DIVISIBILITY OF THE DIRAC MAGNETIC MONOPOLE
AS A TWO-VARIABLE BUNDLE OVER THE THREE-SPHERE

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Abstract. We show that when the gerbe $\mu$ representing a magnetic monopole is viewed as a virtual 2-vector bundle, then it decomposes, modulo torsion, as two times a virtual 2-vector bundle $\varsigma$. We therefore interpret $\varsigma$ as representing half a magnetic monopole, or a semipole.

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§1. Introduction

Let $A$ be a connective $S$-algebra, where $S$ is the sphere spectrum, and let $K(A) = K_0(\pi_0(A)) \times BGL_{\infty}(A)^+$ be its algebraic $K$-theory space. The natural map $w: BGL_1(A) \to K(A)$ is given by the inclusion of $1 \times 1$ matrices $BGL_1(A) \to BGL_{\infty}(A)$, followed by the canonical map into the plus construction. Let $ku$ denote the connective complex $K$-theory spectrum, with $\pi_*ku = \mathbb{Z}[u]$, $|u| = 2$, and let $\pi: ku \to H\mathbb{Z}$ be the unique 2-connected $S$-algebra map to the integral Eilenberg–Mac Lane spectrum. Its homotopy fiber is $bu$, with $\pi_*bu = (u) \subset \mathbb{Z}[u]$. We define $BSL_1(ku)$ and $K(\pi)$ as the homotopy fibers of the induced maps $\pi: BGL_1(ku) \to BGL_1(\mathbb{Z})$ and $\pi: K(ku) \to K(\mathbb{Z})$, respectively, so that we have the following commutative diagram of horizontal homotopy fiber sequences

\begin{equation}
\begin{array}{ccc}
BSL_1(ku) & \longrightarrow & BGL_1(ku) \\
\downarrow & & \downarrow \pi \\
K(\pi) & \longrightarrow & BGL_1(\mathbb{Z}) \\
\downarrow w & & \downarrow w \\
K(ku) & \longrightarrow & K(\mathbb{Z}).
\end{array}
\end{equation}

We have a map from the Eilenberg–Mac Lane complex $K(\mathbb{Z}, 3)$ to the upper left hand corner of this diagram, induced by the infinite loop space inclusion $BU(1) \to$
BU⊗ and the equivalences $K(\mathbb{Z}, 3) \simeq BBU(1)$ and $BBU⊗ \simeq BSL_1(ku)$. Recall that the space $K(\mathbb{Z}, 3)$ represents gerbes with band $U(1)$ [Br93, Ch. V], whereas $K(ku)$ represents virtual 2-vector bundles [BDR04, Thm. 4.10], [BDRR]. A 2-vector bundle of rank 1 is the same as a gerbe, and the composite map

\[(1.2) \quad K(\mathbb{Z}, 3) \to K(ku)\]

represents the construction that views a gerbe as a virtual 2-vector bundle.

We now consider gerbes and 2-vector bundles over the base space $S^3$. There is a map $\mu: S^3 \to K(\mathbb{Z}, 3)$ representing a generator of $H^3(S^3) = \mathbb{Z}$, or dually, corepresenting a generator of $\pi_3 K(\mathbb{Z}, 3) = \mathbb{Z}$. It also represents a $U(1)$-gerbe over $S^3$, which is interpreted in [Br93, Ch. VII] as a mathematical model for a magnetic monopole, stationary in time and localized at one point.

Parallel transport in this gerbe, around closed loops in $S^3$, defines a holonomy line bundle over the free loop space of $S^3$ [Br93, Ch. VI]. Its complex 1-dimensional fibers can be interpreted as the state spaces of these free loops, viewed as strings in $S^3$. Parallel transport over compact surfaces in $S^3$, between tensor products of copies of this line bundle, defines an action functional that makes these state spaces part of a field theory. Here the compact surfaces are viewed as world sheets in $S^3$. In a quantized theory one would consider Hilbert spaces of sections in the holonomy line bundle, rather than its individual fibers, as the state spaces.

Following the point of view explained in [AR, §5.5], we also view 2-vector bundles over a base space as data defining (virtual) state spaces and action functionals for strings in that base. More field theories arise this way, since the state spaces are no longer restricted to being 1-dimensional, hence it is also possible to model more kinds of particles by 2-vector bundles than those arising from gerbes.

In particular we may ask, as the second author did, how the magnetic monopole $\mu$ over $S^3$ decomposes when viewed as a virtual 2-vector bundle. Does it remain a single particle?

In mathematical terms, the question is: “What is the structure of $\pi_3 K(ku) = K_3(ku)$, and what is the image of $\mu \in \pi_3 K(\mathbb{Z}, 3)$ in that group?” In effect, the addition in the abelian group $\pi_3 K(ku)$ is induced by the $H$-group multiplication of $K(ku)$, which represents the direct sum of virtual 2-vector bundles, or in the above terms, the superposition of two particles. The surprising answer, which the title of this paper refers to, is that modulo torsion, $\mu$ becomes divisible by two as a virtual 2-vector bundle. In more detail, there are virtual 2-vector bundles $\varsigma$ and $\nu$ over $S^3$, with $24\nu = 0$, such that

\[(1.3) \quad \mu + \nu = 2\varsigma\]

in $K_3(ku)$. Modulo torsion, $\varsigma$ is therefore half a magnetic monopole. Ignoring torsion is justified in the physical interpretation, since the numerical invariants of a field theory traditionally take torsion-free values, and will send $\nu$ to zero. On the other hand, both $\mu$ and $\varsigma$ have infinite order in $K_3(ku)$.

\section{Statement of results}

Let $i: S \to K(ku)$ be the unit map, and recall that $\pi_3(S) = \mathbb{Z}/24\{\nu\}$ and $K_3(\mathbb{Z}) \cong \mathbb{Z}/48\{\lambda\}$ [LS76]. The composite map $\pi i: S \to K(\mathbb{Z})$ induces the injection $\pi_3(S) \to K_3(\mathbb{Z})$ that takes $\nu$ to $2\lambda$. 
By [Wa78, Prop. 1.2], as generalized in [BM94, Prop. 10.9], the homotopy fiber $K(\pi)$ is 2-connected. Hence $K_i(ku) \to K_i(\mathbb{Z})$ is an isomorphism for $i \leq 2$. Here is what happens in dimension three:

**Theorem 2.1.** (a) The maps $K(\mathbb{Z}, 3) \to BSL_1(ku) \to K(\pi)$ induce isomorphisms

$$\mathbb{Z}\{\mu\} = \pi_3K(\mathbb{Z}, 3) \xrightarrow{\cong} \pi_3BSL_1(ku) \xrightarrow{\cong} K_3(\pi).$$

(b) The unit map $i: S \to K(ku)$ induces a homomorphism

$$\mathbb{Z}/24\nu = \pi_3(S) \xrightarrow{i_*} K_3(ku)$$

that identifies the source with the torsion subgroup in the target. We abbreviate $i_*(\nu)$ to $\nu \in K_3(ku)$.

(c) The homotopy fiber sequence $K(\pi) \to K(ku) \to K(\mathbb{Z})$ induces a short exact sequence

$$0 \to K_3(\pi) \to K_3(ku) \xrightarrow{\pi_*} K_3(\mathbb{Z}) \to 0$$

which is isomorphic to the nontrivial extension

$$0 \to \mathbb{Z}\{\mu\} \to \mathbb{Z}\{\varsigma\} \oplus \mathbb{Z}/24\nu \xrightarrow{\pi_*} \mathbb{Z}/48\lambda \to 0.$$

Here the first map takes $\mu$ to $2\varsigma - \nu$, and the second map takes $\varsigma$ to $\lambda$ and $\nu$ to $2\lambda$.

**Corollary 2.2.** The map $K(\mathbb{Z}, 3) \to K(ku)$ that represents viewing $U(1)$-gerbes as virtual 2-vector bundles induces the homomorphism

$$\mathbb{Z}\{\mu\} = \pi_3K(\mathbb{Z}, 3) \to K_3(ku) = \mathbb{Z}\{\varsigma\} \oplus \mathbb{Z}/24\nu$$

that takes $\mu$ to $2\varsigma - \nu$, where $24\nu = 0$. The image of $\varsigma \in K_3(ku)$ in $K_3(\mathbb{Z})$ is the generating element $\lambda$ of order forty-eight.

**Corollary 2.3.** There is no “determinant map”

$$\det: K(ku) \to BGL_1(ku)$$

such that the composite $\det \circ w$ is an equivalence.

Corollary 2.2 is readily extracted from Theorem 2.1(a) and (c). Corollary 2.3 follows, since $\det: K_3(ku) \to \pi_3BGL_1(ku) \cong \mathbb{Z}\{\mu\}$ cannot map $2\varsigma - \nu$ to $\mu$.

**Remark 2.4.** For commutative rings $R$ there is a determinant map $\det: K(R) \to BGL_1(R)$, which is left inverse to $w$. On the other hand, it follows from [Wa82, Cor. 3.7] that $w: BGL_1(S) \to K(S)$ admits no such retraction up to homotopy. In [AR, §5.2], the first and third authors used the existence of a rational determinant map $\det_Q: K(ku) \to BSL_1(ku)_Q \cong (BBU_1)_Q$ to define the rational anomaly bundle of a 2-vector bundle, generalizing the definition of the anomaly line bundle of a gerbe. Corollary 2.3 shows no such generalization can be integrally defined on all of $K(ku)$. This suggests that an integral anomaly bundle will only be defined on a space covering $K(ku)$, classifying 2-vector bundles with some form of higher orientation.
\section{Proofs}

Proof of Thm. 2.1(a). In view of the infinite loop space splitting $BU \cong BU(1) \times BSU$ it is clear that $K(\mathbb{Z}, 3) \cong BBU(1) \to BBU \cong BSL_1(ku)$ is 4-connected. For the second part, we refer to the proof of [BM94, Prop. 10.9] to see that there is an isomorphism

\begin{equation}
\text{colim}_n M_n(\pi_2(bu))/[GL_n(\pi_0(ku)), M_n(\pi_2(bu))] \cong K_3(\pi).
\end{equation}

Here $M_n$ denotes the ring of $n \times n$ matrices, and $GL_n$ acts on $M_n$ by conjugation. Furthermore, under the isomorphism (3.1), $\pi_3 BSL_1(ku) \to K_3(\pi)$ factors as

\begin{equation}
\pi_3 BSL_1(ku) \cong \pi_2(bu) = M_1(\pi_2(bu))/[GL_1(\pi_0(ku)), M_1(\pi_2(bu))],
\end{equation}

followed by the canonical map from the term $n = 1$ into the colimit in (3.1). For each $n \geq 1$ the matrix trace induces an isomorphism [Ka83, Prop. 1.3]

\[ M_n(\pi_2(bu))/[GL_n(\pi_0(ku)), M_n(\pi_2(bu))] \xrightarrow{\cong} \pi_2(bu)/[\pi_0(ku), \pi_2(bu)] = \pi_2(bu), \]

hence each structure map in the colimit is an isomorphism, and therefore the canonical map from (3.2) to $K_3(\pi)$ is also an isomorphism. \qed

To proceed, we make use of the natural trace map $tr: K(A) \to \text{THH}(A)$ to topological Hochschild homology [BHM93]. We define $\text{THH}(\pi)$ as the homotopy fiber of $\pi: \text{THH}(ku) \to \text{THH}(\mathbb{Z})$, so as to obtain the following commutative diagram of horizontal homotopy fiber sequences

\begin{equation}
\begin{array}{ccc}
K(\pi) & \xrightarrow{\pi} & K(\mathbb{Z}) \\
\downarrow & & \downarrow \text{tr} \\
\text{THH}(\pi) & \xrightarrow{\pi} & \text{THH}(\mathbb{Z}).
\end{array}
\end{equation}

Proof of Thm. 2.1(b) and (c). Passing to homotopy groups, we get the following vertical map of short exact sequences

\begin{equation}
\begin{array}{c}
0 \to K_3(\pi) \to K_3(ku) \xrightarrow{\pi_*} K_3(\mathbb{Z}) \to 0 \\
\downarrow \cong & & \downarrow \text{tr}_* & & \\
0 \to \text{THH}_3(\pi) \to \text{THH}_3(ku) \xrightarrow{\pi_*} \text{THH}_3(\mathbb{Z}) \to 0.
\end{array}
\end{equation}

Here $K_3(\pi) \to K_3(ku)$ is injective because $K_4(\mathbb{Z}) = 0$ [Ro00], and $K_3(ku) \to K_3(\mathbb{Z})$ is surjective because $K_2(\pi) = 0$. Furthermore, $\text{THH}_3(\pi) \to \text{THH}_3(ku)$ is injective because $\text{THH}_4(\mathbb{Z}) = 0$ [Bö], [FP98, Cor. 3.2] and $\text{THH}_3(ku) \to \text{THH}_3(\mathbb{Z})$ is surjective because

\[ \mathbb{Z}/48\{\lambda\} = K_3(\mathbb{Z}) \xrightarrow{\text{tr}_*} \text{THH}_3(\mathbb{Z}) = \mathbb{Z}/2\{\epsilon\}. \]
commutes. The left hand vertical map $K_3(\pi) \to \text{THH}_3(\pi)$ is split injective, by [BM94, Thm. 10.12]. We shall soon see that it is in fact an isomorphism.

The 2-primary homotopy of $\text{THH}(ku)$ is fully computed in [AHL], but in low dimensions the following direct argument suffices. The homotopy cofiber $ku/S$ of $S \to ku$ is 1-connected, with $\pi_2(ku/S) \cong \mathbb{Z}$. By construction, $\text{THH}(ku)$ is the geometric realization of a simplicial spectrum, and the map from the $(n-1)$-skeleton to the $n$-skeleton has cofiber $\Sigma^n ku \wedge (ku/S) \wedge \cdots \wedge (ku/S)$, with $n$ copies of $ku/S$, which is $(3n-1)$-connected. By induction, the map from the 1-skeleton to all of $\text{THH}(ku)$ is 5-connected. Furthermore, the 0-simplices $ku$ split off from the 1-skeleton of $\text{THH}(ku)$ since $ku$ is commutative, so $\text{THH}_3(ku) \cong \pi_3(ku) \oplus \pi_3(\Sigma ku \wedge (ku/S)) \cong \mathbb{Z}\{e\}$, for some choice of generator $e$.

Diagram (3.4) is therefore isomorphic to

$$
\begin{array}{cccccc}
0 & \to & \mathbb{Z}\{\mu\} & \to & K_3(ku) & \xrightarrow{\pi_*} \mathbb{Z}/48\{\lambda\} & \to & 0 \\
& & \cong & & \text{tr}_* & & \\
0 & \to & \mathbb{Z}\{2\epsilon\} & \to & \mathbb{Z}\{\epsilon\} & \xrightarrow{\pi_*} \mathbb{Z}/2\{\epsilon\} & \to & 0 
\end{array}
$$

where the split injection $\mathbb{Z}\{\mu\} \to \mathbb{Z}\{2\epsilon\}$ must be an isomorphism. (We assume that we have chosen our orientations so that $\mu$ maps to $2\epsilon$, rather than $-2\epsilon$.)

The right hand square is a pullback, so there is a short exact sequence

$$
0 \to \mathbb{Z}/24\{\nu\} \xrightarrow{i_*} K_3(ku) \xrightarrow{\text{tr}_*} \mathbb{Z}\{\epsilon\} \to 0,
$$

where the image of the injective homomorphism $i_* : \pi_3(S) \to K_3(ku)$ is identified under $\pi_* : K_3(ku) \to K_3(\mathbb{Z})$ with the kernel of $\text{tr}_* : K_3(\mathbb{Z}) \to \text{THH}_3(\mathbb{Z})$. Hence the image of $i_*$ equals the kernel of $\text{tr}_* : K_3(ku) \to \text{THH}_3(ku)$. To fix a splitting of (3.6), we let $\varsigma \in K_3(ku)$ be the class mapping to $\epsilon$ in $\text{THH}_3(ku)$ and to $\lambda$ in $K_3(\mathbb{Z})$. This is admissible, since both classes map to $e$ in $\text{THH}_3(\mathbb{Z})$.

Then

$$
K_3(ku) \cong \mathbb{Z}\{\varsigma\} \oplus \mathbb{Z}/24\{\nu\},
$$

and $\mu \in K_3(\pi)$ maps to $2\varsigma$ in $K_3(ku)$ modulo the image of $i_*$. Since $\mu$ continues to 0 in $K_3(\mathbb{Z})$, the exact formula must be $2\varsigma - \nu$. □

References


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