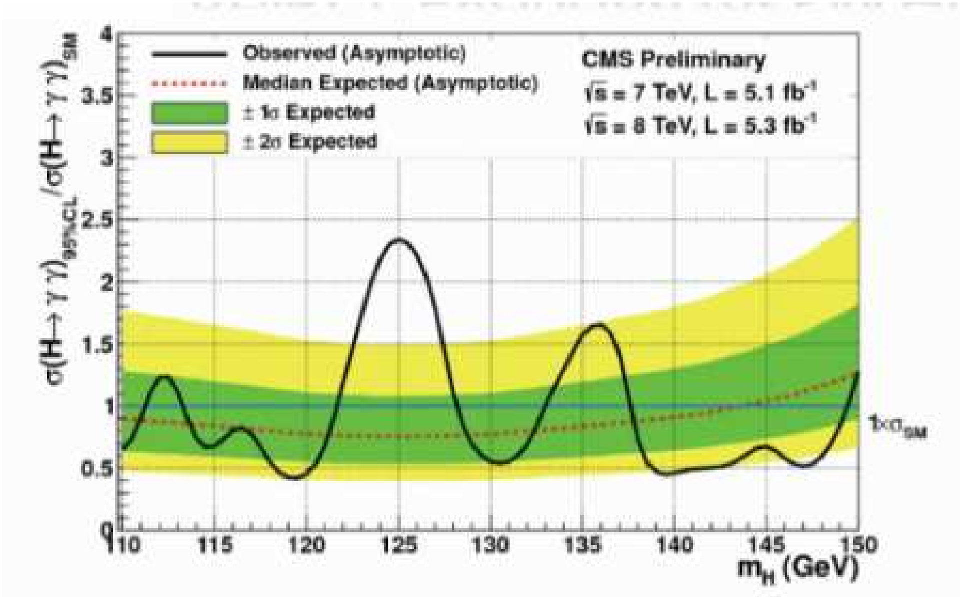
The Higgs field is likely produced by gluon-gluon interactions in the $p - \bar{p}$ collision. The process is of the form



The dominant decay process is the diphoton process, with the Feynman diagram



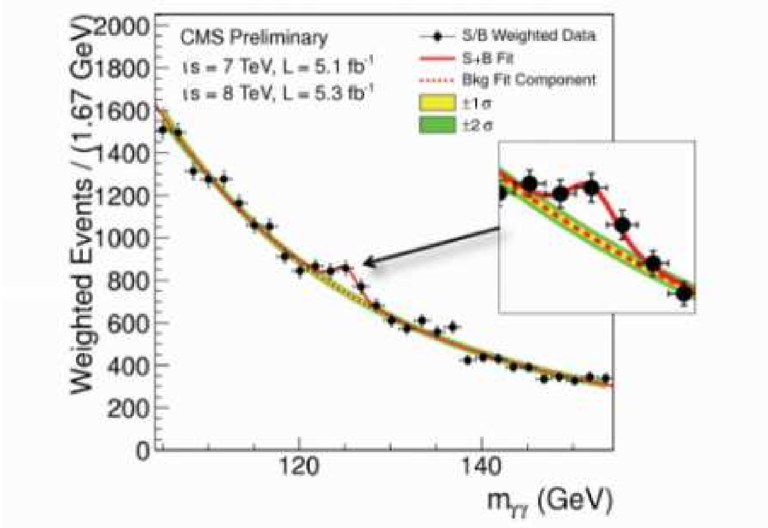
The process involves a triangle Feynman diagram, and there is the triangle anomaly to work through to compute these. Other decay process may involve the top quark, which comes in at 176 GeV, and as a virtual process requires a larger fluctuation of mass, to use the parlance of such explanations. Other processes may involve the than the $W^{\pm}$ for $m_W = 80$ GeV. The diphoton events were the dominant processes computed and were what the detectors were set to trigger on. Combined Atlas and CMS data gave exclusion plots which had $5 - \sigma$ data for the 125 GeV Higgs field. An example of the CMS [4] plot is:



where similar plots are obtained for the Atlas detector. A combination of the data and their statistics has lead to the $5 - \sigma$ discovery.

The difficulty in detecting the Higgs is that the detector had to filter out millions of photon events detected and trigger only on those photon events which correlated with the expectation of the Higgs particle. This required a multi-year process of running the $p - \bar{p}$ beam and accumulating data over a long period of time. The excess in diphoton events which were statistically significant were a small deviation from the overall number of counts. This can be seen in the scale of photon event for the CMS detector

The Higgs particle constitutes a small deviation from the total number of events. It required the accumulation of massive amounts of data over two years in order to gain sufficient statistics to determine the Higgs particle had been detected.



3 Implication for deeper physical and cosmological foundations

The next step beyond find a charged Higgs particle and thus lending support for supersymmetry are possibilities for learning about extra large dimensions and finding signatures for string theory. There may further be implications for cosmology as well. Once the LHC is brought to its full energy at 14 TeV it might be that certain features of the Higgs field might bring to some light matters concerning deeper foundations. Here a different possibility, other than supersymmetry or extra large dimensions, for a deeper foundation to physics is discussed.

Recently I had a conversation with a high school teacher, a brother in fact, on the nature of Newton's laws. He said that Newton could be distilled down to one word, "inertia." I was not in full agreement that this is all, but in one sense inertia is a kernel. The first law of Newton tells us that physics is properly observed from an inertial frame. The second law tells us what dynamics is, and the third law tells us that dynamics operates in a space with homogeneous and isotropic symmetry. Inertia comes into play with the interrelationship between the inertial frame and dynamics. If there were no masses in the universe and every particle-field was massless there would be no physical inertial frames. In addition there would be no mass for there to be $F = ma$, though one can compute with the Dirac equation the motion of a massless charged fermion in a magnetic field. However, this particle's four-momentum would be tangent to a light cone at every point, which is not an accelerated frame. Without mass there would be neither inertial frames or accelerated frames. Mass is the quantity which makes timelike geodesics in spacetime possible, and the dynamics of a particle on such a geodesic

$$\frac{d^2x^a}{ds^2} - \Gamma^a_{bc}\frac{dx^b}{ds}\frac{dx^c}{ds} = 0$$

is entirely due to mass, even though the mass makes no explicit appearance. A mass may be multiplied to both sides of the equation, and there is no difference to the dynamics. The reason is that inertial mass m_i is equal to gravitational mass m_g. As a result $m_i = m_g$ may be multiplied on both sides and scaled $m = \sigma m_0$, $\sigma \in \{0, \infty\}$ and the dynamics is unchanged. On the other hand if there is some external non-gravitational force F then the nongeodesic motion is governed by

$$\frac{D^2x^a}{ds^2} = \frac{d^2x^a}{ds^2} - \Gamma^a_{bc}\frac{dx^b}{ds}\frac{dx^c}{ds} + F/m$$

In this case the mass makes an explicit appearance. In this case the explicit value of the mass is important. An observer on an accelerated frame will however observe a mass m "fall," as if in a local gravity field on Earth, where again the acceleration is independent of the mass.

Does the Higgs particle make inertial possible? Only in part does it do so. Not all mass in the universe is due to the Higgs particle. The mass of quarks is due to the Higgs field with Yukawa Lagrangians $\mathcal{L}_y = g\bar{q}Hq$, where quark masses turn out to be very modest: $m_u = 4.2$ MeV and $m_d = 7.5$MeV. The actual quark masses contribute 1.69 to the mass of a proton and 2.04 to the mass of a neutron [5]. The rest of the mass is due to gluon interactions which confine the quarks with a large mass-energy content. If the Higgs did not give mass to quarks they would still be bound into the QCD bag. In the appendix below the example of a magnetic force on a massless charged particle is given. Consequently even if the Higgs field did not exist it is possible that baryons would still have mass.

We however still have this connection between inertia, gravity and the Higgs field. Now in addition we have gluons which can act to bind particles together with a mass. The article article [6] makes the point that gravity can be thought of as the square of a gauge theory. A graviton is a bound state or entanglement between two gluons . This connects well with string theory sense. For a closed string there are two sets of mode operators $a^\dagger_n$, a_n and $b^\dagger_n$, b_n for modes propagating left and right polarized directions in space. Along the string though modes travel along a σ and $-\sigma$ direction on the string according to whether the n subscript is positive or negative. We then write these modes as $a^\dagger_n$, a_n and $a^\dagger_{-n}$, a_{-n}, which hold for the b operators , and we ignore the zero mode for technical reasons. There is a result which says the Hamiltonian operator must have equal levels in operator products, such as $a^\dagger_n a^\dagger_{-n}$, that act on the string ground state. The reason for this is there is no preferred direction along the string with parameter σ, and this level matching result is a Noether theorem result from this. Each $a^\dagger_n$ or $b^\dagger_n$ is a raising operator for a spin 1 boson field, and the product of the two is a spin 2 field, with no $m = 0$ or 1 component. So the graviton can be thought of as a pair of Yang-Mills gauge bosons.

The operators can be given a spacetime index μ so that we have $(a^\mu)^\dagger_n$ and ${a^\mu}^\dagger_{-n}$. We then consider this index extended to $\mu = \{0, 1, 2, 3\}$ for spacetime and $q = \{4, 5, \ldots, 9\}$. The graviton is defined by the metric $g^{\mu\nu} = {a^\mu}^\dagger_n {a^\nu}^\dagger_{-n}$. Similarly a gauge boson operator in standard QFT is then of the form

$$A^{\mu\dagger} = {a^\mu}^\dagger_n {a^q}^\dagger_{-n}$$

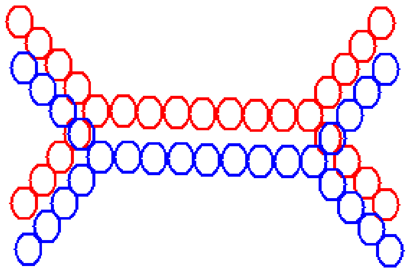
where the right hand side is a graviton, but with one dimension q in an internal space direction. Suppose we have a gauge boson operator of the form

$$A'^{\mu\dagger} = a^{q\dagger}_{n} a^{\mu\dagger}_{-n}.$$

The interaction of the two is of the form $A^{\mu\dagger}A'^{\nu\dagger}$ and this is then

$$A^{\mu\dagger}A'^{\nu\dagger} = a^{\mu\dagger}_{n}\mathbf{a}^{q\dagger}_{-n}\mathbf{a}^{q\dagger}_{n}a^{\nu\dagger}_{-n}$$

where the operators in bold font describe the creation of internal space bosons with opposite mode directions on the string. This is equivalent to opposite gauge charges (opposite colors) and so this is a type of glueball, and the annihilation of the opposite charges leaves a product of two operators which recovers a graviton, or two photons.



The graviton produces a gauge boson when one of its two polarization directions is an internal degree of freedom. Similarly the product of two gauge bosons is $A^{\mu\dagger}A'^{\nu\dagger} = \mathbf{a}^{q\dagger}_{-n}\mathbf{a}^{q\dagger}_{n}g^{\mu\nu}$, where $\mathbf{a}^{q\dagger}_{-n}\mathbf{a}^{q\dagger}_{n}$ sums over color charges and physically serves as the square of a scalar field. Hence the product of two gauge boson operators is a form of graviton. The trace over this graviton then produces the square of a scalar field. For $\mathbf{a}^{q\dagger}_{-n} = \mathbf{a}^{q}{}_{n}$then the square of $A^{a\dagger} = A^{\mu\dagger} + A^{q\dagger}$

$$A^{a\dagger}A^{b\dagger} = |\phi|^2 g^{\mu\nu} + Tr(g)|\phi|^4\delta^{\mu\nu}$$

which has properties similar to the ϕ^4 Higgs potential, $V(\phi) \sim -A^{a\dagger}A^{b\dagger}$, with $Tr(g) < 0$. A kinetic energy term $|\partial\phi|^2$ can be found from the Lagrangian term $\frac{1}{4}F^{\mu q}F_{\mu q}$ with the cyclicity condition $\partial_q A^\mu = 0$.

The gluon gauge field, which confines mass-energy, the graviton and the Higgs particle may then be seen to be different versions of the same field. This is potentially fertile ground to work. The Higgs field defines the mass of particles, as does the QCD field in the confinement of quarks. The confinement of energy into a region with a timelike spacetime path then defines an inertial frame. Only a mass can exist on an inertial frame and only masses can exist on an accelerated frame where the equivalence principle can be tested. This intertwining of gluon, graviton and Higgs field may be a part of a deeper underlying physics. The square of gluons is an aspect of the equivalency between QCD and gravity, which may extend into an equivalency with the Higgs field.

4 Appendix

Consider the Dirac equation

$$i\gamma^\mu \partial_\mu \psi \ = \ 0 \ \rightarrow \ i\gamma^0 \partial_t \psi \ + \ i\gamma \cdot \nabla \psi \ = \ 0$$

for a massless particle. We now consider the momentum operator as gauge covariant and we set the electric potential zero $\nabla \ \rightarrow \nabla \ + \ (ie/\hbar)A$

$$i\gamma^0 \partial_t \psi \ + \ i\gamma \cdot (\nabla \ + \ (ie/\hbar)A)\psi \ = \ 0.$$

This has a Schrdinger equation form by manipulating the Dirac matrices

$$i\frac{\partial \psi}{\partial t} \ = \ c\alpha \cdot (\nabla \ + \ (ie/\hbar)A)\psi,$$

where $H \ = \ c\alpha \cdot (\nabla \ + \ (iec/\hbar)A)$ is the Hamiltonian. This is a fully relativistic form of the motion of a charged particle in an electromagnetic field. We now particularly want to compute \partialp/\partial t. The equation of motion with this Hamiltonian is

$$\frac{\partial p}{\partial t} \ = \ i[H, \ p].$$

We use the operator form of the momentum on the right $p \ = \ -i\hbar\nabla$, and apply this to this equation

$$\frac{\partial p}{\partial t} \ = \ [(ec/\hbar)\alpha \cdot A), \ \hbar\nabla] \ = \ ec\alpha \cdot \nabla \times A \ = \ ec\alpha \times B$$

The factor of c is the speed of the particle perpendicular to the field. This is then a Lorentz force on a particle with zero mass.

5 References

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