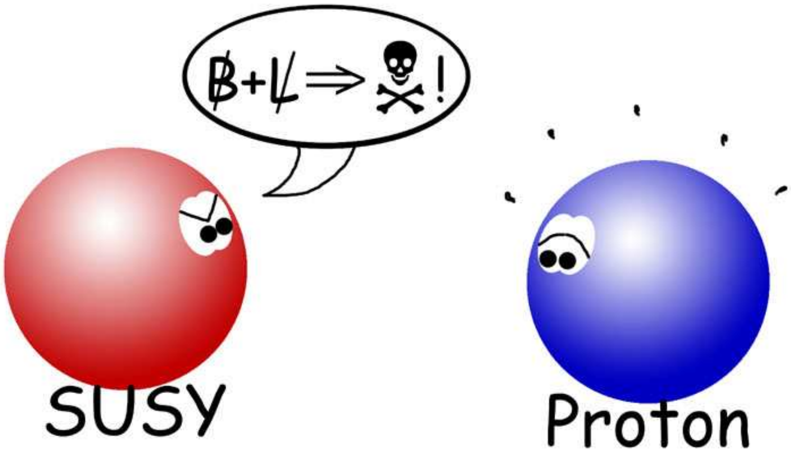
SUPERSYMMETRY

and the life and death of the proton



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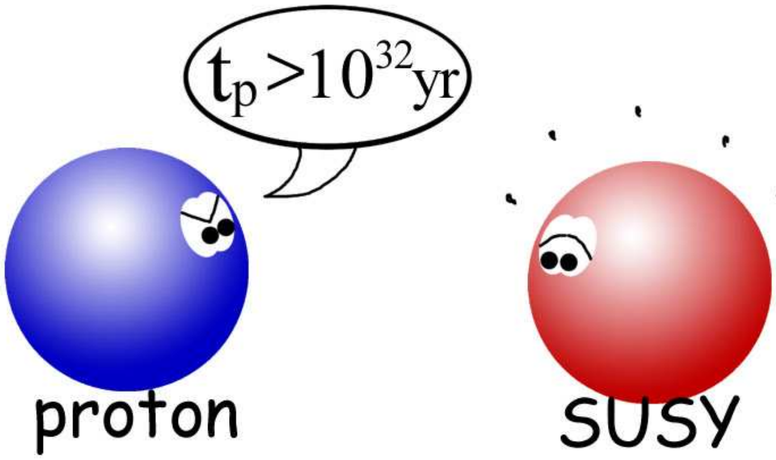
Student Colloquium - March 1, 2001 - Niels Bohr Institute

THE PROTON

and the life and death of supersymmetry



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What have we got?

1. Democritian Hypothesis + Standard Model of Particle Physics

2. Speculations: (4 generations, technicolour, Supersymmetry, Grand Unification, String Theory,...)

Supersymmetry Reminder:

- Symmetry: 1967 (Coleman-Mandula).
- Supersymmetry: 1975 (Haag-Lopuszanski-Sohnius).
- Fermionic Generators (anticommuting, spin $\frac{1}{2}$)
  $\Longrightarrow$ SUSY is a symmetry between bosons and fermions
  $\Longrightarrow$ particle spectrum enriched (at least one sparticle for each SM particle).
- Since sparticles not observed $\Longrightarrow$ SUSY must be broken.
- Most general Lagrangian impossible. Proton decays too fast.

SUSY is popular

MOTIVATIONS:

- Low-Energy SUSY solves Hierarchy problem.
- SUSY $\Longrightarrow$ exact coupling unification $(+$ prediction of $\sin^2\theta_W)$ $\stackrel{?}{\Longrightarrow}$ GUT
- SUSY with conserved R-parity results in stable LSP $\Longrightarrow$ natural WIMP dark matter candidate
- SUSY is the only possible non-trivial extension of the Poincaré group. Since Nature tends to use all possibilities that are not forbidden ...
- String Theory requires Supersymmetry.
- Local Supersymmetry $\Longrightarrow$ New gauge field $\Longrightarrow$ Gravity (Supergravity).
- From the experimentalist: Low-energy SUSY cannot escape detection for long (if it exists).
- SUSY favours a light Higgs as indicated (?) by LEP II.

Still... some people think SUSY is not so attractive

PROBLEMS:

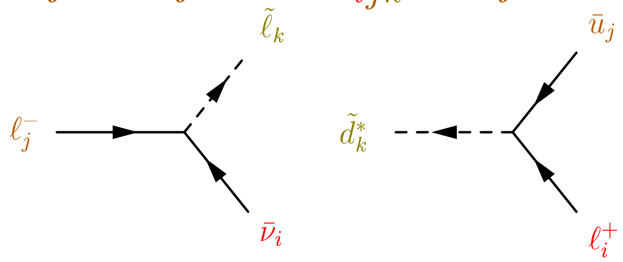
- MANY new particles.
- MANY new parameters (depending on scenario).
- ADDITIONAL symmetry must be imposed to prevent proton decay.
- SUSY nice for GUT, but it is not clear that there should *be* a GUT.
- Even if GUT exists, any (4-dimensional) Supersymmetric theory relying on R-parity is incompatible with *any* more fundamental framework (e.g. GUT) where baryon and lepton number can be violated by the propagation of superheavy particles (subject of this talk).

SUPERSYMMETRY AND THE PROTON

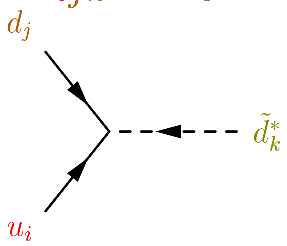
Interactions: $W = W_{MSSM} + W_{\not{L}} + W_{\not{B}}$

$$W_{MSSM} = h^e_{ij} L_i H_1 \bar{E}_j + h^d_{ij} Q_i H_1 \bar{D}_j + h^u_{ij} Q_i H_2 \bar{U}_j + \mu H_1 H_2$$

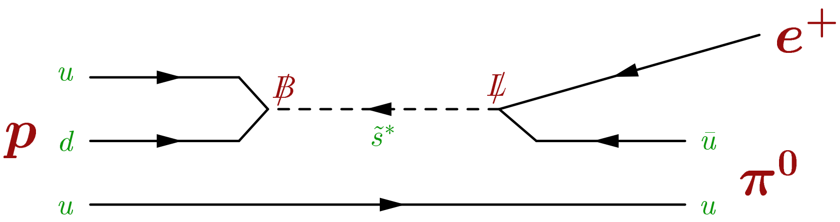
$$W_{\not{L}} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k$$



$$W_{\not{B}} = \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$



SIMULTANEOUS $\not{B}$ and $\not{L}$ necessary for proton decay.



$\Longrightarrow$ Introduce symmetry to forbid one of $W_{\not{L}}$ or $W_{\not{B}}$, or both.

PROTECTING THE PROTON

SUGGESTIONS:

1. Naive, simple guess: Lepton Number is conserved
2. Naive, simple guess: Baryon Number is conserved
3. Naive, complicated guess: $R = (-1)^{3B+L+2S}$ is conserved

1 and 2: self-explanatory (except for small details)

R-parity has interesting consequences:

- Due to $\frac{1}{2}$ spin difference between SM and SUSY particles, all SM particles have $R = +1$ and all SUSY particles have $R = -1$.
- Since SUSY particles have $R = -1$ they must always come in pairs. That is not the case for *any* of the terms in $W_{\not{L}}$ or $W_{\not{B}}$ so they are all forbidden.
- Since SUSY particles must always come in pairs, any supersymmetric particles produced at the Big Bang decay to the LSP without possibility for further decay $\Longrightarrow$ possible solution of the dark matter problem in cosmology.

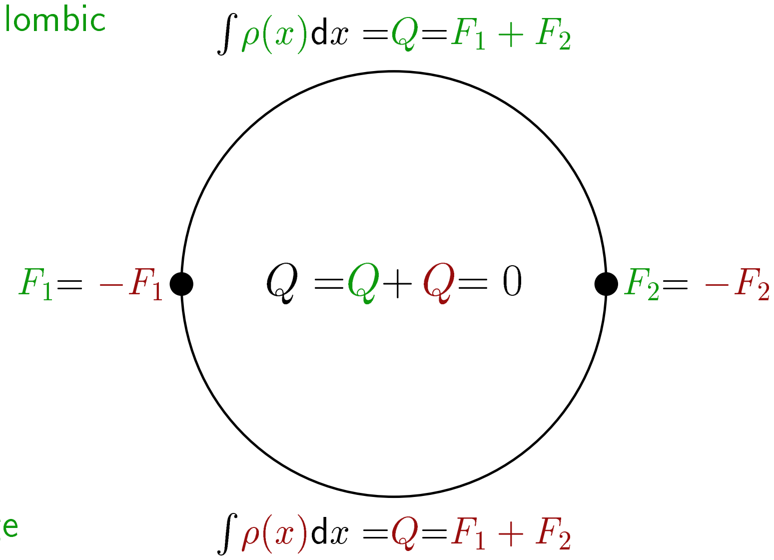
- BUT: R-parity is very fragile, so be careful...

NAIVE GUESSES AIN'T SO BAD!

What can we say about our symmetry?

1. There are strong indications [Gilbert] that only *gauged* symmetries are respected by quantum gravity effects (baby universes containing charges where they are not observable or transporting them to different world points where they will not be associated with the local physics that gave birth to them)

Any gauge charge has a coulombic field associated with itself and thus can be written as a flux integral. Using gauss' law, the total such charge of any closed universe must be zero since the charge in any one half of the universe will always be equal to minus the charge of the other half.



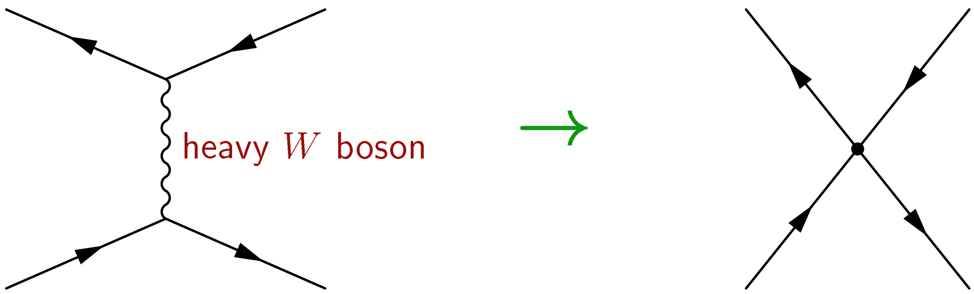
2. $\Longrightarrow$ So the symmetry most likely has a gauge origin

3. A systematic analysis of possible "discrete gauge symmetries" [Ibañez & Ross + others (later)]
$\Longrightarrow$ Only R-parity, and two symmetries equivalent to Baryon number conservation and (to a lesser extent) Lepton number conservation are anomaly-free. All other symmetries are violated by anomalies.

4. Independent of the above: In SUSY GUTs, dangerous operators mediating proton decay are not forbidden by R-parity. They are forbidden by both L and B conservation.

R-PARITY AND THEORIES BEYOND SUPERSYMMETRY

1. Analogously to early electroweak theory:
   Intermediate bosons not yet known (too heavy)



   $\Longrightarrow$ Theory with 4-fermion contact interactions
   (since fermions have $d = \frac{3}{2}$, the mass dimension of these operators must be $= 4 \times \frac{3}{2} = 6$)

2. So suppose there are some superheavy particles from a more fundamental theory (which we cannot resolve but whose presence results in dimension > 4 operators in the effective low-energy theory)

3. In general GUT for example, the superheavy particles do not conserve baryon and lepton number. By construction, R-parity cannot forbid all $\not{B}$ and $\not{L}$ in such a theory

SO WHAT ?

1. So what?
   The mass dimension of the terms in the Lagrangian must be 4. Since these new operators have mass dimensions higher than 4 (and since we are implicitly thinking about contracted heavy propagators), they must be suppressed by powers of the mass scale of the unresolved particles.

2. OK, there's no problem for the SM GUTs (here).
   Since we need 4-*fermion* vertices, we get $d = 6$, so we get two powers of suppression, but in SUSY there are many *scalars* (with $d = 1$), so it is almost impossible to avoid $d = 5$ operators.

3. $d = 5$ operators must be suppressed by several orders of magnitude to avoid bounds from proton decay! [Hincliffe & Kaeding + Ibañez & Ross]

CONCLUSIONS:

1. SUSY solves the fundamental problem of scale hierarchy in the SM.

2. SUSY has other nice features such as compatibility (and requirement) in more fundamental frameworks.

3. Problem with proton decay can be circumvented by introducing discrete symmetries.

4. Several candidates for this symmetry exist which so far have survived theoretical bombardments.

5. R-parity is disfavoured to the point of exclusion (on very rigorous grounds) when embedding SUSY models into more fundamental frameworks (in 4D) where $\not{B}$ and $\not{L}$ occur through exchange of superheavy particles.

6. Onwards, Christian soldiers...