Astrophys. Space Sci. Trans., 7, 419–423, 2011
www.astrophys-space-sci-trans.net/7/419/2011/
doi:10.5194/astra-7-419-2011

Astrophysics and **S**pace Sciences **Tr**ans**a**ctions

Lower limits on the lifetime of massive neutrino radiative decay from the 2006 total solar eclipse

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Received: 14 November 2010 – Revised: 2 March 2011 – Accepted: 10 April 2011 – Published: 22 September 2011

Abstract. We report on the search for signatures of possible neutrino radiative decays, in occasion of the 2006 total solar eclipse (TSE). The lower lifetime limits obtained in the hypothesis of normal mass hierarchy ($m_3 \gg m_2 > m_1$) are about 3 orders of magnitude better than the previous results. The inverted mass hierarchy scenario ($m_2 > m_1 \gg m_3$) is also investigated. The reached sensitivity suggests that the limits presented here are the best obtainable using this technique.

1 Introduction

The evidence of neutrino oscillations implies that neutrinos have non-vanishing masses, and that neutrino flavor eigenstates are superpositions of mass eigenstates. The Sun is a very strong source of ν_e neutrinos; the expected flux at Earth (neglecting oscillation effects) is $\Phi \simeq 7 \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The SNO result (Ahmad et al., 2002) demonstrate that a fraction of this flux reaches the Earth as neutrinos of different flavors than ν_e. In the two generation approximation, this lead to $\Delta m^2_{1,2} = 6 \times 10^{-5}\,\mathrm{eV}^2$, corresponding to $\nu_e \leftrightarrow \nu_\mu$ oscillations. A more refined approach, considering all 3 neutrino generations, yields $\Delta m^2_{1,2} = 7.65 \times 10^{-5}\,\mathrm{eV}^2$ (Schwetz et al., 2010); we estimate that the effect of this update on the lifetime limits presented in this paper is less than 1%. Returning to the simplified 2 generation approach, the radiative transition between the neutrino mass eigenstates composing the electron neutrino is allowed ($\nu_H \to \nu_L + \gamma$, where ν_H stands for the heavier component and ν_L for the lighter one), and some of the emitted photons could appear (in the observer frame) as visible. The existing very stringent limits on the neutrino magnetic moment, $\mu_\nu < 1.3 \times 10^{-10}\,\mu_B$ (Amsler et al., 2008) refer only to the neutrino flavor eigenstates; furthermore, exotic decay mechanisms cannot be excluded.

Direct searches for radiative (anti)-neutrino decays were performed in the vicinity of nuclear reactors (e.g. Bouchez et al., 1988, yielding limits between $\tau_0/m > 10^{-8}$ s/eV and $\tau_0/m > 0.1$ s/eV, for $\Delta m/m$ between 10^{-7} and 0.1); the Borexino Counting Test Facility at Gran Sasso yielded limits at the level of $\tau_0/m \sim 10^3$ s/eV (Derbin and Smirnov, 2002).

Very strong limits were inferred from cosmological or astrophysical considerations, but such limits are indirect and rather speculative. Some of them are shortly reviewed in Cecchini et al. (2011).

In a pioneering experiment performed in occasion of the 24 October 1995 TSE, a search was made for visible photons emitted through radiative decays of solar neutrinos during their flight between the Moon and the Earth (Birnbaum et al., 1997). The authors assumed that neutrinos have masses of the order of few eV, $\Delta m^2_{12} \simeq 10^{-5}\,\mathrm{eV}^2$, an energy of 860 keV and that all decays yield visible photons, which travel nearly in the same direction as the parent neutrinos. From the absence of a positive signal they estimated a lower limit on τ_0 (97 s) which, in view of the assumptions made, is now not reliable.

Another search for solar neutrino radiative decays was made during the 21 June 2002 TSE, in Zambia (Cecchini et al., 2004b). The proper lower time limits (95% C.L.) obtained for the $\nu_2 \to \nu_1 + \gamma$ decays of left-handed neutrinos ranged from $\tau_0/m_2 \simeq 10$ to $\simeq 10^9$ s/eV, for $10^{-3}\,\mathrm{eV} < m_1 < 0.1\,\mathrm{eV}$.

In this paper we report on the observations performed in occasion of the 29 March 2006 TSE, from Waw an Namos, Libya (Cecchini et al., 2011). The hypothesis of the inverted mass neutrino hierarchy is considered for the first time in such a contest.

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Published by Copernicus Publications on behalf of the Arbeitsgemeinschaft Extraterrestrische Forschung e.V.

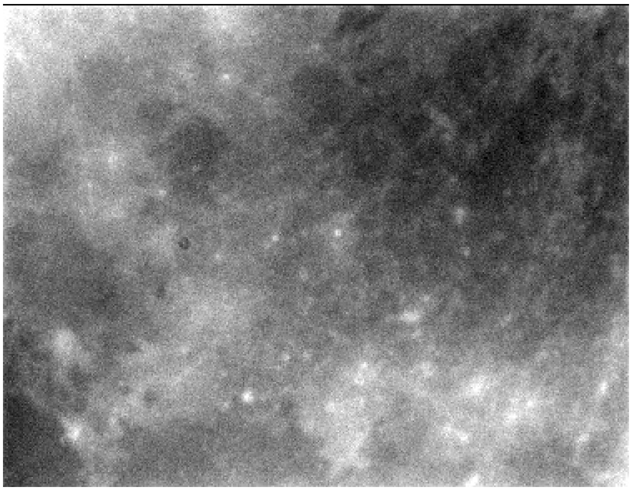

Fig. 1. One of the frames recorded during the totality. The center of the image corresponds to the position of the center of the Sun behind the Moon. (From (Cecchini et al., 2011))

2 The experiment

The total solar eclipse of 29 March 2006 was observed from a campus in the Southern Libyan Sahara (17.960° E longitude, 24.496° N latitude and 465 m altitude) with a Matsukov-Cassegrain telescope ($\Phi = 235$ mm, $f = 2350$ mm) equipped with a fast 16 bit Mx916 CCD camera.

The night before the eclipse we aligned the system, adjusted the focus and took calibration images of some standard luminosity stars (SAO99215 and SAO99802). The photometric analysis showed that an acquisition digital unit (ADU) corresponds to 6.1 ± 0.1 photons.

The telescope movement was set to follow the Sun in order to have always the center of the acquired images coincident with the Sun center. We implemented a special CCD exposure algorithm in order to adapt the exposure times to the luminosity level of the Moon image. The ashen light (the Sun's light reflected by the Earth back to the Moon) is one of the main background sources, but allows the reconstruction, frame by frame, of the real position of the Sun behind the Moon, eliminating the risk of pointing errors. More technical details are described in Cecchini et al. (2011).

The data collected consist in 212 digital pictures of the central part of the "dark" disk of the Moon. Each image pixel covers a solid angle of 1.99" $\times$ 1.95". The analysis is based on the wavelet decomposition of the images; we selected only the central largest dyadic square from each frame (256×256 square pixels); the total coverage was $8.49' \times 8.32'$ (the Moon apparent diameter is $31'$).

Figure 1 shows one of the frames recorded during the totality phase; details on the Moon surface seen in the ashen light are clearly visible.

3 Monte Carlo simulations

The analysis of the data obtained by this experiment required a detailed Monte Carlo simulation, including the neutrino production in the solar core, its propagation, decay, and the photon detection on Earth. Such a code was developed for the analysis of the data collected during the 2001 eclipse and was adapted to the conditions of the 2006 observations. The model is described in detail in Cecchini et al. (2004a).

Solar neutrino production was simulated according to the "BP2000" Standard Solar Model (SSM) (Bahcall et al., 2001). We chose a specific reaction/decay yielding neutrinos (both from the p–p and the CNO cycles); the neutrino energy and the position of its production point in the core of the Sun were generated according to the SSM. As we are interested only in neutrinos that could undergo radiative decays between the area of the Moon seen by our experiment and the Earth, a decay point was generated and the arrival direction of the decay photon was chosen. Once the geometry of the event is known, the photon energy is computed taking into account the Lorentz boost, and for visible photons the probability density of the angular distribution, depending on whether the neutrino is a Dirac neutrino, left or right-handed, or a Majorana neutrino. The number of visible photons is about $5 \cdot 10^{-4}$ of the total spectrum; this quantity is integrated over all directions accessed by the instrument aperture.

The interpretation of the solar neutrino oscillation data in the simplest two flavor model (assuming that the electron neutrino ν_e is just the superposition of two mass eigenstates ν_1 and ν_2) yields a square mass difference of $\Delta m^2_{1,2} = 6 \times 10^{-5}\,\mathrm{eV}^2$ (Ahmad et al., 2002). This mass difference was used in simulating the possible $\nu_2 \to \nu_1 + \gamma$ decays. There is also the possibility of a more complex scenario, assuming a mixing between all 3 mass eigenstates. Since $\Delta m^2_{1,3} \simeq \Delta m^2_{2,3} = 2.4 \times 10^{-3}\,\mathrm{eV}^2$ (as known from atmospheric neutrino (Ambrosio et al, 2004; Ashie et al., 2005) and long baseline oscillation experiments (Adamson et al., 2008)), the $\nu_3 \to \nu_2 + \gamma$ and the $\nu_3 \to \nu_1 + \gamma$ decays should be similar.

The simulation yields the probabilities that the emitted photon is in the visible bandwidth. They are obtained in the a priori assumption that heavier neutrino mass eigenstates undergo radiative decays in the space between the Moon and the Earth, and the photon reaches the detector.

The $\nu_2 \to \nu_1 + \gamma$ decays should produce a spot of light coincident with the center of the Sun behind the Moon disk, about 60" large, while the signal from the $\nu_3 \to \nu_{1,2} + \gamma$ decays would consists of light rings about 20" thick, with diameters of about 200" and 250", also centered in the center of the Sun. The difference originates in the condition that the photon appears as visible in the Earth's frame of reference. The energy in the proper frame of the decaying neutrino depends on the mass difference between the two neutrinos, thus

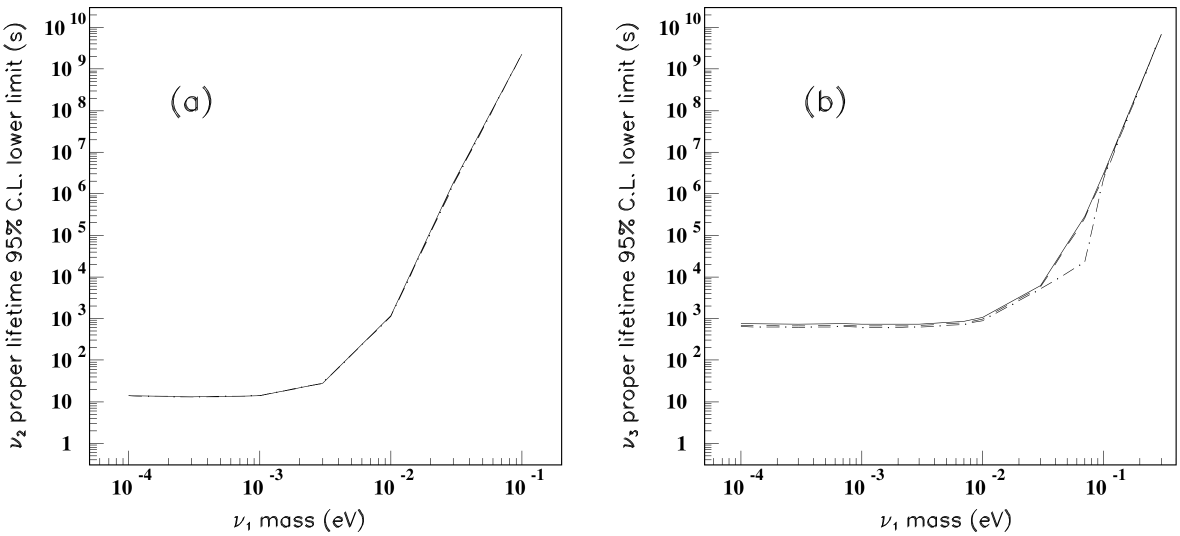

Fig. 2. (a): 95% C.L. lower limits for the ν_2 proper lifetime, assuming normal hierarchy. The differences between different polarization states cannot be seen at this scale. **(b)**: 95% C.L. lower limits for the ν_3 proper lifetime, assuming $\sin^2\theta_{13} = 0.1$ and normal mass hierarchy. The graphs correspond from up to down to lefthanded, Majorana and righthanded neutrinos. (from Cecchini et al., 2011)

in the ν_2 decay is much smaller than in the ν_3 case; the photon energy is boosted in the visible spectrum for directions along the direction of the parent neutrino. For the ν_3 decay the condition is satisfied for photons emitted at larger angles.

The above discussion assumes the normal neutrino mass hierarchy; as the only input for the simulation related to neutrinos is one of the mass values, the mass differences and the polarity, the Monte Carlo results are independent on the hierarchy scenario.

4 Data analysis and results

The search for the $\nu_2 \to \nu_1 + \gamma$ and the $\nu_3 \to \nu_{1,2} + \gamma$ signatures from the frames recorded during the 2006 TSE is based on the analysis of the superposition of 195 good quality images similar to Fig. 1. As the images are aligned with respect to the position of the Sun behind the Moon, most of the Moon scape details in Fig. 1 are washed off. The obtained image was analyzed using the wavelet decomposition, in the simple Haar basis. The n-order term of the decomposition is obtained by dividing the $N \times N$ pixels^2 image in square fields of $N/2^n \times N/2^n$ pixels^2 and averaging the luminosity in each field; the averages are then removed and the resulting image, the n-order residual, can be used to obtain the $(n+1)$-order term. Thus, each decomposition term results in an image that enhances the contrast of the objects on the corresponding scale, while the residuals contain information for smaller dimension scales.

The decay signal is searched for by averaging the luminosity of the images over "rings" concentric to the position of the center of the Sun. As the wavelet analysis requires a dyadic dimension of the field (the number of pixels on each border have to be an integer power of 2), there is no "central pixel", so we have considered the four pixels adjacent to the image center as "central" and then averaged the obtained luminosity profiles.

The used image has 256×256 pixels^2, so we could go as far as the 7^{th} order in the wavelet decomposition. None of the image decomposition terms or residuals show structures as would be expected from solar neutrino radiative decays; thus we might infer that a possible signal cannot be larger than the statistical fluctuations.

4.1 Lifetime limits in the normal mass hierarchy hypothesis

The expected scale of the decay signal (few tens of seconds of arc) suggest that the wavelet term most sensitive to the $\nu_2 \to \nu_1 + \gamma$ and $\nu_3 \to \nu_{1,2} + \gamma$ decays should be the 5^{th} order, with a typical scale of about 16". The number of visible photons originating from solar neutrino radiative decays that could be recorded by the telescope CCD may be computed as

$$N_\gamma = P\,\Phi_{(2,3)} S_M t_{obs} \left(1 - e^{\frac{\langle t_{ME}\rangle}{\tau}}\right) e^{-\frac{t_{SM}}{\tau_{(2,3)}}}, \tag{1}$$

where P are the mass-dependent Monte Carlo probabilities and $\Phi_{(2,3)}$ represents the flux of ν_2 or ν_3 solar neutrino components at the Earth level

$$\begin{aligned} \Phi_2 &= \Phi_\nu \sin^2\theta_{12} \\ \Phi_3 &= \Phi_\nu \sin^2\theta_{13}, \end{aligned} \tag{2}$$

where $\Phi_\nu \simeq 7 \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ is the expected solar neutrino flux on the Earth (neglecting oscillations) and θ_{12} is the

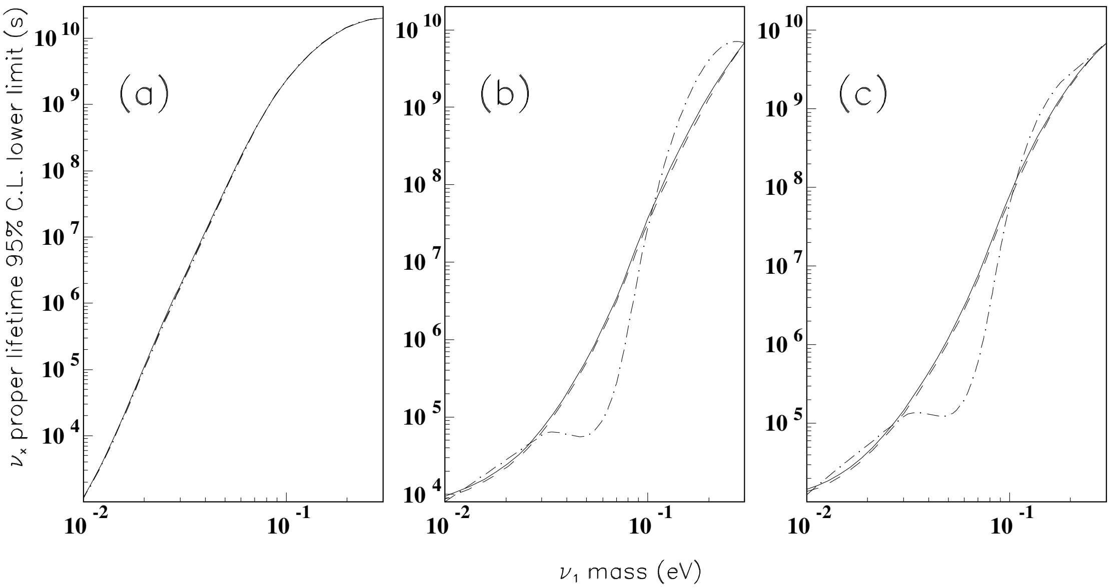

Fig. 3. **(a)**: 95% C.L. lower limits for the $\nu_2 \to \nu_1 + \gamma$ proper lifetime, assuming inverted hierarchy. The differences between different polarization states cannot be seen at this scale. **(b)**: 95% C.L. lower limits for the $\nu_2 \to \nu_3 + \gamma$ proper lifetime, assuming inverse mass hierarchy. The graphs correspond lefthanded (solid line), Majorana (dashed line) and righthanded (dot-dashed line) neutrinos. **(c)**: 95% C.L. lower limits for the $\nu_1 \to \nu_3 + \gamma$ proper lifetime, assuming inverse mass hierarchy. The lines follow the same convention as in **(b)**.

mixing angle determined from oscillation experiments (the vacuum solution) in the two flavor approximation. The preferred solar neutrino oscillation solution assumes the matter enhancement effects, that dramatically alter the value of θ_{12} in the solar interior, but our experiment is sensitive only to possible decays occurring between the Moon and the Earth, thus we use the vacuum value of θ_{12}. At this time the mixing θ_{13} is unknown; in our calculations $\sin^2\theta_{13}$ we arbitrarily used $\sin^2\theta_{13} = 0.1$. If $\theta_{13} = 0$, the corresponding lifetime lower limits are meaningless; the lower the value of θ_{13}, the lower the resulting limits would be.

In Eq. (1) S_M is the area on the Moon surface covered by our observations, t_{obs} is the total acquisition time, $\langle t_{ME}\rangle$ is the average travel time of the neutrinos from the Moon to the Earth (assuming that the decay point is uniformly distributed on that distance $\langle t_{ME}\rangle$ is one third of the flying time), t_{SM} is the flight time from the Sun to the Moon and $\tau_{(2,3)}$ the lifetime of the ν_2 and ν_3 neutrino mass higher states. All time variables in Eq. (1) are defined in the laboratory frame of reference.

As no structure compatible with one of the two radiative neutrino decay hypotheses were found in our analysis, we can extract only lower limits for the lifetimes of the heavy neutrino components. We assume that the number of photons produced trough radiative decays between the Moon and the Earth reaching our detector should be $N_\gamma \le 3\sigma_{T5}$, where σ_{T5} is the standard deviation of the luminosity of the 5^{th} term in the wavelet decomposition of the data. The 95% C.L. lower limits for the ν_2 proper lifetimes are shown in Fig. 2**(a)**. Although they were computed assuming three possible ν_2 polarizations, the results are so close that they cannot be separated on the graph. For the ν_3 proper lifetimes, the tentative 95% C.L. upper limits (computed assuming $\sin^2\theta_{13} = 0.1$) are shown in Fig. 2**(b)**. The solid line corresponds to lefthanded Dirac neutrinos, the dash-dotted line to Majorana neutrinos and the dashed line to righthanded Dirac neutrinos. Note that in this case, ν_1 represents the lowest mass neutrino state.

4.2 Lifetime limits in the inverted mass hierarchy hypothesis

As already mentioned, the Monte Carlo output is independent on the hierarchy hypothesis, so lifetime limits may be computed for the inverted hierarchy just permutating the indexes in Eq. (1) and restricting the mass range of ν_1 to larger values. Furthermore, as the lowest mass neutrino state is now ν_3, the results are no more dependent on the unknown mixing θ_{13}. Limits for the ν_2 radiative decays may be obtained directly using Eq. (1). The resulting 95% C.L. lower lifetime for the $\nu_2 \to \nu_1 + \gamma$ and $\nu_2 \to \nu_3 + \gamma$ decays are shown in Fig. 3**(a)** and, respectively, 3**(b)**. For the $\nu_1 \to \nu_3 + \gamma$ process, Eq. (1) should be modified by adding to Φ_1 the surviving component of ν_1 neutrinos produced trough ν_2 decays between the Sun and the Moon:

$$\Phi_2 \cdot \left(1 - e^{-\frac{t_{SM}}{\tau_{2\to1}}}\right) e^{-\frac{\langle t_{SM}\rangle}{\tau_{1\to3}}}.$$

The very large values of $\tau_{2\to 1}$ (between 10^9 and 10^{16}s in the laboratory frame) make this correction negligible. For the same reason we neglect the enhancements effects during the crossing of the solar matter. The resulting 95% C.L. lower limits are shown in Fig. 3**(c)**.

5 Conclusions

The analysis of the 195 frames recorded in occasion of the 26 March 2006 total solar eclipse did not evidence signals compatible with the Monte Carlo predictions for the radiative decays of the heavier components of the solar neutrinos.

In the normal mass hierarchy hypothesis ($m_3 \gg m_2 > m_1$), we obtained lower lifetime limits for the $\nu_2 \to \nu_1 + \gamma$ and $\nu_3 \to \nu_{2,1} + \gamma$ decays about 3 orders of magnitude better than the similar results published by Cecchini et al. (2004b). The new limits are in the range $10 \div 10^9$ s, for neutrino masses $10^{-4} < m_{\nu 1} < 0.1$ eV. In the inverted hierarchy scenario ($m_2 > m_1 \gg m_3$) we find similar lifetime limits for the corresponding possible decays, and neutrino masses $10^{-3} < m_{\nu 1} < 0.3$ eV.

The clear detection of the ashen light combined with the negative result, demonstrate that the searched signal should be fainter than the ashen light itself; thus the limits presented in this paper are the best obtainable using this technique, since there is no way to avoid the ashen light background.

Acknowledgements. The author acknowledges the essential contribution of his colleagues and friends to the experiment, simulation and data analysis: S. Cecchini, D. Centomo, G. Giacomelli, R. Giacomelli, M. Giorgini, L. Patrizii, and C. G. Şerbănuţ. The experiment was founded by the University and INFN Section of Bologna. We acknowledge also the support from the Italian Institute of Culture of Tripoli. The analysis was partially founded under CNCSIS Contract 539/2009. Special thanks are due to the referees of the first version of this paper for their competent and constructive observations. Last but not least, the author thanks the organizers of the 2010 ECRS, Turku, Finland, for the excellent and stimulating atmosphere during the symposium.

Edited by: K.-H. Kampert
Reviewed by: two anonymous referees

References

Adamson, P. et al. (MINOS Coll.): Search for active neutrino disappearance using neutral-current interactions in the MINOS long-baseline experiment., Phys. Rev. Lett., 101, 131802, 2008.

Ahmad, Q. R. et al. (SNO Coll.): Measurement of day and night neutrino energy spectra at SNO and constraints on neutrino mixing parameters, Phys. Rev. Lett., 89, 011302, 2002.

Ambrosio, M. et al. (MACRO Coll.): Measurements of atmospheric muon neutrino oscillations, global analysis of the data collected with MACRO detector, Eur. Phys. J., 36, 323–339, 2004.

Amsler, C. et al. (Particle Data Group): Review of particle properties, Phys. Lett. B, 667, 1, 2008.

Ashie, Y. et al. (SuperK Coll.): A Measurement of atmospheric neutrino oscillation parameters by SUPER-KAMIOKANDE I, Phys. Rev., 71, 112005, 2005.

Bahcall, J. N., Pinsonneault, M. H., and Basu, S.: Solar models: Current epoch and time dependences, neutrinos, and helioseismological properties, Astrophys. J., 555, 990–1012, 2001.

Birnbaum, C. D., Foussard, P., Schwemling, P., and Vanucci, F.: An experimental limit on radiative decays of solar neutrinos, Phys. Lett. B, 397, 143–146, 1997.

Bouchez, B., Pichard, B., Soirat, J. P. et al.: New experimental limits on radiative neutrino decay, Phys. Lett. B, 207, 217–221, 1988.

Cecchini, S., Centomo, D., Giacomelli, G. et al.: Monte Carlo simulation of an experiment looking for radiative solar neutrino decays, Astropart. Phys., 21, 35–43, 2004a.

Cecchini, S., Centomo, D., Giacomelli, G. et al.: Search for possible neutrino radiative decays during the 2001 total solar eclipse, Astropart. Phys., 21, 183–194, 2004b.

Cecchini, S., Centomo, D., Giacomelli, G. et al.: New lower limits on the lifetime of heavy neutrino radiative decay, Astropart. Phys., 34, 486–492, 2011.

Derbin, A. V. and Smirnov, O. Ju.: Search for neutrino radiative decay with a prototype Borexino detector, JETP Lett., 76, 409–413 2002.

Schwetz, T., Tortola, M., and Valle, J. W. F.: Three-flavour neutrino oscillation update, New J. Phys., 10, 113011, 2008.