Galilean type IIA backgrounds and a map

Harvendra Singh

Theory Division, Saha Institute of Nuclear Physics
1/AF Bidhannagar, Kolkata 700064, India

E-mail: h.singh [AT] saha.ac.in

Abstract

We study non-relativistic $AdS_4 \times CP^3$ solutions with dynamical exponent 3 in type IIA string theory, both with and without Romans mass. The compactifications to four dimensions are found to describe Proca fields in anti-de Sitter spacetime. This leads us to conclude that the massive and massless IIA theories should be identified in four dimensions and the Romans’ mass should be identified with the ‘flux’ along $CP^3$. From supergravity point of view, it is suggestive of a four-dimensional symmetry that rotates Romans mass into the flux along $CP^3$. We also identify M-theory Galilean (ABJM) background which gives rise to the nonrelativistic type IIA solution.
1 Introduction

Recent applications of AdS/CFT holography [1,2,3] to strongly coupled non-relativistic systems, showing scaling behaviour near quantum critical points, have been a subject of wide attention [4]-[22]. For studying the behaviour near quantum critical points one considers the nonrelativistic case of AdS/CFT holography which exhibits a reduced conformal symmetry [4,5] or ‘Schroedinger group’ [23, 24, 25]. Particularly holographic study of strongly coupled fermionic systems at finite density has been termed as ‘AdS/Atoms’ [4,5]. The Galilean symmetries in physical systems have been studied even earlier [26, 27]. For the study of finite temperature properties like phase transitions, transport and viscosity etc, one includes black holes in the AdS backgrounds [6,7]. In parallel studies of superconductivity under the probe approximations, the bulk AdS geometry generically involves spontaneously broken (Higgs) phases where the Abelian field coupled to a complex scalar field becomes massive [6,10].

By now there have been quite a few explicit examples where non-relativistic anti-de-Sitter (NRadS) geometries could be embedded in type II string theory and M-theory, see [9,11,12,13,14,15,18,19,20,21]. Also recently there have been some attempts to obtain non-relativistic solutions in the massive type IIA supergravity of Romans [28]. The Romans theory is the only known example of a 10-dimensional maximal supergravity where \( B_{\mu \nu} \) field is explicitly massive to begin with. There is also a cosmological constant in the theory. Thus massive type IIA sugra provides an unique case to study interesting N RadS solutions and the holographic dual Galilean field theory. In a recent work [20] we specifically obtained a non-relativistic \( AdS_4 \times M^6 \) solution, where \( M^6 \) is a Einstein space, e.g. \( CP^3, S^3 \times S^3 \) or \( S^6 \). It is intriguing to ask what is its relationship with the \( AdS_4 \times CP^3 \) ABJM backgrounds of ordinary type IIA [29], and its Galilean generalisation which we find in this paper. To recall, there also exists this fact for long, that the type IIA can be lifted to M-theory while there is no 11-dimensional analogue for the Romans massive type IIA theory. However, the two theories when compactified to lower dimensions could be mapped into each other via T-dualities [31,32,33], by switching on appropriate fluxes. We would like to see if there does exist such a map for the Galilean solutions in the two theories.

In this work we want to discuss some Galilean examples involving \( CP^3 \) compactifications and explore the relationship between ordinary type IIA and its only known massive cousin. In section-2 we construct Galilean solution of type IIA with dynamical exponent 3. We identify this as a non-relativistic generalisation of the ABJM solution. We also discuss its M-theory origin and also find 4-dimensional compactified effective action. In section-3 we review previously known Galilean so-
lution in Romans’ theory which has almost identical features. The section-4 contains
the map involving Galilean solutions of ordinary type IIA and the Romans theory.
We summarize in section-5.

2 Galilean type-IIA solution

We look for a non-relativistic generalisation of the ABJM solution [29] of type IIA
string theory. To solve the equations of motion of type IIA theory we take the
following non-relativistic ansatz for \( \text{AdS}_4 \times \mathbb{C}P^3 \) metric (Einstein frame) and fields
(particularly with dynamical exponent 3)

\[
\begin{align*}
    ds^2_{\text{IIA}} &= \sqrt{R^3k} \left( \frac{1}{4} \left( -\frac{2\beta^2(dx^+)^2}{z^6} + \frac{-2dx^+dx^- + dy^2 + dz^2}{z^2} \right) + ds^2_{\mathbb{C}P^3} \right), \\
    e^\phi &= \frac{R}{k}, \quad F_{+-yz} = \frac{3R^2k}{8z^4}, \\
    B_{+y} &= \beta \frac{R^2p}{z^4}, \quad C = \beta \frac{qk}{z^3} dx^+ + k\omega
\end{align*}
\]

(1)

where \( J = d\omega \) defines the Kähler 2-form over \( \mathbb{C}P^3 \). These Galilean solutions exist
provided

\[
    q = 2p = \frac{1}{\sqrt{2}}.
\]

The string coupling is fixed by the ratio \( \frac{R}{k} \equiv g_o \). The parameters \( R \) and \( k \) have
interpretation as in the ABJM work [29]. That is, \( R \) is the measure of the radius of
\( \mathbb{C}P^3 \) in the string frame \( (\alpha' = 1) \) and \( k \) is the quantum of 2-form flux along \( \mathbb{C}P^3 \).
While in M-theory picture \( k \) is the order of the orbifold \( R^8/\mathbb{Z}_k \). Since \( k \) fixes the
string coupling, therefore \( k \) must be taken sufficiently large to remain in the type IIA
framework. The constant \( \beta \) in the above is arbitrary and can be easily scaled away.
However we have kept it here because a relativistic solution is readily obtained by
simply setting \( \beta = 0 \) in (1).

The D-brane interpretation remains the same as of the ABJM except that we
have got extra non-relativistic matter fields \( B_{+y} \) and \( C_+ \) contributing as the ‘dust’.
Due to this the \( T_{++} \) component of energy-momentum tensor is nontrivial which
otherwise would vanish in the relativistic case. Rest of the components of the energy
momentum tensor stay as in the relativistic ABJM case. We also note that the
transverse \( \mathbb{C}P^3 \) metric is undeformed.

Thus to summarise, there exists a non-relativistic \( \text{AdS}_4 \times \mathbb{C}P^3 \) background in
type IIA string theory with the dynamical exponent being 3. These solutions have
Schrödinger deformation \( (dx^+)^2 \) in the metric and have \( B \) field. So these are more
like the Schrödinger solutions (with dynamical exponent 2) of [9] and should be
obtainable via TsT duality transformation. We shall comment about the supersymmetries in the next subsection.

2.1 Galilean ABJM theory

An M-theory lift of the type IIA Galilean solutions (1) can be done and the corresponding 11-dimensional background is

\[ ds_{11}^2 = \frac{\hat{R}^2}{4}(-2e^+e^- + e^y e^y + e^z e^z) + \hat{R}^2 d\sigma_{CP^3} + \frac{\hat{R}^2}{k^2} e^\psi e^\psi, \]

\[ C_3 = \frac{\hat{R}^3}{8} e^+ \wedge e^- \wedge e^y + \frac{\hat{R}^3}{2\sqrt{2k}} e^+ \wedge e^y \wedge e^\psi \] (2)

where the vielbeins are

\[ e^+ = \frac{\beta dx^+}{z^3}, \quad e^- = \frac{z}{\beta} dx^- + \frac{\beta dx^+}{z^3}, \quad e^y = \frac{dy}{z}, \quad e^z = \frac{dz}{z}, \quad e^\psi = \frac{d\psi + \beta k}{\sqrt{2z^3}} dx^+ + k\omega. \] (3)

In the above \( R^2 = \hat{R}^3/k \) and \( \psi \sim \psi + 2\pi \) is the 11-th direction fibered over the base \( CP^3 \). The \( CP^3 \) radius, \( \hat{R} \), is however measured in 11-dimensional Planck length units. The solution (2) describes a Galilean generalisation of the M-theory background [29] corresponding to a stack of \( N \) M2-branes placed on \( R_8/\mathbb{Z}_k \) orbifold singularity. We especially mention that when compared to the relativistic case (\( \beta = 0 \)) the coordinate \( \psi \) here appears to be twisted along \( AdS_4 \) as well as being fibered over the base \( CP^3 \). (Note that one should not try to set \( \beta = 0 \) directly into the vielbeins (3) instead it should be done at the level of the solution (2).) The solutions (2) exist for arbitrary \( k \) value. Fortunately these 11-dimensional solutions were already constructed in [11] but the relationship to ABJM work was not explored by the authors there. Our study makes this aspect vividly clear. According to [11] these 11-dimensional solutions do preserve two of the Poincaré supersymmetries while all conformal supersymmetries are broken, see [12].

2.2 Skew-whiffed case

However, it has been shown in [11] [12] that the flipping of the sign of the 4-form flux in 11-dimensional solution (2) breaks supersymmetries completely. Thus, a skew-whiffed 11-dimensional background can be written as

\[ ds_{11}^2 = \frac{\hat{R}^2}{4}(-2e^+e^- + e^y e^y + e^z e^z) + \hat{R}^2 d\sigma_{CP^3} + \frac{\hat{R}^2}{k^2} e^\psi e^\psi, \]

\[ C_3 = -\frac{\hat{R}^3}{8} e^+ \wedge e^- \wedge e^y - \frac{\hat{R}^3}{2\sqrt{2k}} e^+ \wedge e^y \wedge e^\psi \] (4)

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1I am grateful to Oscar Varela for pointing out error in the supersymmetry analysis and introducing the reference [11].
where the vielbeins are as in (3). Corresponding to this, the type II A solution (1) will have the signs of $F_{+yz}$ and $B_{+y}$ both negative

$$ ds_{IIA}^2 = \sqrt{R^3 k} \left( \frac{1}{4} \left( -\frac{2\beta^2(dx^+)^2}{z^6} + \frac{-2dx^-dx^+ + dy^2 + dz^2}{z^2} \right) + ds_{CP^3}^2 \right), $$

$$ e^\phi = \frac{R}{k}, \quad F_{+yz} = -\frac{3R^2 k}{8z^4}, $$

$$ B_{+y} = -\beta \frac{R^2}{2\sqrt{2} z^4}, \quad C = \beta \frac{k}{\sqrt{2} z^3} dx^+ + k\omega. \quad (5) $$

We are specifically interested in nonsupersymmetric Galilean solution because the solution (8) which we are going to compare it with is also nonsupersymmetric.

### 2.3 Compactification to $D = 4$

The $D = 4$ truncation of the skew-whiffed 11-dimensional background (4) can be performed consistently, see for details [11]. An effective action describing the compactification of the 11-dimensional (nonsupersymmetric) solution (4) to four dimensions is

$$ S_4 \sim \int d^4x \sqrt{-g} \left[ R - \frac{1}{2} \frac{1}{2!} (F_{\mu\nu})^2 - \frac{1}{2} \frac{12}{2!} \frac{l_0^2}{l_o^2} (A_\mu)^2 + \frac{6}{l_o^2} \right] \quad (6) $$

along with the null conditions, which need to be imposed from outside, $F \wedge *F = A \wedge *A = 0$. The action (6) describes a vector field in anti-de Sitter spacetime with mass square as $12/l_o^2$. Note that $l_0^2 = (R^3 k)^{1/2}/4$. The Proca action (6) admits a Galilean solution

$$ ds^2 = l_o^2 \left( \frac{2}{z^6} (dx^+)^2 + \frac{-2dx^-dx^+ + dy^2 + dz^2}{z^2} \right), $$

$$ A_+ = \frac{2\sqrt{2}}{\sqrt{3}} \frac{l_o}{z^3} \quad (7) $$

with dynamical exponent as 3, whose 11-dimensional uplifted solution is (4).

All this is quite similar to a Galilean solution of massive type IIA obtained in [20], but with subtle differences. Namely, the ordinary type IIA solution (1) and the skew-whiffed case are supported by 2-form flux along $CP^3$, while the massive type IIA solution (8) is devoid of the 2-form flux. So in the next section we first review the Galilean solution of massive type IIA supergravity for our comparative study.

### 3 A Galilean background in massive type IIA

The Romans type IIA supergravity theory in ten dimensions includes massive tensor field and cosmological constant while being maximally supersymmetric. It was
recently found in [20] that the theory admits non-relativistic anti-de Sitter vacua, \( NRadS_4 \times CP^3 \), a Galilean solution with dynamical exponent 3,

\[
ds^2 = L^2 \left( \frac{-2\beta^2}{z^6} (dx^+)^2 + \frac{-2dx^- dx^+}{z^2} + dy^2 + dz^2 + \frac{5}{2} ds^2_{CP^3} \right),
\]
\[
e^{2\phi} = \frac{f^2}{m_0}, \quad F_{+yz} = \sqrt{5} f L^4 z^4
\]
\[
B_{+y} = \beta g m^4 \sqrt{2} L^2 z^2, \quad C_+ = \beta g m^4 \frac{2\sqrt{5} L}{3z^3},
\]

where \( L^2 = \frac{2}{(m_0^2 g^2 m^4)} \). In the above \( m_0 \) is the Romans mass while \( f \) is the measure of 4-form flux. The flux \( f \) fixes the string coupling of the background. To distinguish it from \( g_0 \) we shall denote the string coupling here as \( g_m \equiv f/m_0 \). Note the metric in (8) is written in the Einstein frame. This Galilean solution preserves no supersymmetry even in the relativistic case (\( \beta = 0 \)).

On compactification over \( CP^3 \), a 4-dimensional effective action can be written as [20]

\[
S_4 \sim \int d^4x \sqrt{-g} \left[ R - \frac{1}{2.3!} \frac{1}{g_m} (H_{\mu\nu\lambda})^2 - \frac{1}{2.2!} \frac{4}{g_m^2} (G_{\mu\nu})^2 + \frac{6}{L^2} \right] - \sqrt{5} m_0 \frac{g_{\phi}^2}{2!2!} \int d^4x \epsilon^{\mu\nu\lambda\rho} \left( B_{\mu\nu} G_{\lambda\rho} - \frac{m_0}{2} B_{\mu\nu} B_{\lambda\rho} \right),
\]

where \( G_2 \equiv dC_1 + m_0 B \). A simple exercise determines that if we integrate out \( G \) by using its field equation, we simply obtain an action for the tensor field

\[
S_4 \sim \int d^4x \sqrt{-g} \left[ R - \frac{1}{2.3!} \frac{1}{g_m} (H_{\mu\nu\lambda})^2 - \frac{5m_0^2}{2.2!} \frac{4}{g_m^2} (B_{\mu\nu})^2 + \frac{6}{L^2} \right] + \sqrt{5} m_0^2 \frac{g_{\phi}^2}{2!2!} \int d^4x \epsilon^{\mu\nu\lambda\rho} B_{\mu\nu} B_{\lambda\rho}.
\]

At this stage, we can introduce a vector field through a generalised Hodge-duality relation [20] in 4-dimensions as

\[
\star H_3 = d\chi + \tilde{A}_1,
\]

where \( \chi \) is the axion. We have introduced gauge field via Hodge-dual relation in (11), but in doing so the gauge field \( \tilde{A} \) actually gauges the axionic shift symmetry. The axion field serves as a Goldstone mode and corresponding local shifts (Stueckelberg) are

\[
\delta \chi = -l, \quad \delta \tilde{A}_1 = dl.
\]

6
This shift symmetry can eventually be used to set $\chi = 0$. Correspondingly the Proca action involving $\tilde{A}_\mu$ can be written as

$$S_4 \sim \int d^4x \sqrt{-g} \left[ R - \frac{1}{2} \frac{2}{2!} (\tilde{F}_{\mu\nu})^2 - \frac{1}{2} \frac{12}{L^2} (\tilde{A}_\mu)^2 + \frac{6}{L^2} \right].$$

(13)

where $2L^{-2} = m_0^2 g_{m,\frac{5}{2}}$ as given earlier.

4 Identification of Romans mass with type IIA flux

The two separate actions (6) and (13) describe the dynamics of Proca fields coupled to anti-de Sitter gravity. The former comes from ordinary type IIA having fluxes along $CP^3$ while the latter comes from the $CP^3$ compactification of Romans theory. Since we do not have any precise relationship between two ten-dimensional theories when $CP^3$ flux compactifications are involved, the similarity of the Proca actions (6) and (13) could be taken as a hint. So it will be appropriate to identify these two actions.

An identification between 4D actions (6) and (13) can be achieved by comparing the $AdS_4$ radii of 10-dimensional solutions (5) and (8). That is we would, in fact, identify $l_o^2 \equiv L^2$ hence

$$m_0^2 g_{m,\frac{5}{2}} \equiv \frac{8}{\sqrt{R^3 k}}.$$  

(14)

Thus we already see that the mass parameter $m_0$ gets related to the 2-form flux $k$ of the type IIA ABJM background in some manner. Note, however, that in the Galilean solutions the $AdS_4$ radius of curvature is tied to $CP^3$ radius in a definite way. The two $CP^3$ radii should then be related as

$$\left( \frac{R_{m,CP^3}}{R_{o,CP^3}} \right)^2 = \frac{5}{8}.  

(15)

(The suffixes $m$ and $o$ are used in order to distinguish massive and ordinary type IIA cases.) However to be precise we also need to relate the Newton’s constants in 4D actions (6) and (13). So if we identify the 4-dimensional Newton’s constants we find that 10-dimensional string couplings must be related as

$$g_m = c g_o  

(16)

2 The 4D Newton’s constant is $G_4^N = \frac{G_6^N}{V_6} \propto \frac{\alpha'^4}{(R_{CP^3})^7}$, where $V_6 = \frac{2}{5} R_{CP^3}^6$ represents volume of a $CP^3$ manifold.
with $c = (5/8)^{\frac{3}{4}}$ being a numerical constant. So we get

$$\frac{f}{m_0} = c \frac{R}{k}. \quad (17)$$

Following from Eqs. (14) and (17) a precise map can now be summarised as

$$f \leftrightarrow \frac{2\sqrt{2}}{c^{3/4}} \frac{1}{R}, \quad m_0 R \leftrightarrow \frac{2\sqrt{2}}{c^{3/4}} k. \quad (18)$$

This indicates that the ‘mass’ $m_0$ of Romans’ background indeed gets mapped to the ABJM ‘flux’ $k$ in ordinary type IIA solution.

In summary, it is interesting to have explicitly obtained this relationship from $CP^3$ compactifications especially involving Galilean non-supersymmetric solutions. But this may not be the first instance where such an equivalence has arisen. A somewhat similar type of situation has been reported in recent works [36] on ABJM theory with Romans mass. In these works there is an overall Chern-Simons level

$$k = k_1 + k_2 \neq 0$$

appearing in the ABJM theory. Actually it happens when the Chern-Simons levels in the product group $U(N)_{k_1} \times U(N)_{k_2}$ do not exactly cancel. The unbalanced flux $k$ deforms the original ABJM theory. This setting also breaks all the supersymmetries [36, 37]. Earlier too, Romans mass has been mapped through T-dualities into the fluxes on ordinary type IIA side, especially in toroidal [30, 31] and $K3$ compactifications [31, 32, 33], as well as Calabi-Yau compactifications [34, 35].

**Symmetries:**

Further strong evidence in favour of our proposal is the nature of symmetries of two type IIA solutions we have discussed. The Galilean type IIA solutions (11) and (5) have non-relativistic $AdS_4$ symmetries as well as they inherit global $SU(4)$ symmetry coming from round $CP^3$’s. We see that precisely the same amount of symmetries are exhibited by the massive type IIA Galilean solutions [8] as well.

## 5 Conclusion

We obtained a Galilean type IIA background as a direct deformation of the ABJM solution [29] and in this way we have been able to point out the parametric relationship with the brane configurations of ABJM. We then compactified our theory on $CP^3$ and tried to find a relationship with the corresponding $CP^3$ compactification of the Galilean solution of the massive type IIA string theory [20]. We would like to conclude that the two type IIA theories compactified over $CP^3$, the massive
one and the massless one with 2-form flux over $CP^3$, appear to be the same in the non-relativistic case. In the relativistic ABJM scenario, similar comparisons were studied in [36, 37] involving $CP^3$ compactifications.

Our map seems to be true for the Galilean backgrounds with dynamical exponent being 3 and obviously without supersymmetry. Although the respective 10-dimensional solutions make distinct backgrounds but those appear to be related via our map in four dimensions. The global symmetries shared by these solutions are also found to be the same. We do not know what would be the situation with other such non-relativistic solutions in the two theories. Particularly, the case of Galilean solutions with dynamical exponent 2 would be interesting as those correspond to conformal Galilean CFTs.

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