MeV gamma from Q-ball decay

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Ref SK, M.Kawasaki, N.Tsuji, Phys. Rev. D **109**, 083039 (2024) [arXiv:2403.01675 [hep-ph]].

Abstract

We study the supersymmetric Q balls which decay at present and find that they create a distinctive spectrum of gamma rays at around O(10) MeV. The charge of the Q ball is lepton numbers in order for the lifetime to be as long as the present age of the universe, and the main decay products are light leptons. However, as the charge of the Q ball decreases, the decay channel into pions becomes kinematically allowed towards the end of the decay, and the pions are produced at rest. Immediately, π^0 decays into two photons with the energy of 67.5 MeV, half the pion mass, which exhibits a unique emission line. In addition, $\pi^\pm$ decay into $\mu^\pm$, which further decay with emitting internal bremsstrahlung, whose spectrum has a sharp cutoff at 50 MeV. If the observations would find these peculiar features of the gamma-ray spectrum in the future, it could be a smoking gun of the supersymmetric Q-ball decay at present.

1. What is the Q ball?

A Q ball is a kind of non-topological soliton, the energy minimum configuration of the scalar field ϕ with non-zero charge Q.
Coleman, Nucl. Phys. B **262**, 263 (1985).

Spherical symmetric profile + charge Q ⇒ The Q ball

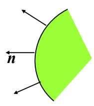
2. Decay of the Q ball

Q balls can decay if there are couplings to lighter particles which carry the same kind of charge.

⇒ The decay takes place when $\omega_Q > m_{\rm decay}$.
(ω_Q: the mass per unit charge)

Once the Fermi sea is filled, further decays proceed only when the fermions escape from the surface of the Q ball.

Evaporation of the charge
Cohen et al., Nucl. Phys. B **272**, 301 (1985).



Q balls must be very large in order to decay at present.

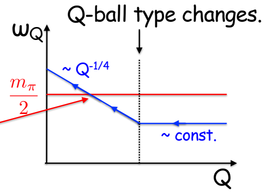
Such large Q balls are only known to form in supersymmetry (SUSY), where the the scalar field ϕ consists of the combination of squarks and sleptons, and the charge Q should be the lepton number L.

(Ex.) $\Phi^5 = \mathcal{Q}u\mathcal{Q}ue$ ⟶ Decay into particles with L=-1.
($\mathcal{Q}$: LH doublet squarks, u: RH squarks, e: RH sleptons)

Decay products

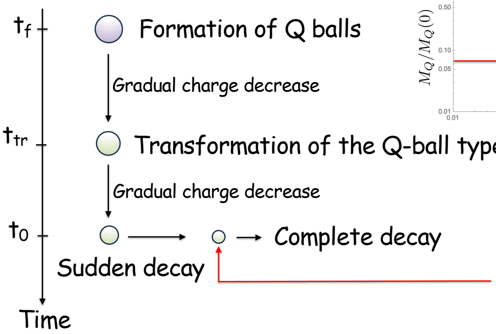
Pion production is kinematically forbidden:
$\bar{\nu}_e$ (L=-1) + $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau, e^+, e^-$

Pion production is kinematically allowed:
$\bar{\nu}_e$ (L=-1) + $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau, e^-$, π^+, π^-, π^0
e^+ (L=-1) + $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$, π^+, π^-, π^0

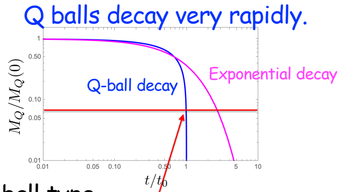


(The electric charge neutrality conservation must be taken into account.)

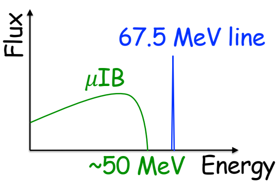
3. Schetch of the scenario



Q balls decay very rapidly.



Pion production is kinematically allowed at this moment.



67.5 MeV monochromatic line emission from π^0 at rest.

$\mu^\pm$ (from $\pi^\pm$ decay) emit Internal Bremsstrahlung (IB).

4. Photon spectrum (Galactic emissions)

Pions are produced at rest just after kinematically allowed.

(i) $\pi^0 \to 2\gamma$ 67.5 MeV line emission
(ii) Radiative $\pi^\pm$ & $\mu^\pm$ decay (Internal Bremsstrahlung)

$$\varepsilon_\gamma^2 \frac{d\Phi_{\rm dp}}{d\varepsilon_\gamma} = \frac{1}{4\pi} \frac{\Omega_Q \mathcal{D}}{\omega_Q \Delta\tau_Q} \frac{Q_\pi}{Q_{\rm D}} f_{\rm dp} \frac{dN_{\gamma,{\rm dp}}}{d\varepsilon_\gamma} \varepsilon_\gamma^2 \qquad ({\rm dp} = \pi^0, \pi^\pm, \mu^\pm)$$

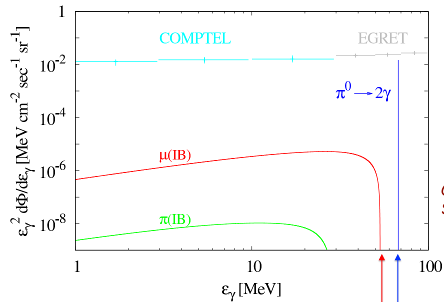
\# of ϕ-particles decayed during $\Delta\tau_Q$ ($\Delta\tau_Q = \xi t_0$: Decay period)

Charge fraction that decays into pions

Energy spectrum $\left(\frac{dN_{\gamma,{\rm dp}}}{d\varepsilon_\gamma} = \frac{1}{\Delta\varepsilon_\gamma}, \frac{dB_{\mu{\rm IB}}}{d\varepsilon_\gamma}, \frac{dB_{\pi{\rm IB}}}{d\varepsilon_\gamma}\right)$

\# of dp per unit charge ($f_{\pi^0} = 1/12, f_{\pi^+} = 1/20, f_{\pi^-} = 1/15, f_{\mu^-} = 1/60$)

D-factor: $\mathcal{D} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{\rm los} ds \rho_{\rm NFW}(r)$ $\left[\rho_{\rm NFW}(r) = \frac{\rho_0}{\frac{r}{r_0}\left(1+\frac{r}{r_0}\right)^2}\right]$



$|\ell| < 30°, |b| < 5°$
$\Delta\varepsilon_\gamma/\varepsilon_\gamma = 0.15$ (From EGRET)
$m_{3/2} \simeq 3\,{\rm MeV}$
$\phi_0 = 0.3 M_P$
$|K| = 0.02$
$\Omega_Q/\xi \simeq 1\times 10^{-8}$

COMPTEL: Strong et al., ApJL&C **39**, 209 (1999).
EGRET: Strong et al., ApJ **613**, 962 (2004).

Sharp edge at ~50 MeV — 67.5 MeV line

Distinctive spectrum from the Q-ball decay

GRAMS has 67.5 MeV line sensitivity of ~10^{-6} MeV/cm²/s.
Aramaki et al., Astropart. Phys. **114**, 107 (2020).

(Cf. Extragalactic emissions are very similar to Galactic emissions.)

5. Summary

MeV gamma rays from the SUSY Q-ball Decay

Q balls decay NOW, and produce pions at rest.
Unique property of the Q-ball decay
($n_{\pi^0} \sim n_{\pi^+} \sim n_{\pi^-}$)

▶ $\pi^0 \to 2\gamma$ 67.5 MeV monochromatic line emission.

▶ $\pi^\pm \to \mu^\pm + \gamma({\rm IB}) \to e^\pm + \gamma({\rm IB})$
Internal Bremsstrahlung
Smooth spectrum with a sharp edge at ~50 MeV

Future MeV gamma experiments could detect these signals.
(AMEGO-X, CubeSat for MeV observations (MeVCube), e-ASTROGAM, GECCO, GRAINE, GRAMS, and SMILE-3.)

If detected, it should be a smoking gun of SUSY Q balls.