Nonrelativistic Open String Model – Photon Mass and Lifetime Values

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Abstract

Candidate photon string parameters are investigated using a nonrelativistic open string model with fixed endpoints. String parameters and lifetime values are derived as a function of the photon mass. A wide variation in string parameter and lifetime values is predicted for the various photon mass values utilized in this paper. The photon averaged logarithmic lifetime values exceed 10^{74} yr for the 10^{-36} to 10^{-21} MeV/c^2 mass range considered in this paper.

1.0 Introduction

String theory is an elegant mathematical formulation[1-7] that has yet to be experimentally verified. Specific particle parameter values and associated decay modes are uncertain and have been qualitatively discussed[8-31]. These uncertainties are exemplified by estimates of the photon mass and lifetime values[25]. This paper applies the nonrelativistic open string model proposed in Refs. 28 - 31 to calculate a range of photon string parameter and lifetime values as a function of assumed photon masses. Since the photon mass is uncertain[25], a wide range of values, encompassing 10^{-36} to 10^{-21} MeV/c^2, is utilized in this paper[25]. This range of photon masses is derived from Ref. 25.

Zero photon mass is an inherent aspect of many gauge theories. For example, the photon mass is presumed to be zero in the Standard Model of Particle Physics that incorporates the unification of the electromagnetic and weak interactions[32-34]. In particular, the electroweak interaction consists of symmetries associated with the electromagnetic as well as weak interaction.

Within the electroweak interaction, both symmetries $SU(2)_L$ and U(1) must be spontaneously broken where the subscript L indicates the group $SU(2)_L$ is purely left-handed . Considering the scope of known interactions, only the electromagnetic and color interactions occur as a consequence of an unbroken symmetry in that massless bosons (photons and gluons) are the exchanged particles mediating their interaction. The uniqueness of the electroweak interaction is that $SU(2)_L$ and U(1) are simultaneously broken in a manner that a subgroup of the product of the two groups (i.e., U(1)) results in an unbroken symmetry that yields a massless photon.

A photon that is not massless would have profound implications in the development of gauge theories. It would impact development of gauge theories beyond the Standard Model, as well as the development of more comprehensive approaches including a better quantification of realistic Grand Unification Theories, and the possible development of a Theory of Everything. In addition, detection of photons with mass would open new research avenues in both particle physics and cosmology.

Using Refs. 25 and 27-31 as a guide, this paper defines a model to calculate the photon lifetime and associated string parameters as a function of photon mass using the nonrelativistic open string model with fixed endpoints[28-31]. By constraining the model to reproduce a selected photon mass, an initial representation for the photon string parameters and associated lifetime are derived.

Determination of these string parameters and lifetime values is fraught with obvious uncertainty. The present approach provides string parameters that establish an initial, but not definitive, set as the basis to explore in future work. As noted in Refs. 28 - 31, subsequent work will include a model string incorporating charge, electric and magnetic fields, multiple interacting strings including loops, various boundary conditions, interaction types, gauge theories, and symmetry conditions. The deviation in string parameters from the base case values established in this paper will illuminate the dependence of the various parameters on specific string properties.

2.0 Nonrelativistic Open String Model Overview

The model proposed in this paper assumes the production of cosmic strings following the big bang or during a big bang/crunch cycle of cosmic events. In this paper, it is assumed that particles result from the emission of the vibrational energy of the string. The fields associated with these particles can be derived from a number of symmetry classes. A simple example would be an Abelian-Higgs theory with a complex scalar field and a U(1) gauge field[27-31]. This class of fields is shown by Matsunami et al.[27] to produce a string with a lifetime, defined in Section 6.0 that is proportional to the square of the string length.

Following the Abelian-Higgs field theory with a U(1) gauge approach, the decay of strings into requisite particles occurs episodically with an associated energy loss. Within the context of this paper, the energy loss is associated with the photon mass

In Ref. 28, a representative sample of string parameters for a set of baryons, leptons, and mesons was determined. This determination was based on specific mass and lifetime values for the set of selected particles that included the proton, neutron, and lambda baryons; electron, muon, and tau leptons; and charged pions and charged B mesons[28]. In Ref. 29, neutrino string parameters and lifetime values were determined in a similar manner. Magnetic monopole and axion string parameter and lifetime values were provided in Ref. 30 and 31, respectively.

Since the photon mass values are assumed to be zero but have an experimental upper bound[25] of 10^{-18} eV/c^2, calculations require a somewhat different approach than utilized in Ref. 28. The approach that is utilized is based on the methodology of Refs. 29 - 31. Given these uncertainties, photon masses are assumed to vary between 10^{-36} to 10^{-21} MeV/c^2 where this mass range is suggested by the upper bound of Ref. 25. For each assumed photon mass, string parameter and lifetime values are derived from the best three fits to the mass value. These parameter values and lifetimes are summarized in Table 1 – 5 and Figures 1 – 5.

3.0 Model Parameter Specification

The string model utilized in this paper is limited to nonrelativistic velocities. The energy of the string available for photon emission is based on its total vibrational energy (kinetic plus potential energy). In this paper, assumed photon masses are utilized to calculate the associated lifetime and string parameter values. However, specific decay modes have not been included in the current model.

Key model parameters include the string density, which is related to the tension, and the length, amplitude, and velocity. Bounds on the string tension (S), derived from pulsar timing measurements [22-24, 27], are based on the gravitational wave background produced by decaying cosmic string loops. This bound, $GS \leq 10^{-11}$, is based on Newton's gravitational constant (G) and is derived from simulations that ignore the field composition of the string. This would correspond to a string mass density of about 1.4×10^{17} kg/m. As a matter of comparison, a density of 1.4×10^{27} kg/m is derived from the Planck energy divided by the Planck length. Ref. 20 suggests that a string density of 10^{21} kg/m is an appropriate string density. These results imply that a range of density values are possible. Accordingly, the string density is permitted to vary over a range of values.

Matsunami et al.[27] suggest that particle radiation is associated with a string length that is $< 10^{19}$ m. Longer-lived particles that do not decay or that have extended lifetimes (e.g., protons and electrons) would be expected to have significantly longer string lengths. This assertion was also noted in Refs. 28 - 31. In addition, cosmological strings are expected to be mildly relativistic[27]. Ref. 27 utilizes values of 0.33 c and 0.6 c in their calculations. The model proposed in this paper[28-31] uses a nonrelativistic approach and limits the string velocity to values less than used in Ref. 27 (i.e., $\beta \leq 0.05$).

These parameter values will be used as a guide and not a specific limitation in this paper. Reasonable variations will be considered in subsequent discussion. In particular, the density is permitted to vary between 10^{7} and 1.4×10^{27} kg/m. The string length is permitted to vary within the 10^{-21} to 10^{46} m. As noted above, the string velocity is assumed to be nonrelativistic. Amplitude values are restricted to be less than the string length.

4.0 Base Case String Model

Cosmic strings have extremely large masses that greatly exceed the values considered in this paper. The particle masses are assumed to be generated by the kinetic and potential energies of the vibrating string. The resulting particle mass does not depend on the total inclusive string mass. In this paper, the inherent string mass is treated as a renormalized vacuum or zero point energy with particles associated with the vibrational energy of the string.

As a base case, a one-dimensional string of finite length and fixed endpoints is assumed. The model details are provided in Refs. 28 - 31 and only salient features will be addressed in this paper.

5.0 Photon Mass

Assuming a uniform energy density over the string length, the energy (E) of a particle corresponding to the string vibrational energy density[28-31] with total length L is

$$E = \frac{1}{2}\mu A^2 \omega^2 L \quad (1)$$

where μ is the string mass per unit length, A is the amplitude, and ω is the angular frequency.

An application of Eq. 1 permits an estimate of the photon's rest mass energy (ε). As noted in Refs. 28 - 31, Eq. 1 can be written as

$$E = 2\pi^2 \mu A^2 \frac{v^2}{\lambda^2} L = \frac{\pi^2}{2} \mu A^2 \frac{v^2}{L} \approx \epsilon \quad (2)$$

where λ = 2L is based on a first harmonic assumption[28-31] and v is the string velocity.

6.0 Photon Lifetime

Matsunami et al.[27] provide a relationship for the string lifetime (τ)

$$\tau \approx \frac{SL^2}{\xi \epsilon c} = \frac{v^2 \mu L^2}{\xi \epsilon c} \quad (3)$$

where ξ is the number of episodes per period, and ε is the average energy lost per unit time which the model assumes to be the photon rest mass energy. The string described in Section 4 is used as the basis for estimating the photon lifetime.

7.0 Model Assumptions and Limitations

The photon lifetime and associated string parameters are derived by assuming the following:

1. The model, defined in Sections 2 – 4, specifies the string parameters that characterize the photon.
2. One episode per period is assumed which is consistent with the fundamental mode assumption of Section 5.
3. The average energy lost per unit time (e.g., over a period) is the string kinetic plus potential energy. Since the string is nonrelativistic, this is assumed to be the photon’s rest mass. The photon lifetime is derived from the rest mass energy of the particle (ε) and these quantities are defined by Eqs. 2 and 3.
4. Only the string kinetic plus potential energy contributes to the photon mass. The inherent string mass (ρL) is essentially a renormalizable constant (i.e., it is the vacuum or zero point energy), because the photon energy is much smaller than this inherent mass.
5. The specific photon decay modes and their associated decay products are not specified or considered.

8.0 Results and Discussion

The model results provide specific photon string parameter and lifetime values as a function of mass. Model results suggest that long-lived photon lifetime values are obtained for a wide range of string parameters. The string parameters (i.e., density, length, amplitude, and velocity) supporting these lifetime values are addressed, and their variation with photon mass are discussed in subsequent commentary. Tables 1, 2, 3, 4, and 5 summarize, as a function of photon mass, the photon string density, length, amplitude, beta value, and lifetime values, respectively. The three best fits to the assumed photon mass are provided in these tables.

Given the nature of the proposed calculations and associated uncertainties, a preliminary goal of fitting the particle masses to within 1% of their assumed values was set. This appears to be a reasonable criterion for the initial calculations.

In Tables 1 – 5, the notation H (high), M (medium), and L (low) is used to label the columns of the three best parameter fits to the assumed photon mass value. The parameter set yielding the largest lifetime for each photon mass is listed under the H column. The L (M) columns record the lowest (middle) lifetime for each of the assumed photon mass values.

8.1 Photon Masses

The photon masses summarized in Tables 1 – 5 are limited to values from 10^{-36} to 10^{-21} MeV/c^2 [25]. The string parameters and lifetime values are calculated as a function of these assumed photon mass values. Photon mass values were fit to within 0.1% for all masses considered in Tables 1 – 5.

Given the simplistic nonrelativistic, uncharged, fixed endpoint open string model, the mass results are encouraging. However, the model parameter assumptions and associated parameter ranges are still lacking in experimental verification.

8.2 String Density

As noted in Table 1, there is significant variation in the string density as a function of photon mass for the L, M, and H Cases. In particular, the string density values reside within the range of 10^{10} – 10^{25} kg/m. In view of this variation, definitive conclusions regarding the string density are not possible. This density range is similar to the values calculated for a magnetic monopole[30] and axion[31]. Therefore, a more global analysis must be utilized.

Table 1

Photon String Density (kg/m)[a]

Photon Mass (MeV)	Case L	Case M	Case H
10^{-36}	7.49×10^{10}	2.01×10^{13}	3.03×10^{11}
10^{-35}	1.15×10^{13}	2.29×10^{11}	7.62×10^{14}
10^{-34}	7.02×10^{11}	6.57×10^{12}	3.03×10^{11}
10^{-33}	1.40×10^{10}	1.01×10^{15}	1.76×10^{15}
10^{-32}	5.31×10^{11}	5.13×10^{20}	1.95×10^{22}
10^{-31}	4.28×10^{10}	6.15×10^{13}	2.70×10^{17}
10^{-30}	4.65×10^{13}	1.23×10^{12}	5.13×10^{20}
10^{-29}	9.28×10^{11}	7.49×10^{10}	5.86×10^{18}
10^{-28}	2.15×10^{12}	2.93×10^{20}	9.13×10^{24}
10^{-27}	1.01×10^{15}	1.76×10^{15}	4.97×10^{12}
10^{-26}	1.88×10^{14}	6.36×10^{21}	1.38×10^{23}
10^{-25}	1.15×10^{13}	1.02×10^{19}	1.04×10^{23}
10^{-24}	9.28×10^{11}	5.76×10^{14}	9.59×10^{19}
10^{-23}	7.49×10^{10}	1.02×10^{19}	1.88×10^{14}
10^{-22}	1.31×10^{11}	1.88×10^{14}	5.67×10^{10}
10^{-21}	1.52×10^{13}	5.48×10^{19}	1.27×10^{20}

[a]Cases L(low), M(Medium), and H(high) are based on the relative mean lifetime values of Table 5.

To facilitate a global analysis, an averaged logarithmic string parameter (ALSP) Ω(m) is defined in terms of the photon mass by the relationship:

$$log_{10}\Omega(m) = \frac{log_{10}\Omega_L(m) + log_{10}\Omega_M(m) + log_{10}\Omega_H(m)}{3} \quad (4)$$

where the averaged logarithmic string parameters are ALSμ for the string density, ALSL for the string length, ALSA for the string amplitude, and ALAτ for the string lifetime. The averaged string velocity (ASβ) is addressed in subsequent discussion.

The ALSμ for the string density is plotted as a function of photon mass in Fig. 1. As expected, the ALSμ (Fig. 1 dashed curve derived from the Table 1 data) still exhibits considerable variation, but it is less severe than the individual Case L, M, and H variations

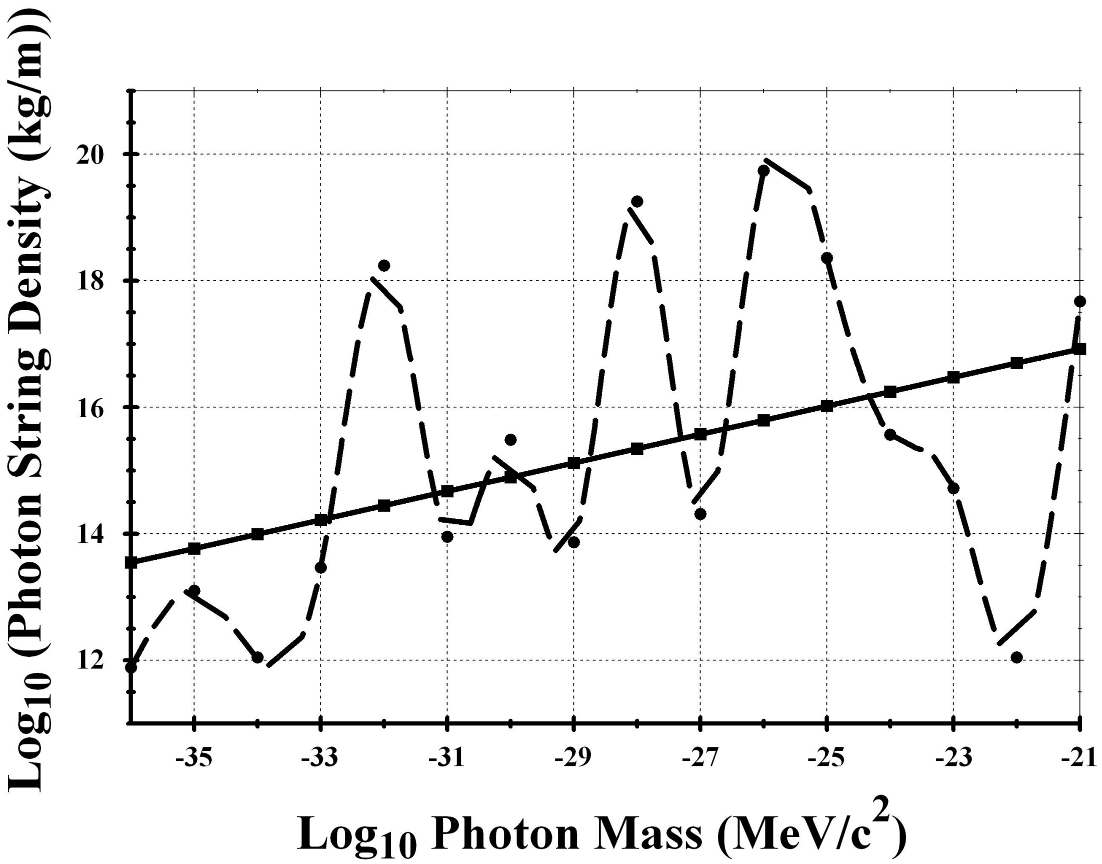

Figure 1 Photon string density as a function of photon mass

The solid curve in Figure 1 represents a linear fit to the ALSμ values defined by the relationship:

$$\mu(m) = a \log_{10}\mu_{ALS\mu}(m) + b (5)$$

where a = 0.225161937 kg/m and b = 21.65052166 kg/m. The linear fit suggests an averaged string density that decreases from about 10^{18} to 10^{16} kg/m[31] for axion masses in the range of 10^{20} – 1 MeV/c^2, respectively. Linear photon fits increase from about 10^{14} to 10^{17} kg/m for the mass range of 10^{36} to 10^{-21} MeV/c^2.

The photon sting density is generally higher than noted in Ref. 28 for unstable baryons (neutrons and lambdas), leptons (muons and taus), and mesons (charged pions and charged B mesons). However, the electron and proton string density range of values encompasses the range of photon values[28].

Baryon densities derived in Ref. 28 were $10^{12} – 10^{18}$ kg/m for neutrons, $10^{10} – 10^{27}$ for protons, and about 10^{12} kg/m for lambdas. Lepton string densities also tend to be lower than the corresponding photon values with values of $10^{11} – 10^{21}$ kg/m, $10^{12} – 10^{16}$ kg/m, and $10^{11} – 10^{12}$ kg/m for electron, muon, and tau leptons, respectively[28]. Meson string densities for charged pions ($10^{11} – 10^{14}$ kg/m) and charged B mesons ($\approx 10^{11}$ kg/m) also exhibit a lower value than the photon string density.

The results of Ref. 28 suggest that higher string densities are exhibited for longer-lived particles. The photon string density results and the verification that it is also a long-lived particle with a lifetime range that is noted in Table 5 provide additional support for the credibility of the nonrelativistic open string model with fixed endpoints.

8.3 String Length

Following Ref. 27, the string length associated with the decay of unstable particles should be $<10^{-19}$ m. As noted in previous discussion, this value provides an indication of an expected unstable particle string length, and the results of other open string nonrelativistic models may differ.

The photon length values summarized in Table 2 vary over a range of $10^{6} – 10^{17}$ m that is similar to the axion range[31]. These string length values are much larger than noted for unstable particles[27,28], but similar to the magnetic monopole values[30].

For baryons, the neutron and lambda string lengths are in the range of 10^{-15} to 10^{-12} m and $\approx 10^{-19}$ m, respectively[28]. A similar range of string values is found for short-lived leptons. The muon and tau string lengths are in the range of 10^{-19} to 10^{-17} m and $\approx 10^{-19}$ m, respectively. The meson values are 10^{-19} to 10^{-17} m and $\approx 10^{-19}$ m for the charged pion and B meson, respectively.

For long-lived particles, string lengths have an increased value. Proton and electron string lengths are in the range of $10^{6} – 10^{11}$ m and $10^{4} – 10^{14}$ m, respectively[28]. Eq. 3 suggests that the increased proton and electron lifetime values should correspond with string lengths that are much longer than those values encountered in unstable baryons, leptons, and mesons[28]. The results summarized in Table 2 further support the model's credibility by predicting a long-lived photon.

Table 2

Photon String Length (m)[a]

Photon Mass (MeV)	Case L	Case M	Case H
10^{-36}	$5.34x10^{11}$	$8.76x10^{12}$	$3.70x10^{15}$
10^{-35}	$8.35x10^{11}$	$5.90x10^{13}$	$1.50x10^{14}$
10^{-34}	$3.17x10^{13}$	$1.75x10^{14}$	$3.70x10^{15}$
10^{-33}	$5.22x10^{10}$	$1.59x10^{15}$	$9.18x10^{15}$
10^{-32}	$2.30x10^{8}$	$1.52x10^{15}$	$3.75x10^{15}$
10^{-31}	$1.45x10^{9}$	$9.64x10^{14}$	$1.11x10^{13}$
10^{-30}	$7.48x10^{10}$	$1.72x10^{13}$	$1.52x10^{15}$
10^{-29}	$1.17x10^{7}$	$5.34x10^{11}$	$1.85x10^{14}$
10^{-28}	$2.69x10^{11}$	$7.64x10^{12}$	$1.69x10^{15}$
10^{-27}	$1.93x10^{9}$	$4.45x10^{13}$	$1.89x10^{15}$
10^{-26}	$8.15x10^{12}$	$1.87x10^{12}$	$1.83x10^{16}$
10^{-25}	$6.42x10^{7}$	$1.21x10^{8}$	$5.39x10^{14}$
10^{-24}	$6.06x10^{14}$	$1.51x10^{14}$	$7.68x10^{11}$
10^{-23}	$2.12x10^{6}$	$1.21x10^{8}$	$1.79x10^{16}$
10^{-22}	$3.78x10^{15}$	$1.68x10^{15}$	$7.47x10^{16}$
10^{-21}	$5.96x10^{15}$	$2.77x10^{13}$	$9.82x10^{15}$

[a]Cases L(low), M(Medium), and H(high) are based on the relative mean lifetime values of Table 5.

The photon string length results are further summarized in Fig. 2. In Fig. 2, the dashed curve represents the ALSL values derived from Table 2 for masses in the range of 10^{-36} to 10^{-21} MeV/c^2.

The solid curve in Fig. 2 represents a linear fit to the ALSL values:

$$L(m) = alog_{10}L_{ALSL}(m) + b(6)$$

where a = -0.0036076028 m and b = 12.98420091 m. The linear fit of Eq. 6 suggests an averaged string length of about 10^{13} m that falls within the 10^{14} - 10^{10} m range for axion masses between 10^{20} and 1 MeV/c^2 [31]. This range is similar to the calculated magnetic monopole length of about 10^{11} - 10^{12} m for monopole masses between 10 and 10^{18} MeV/c^2 noted in Ref. 30.

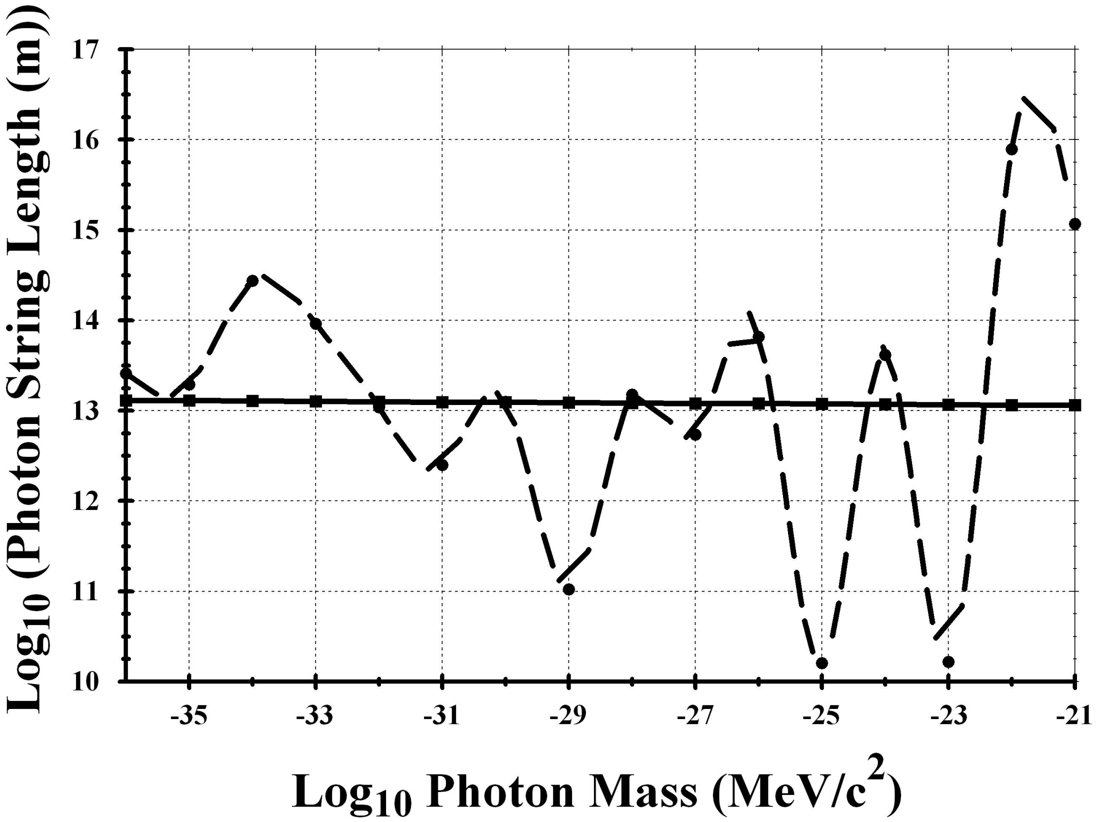

Figure 2 Photon string length as a function of photon mass

8.4 String Amplitude

The photon amplitude summarized in Table 3 has a range between 10^{33} and 10^{-22}. This range partially overlaps the axion amplitude range of 10^{-30} and 10^{-14} m[31] that is significantly smaller than the magnetic monopole values of 10^{22} and 10^{-4} m summarized in Ref. 30. As noted with the other string parameters, there is considerable variability in the amplitude values. This variability is reduced using the ALSA values.

Table 3

Photon String Amplitude (m)[a]

Photon Mass (MeV)	Case L	Case M	Case H
10^{-36}	7.20×10^{-32}	1.69×10^{-32}	2.41×10^{-29}
10^{-35}	2.69×10^{-32}	7.12×10^{-31}	1.74×10^{-32}
10^{-34}	8.10×10^{-31}	2.53×10^{-30}	2.41×10^{-29}
10^{-33}	2.82×10^{-30}	2.32×10^{-30}	1.08×10^{-29}
10^{-32}	8.92×10^{-32}	2.29×10^{-32}	9.41×10^{-34}
10^{-31}	8.68×10^{-31}	3.58×10^{-29}	2.92×10^{-32}
10^{-30}	1.04×10^{-30}	5.52×10^{-29}	2.29×10^{-32}
10^{-29}	6.27×10^{-31}	1.14×10^{-28}	3.26×10^{-31}
10^{-28}	1.42×10^{-27}	2.60×10^{-32}	1.78×10^{-33}
10^{-27}	1.64×10^{-30}	8.44×10^{-29}	9.02×10^{-27}
10^{-26}	3.01×10^{-28}	3.22×10^{-32}	1.27×10^{-30}
10^{-25}	1.35×10^{-29}	8.70×10^{-31}	3.07×10^{-31}
10^{-24}	3.81×10^{-25}	8.37×10^{-27}	2.62×10^{-30}
10^{-23}	5.39×10^{-28}	8.70×10^{-31}	6.80×10^{-25}
10^{-22}	2.61×10^{-23}	2.56×10^{-24}	1.70×10^{-22}
10^{-21}	7.83×10^{-24}	1.86×10^{-27}	1.86×10^{-26}

[a]Cases L(low), M(Medium), and H(high) are based on the relative mean lifetime values of Table 5.

Using Eq. 4, an ALSA value is calculated and is represented by the dashed curve in Fig. 3. The solid curve in Fig. 3 represents the linear fit to the ALSA values

$$A(m) = a\log_{10}A_{ALSA}(m) + b \quad (7)$$

where a = 0.38427897 m and b = -17.88689188 m. Over the photon mass range of 10^{36} to 10^{-21} MeV/c^2, the linear amplitude fit increases from about 10^{-32} to to 10^{-26} m. This range is smaller than the axion mass range of about 10^{25} and 10^{-17} m[31].

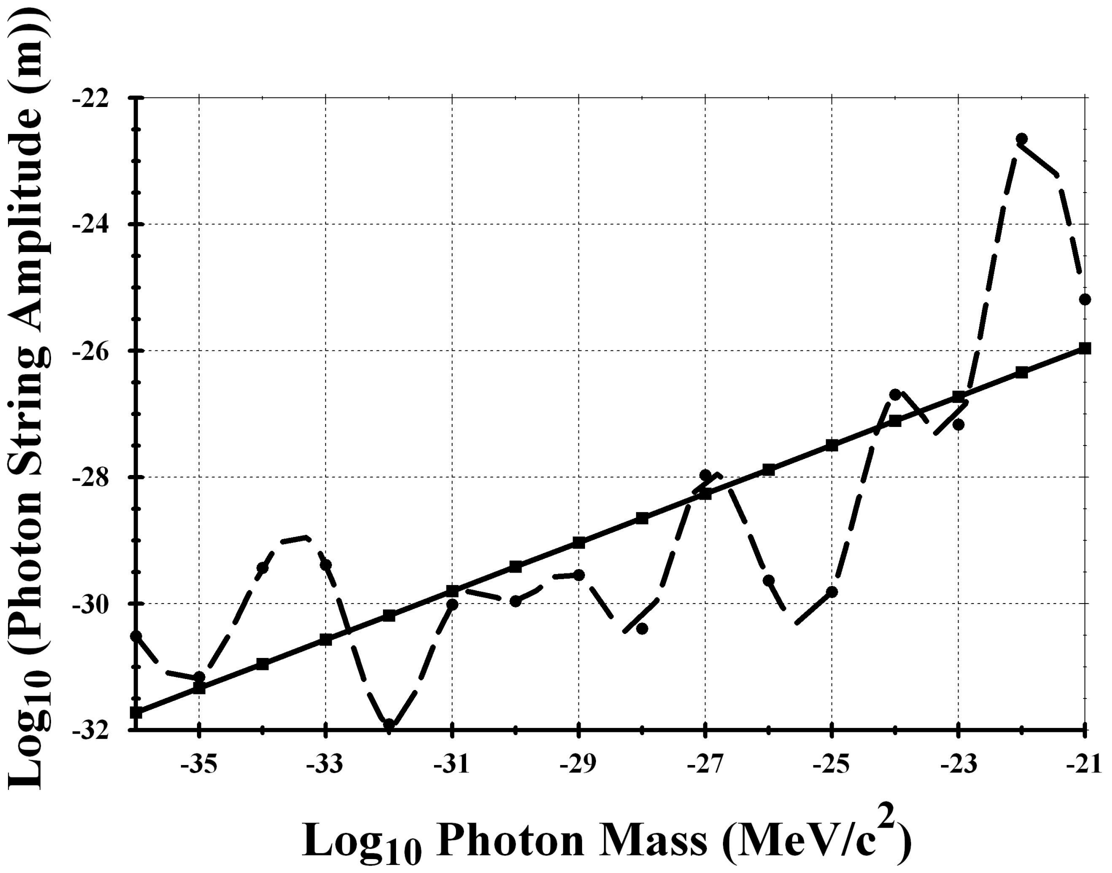

Figure 3 Photon string amplitude as a function of photon mass

The neutron amplitude is in the range of 10^{29} to 10^{-25} m, and the heavier lambda amplitude is $\approx 10^{28}$ m. For short-lived leptons and mesons, larger amplitude values suggest a larger mass and shorter lifetime. The muon amplitude is in the range of 10^{-30} to 10^{-27} m, and the heavier tau has an amplitude of $\approx 10^{27}$ m. Meson amplitudes follow a similar pattern, but the differences are not as large. The charged pion amplitude is in the range of 10^{-29} to 10^{-26} m, and the heavier charged B meson has a value of $\approx 10^{-27}$ m.

As noted in Reference 28, the proton and electron amplitude values are in the range of 10^{30} – 10^{-13} m and 10^{-19} – 10^{-17} m, respectively. The photon amplitude is generally smaller in magnitude than the proton and electron values[28].

8.5 String Velocity

The string velocity is restricted to $\beta \leq 0.05$. In Reference 28, the baryon, lepton, and meson results suggest that there is no general velocity relationship between values of β and the particle mass or lifetime and associated string parameters. Similar results occur for the neutrino[29], magnetic monopole[30], and axion[31] results. There is also considerable scatter in the photon string velocity values summarized in Table 4.

Table 4

Photon String Beta[a]

Photon Mass (MeV)	Case L	Case M	Case H
10^{-36}	0.0223	0.0235	0.00275
10^{-35}	0.0190	0.0428	0.0485
10^{-34}	0.0498	0.0123	0.0275
10^{-33}	0.0130	0.0103	0.00400
10^{-32}	0.0140	0.00450	0.0280
10^{-31}	0.0403	0.0210	0.0418
10^{-30}	0.0233	0.0408	0.0450
10^{-29}	0.0108	0.0443	0.0328
10^{-28}	0.00150	0.0373	0.0458
10^{-27}	0.0160	0.0358	0.0410
10^{-26}	0.0415	0.0320	0.0173
10^{-25}	0.0333	0.000750	0.0445
10^{-24}	0.0403	0.0368	0.0205
10^{-23}	0.0188	0.00750	0.0273
10^{-22}	0.0390	0.00700	0.0405
10^{-21}	0.0480	0.00725	0.00900

[a]Cases L(low), M(Medium), and H(high) are based on the relative mean lifetime values of Table 5.

The L, M, and H Case values were averaged to obtain the ASβ value:

$$\beta_{AS\beta}(m) = \frac{\beta_L(m) + \beta_M(m) + \beta_H(m)}{3} \quad (8)$$

where the $\beta_{AS\beta}(m)$ values were fit to the linear relationship

$$\beta(m) = a\beta_{AS\beta}(m) + b (9)$$

with a = 0.00013404412 and b = 0.0303004657.

In Fig. 4, the dashed curve represents the $\beta_{AS\beta}(m)$ values, and the solid curve illustrates the linear fit values of Eq. 9. The averaged $\beta_{AS\beta}(m)$ values still exhibit considerable scatter, but the linear fit suggests the photon velocity values lie in the range of about 0.026 – 0.028 c.

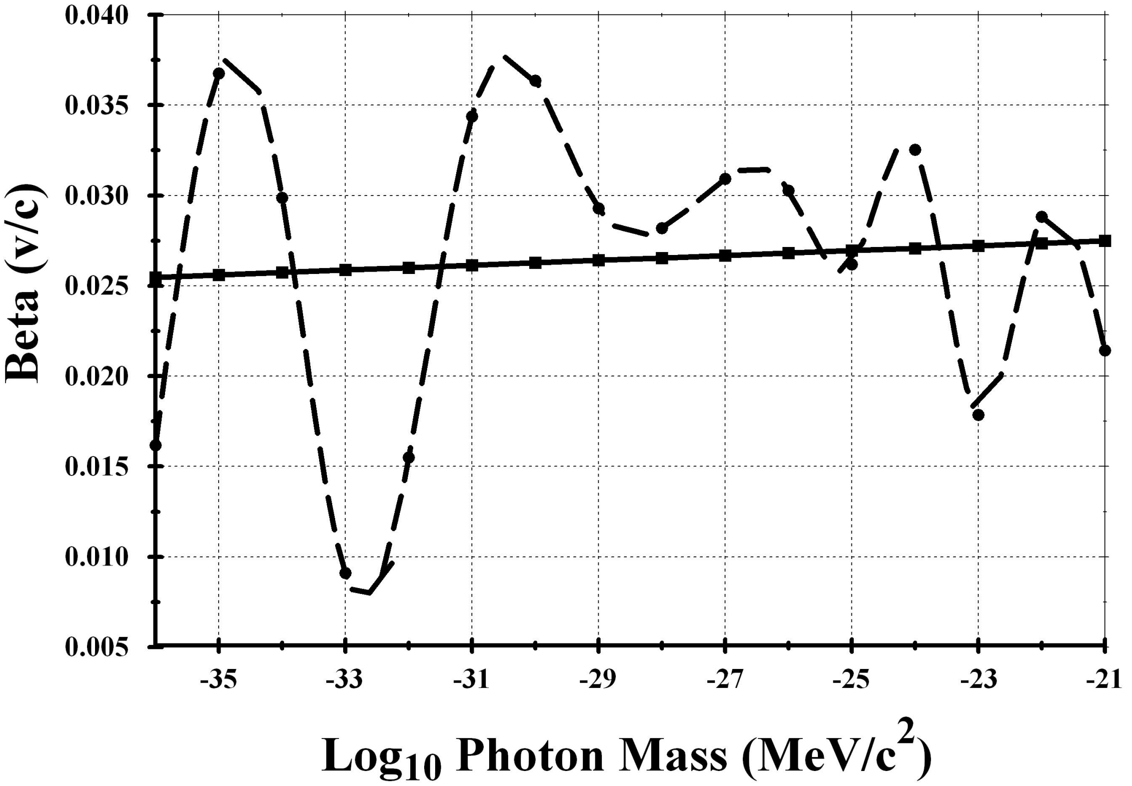

Figure 4 Photon string velocity as a function of photon mass

The Table 4 and Fig. 4 values are not clustered near the maximum β value (i.e., 0.05) that suggests that the model is favoring a nonrelativistic solution. This conclusion is model dependent and must be verified with a more refined approach including electromagnetic fields and other symmetry assumptions that were noted previously.

8.6 Particle Lifetime

Following Eq. 3 and the associated discussion, the particle lifetime values are strongly dependent on the string length, tension, and particle mass. The particle mass (Eq. 2) involves multiple parameters, but the lifetime (Eq. 3) only depends on a subset of these parameters.

The variation in lifetime values as a function of photon mass is illustrated by an examination of Table 5. As summarized in Table 5, the photon lifetime values vary significantly and range between about 10^{56} and 10^{96} yr. The magnetic monopole lifetime values also vary significantly and range between about 10^{22} and 10^{66} yr[30]. In the spirit of the model assumptions and limitations, the results of Table 5 were fit to the functional form of Eq. 4.

Table 5

Photon String Mean Lifetime (yr)[a]

Photon Mass (MeV)	Case L	Case M	Case H
10^{-36}	$6.27x10^{80}$	$5.07x10^{85}$	$1.86x10^{87}$
10^{-35}	$1.72x10^{82}$	$8.68x10^{84}$	$2.39x10^{89}$
10^{-34}	$1.03x10^{84}$	$1.80x10^{85}$	$1.86x10^{87}$
10^{-33}	$3.83x10^{74}$	$1.58x10^{88}$	$1.41x10^{89}$
10^{-32}	$3.26x10^{70}$	$1.42x10^{92}$	$1.27x10^{96}$
10^{-31}	$8.70x10^{70}$	$1.50x10^{85}$	$8.46x10^{85}$
10^{-30}	$8.36x10^{75}$	$3.60x10^{79}$	$1.42x10^{92}$
10^{-29}	$8.73x10^{64}$	$2.48x10^{74}$	$1.28x10^{87}$
10^{-28}	$2.07x10^{71}$	$1.41x10^{85}$	$3.23x10^{94}$
10^{-27}	$5.71x10^{70}$	$2.65x10^{80}$	$1.77x10^{81}$
10^{-26}	$1.28x10^{77}$	$1.35x10^{83}$	$8.12x10^{91}$
10^{-25}	$3.11x10^{64}$	$5.02x10^{67}$	$3.56x10^{88}$
10^{-24}	$3.28x10^{76}$	$1.06x10^{78}$	$1.41x10^{78}$
10^{-23}	$7.06x10^{56}$	$5.02x10^{67}$	$2.67x10^{80}$
10^{-22}	$1.69x10^{75}$	$1.55x10^{76}$	$3.08x10^{77}$
10^{-21}	$7.38x10^{76}$	$1.31x10^{77}$	$5.88x10^{82}$

[a]Cases L(low), M(Medium), and H(high) are based on the relative mean lifetime values.

The ALSτ values are plotted in Fig. 5 (dashed curve) and exhibit considerable variation. In Fig. 5, the solid curve represents the linear fit to the ALSτ values

$$\tau(E) = a log_{10}\tau_{ALS\tau}(E) + b \quad (10)$$

where the parameters a = -0.78025542 yr and b = 58.03982159 yr. The linear fit provides a more stable set of lifetime values, but there is still a significant variation with mass. The photon lifetime values exceed those calculated in Refs. 28 – 31.

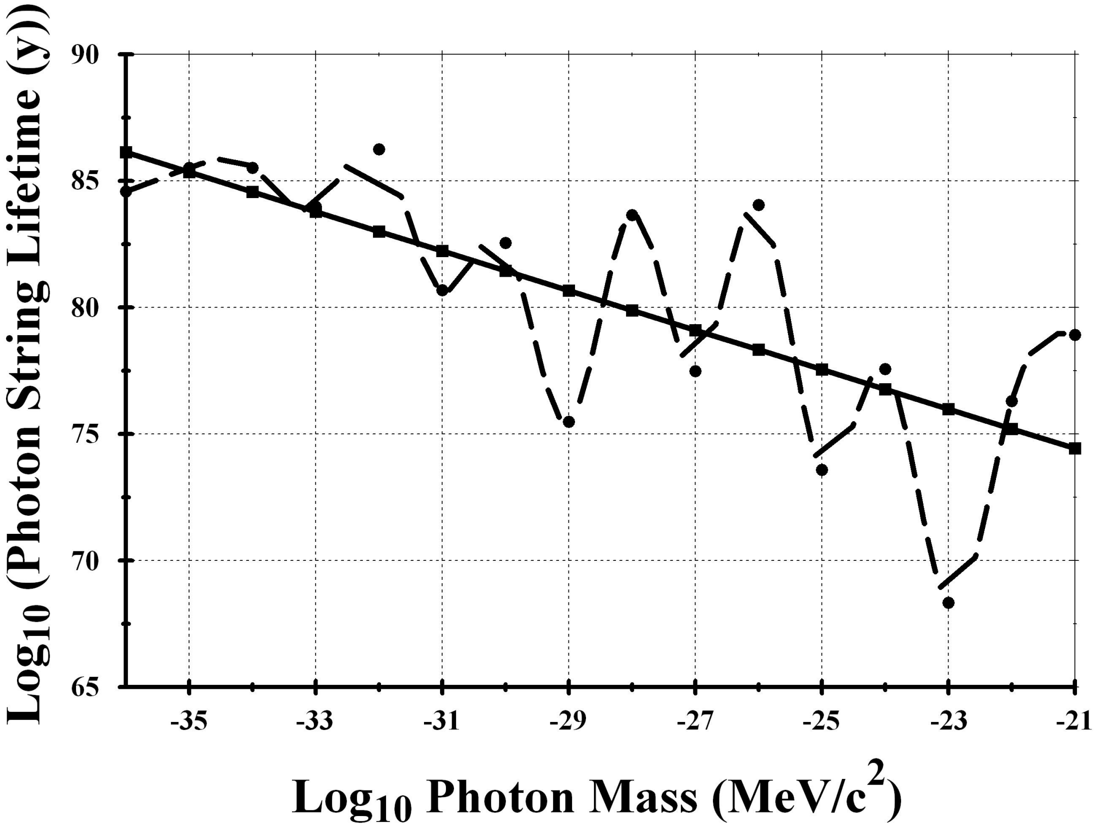

Figure 5 Photon mean lifetime as a function of photon mass

Linear fit photon lifetime values derived from Eq. 10 decrease from about 10^{86} to 10^{74} yr for the range of mass values between 10^{-36} and 10^{-21} MeV/c^2, respectively. Axion lifetime values[31] are much shorter and decrease from about 10^{75} to 10^{47} yr for the range of mass values between 10^{20} and 1 MeV/c^2, respectively. The linear fit photon lifetime values are larger than magnetic monopole values[30] that decrease from about 10^{50} to 10^{35} yr for the range of mass values between 10 and 10^{18} MeV/c^2, respectively. The linear fit photon lifetime values are also larger than the predicted neutrino lifetime values[29], and the proton and electron values[28].

Nonrelativistic string model predictions for the proton (electron) lifetime are 10^{37} - 10^{58} yr (10^{29} – 10^{59} yr), respectively. The relative consistency of the string density, length, and amplitude values for the proton, electron, and neutrino further support a long-lived value for the photon lifetime[28,29].

9.0 Generalization to Closed String Models

Bagchi et al.[26] note that there is a natural emergence of an open string from a closed string given selected parameter limits. There is also a condensation of perturbative closed string modes to an open string. Ref. 26 provides an important calculation that has the potential to generalize the open string model of this paper to a closed string model.

10.0 Conclusions

The proposed nonrelativistic open string model with fixed endpoints provides an initial set of photon string parameters that yield mean lifetime values that decrease from about 10^{86} to 10^{74} yr for the range of mass values between 10^{36} and 10^{-21} MeV/c^2, respectively. The derived photon string parameters and lifetime values are based on a simplistic open string model, and will likely change as the model becomes more complex through the inclusion of charge, electric and magnetic fields, multiple strings with loops, additional boundary conditions, and specific symmetries and gauge theories. The validity of the proposed and subsequent models will be determined by experimental verification. Experimental verification is ultimately the requirement that will determine the validity of all string theories. However, this initial set of photon parameters provides a base case for future investigation, development, and determination of observable string characteristics.

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