Chapter 33: PARTICLE PHYSICS

# 33.1 THE YUKAWA PARTICLE AND THE HEISENBERG UNCERTAINTY PRINCIPLE REVISITED

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| 1. | *A virtual particle having an approximate mass of*  *may be associated with the unification of the strong and electroweak forces. For what length of time could this virtual particle exist (in temporary violation of the conservation of mass-energy as allowed by the Heisenberg uncertainty principle)?* |
| Solution |  |
| 2. | *Calculate the mass in*  *of a virtual carrier particle that has a range limited to*  *m by the Heisenberg uncertainty principle. Such a particle might be involved in the unification of the strong and electroweak forces.* |
| Solution |  |
| 3. | *Another component of the strong nuclear force is transmitted by the exchange of virtual K-mesons. Taking K-mesons to have an average mass of* *, what is the approximate range of this component of the strong force?* |
| Solution |  |

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| 33.2 THE FOUR BASIC FORCES | |
| 4. | *(a) Find the ratio of the strengths of the weak and electromagnetic forces under ordinary circumstances. (b) What does that ratio become under circumstances in which the forces are unified?* |
| Solution | (a) From Table 33.1, we know that the ratio of the weak force to the electromagnetic force is .  In other words, the weak force is 11 orders of magnitude weaker than the electromagnetic force.  (b) When the forces are unified, the idea is that the four forces are just different manifestations of the same force, so under circumstances in which the forces are unified, the ratio becomes 1 to 1. (See Section 33.6.) |
| 5. | *The ratio of the strong to the weak force and the ratio of the strong force to the electromagnetic force become 1 under circumstances where they are unified. What are the ratios of the strong force to those two forces under normal circumstances?* |
| Solution |  |
| 33.3 ACCELERATORS CREATE MATTER FROM ENERGY | |
| 6. | *At full energy, protons in the 2.00-km-diameter Fermilab synchrotron travel at nearly the speed of light, since their energy is about 1000 times their rest mass energy. (a) How long does it take for a proton to complete one trip around? (b) How many times per second will it pass through the target area?* |
| Solution | (a)  (b) |
| 7. | *Suppose a  created in a bubble chamber lives for* *. What distance does it move in this time if it is traveling at 0.900c? Since this distance is too short to make a track, the presence of the  must be inferred from its decay products. Note that the time is longer than the given  lifetime, which can be due to the statistical nature of decay or time dilation.* |
| Solution |  |
| 8. | *What length track does a  traveling at 0.100c leave in a bubble chamber if it is created there and lives for ? (Those moving faster or living longer may escape the detector before decaying.)* |
| Solution |  |
| 9. | *The 3.20-km-long SLAC produces a beam of 50.0-GeV electrons. If there are 15,000 accelerating tubes, what average voltage must be across the gaps between them to achieve this energy?* |
| Solution |  |
| 10. | *Because of energy loss due to synchrotron radiation in the LHC at CERN, only 5.00 MeV is added to the energy of each proton during each revolution around the main ring. How many revolutions are needed to produce 7.00-TeV (7000 GeV) protons, if they are injected with an initial energy of 8.00 GeV?* |
| Solution |  |
| 11. | *A proton and an antiproton collide head-on, with each having a kinetic energy of 7.00 TeV (such as in the LHC at CERN). How much collision energy is available, taking into account the annihilation of the two masses? (Note that this is not significantly greater than the extremely relativistic kinetic energy.)* |
| Solution |  |
| 12. | *When an electron and positron collide at the SLAC facility, they each have 50.0 GeV kinetic energies. What is the total collision energy available, taking into account the annihilation energy? Note that the annihilation energy is insignificant, because the electrons are highly relativistic.* |
| Solution |  |
| 33.4 PARTICLES, PATTERNS, AND CONSERVATION LAWS | |
| 13. | *The  is its own antiparticle and decays in the following manner: . What is the energy of each*  *ray if the  is at rest when it decays?* |
| Solution | If the  is at rest when it decays, its total energy is just . Since its initial momentum is zero, each  ray will have equal but opposite momentum. Since a  ray is a photon, . Therefore, since the momenta are equal in magnitude the energies of the  rays are equal: .Then, by conservation of energy, the initial energy of the  equals twice the energy of one of the  rays: Finally, from Table 33.2, we can determine the rest mass energy of the , and the energy of each  ray is: |
| 14. | *The primary decay mode for the negative pion is . What is the energy release in MeV in this decay?* |
| Solution |  |
| 15. | *The mass of a theoretical particle that may be associated with the unification of the electroweak and strong forces is . (a) How many proton masses is this? (b) How many electron masses is this? (This indicates how extremely relativistic the accelerator would have to be in order to make the particle, and how large the relativistic quantity*  *would have to be.)* |
| Solution | (a)  (b) |
| 16. | *The decay mode of the negative muon is  (a) Find the energy released in MeV. (b) Verify that charge and lepton family numbers are conserved.* |
| Solution | (a)  (b) |
| 17. | *The decay mode of the positive tau is . (a) What energy is released? (b) Verify that charge and lepton family numbers are conserved. (c) The  is the antiparticle of the .Verify that all the decay products of the  are the antiparticles of those in the decay of the  given in the text.* |
| Solution | (a)  (b)  (c) |
| 18. | *The principal decay mode of the sigma zero is . (a) What energy is released? (b) Considering the quark structure of the two baryons, does it appear that the  is an excited state of the ? (c) Verify that strangeness, charge, and baryon number are conserved in the decay. (d) Considering the preceding and the short lifetime, can the weak force be responsible? State why or why not.* |
| Solution | (a)  (b) Yes, since they have the same quark composition (uds).  (c)  (d) No. Strangeness is conserved, and the short lifetime indicates that the strong force is responsible. |
| 19. | *(a) What is the uncertainty in the energy released in the decay of a  due to its short lifetime? (b) What fraction of the decay energy is this, noting that the decay mode is  (so that all the  mass is destroyed)?* |
| Solution | (a) Using  we can calculate the uncertainty in the energy, given the lifetime of the  from Table 33.2:    (b) The fraction of the decay energy is determined by dividing this uncertainty in the energy by the rest mass energy of the  found in Table 33.2: |
| 20. | *(a) What is the uncertainty in the energy released in the decay of a  due to its short lifetime? (b) Is the uncertainty in this energy greater than or less than the uncertainty in the mass of the tau neutrino? Discuss the source of the uncertainty.* |
| Solution | (a)  (b) It is much less; the uncertainty in the mass of the tau neutrino is 31 MeV. |

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| 33.5 QUARKS: IS THAT ALL THERE IS? | |
| 21. | *(a) Verify from its quark composition that the  particle could be an excited state of the proton. (b) There is a spread of about 100 MeV in the decay energy of the , interpreted as uncertainty due to its short lifetime. What is its approximate lifetime? (c) Does its decay proceed via the strong or weak force?* |
| Solution | (a)  (same quarks as for a proton) See Table 33.4.  (b)  (c) Strong, as shown by the short lifetime. |
| 22. | *Accelerators such as the Triangle Universities Meson Facility (TRIUMF) in British Columbia produce secondary beams of pions by having an intense primary proton beam strike a target. Such “meson factories” have been used for many years to study the interaction of pions with nuclei and, hence, the strong nuclear force. One reaction that occurs is* *, where the  is a very short-lived particle. The graph in Figure 33.26 shows the probability of this reaction as a function of energy. The width of the bump is the uncertainty in energy due to the short lifetime of the . (a) Find this lifetime. (b) Verify from the quark composition of the particles that this reaction annihilates and then re-creates a d quark and a  antiquark by writing the reaction and decay in terms of quarks. (c) Draw a Feynman diagram of the production and decay of the  showing the individual quarks involved.* |
| Solution | (a)  (b)  (c) |
| 23. | *The reaction*  *(described in the preceding problem) takes place via the strong force. (a) What is the baryon number of the  particle? (b) Draw a Feynman diagram of the reaction showing the individual quarks involved.* |
| Solution | (a)  (b) |
| 24. | *One of the decay modes of the omega minus is* *. (a) What is the change in strangeness? (b) Verify that baryon number and charge are conserved, while lepton numbers are unaffected. (c) Write the equation in terms of the constituent quarks, indicating that the weak force is responsible.* |
| Solution | (a)  (b)  All lepton #’s are 0 before and after.  (c)  strangeness violation; i.e., quark flavor changeweak force |
| 25. | *Repeat the previous problem for the decay mode .* |
| Solution | (a) From Table 33.4, we know the quark composition of each of the particles involved in this decay: Then:    (b) Using Table 33.3, we see that the baryon number initially is , and the final baryon number , so the baryon number is indeed conserved. Again, using Table 33.3, the charge is: , so charge is indeed conserved. This decay does not involve any electrons or neutrinos, so all lepton numbers are zero before and after, and the lepton numbers are unaffected by the decay.  (c) Using Table 33.4, we can write the equation in terms of its constituent quarks: . Since there is a change in quark flavor, the weak nuclear force is responsible for the decay. |
| 26. | *One decay mode for the eta-zero meson is* *.(a) Find the energy released. (b) What is the uncertainty in the energy due to the short lifetime? (c) Write the decay in terms of the constituent quarks. (d) Verify that baryon number, lepton numbers, and charge are conserved.* |
| Solution | (a)  (b)  (c)  (d)  All lepton #’s are zero before and after. |
| 27. | *One decay mode for the eta-zero meson is . (a) Write the decay in terms of the quark constituents. (b) How much energy is released? (c) What is the ultimate release of energy, given the decay mode for the pi zero is ?* |
| Solution | (a)  (b)  (c) |
| 28. | *Is the decay*  *possible considering the appropriate conservation laws? State why or why not.* |
| Solution | No, the baryon number is not conserved. |
| 29. | *Is the decay  possible considering the appropriate conservation laws? State why or why not.* |
| Solution | No. Charge and baryon numbers are conserved.  is not conserved. |
| 30. | *(a) Is the decay*  *possible considering the appropriate conservation laws? State why or why not. (b) Write the decay in terms of the quark constituents of the particles.* |
| Solution | (a) Yes. Charge is conserved. The baryon number is conserved. All lepton numbers are conserved.  (b) |
| 31. | *(a) Is the decay*  *possible considering the appropriate conservation laws? State why or why not. (b) Write the decay in terms of the quark constituents of the particles.* |
| Solution | (a) From Table 33.4, we know the quark composition of each of the particles involved in the decay: . The charge is conserved at -1. The baryon number is conserved at B=1. All lepton numbers are conserved at zero, and finally the mass initially is larger than the final mass: , so, yes, this decay is possible by the conservation laws.  (b) Using Table 33.4, we can write the equation in terms of its constituent quarks: |
| 32. | *The only combination of quark colors that produces a white baryon is RGB. Identify all the color combinations that can produce a white meson.* |
| Solution | or mixtures of these. |
| 33. | *(a) Three quarks form a baryon. How many combinations of the six known quarks are there if all combinations are possible? (b) This number is less than the number of known baryons. Explain why.* |
| Solution | (a)  (b) There are more baryons observed because we have the 6 antiquarks and various mixtures of quarks (as for the -meson) as well. |
| 34. | *(a) Show that the conjectured decay of the proton,* *, violates conservation of baryon number and conservation of lepton number. (b) What is the analogous decay process for the antiproton?* |
| Solution | (a)  (b) |
| 35. | *Verify the quantum numbers given for the  in Table 33.2 by adding the quantum numbers for its quark constituents as inferred from Table 33.4.* |
| Solution |  |
| 36. | *Verify the quantum numbers given for the proton and neutron in Table 33.2 by adding the quantum numbers for their quark constituents as given in Table 33.4.* |
| Solution |  |
| 37. | *(a) How much energy would be released if the proton did decay via the conjectured reaction* *? (b) Given that the  decays to two* *s and that the*  *will find an electron to annihilate, what total energy is ultimately produced in proton decay? (c) Why is this energy greater than the proton’s total mass (converted to energy)?* |
| Solution | (a) The energy released from the reaction is determined by the change in the rest mass energies:  Using Table 33.2, we can then determine this difference in rest mass energies:    (b) The two  rays will carry a total energy of the rest mass energy of the :  The positron/electron annihilation will give off the rest mass energies of the positron and the electron:    So, the total energy would be the sum of all these energies:  (c) The total energy includes the annihilation energy of an extra electron. So the full reaction should be . |
| 38. | *(a) Find the charge, baryon number, strangeness, charm, and bottomness of the  particle from its quark composition. (b) Do the same for the*  *particle.* |
| Solution | (a)  (b) |
| 39. | *There are particles called D-mesons. One of them is the  meson, which has a single positive charge and a baryon number of zero, also the value of its strangeness, topness, and bottomness. It has a charm of . What is its quark configuration?* |
| Solution | is a meson, so it is composed of two quarks, one of which must be a charm quark (). The charm quark has , so the other quark must have  to give a total charge of .  has no strangeness or bottomness, so the only possible quark with  is the antidown . Therefore, . |
| 40. | *There are particles called bottom mesons or B-mesons. One of them is the*  *meson, which has a single negative charge; its baryon number is zero, as are its strangeness, charm, and topness. It has a bottomness of . What is its quark configuration?* |
| Solution | is a meson, so it is composed of two quarks, one of which must be a bottom (). The bottom quark has charge , so the other quark must have charge  to give a total charge of .  has no charm or top quark. The only remaining possibility is the anti-up quark . Therefore . |
| 41. | *(a) What particle has the quark composition* *? (b) What should its decay mode be?* |
| Solution | (a)  (b) |
| 42. | *(a) Show that all combinations of three quarks produce integral charges. Thus baryons must have integral charge. (b) Show that all combinations of a quark and an antiquark produce only integral charges. Thus mesons must have integral charge.* |
| Solution | (a) Two possible quark charges  Then there are 4 possible combinations:  (b) The 4 possible combinations: |
| 33.6 GUTS: THE UNIFICATION OF FORCES | |
| 43. | ***Integrated Concepts*** *The intensity of cosmic ray radiation decreases rapidly with increasing energy, but there are occasionally extremely energetic cosmic rays that create a shower of radiation from all the particles they create by striking a nucleus in the atmosphere as seen in the figure given below. Suppose a cosmic ray particle having an energy of  converts its energy into particles with masses averaging . (a) How many particles are created? (b) If the particles rain down on a* *area, how many particles are there per square meter?* |
| Solution | (a)  (b) Divide the number of particles by the area they hit: |
| 44. | ***Integrated Concepts*** *Assuming conservation of momentum, what is the energy of each*  *ray produced in the decay of a neutral at rest pion, in the reaction ?* |
| Solution | If the  rays have equal and opposite momentum, then they will have equal energies since  The energy will come from the converted rest mass of the pion. Thus, |
| 45. | ***Integrated Concepts*** *What is the wavelength of a 50-GeV electron, which is produced at SLAC? This provides an idea of the limit to the detail it can probe.* |
| Solution |  |
| 46. | ***Integrated Concepts*** *(a) Calculate the relativistic quantity  for 1.00-TeV protons produced at Fermilab. (b) If such a proton created a  having the same speed, how long would its life be in the laboratory? (c) How far could it travel in this time?* |
| Solution | (a)  (b)  (c) |
| 47. | ***Integrated Concepts*** *The primary decay mode for the negative pion is . (a) What is the energy release in MeV in this decay? (b) Using conservation of momentum, how much energy does each of the decay products receive, given the  is at rest when it decays? You may assume the muon antineutrino is massless and has momentum* *, just like a photon.* |
| Solution | (a)  (b) By conservation of momentum, .  By conservation of energy,  . |
| 48. | ***Integrated Concepts*** *Plans for an accelerator that produces a secondary beam of K-mesons to scatter from nuclei, for the purpose of studying the strong force, call for them to have a kinetic energy of 500 MeV. (a) What would the relativistic quantity  be for these particles? (b) How long would their average lifetime be in the laboratory? (c) How far could they travel in this time?* |
| Solution | (a)  (b)  (c) |
| 49. | ***Integrated Concepts*** *Suppose you are designing a proton decay experiment and you can detect 50 percent of the proton decays in a tank of water. (a) How many kilograms of water would you need to see one decay per month, assuming a lifetime of* *? (b) How many cubic meters of water is this? (c) If the actual lifetime is* *, how long would you have to wait on an average to see a single proton decay?* |
| Solution | (a) On average, one proton decays every , which is . For one decay every month, you would need:    Since you detect only 50% of the actual decays, you need twice this number of protons to observe one decay per month, or . Now, we know that one  molecule has 10 protons (1 from each hydrogen plus 8 from the oxygen), so we need . Finally, since we know how many molecules we need, and we know the molar mass of water, we can determine the number of kilograms of water we need.    (b) Now, we know the density of water, so we can determine the volume of water we need:  (c) If we had  of water, and the actual decay rate was , rather than , a decay would occur 100 times less often, and we would have to wait on average 100 months to see a decay. |
| 50. | ***Integrated Concepts*** *In supernovas, neutrinos are produced in huge amounts. They were detected from the 1987A supernova in the Magellanic Cloud, which is about 120,000 light years away from the Earth (relatively close to our Milky Way galaxy). If neutrinos have a mass, they cannot travel at the speed of light, but if their mass is small, they can get close. (a) Suppose a neutrino with a  mass has a kinetic energy of 700 keV. Find the relativistic quantity  for it. (b) If the neutrino leaves the 1987A supernova at the same time as a photon and both travel to Earth, how much sooner does the photon arrive? This is not a large time difference, given that it is impossible to know which neutrino left with which photon and the poor efficiency of the neutrino detectors. Thus, the fact that neutrinos were observed within hours of the brightening of the supernova only places an upper limit on the neutrino’s mass. (Hint: You may need to use a series expansion to find v for the neutrino, since its  is so large.)* |
| Solution | (a)  (b)  The large value of  means  is close to 1. The value is too small for most calculator displays, so we will use the approximation for small. In this case,  is . The distance  is related to time of travel  as , so . Therefore the difference is .  Using the expansion, .  Therefore, . |

# Test Prep For AP® Courses

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| 1. | *Two intact (not ionized) hydrogen atoms are 10 cm apart. Which of the following are true?*  (A) Gravity, though very weak, is acting between them.  (B) The neutral charge means the electromagnetic force between them can be ignored.  (C) The range is too long for the strong force to be involved. (D) All of the above. |
| Solution | (d) |
| 2. | *Explain why we only need to concern ourselves with gravitational force to describe the orbit of the Earth around the Sun.* |
| Solution | The weak and strong forces have very limited range, much shorter than the Earth-Sun distance. Electromagnetic force has unlimited range, but the net charge on both the Earth and Sun is very nearly zero. Only gravity is left. |
| 3. | *Consider four forces: the gravitational force between the Earth and the Sun; the electrostatic force between the Earth and the Sun; the gravitational force between the proton and electron in a hydrogen atom, and the electrostatic force between the proton and electron in a hydrogen atom. What is the proper ordering of the magnitude of these forces, from greatest to least?*  (A) gravity, Earth-Sun; electrostatic, Earth-Sun; gravity, hydrogen; electrostatic, hydrogen  (B) electrostatic, Earth-Sun; gravity, Earth-Sun; electrostatic, hydrogen; gravity, hydrogen  (C) gravity, Earth-Sun; gravity, hydrogen; electrostatic, hydrogen; electrostatic, Earth-Sun (D) gravity, Earth-Sun; electrostatic, hydrogen; gravity, hydrogen; electrostatic, Earth-Sun |
| Solution | (d) |
| 4. | *Deep within a nucleon, which is the stronger force between two quarks, gravity or the weak force? Why do you think so?* |
| Solution | The weak force. Despite the name, it is still much stronger than gravity. While the distances in a nucleon are tiny, the masses are tinier still. |
| 5. | *Consider the Earth-Moon system. If we were to place equal charges on the Earth and the Moon, how large would they need to be for the electrostatic repulsion to counteract the gravitational attraction?*  (A) 5.1×1013 C  (B) 5.7×1013 C  (C) 6.7×1013 C (D) 3.3×1027 C |
| Solution | (b) |
| 6. | *What is the strength of the magnetic field created by the orbiting moon, at the center of the orbit, in the system in the previous problem? (Treat the charge going around in orbit as a current loop.) How does this compare with the strength of the Earth’s intrinsic magnetic field?* |
| Solution | B = μ0I/2R = 4πx10-7(5.7x1013)/[2(27.3)(24)(3600)(3.8x108)]= 40 nT, which is about 1000 times less than the Earth’s intrinsic field |
| 7. | *An atomic nucleus consists of positively charge protons and neutral neutrons, so the electrostatic repulsion should destroy it by making the protons fly apart. This doesn’t happen because:*  (A) The strong force is ~100 times stronger than electromagnetism.  (B) The weak force generates massive particles that hold it together.  (C) Electromagnetism is sometimes attractive. (D) Gravity is always attractive. |
| Solution | (a) |
| 8. | *The atomic number of an atom is the number of protons in that atom’s nucleus. Make a prediction as to what happens to electromagnetic repulsion as the atomic number gets larger. Then, make a further prediction about what this implies about the number of neutrons in heavy nuclei.* |
| Solution | The electromagnetic repulsion increases. To hold things together with the strong force, the number of neutrons must increase. The only stable atom with fewer neutrons than protons is Helium-3. As we get to very heavy nuclei, they need more neutrons than protons to hold together. Above lead, even this no longer works and nuclei heavier than lead undergo radioactive decay. |
| 9. | *Which of the below was the first hint that conservation of mass and conservation of energy might need to be combined into one concept?*  (A) The Van de Graaff generator.  (B) New particles showing up in accelerators.  (C) Yukawa’s theory. (D) They were always related. |
| Solution | (c), though this comes from Einstein’s special relativity |
| 10. | *How fast would two 7.0-kg bowling balls each have to be going in a collision to have enough spare energy to create a 0.10-kg tennis ball? (Ignore relativistic effects.) Can you explain why we don’t see this in daily situations?* |
| Solution | 3.6×107 m/s, each. Which is over 10% the speed of light, and hence unlikely to come about outside of a particle accelerator. |
| 11. | *Taking only energy and mass into consideration, what is the minimum amount of kinetic energy a K- must have when colliding with a stationary proton to produce an Ω?*  (A) 240.5 MeV  (B) 120.0 MeV  (C) 15.5 MeV (D) 57.6 GeV |
| Solution | (a) |
| 12. | *Using only energy-mass considerations, how many K0 could a Z boson decay into? How many electrons and positrons could be produced this way?* |
| Solution | 183 K0 or 178,454, or 89,227 each electrons and positrons. |
| 13. | *A π+ and π- are moving toward each other extremely slowly. When they collide, two π0 are produced. How fast are they going? (Ignore relativistic effects.)*  (A) Barely moving  (B) 1.0×107 m/s  (C) 2.0×107 m/s (D) 7.8×107 m/s |
| Solution | (d) |
| 14. | *Assume that when a free neutron decays, it transforms into a proton and an electron. Calculate the kinetic energy of the electron.* |
| Solution | By conservation of momentum, this needs to be split between the proton and the electron. However, the proton is ~2000 times more massive, so we can simplify the calculation by assuming that it all goes to the electron. 0.8MeV. |
| 15. | *When a π- decays, the products may include:*  (A) A positron.  (B) A muon.  (C) A proton. (D) All of the above. |
| Solution | (b) |
| 16. | *Notice in Table 33.2 that the neutron has a half-life of 882 seconds. This is only for a free neutron, not bound with other neutrons and protons in a nucleus. Given the other particles in the table, and using both their charge and masses, what do you think the most likely decay products for a neutron are? Justify your answer.* |
| Solution | The correct answer is a proton, an electron, and an electron antineutrino. The students need to come up with a total charge of zero, and a total mass less than the neutron’s. |
| 17. | *How many pointlike particles would an experiment scattering high energy electrons from any meson discover within the meson?*  (A) 1  (B) 2  (C) 3 (D) 4 |
| Solution | (b) |
| 18. | *In Figure 33.16, a K- initially hits a proton, and creates three new particles. Identify them, and explain how quark flavors are conserved.* |
| Solution | A K- is anti-*u* and *s*, while a proton is uud. So we start off with the equivalent of one each of *u*, *d*, and *s* because an anti-*u* and *u* cancel each other out. The three new particles are Ω- (*sss*), K0 (*d* anti-*s*), and K+ (*u* anti-*s*). The two anti-*s* cancel with two of the *s*, so the resulting particles have the same total of one each of *u*, *d*, and *s*. Note that the original K- must have been quite energetic to create all these particles. |

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