Non-BPS Dirichlet branes

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based on work with Oren Bergman

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1. Motivation

2. The boundary state approach to Dirichlet branes

3. Non-BPS states in heterotic - type II duality

4. Conclusions

1. Motivation

- Can one understand string duality beyond the BPS spectrum ?

- Is there string duality for non-susy theories ?

Key ingredient:

Dirichlet - branes that are not BPS .

2. The boundary state approach to Dirichlet branes

Describe Dirichlet-branes as coherent (boundary) states of closed string theory.

Callan et al.
Polchinski & Cai
Green & Gutperle
Li
⋮

Condition that open strings can end on these states

$$(\partial X^i - \bar{\partial} X^i)\ |B\rangle = 0 \qquad \text{Dirichlet}$$

$$(\partial X^I + \bar{\partial} X^I)\ |B\rangle = 0 \qquad \text{Neumann}$$

Work in NS-R formalism in light-cone gauge

[light-cone directions $\mu = 0, 1$ – both Dirichlet]

Consider Dirichlet p-brane :

$$\left.\begin{aligned} (\alpha^\mu_n - \tilde{\alpha}^\mu_{-n})\,|B_p,\eta\rangle &= 0 \\ (\psi^\mu_r - i\eta\,\tilde{\psi}^\mu_{-r})\,|B_p,\eta\rangle &= 0 \end{aligned}\right\}\quad \mu = 2,\dots,p+2 \qquad D$$

$$\left.\begin{aligned} (\alpha^\mu_n + \tilde{\alpha}^\mu_{-n})\,|B_p,\eta\rangle &= 0 \\ (\psi^\mu_r + i\eta\,\tilde{\psi}^\mu_{-r})\,|B_p,\eta\rangle &= 0 \end{aligned}\right\}\quad \mu = p+3,\dots,9 \qquad N$$

$\eta = \pm$ —— spin structures

For both $\eta = \pm$, solutions to these equations exist in NS⊗NS and R⊗R sector, and are unique (up to normalisation) :

$$|B_{p},\eta\rangle = \exp\left\{ \sum_{n>0} \left[-\frac{1}{n} \sum_{\mu=2}^{p+2} \alpha^{\mu}_{-n} \tilde{\alpha}^{\mu}_{-n} + \frac{1}{n} \sum_{\mu=p+3}^{9} \alpha^{\mu}_{-n} \tilde{\alpha}^{\mu}_{-n} \right] + i\eta \sum_{r>0} \left[-\sum_{\mu=2}^{p+2} \psi^{\mu}_{-r} \tilde{\psi}^{\mu}_{-r} + \sum_{\mu=p+3}^{9} \psi^{\mu}_{-r} \tilde{\psi}^{\mu}_{-r} \right] \right\} |B_{p},\eta\rangle^{0}$$

NS⊗NS: $r \in \mathbb{Z} + \frac{1}{2}$, $|B_{p},\eta\rangle^{0} = |0\rangle \otimes |0\rangle$

R⊗R: $r \in \mathbb{Z}$, $|B_{p},\eta\rangle^{0}$ satisfies equation with $r=0$.

Actual Dirichlet-brane state: linear combination of such states in different sectors and with different spin-structures.

[Bergman & MRG]

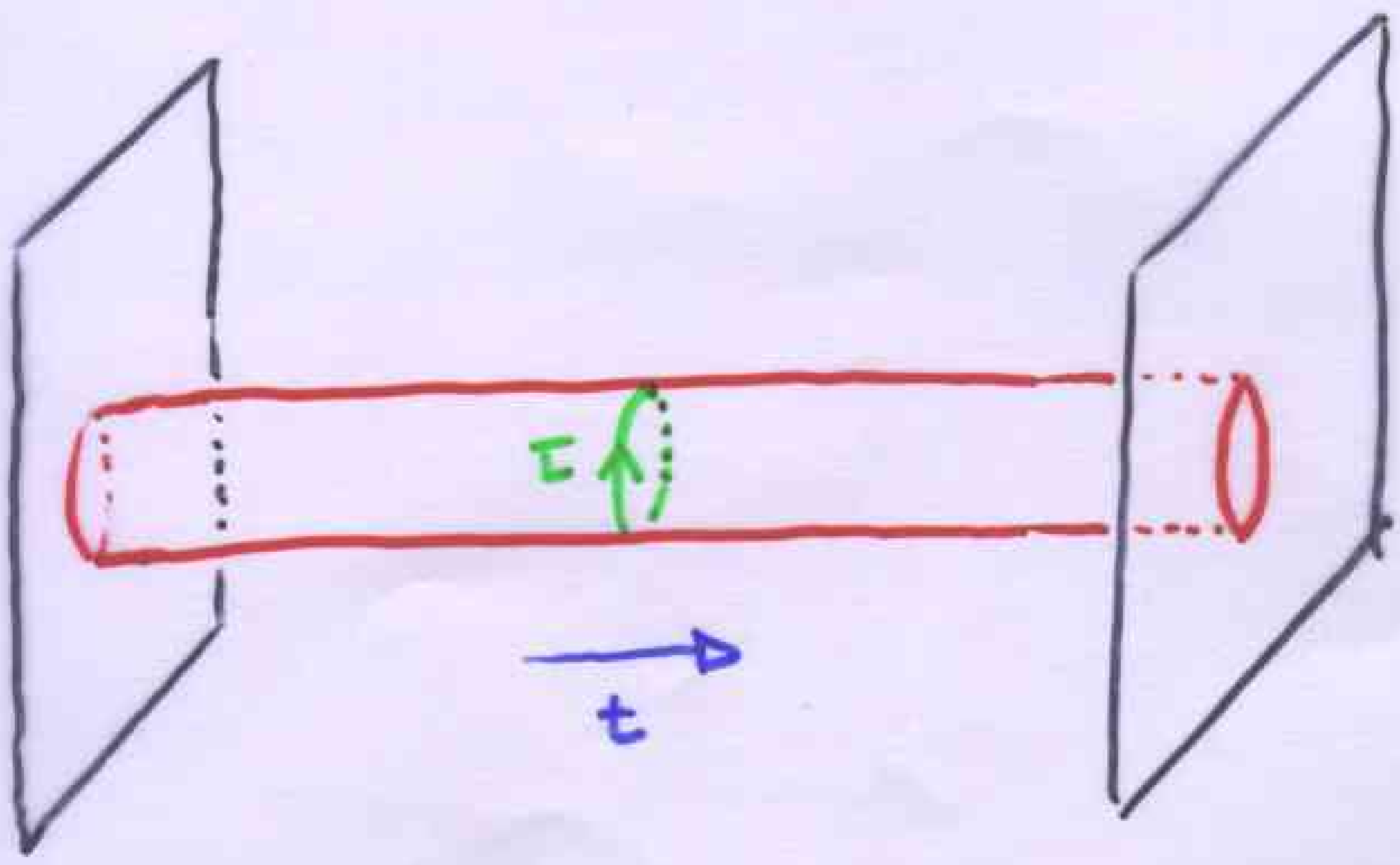
This linear combination must satisfy the following consistency conditions:

(i) It must be a physical state of the closed string theory, i.e.

- GSO - invariant
- orbifold / orientifold invariant

(ii) Open strings that are introduced by presence of D-branes have consistent string field interactions with closed string theory.

Key relation:



closed string tree diagram $\cong$ open string 1-loop diagram

Mainly interested in stable D-branes; this

requires that open string

No Tachyon!

D-brane

These conditions are intrinsic consistency

conditions of interacting string (field) theory.

More fundamental than

spacetime supersymmetry!

Example: II A / II B

NS $\otimes$ NS: $$|Bp\rangle_{NSNS} = \left(|Bp,+\rangle_{NSNS} - |Bp,-\rangle_{NSNS} \right)$$

is invariant under GSO-projection.

BUT not stable by itself since

$$\langle Bp | e^{-lH_c} | Bp \rangle_{NSNS} \cong \text{open } [NS - R]$$

closed string tree

open string loop

NS-sector has tachyon!

Need to add R $\otimes$ R component

R $\otimes$ R: $$|Bp\rangle_{RR} = \left(|Bp,+\rangle_{RR} + |Bp,-\rangle_{RR} \right)$$

only invariant under GSO if $\begin{Bmatrix} p \text{ even} & \text{IIA} \\ p \text{ odd} & \text{IIB} \end{Bmatrix}$

Since

$$\langle B_p | e^{-\ell H_c} | B_p \rangle_{RR} \cong \text{open NS } (-1)^F$$

closed string tree

open string loop

can find suitable linear combination

$$\boxed{|Dp\rangle = |Bp\rangle_{NSNS} \pm |Bp\rangle_{RR}}$$

± brane/antibrane

which describes Dirichlet p-brane !

- $\langle Dp | e^{-\ell H_c} | Dp \rangle \cong$ open $[NS-R]\,\frac{1}{2}(1+(-1)^F)$

- $|Dp\rangle$ GSO-invariant if

p even	IIA
p odd	IIB

3. Non-BPS states in Heterotic - Type II

duality

Many string theories contain states that are not BPS but are stable due to the fact that they are the lightest states of a given charge.

Because of their stability these states must be present in the dual theory. Sen

Interesting example that can be analysed in detail

$$\mathrm{IIA}\ T^4/I_4 \xrightarrow{\ S\ } \text{Heterotic}\ T^4$$

$$\shortparallel$$

orbifold limit of K3

At orbifold point of K3, Heterotic SO(32) theory has Wilson lines

$$A^1 = \left(\left(\tfrac{1}{2}\right)^8, 0^8 \right)$$

$$A^2 = \left(\left(\tfrac{1}{2}\right)^4, 0^4, \left(\tfrac{1}{2}\right)^4, 0^4 \right)$$

$$A^3 = \left(\left(\tfrac{1}{2}\right)^2, 0^2, \left(\tfrac{1}{2}\right)^2, 0^2, \left(\tfrac{1}{2}\right)^2, 0^2, \left(\tfrac{1}{2}\right)^2, 0^2 \right)$$

$$A^4 = \left(\tfrac{1}{2}, 0, \tfrac{1}{2}, 0, \tfrac{1}{2}, 0, \tfrac{1}{2}, 0, \tfrac{1}{2}, 0, \tfrac{1}{2}, 0, \tfrac{1}{2}, 0, \tfrac{1}{2}, 0 \right)$$

This breaks $SO(32) \rightarrow SO(2)^{16}$

The actual form of the Heterotic Wilson lines can be confirmed by comparing the masses of various BPS states:

(i) Bulk BPS D0-branes

$$|D0,\varepsilon\rangle = |U0\rangle_{NS} + \varepsilon\, |U0\rangle_{R}$$

Heterotic state: KK excitation

$$P_L = \left(0^{16};\, 0^3,\, \frac{\varepsilon}{R_4}\right) \qquad P_R = \left(0^3,\, \frac{\varepsilon}{R_4}\right) \qquad [N_L = 1]$$

(ii) Fractional BPS D0-brane

$$|D0,\varepsilon_1,\varepsilon_2\rangle = \frac{1}{2}\Big[\left(|U0\rangle_{NS} + \varepsilon_1\, |U0\rangle_R\right)$$

$$+\, \varepsilon_2 \left(|T0\rangle_{NS} + \varepsilon_1\, |T0\rangle_R\right)\Big]$$

16 different fixed planes: $2\cdot 2\cdot 16 = 64$ such states

[D2-branes wrapped on vanishing 2-cycles] Douglas & Moore
Aspinwall

Heterotic duals:

$$P_L = \Big(\varepsilon_1\varepsilon_2\, \underbrace{(0^{2n}, 1, \pm 1, 0^{14-2n})}_{16 \text{ such states}};\, 0^3,\, \frac{\varepsilon_1}{2R_4}\Big) \qquad P_R = \left(0^3, \frac{\varepsilon_1}{2R_4}\right)$$

Simplest stable non-BPS state in Heterotic theory:

$$P_L = (0^{2n}, 2, 0^{15-2n}; 0^4) \qquad P_R = (0^4) \qquad [N_R - c_R = 1]$$

Charged under precisely two of the 16 $U(1)$s associated with fixed planes (and no other $U(1)$s).

For each pair of disjoint $U(1)$s there are 4 such states — charge ± 1 w.r.t. each of the two $U(1)$s.

Above state carries same charges as 2 BPS states

$$P_L^{(1)} = (0^{2n}, 1, 1, 0^{14-2n}; 0^3, \tfrac{1}{2R_4}) \qquad P_R^{(1)} = (0^3, \tfrac{1}{2R_4})$$

$$P_L^{(2)} = (0^{2n}, 1, -1, 0^{14-2n}; 0^3, -\tfrac{1}{2R_4}) \qquad P_R^{(2)} = (0^3, -\tfrac{1}{2R_4})$$

Non-BPS state stable in Heterotic theory if

$$R_{Hj} < \frac{1}{2\sqrt{2}} \qquad j = 4 \quad (j = 1, 2, 3)$$

In dual IIA theory, the two BPS states correspond to fractional D0-branes that are localised at different fixed points and that have opposite bulk charge. The non-BPS state corresponds therefore to non-BPS D1-brane that stretches between a pair of fixed planes

[cf. Sen]

$$|D1,\theta,\varepsilon\rangle = \frac{1}{\sqrt{2}}\left[|U1,\theta\rangle_{NS} + \frac{\varepsilon}{\sqrt{2}}\left(|T1;1\rangle_{R} + e^{i\theta}\,|T1;2\rangle_{R}\right)\right]$$

$\theta = 0, \pi$ Wilson line on D-string

$$|U1;\theta\rangle_{NS} = \sum_{\omega} e^{i\theta\omega}\ \underset{\text{winding number}}{|U1;\omega\rangle}$$

4 different such states for each pair of fixed points !

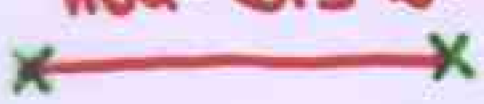
D-string (stretching along x^4) is stable if

$$R_{A4} < \sqrt{2} \qquad R_{Aj} > \frac{1}{\sqrt{2}} \qquad j=1,2,3$$

Two regimes of stability qualitatively related by duality map.

Actually, D-string related by T-duality to non-BPS D0-brane

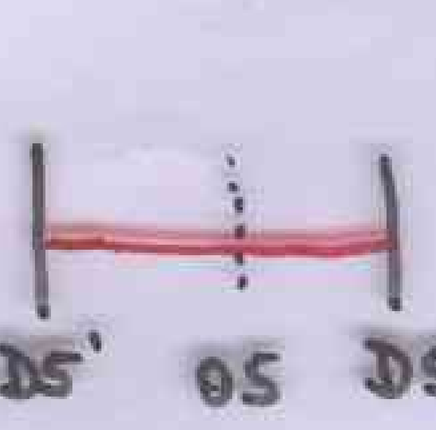
non-BPS D1



non-BPS D0

$$\begin{array}{ccc} \text{IIA } T^4/I_4 & \xrightarrow{\ T\ } & \text{IIB } T^4/(-1)^{F_L} I_4 \\ \Big| S & & \Big| S \\ \text{Heterotic } T^4 & & \text{IIB } T^4/\Omega I_4 \end{array}$$

$V = (0^{2n}, 2, 0^{15-2n})$



There are also other stable non-BPS states in Heterotic theory that do not correspond to Dirichlet branes.

They may correspond to

- bound states of Dirichlet branes
- states involving the NS 5-brane

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It is also interesting to analyse these states at more generic points in moduli space (away from the orbifold point of K3).

See Majumder & Sen

4. Conclusions

- can probe string dualities beyond BPS spectrum using non-BPS D-branes

- for Heterotic T^4 — IIA K3 both sides are quantitatively under control: can compare stability of non-BPS states.

- these techniques should also allow one to analyse further proposed non-susy dualities

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Kachru/Silverstein
⋮