Magnetic field @ EW phase transition

Y.F. NG, Bess

Case Western Reserve University
Cleveland, OH

Outline

1. Introduction
   - Cosmic magnetism in large scale — astrophysics
   - Cosmic magnetism from small scale — particle physics
   - Primordial Magnetic seed field @ EW scale
   - (brief) Conclusions

Outline

Observational evidence of cosmic magnetic field

- Origin of cosmic magnetism — unsolved astrophysical problem
- Magnetic field present in (almost) all galaxies $10^{-7} - 10^{-5} G$ over large spatial scale $1 Mpc$
- Also found in some galaxy clusters
- Observational techniques:
  Measurement of intensity and polarization of syncrotron emission from free relativistic e^-
  Faraday rotation of ionized EM radiation through ionized medium
  Zeeman splitting of spectral lines
  Optical polarization of starlight
- Puzzle: coherence over large scales

Observational evidence of cosmic magnetic field

- Origin of cosmic magnetism — unsolved astrophysical problem
- Magnetic field present in (almost) all galaxies $10^{-7} - 10^{-5} G$ over large spatial scale $1 Mpc$
- Also found in some galaxy clusters
- Observational techniques:
  Measurement of intensity and polarization of syncrotron emission from free relativistic e^-
  Faraday rotation of ionized EM radiation through ionized medium
  Zeeman splitting of spectral lines
  Optical polarization of starlight
- Puzzle: coherence over large scales

Observational evidence of cosmic magnetic field

- Origin of cosmic magnetism — unsolved astrophysical problem
- Magnetic field present in (almost) all galaxies $10^{-7} - 10^{-5} G$ over large spatial scale $1 Mpc$
- Also found in some galaxy clusters
- Observational techniques:
  Measurement of intensity and polarization of syncrotron emission from free relativistic e^-
  Faraday rotation of ionized EM radiation through ionized medium
  Zeeman splitting of spectral lines
  Optical polarization of starlight
- Puzzle: coherence over large scales

Observational evidence of cosmic magnetic field

- Origin of cosmic magnetism — unsolved astrophysical problem
- Magnetic field present in (almost) all galaxies $10^{-7} - 10^{-5} G$ over large spatial scale $1 Mpc$
- Also found in some galaxy clusters
- Observational techniques:
  Measurement of intensity and polarization of syncrotron emission from free relativistic e^-
  Faraday rotation of ionized EM radiation through ionized medium
  Zeeman splitting of spectral lines
  Optical polarization of starlight
- Puzzle: coherence over large scales

Observational evidence of cosmic magnetic field

- Origin of cosmic magnetism — unsolved astrophysical problem
- Magnetic field present in (almost) all galaxies $10^{-7} - 10^{-5} G$ over large spatial scale $1 Mpc$
- Also found in some galaxy clusters
- Observational techniques:
  Measurement of intensity and polarization of syncrotron emission from free relativistic e^-
  Faraday rotation of ionized EM radiation through ionized medium
  Zeeman splitting of spectral lines
  Optical polarization of starlight
- Puzzle: coherence over large scales

Astrophysical sources

- Harrison mechanism (1970) Vorticity from radiation era:
  differential rotation velocities of electron-photon fluid (relativistic)
  positively charged fluid (non-relativistic)
  -> Current J
  -> Magnetic field B
- Biermann battery (Biermann,1950)
  Electric current resulted from different surfaces of constant pressure and density from rotating systems
- galactic dynamo

Astrophysical sources

- Harrison mechanism (1970) Vorticity from radiation era:
  differential rotation velocities of electron-photon fluid (relativistic) positively charged fluid (non-relativistic)
  -> Current J
  -> Magnetic field B
- Biermann battery (Biermann,1950)
  Electric current resulted from different surfaces of constant pressure and density from rotating systems
- galactic dynamo

Astrophysical sources

- Harrison mechanism (1970) Vorticity from radiation era:
  differential rotation velocities of electron-photon fluid (relativistic)
  positively charged fluid (non-relativistic)
  -> Current J
  -> Magnetic field B
- Biermann battery (Biermann,1950)
  Electric current resulted from different surfaces of constant pressure and density from rotating systems
- galactic dynamo

- Vector (rotaion) perturbation decreases with expansion of universe
  Sizable effects expected at radiation-matter equality but incomapatible with galxy foramtion theory (Rees,1987)
- Possible to be generated much earlier?!

- Vector (rotaion) perturbation decreases with expansion of universe
  Sizable effects expected at radiation-matter equality but incomapatible with galxy foramtion theory (Rees,1987)
- Possible to be generated much earlier?!

Outline

(Cosmic) Magnetism from small scales

- Details of primodial magnetic field from first order cosmological phase transition first studied by Hogan (1983)
  Analyzed the spectrum, amplitude and evolution of tangled primordial B field produced by the ordered release of free energy during PT
- First elaborate model for QCD phase transition (Quashnock,Loeb Spergel,1989)
  Spontaneous charge separation:
  Formation of electric field behind shock fronts that precede the expanding bubbles
  (due to net baryon asymmetry and difference in equation of states of +ve and -ve charged quarks and leptons in the plasma)
- Requires intricate microphysics (i.e. bubble collisions,turbulence) to stretch the random field length

(Cosmic) Magnetism from small scales

- Details of primodial magnetic field from first order cosmological phase transition first studied by Hogan (1983)
  Analyzed the spectrum, amplitude and evolution of tangled primordial B field produced by the ordered release of free energy during PT
- First elaborate model for QCD phase transition (Quashnock,Loeb Spergel,1989)
  Spontaneous charge separation:
  Formation of electric field behind shock fronts that precede the expanding bubbles
  (due to net baryon asymmetry and difference in equation of states of +ve and -ve charged quarks and leptons in the plasma)
- Requires intricate microphysics (i.e. bubble collisions,turbulence) to stretch the random field length

(Cosmic) Magnetism from small scales

- Details of primodial magnetic field from first order cosmological phase transition first studied by Hogan (1983)
  Analyzed the spectrum, amplitude and evolution of tangled primordial B field produced by the ordered release of free energy during PT
- First elaborate model for QCD phase transition (Quashnock,Loeb Spergel,1989)
  Spontaneous charge separation:
  Formation of electric field behind shock fronts that precede the expanding bubbles
  (due to net baryon asymmetry and difference in equation of states of +ve and -ve charged quarks and leptons in the plasma)
- Requires intricate microphysics (i.e. bubble collisions,turbulence) to stretch the random field length

Outline

1. Introduction
   - Cosmic magnetism in large scale — astrophysics
   - Cosmic magnetism from small scale — particle physics
   - Primordial Magnetic seed field @ EW scale
   - (brief) Conclusions

(Cosmic) Magnetism from the fundamental blocks: (hyper)magnetic gauge fields

- $SU(2)xU(1)_Y --- > U(1)_{EM}$
- Bubble collisons
  Higgs phase is important!
- Kibble Vilenkin (1995) showed in toy Abelian U(1) model that phase equilibration during bubble collsion has real physical effects

(Cosmic) Magnetism from the fundamental blocks: (hyper)magnetic gauge fields

- $SU(2)xU(1)_Y - -- > U(1)_{EM}$
- Bubble collisons
  Higgs phase is important!
- Kibble Vilenkin (1995) showed in toy Abelian U(1) model that phase equilibration during bubble collsion has real physical effects

(Cosmic) Magnetism from the fundamental blocks: (hyper)magnetic gauge fields

- $SU(2)xU(1)_Y - -- > U(1)_{EM}$
- Bubble collisons
  Higgs phase is important!
- Kibble Vilenkin (1995) showed in toy Abelian U(1) model that phase equilibration during bubble collsion has real physical effects

Sphaleron — link between baryogenesis B field

- Sphaleron: static solution to the EW field equations of the Standard Model (Klinkhamer,F.R. and Manton,N.S. (1984) Phys. Rev. D 30)
- Chern-Simon number change = baryonic number change

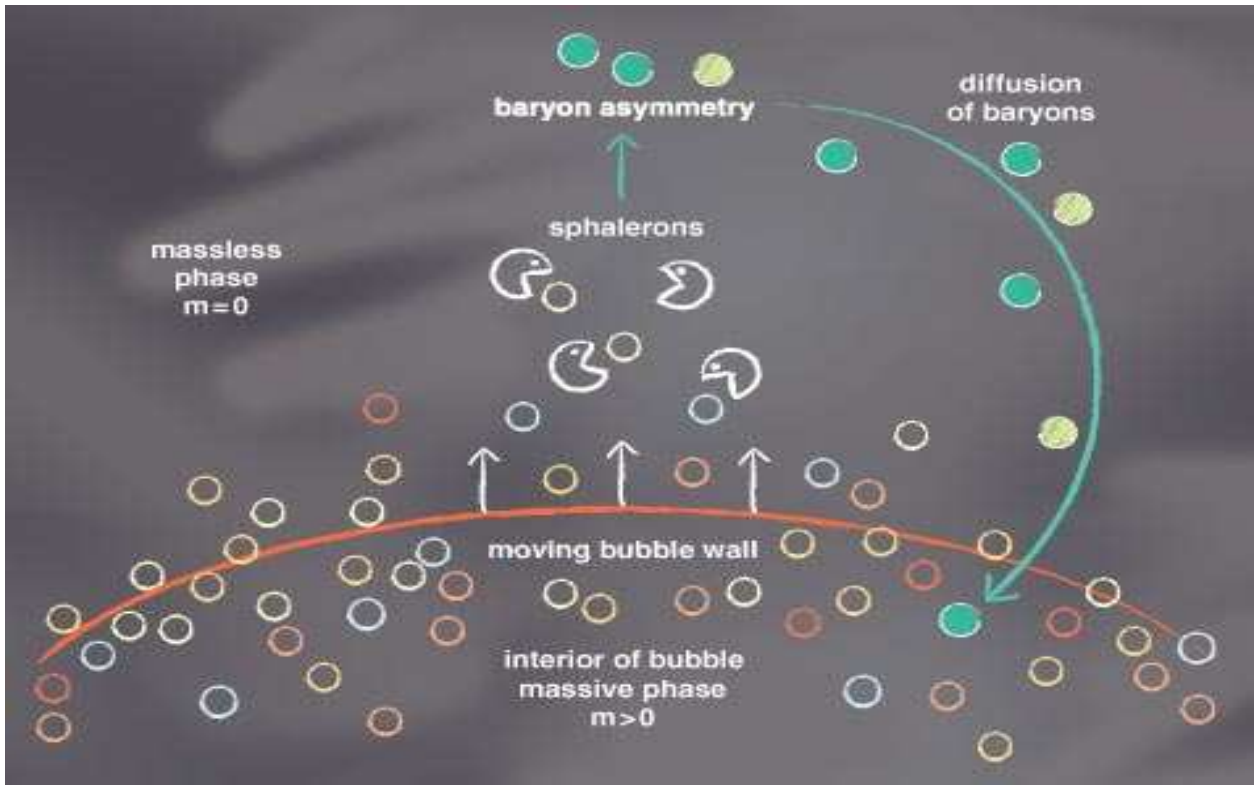

Figure: Schematic picture of sphaleron and bubbles in 1st order phase

Sphaleron — link between baryogenesis B field

- Sphaleron: static solution to the EW field equations of the Standard Model (Klinkhamer,F.R. and Manton,N.S. (1984) Phys. Rev. D 30)
- Chern-Simon number change = baryonic number change

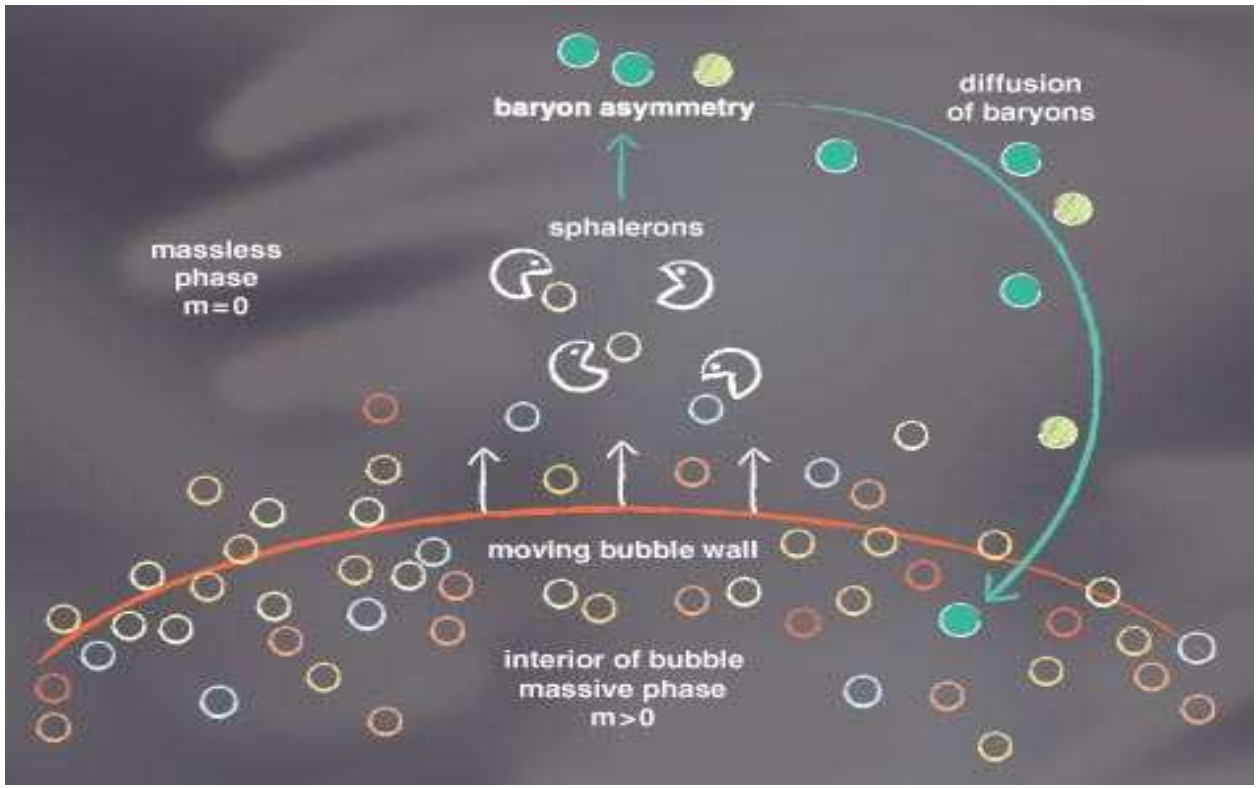

Figure: Schematic picture of sphaleron and bubbles in 1st order phase

Sphaleron Magnetic Dipole Moment

- For non-zero Weinberg angle, sphaleron has a large magnetic moment μ
  $\approx \frac{e}{\alpha_W M_W}$, owing to a loop of electric current and also a magnetic monopole-antimonopole pair.
  (Y.Nambu, Nucl. Phys, B130, 505(1977), M. Hindmarsh and M. James, Phys.Rev.D 49 6109 (1994))

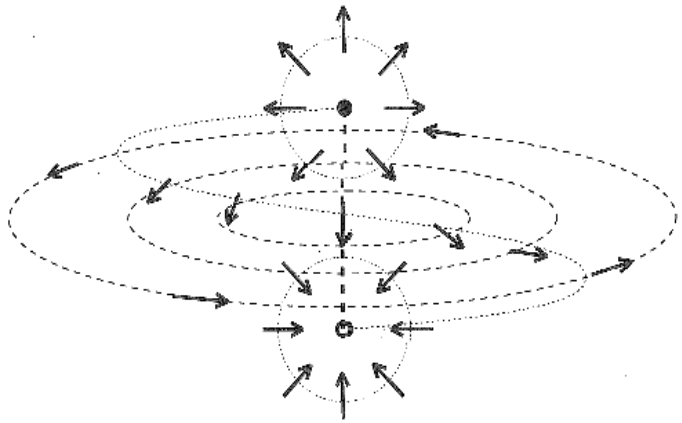

Figure 3. Isovector field configuration around the stretched sphaleron. Only one line of magnetic flux is shown. Note the twist as it travels between the ends of the line of Higgs field zeroes.

Figure: Magnetic moment of sphaleron

Sphaleron Magnetic Dipole Moment

- For non-zero Weinberg angle, sphaleron has a large magnetic moment μ
  $\approx \frac{e}{\alpha_W M_W}$, owing to a loop of electric current and also a magnetic monopole-antimonopole pair.
  (Y.Nambu, Nucl. Phys, B130, 505(1977), M. Hindmarsh and M. James, Phys.Rev.D 49 6109 (1994))

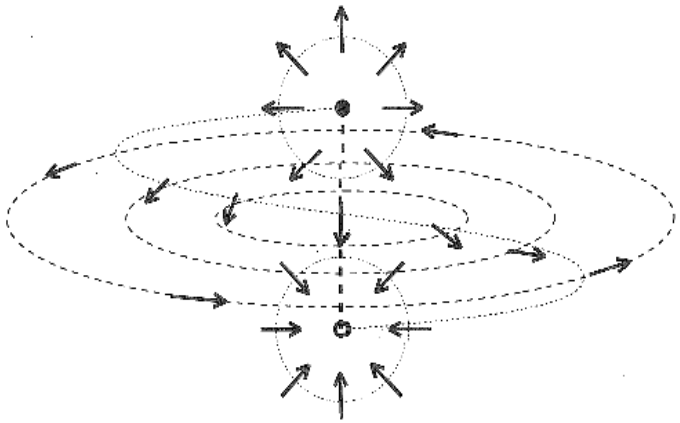

Figure 3. Isovector field configuration around the stretched sphaleron. Only one line of magnetic flux is shown. Note the twist as it travels between the ends of the line of Higgs field zeroes.

Figure: Magnetic moment of sphaleron

Sphaleron Magnetic Field

- Sphaleron is an intermediate state in the CS number changing process for baryogenesis. Any slight perturbation would cause it to decay.
- Inside the bubbles, the conductivity of plasma is very high. The magnetic field lines essentially get frozen out after sphaleron decay.
  -> Magnetic seed field!
- Natural mechanism for generation. How do we sustain and amplify the field?!
- Twisted field configurations — linking number not equal to zero.

Sphaleron Magnetic Field

- Sphaleron is an intermediate state in the CS number changing process for baryogenesis. Any slight perturbation would cause it to decay.
- Inside the bubbles, the conductivity of plasma is very high. The magnetic field lines essentially get frozen out after sphaleron decay.
  -> Magnetic seed field!
- Natural mechanism for generation. How do we sustain and amplify the field?!
- Twisted field configurations — linking number not equal to zero.

Sphaleron Magnetic Field

- Sphaleron is an intermediate state in the CS number changing process for baryogenesis. Any slight perturbation would cause it to decay.
- Inside the bubbles, the conductivity of plasma is very high. The magnetic field lines essentially get frozen out after sphaleron decay.
  -> Magnetic seed field!
- Natural mechanism for generation. How do we sustain and amplify the field?!
- Twisted field configurations — linking number not equal to zero.

Sphaleron Magnetic Field

- Sphaleron is an intermediate state in the CS number changing process for baryogenesis. Any slight perturbation would cause it to decay.
- Inside the bubbles, the conductivity of plasma is very high. The magnetic field lines essentially get frozen out after sphaleron decay.
  -> Magnetic seed field!
- Natural mechanism for generation. How do we sustain and amplify the field?!
- Twisted field configurations — linking number not equal to zero.

Helical field and inverse cascade

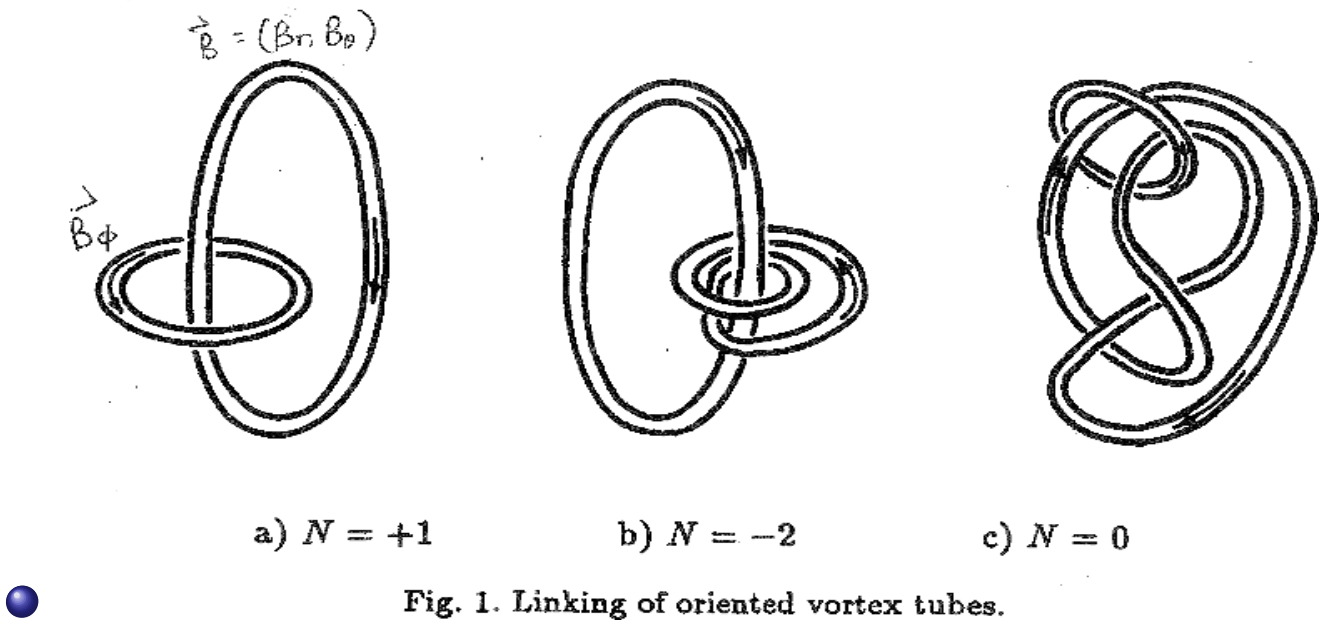

Fig. 1. Linking of oriented vortex tubes.

Figure: schematic drawing of sphaleron as source of linked B fields

- Helicity conservation and energy conservation
- Inverse cascade: helical field is stretched from small to larger length scales

Helical field and inverse cascade

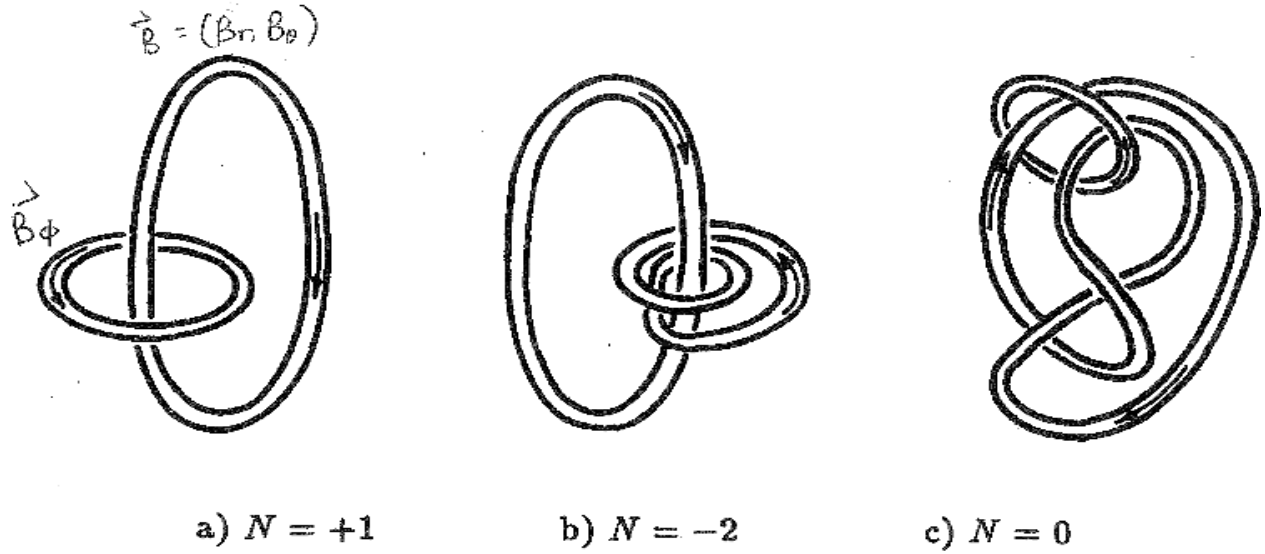

Fig. 1. Linking of oriented vortex tubes.

Figure: schematic drawing of sphaleron as source of linked B fields

- Helicity conservation and energy conservation
- Inverse cascade: helical field is stretched from small to larger length scales

Helical field and inverse cascade

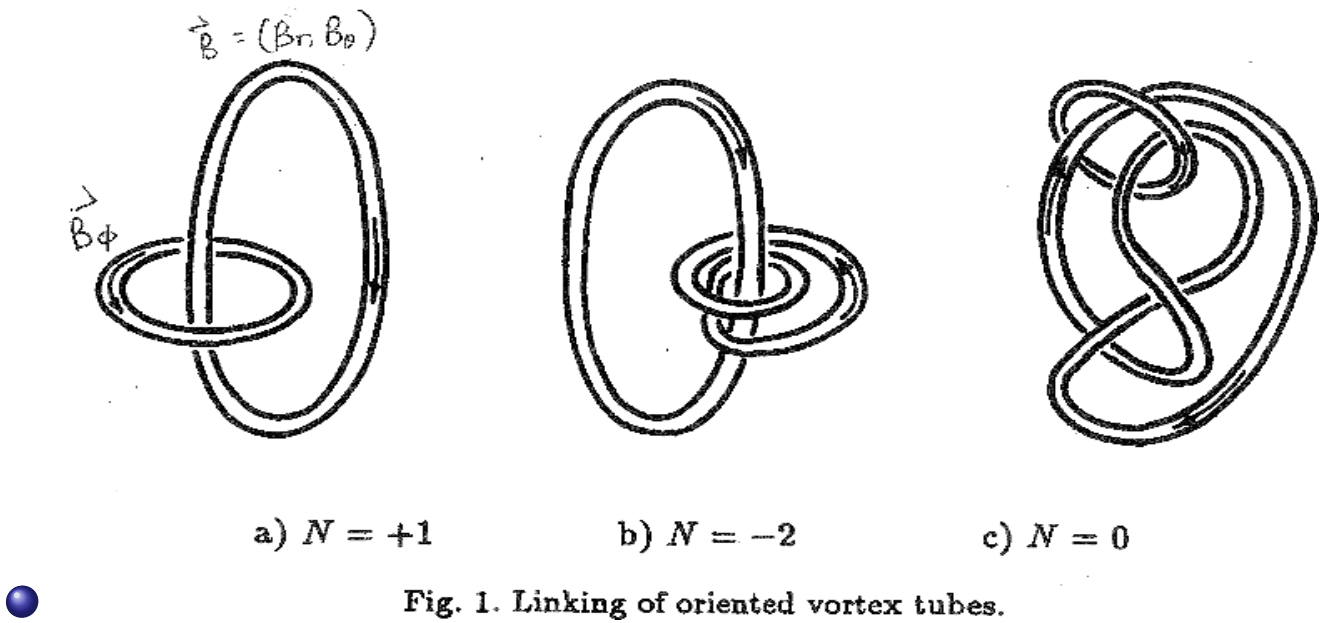

Fig. 1. Linking of oriented vortex tubes.

Figure: schematic drawing of sphaleron as source of linked B fields

- Helicity conservation and energy conservation
- Inverse cascade: helical field is stretched from small to larger length scales

(Hyper)magnetic field Baryogenesis

- Effect of magnetic dipole moment of sphaleron with background (hyper)magnetic field (hep-ph/9903227)
- Conclusions: Lowers energy barrier between vacua. Does not help baryogenesis.
- Helicity of hypermagnetic field on rate of baryogenesis near bubble walls?! (hep-ph: 0002197)
- turbulence — kinetic magnetic?!

(Hyper)magnetic field Baryogenesis

- Effect of magnetic dipole moment of sphaleron with background (hyper)magnetic field (hep-ph/9903227)
- Conclusions: Lowers energy barrier between vacua. Does not help baryogenesis.
- Helicity of hypermagnetic field on rate of baryogenesis near bubble walls?! (hep-ph: 0002197)
- turbulence — kinetic magnetic?!

(Hyper)magnetic field Baryogenesis

- Effect of magnetic dipole moment of sphaleron with background (hyper)magnetic field (hep-ph/9903227)
- Conclusions: Lowers energy barrier between vacua. Does not help baryogenesis.
- Helicity of hypermagnetic field on rate of baryogenesis near bubble walls?! (hep-ph: 0002197)
- turbulence — kinetic magnetic?!

(Hyper)magnetic field Baryogenesis

- Effect of magnetic dipole moment of sphaleron with background (hyper)magnetic field (hep-ph/9903227)
- Conclusions: Lowers energy barrier between vacua. Does not help baryogenesis.
- Helicity of hypermagnetic field on rate of baryogenesis near bubble walls?! (hep-ph: 0002197)
- turbulence — kinetic magnetic?!

Outline

- Possible (and natural?! depending on your taste) to generate primordial magnetic seed field,but hard to amplify the length scale
- Richness of non-perturbative phenomena (i.e. sphaleron, higgs phases)
- Understanding of full bubble dynamics (i.e. turbulence) MHD studies are essential
- (very) upcoming experimental probe: CMB polarizations data of PLANCK!
- further understanding of (hyper)magnetic field background field in EW baryogenesis scenario

- Possible (and natural?! depending on your taste) to generate primordial magnetic seed field,but hard to amplify the length scale
- Richness of non-perturbative phenomena (i.e. sphaleron, higgs phases)
- Understanding of full bubble dynamics (i.e. turbulence) MHD studies are essential
- (very) upcoming experimental probe: CMB polarizations data of PLANCK!
- further understanding of (hyper)magnetic field background field in EW baryogenesis scenario

- Possible (and natural?! depending on your taste) to generate primordial magnetic seed field,but hard to amplify the length scale
- Richness of non-perturbative phenomena (i.e. sphaleron, higgs phases)
- Understanding of full bubble dynamics (i.e. turbulence) MHD studies are essential
- (very) upcoming experimental probe: CMB polarizations data of PLANCK!
- further understanding of (hyper)magnetic field background field in EW baryogenesis scenario

- Possible (and natural?! depending on your taste) to generate primordial magnetic seed field,but hard to amplify the length scale
- Richness of non-perturbative phenomena (i.e. sphaleron, higgs phases)
- Understanding of full bubble dynamics (i.e. turbulence) MHD studies are essential
- (very) upcoming experimental probe: CMB polarizations data of PLANCK!
- further understanding of (hyper)magnetic field background field in EW baryogenesis scenario

- Possible (and natural?! depending on your taste) to generate primordial magnetic seed field,but hard to amplify the length scale
- Richness of non-perturbative phenomena (i.e. sphaleron, higgs phases)
- Understanding of full bubble dynamics (i.e. turbulence) MHD studies are essential
- (very) upcoming experimental probe: CMB polarizations data of PLANCK!
- further understanding of (hyper)magnetic field background field in EW baryogenesis scenario

(References)

- Review on Cosmic Magnetic Fields:
  astro-ph/9707300 (Enqvist) astro-ph/0009061 (Drasso Robinstein)more particle physics);
  hep-ph/0208152 (Giovannini, more on cosmological observables constraints);
  astro-ph/0207240 (Widrow,galactic and extragalactic); P.P. Kronberg, Rep. Prog. Phys. 57 (1994) 325
- Astrophysical magnetic field dynamo studies:
  astro-ph: 0405052 (Brandenburg Subramanian)
- Electroweak string discussion (on sphaleron, referencedin)
  hep-ph/9904229V (Vachaspati Achucarro)
- Analytical studies of observational remanents of B field from cosmological phase transitions
  CMB: astro-ph; GW: astro-ph/0905.0641 Tina Kahniashvili is coming in late July!

(References)

- Review on Cosmic Magnetic Fields:
  astro-ph/9707300 (Enqvist) astro-ph/0009061 (Drasso Robinstein)more particle physics);
  hep-ph/0208152 (Giovannini, more on cosmological observables constraints);
  astro-ph/0207240 (Widrow,galactic and extragalactic); P.P. Kronberg, Rep. Prog. Phys. 57 (1994) 325
- Astrophysical magnetic field dynamo studies:
  astro-ph: 0405052 (Brandenburg Subramanian)
- Electroweak string discussion (on sphaleron, referencedin)
  hep-ph/9904229V (Vachaspati Achucarro)
- Analytical studies of observational remanents of B field from cosmological phase transitions
  CMB: astro-ph; GW: astro-ph/0905.0641 Tina Kahniashvili is coming in late July!

(References)

- Review on Cosmic Magnetic Fields:
  astro-ph/9707300 (Enqvist) astro-ph/0009061 (Drasso Robinstein)more particle physics);
  hep-ph/0208152 (Giovannini, more on cosmological observables constraints);
  astro-ph/0207240 (Widrow,galactic and extragalactic); P.P. Kronberg, Rep. Prog. Phys. 57 (1994) 325
- Astrophysical magnetic field dynamo studies:
  astro-ph: 0405052 (Brandenburg Subramanian)
- Electroweak string discussion (on sphaleron, referencedin)
  hep-ph/9904229V (Vachaspati Achucarro)
- Analytical studies of observational remanents of B field from cosmological phase transitions
  CMB: astro-ph; GW: astro-ph/0905.0641 Tina Kahniashvili is coming in late July!

(References)

- Review on Cosmic Magnetic Fields:
  astro-ph/9707300 (Enqvist) astro-ph/0009061 (Drasso Robinstein)more particle physics);
  hep-ph/0208152 (Giovannini, more on cosmological observables constraints);
  astro-ph/0207240 (Widrow,galactic and extragalactic); P.P. Kronberg, Rep. Prog. Phys. 57 (1994) 325
- Astrophysical magnetic field dynamo studies:
  astro-ph: 0405052 (Brandenburg Subramanian)
- Electroweak string discussion (on sphaleron, referencedin)
  hep-ph/9904229V (Vachaspati Achucarro)
- Analytical studies of observational remanents of B field from cosmological phase transitions
  CMB: astro-ph; GW: astro-ph/0905.0641 Tina Kahniashvili is coming in late July!