Sensitivity to SUSY Seesaw Parameters and Lepton Flavour Violation

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We address the constraints on the SUSY seesaw parameters arising from Lepton Flavour Violation observables. Working in the Constrained Minimal Supersymmetric Standard Model extended by three right-handed (s)neutrinos, we study the predictions for the branching ratios of $l_i \rightarrow l_j \gamma$ and $l_i \rightarrow 3l_i$ channels. We impose compatibility with neutrino data, electric dipole moment bounds, and further require a successful baryon asymmetry of the Universe (via thermal leptogenesis). We emphasise the interesting interplay between $\theta_{13}$ and the LFV muon decays, pointing out the hints on the SUSY seesaw parameters that can arise from measurements of $\theta_{13}$ and LFV branching ratios. This is a brief summary of the work of Ref. [1].

1. Introduction

Supersymmetric (SUSY) extensions of the Standard Model (SM), including three right-handed neutrino superfields, are well motivated models which can accommodate a seesaw mechanism [2], and at the same time stabilise the hierarchy between the scale of new physics and the electroweak (EW) scale. One of the most striking phenomenological implications of SUSY seesaw models is the prediction of sizable rates for lepton flavour violating (LFV) processes [3], many orders of magnitude larger than those expected from the SM seesaw. In this sense, the $l_j \rightarrow l_i \gamma$ and $l_j \rightarrow 3l_i$ ($i \neq j$) lepton decay channels, as well as $\mu \rightarrow e \gamma$ conversion in heavy nuclei, are among the most interesting processes. Experimentally, the most promising decay is the $\mu \rightarrow e \gamma$ process, which exhibits the most stringent present bounds, and offers a significant improvement regarding the future sensitivity.

Given the fact that both light and heavy neutrinos enter in the determination of the LFV rates (via the Yukawa interactions), a powerful link between the low- and high-energy neutrino parameters can be obtained from these LFV processes. From the requirement of compatibility with current LFV bounds and with low-energy neutrino data, one can then extract information on the heavy neutrino sector, thus providing an indirect access to the heavy neutrino parameters.

In Ref. [1], we have systematically explored the sensitivity of LFV processes to $\theta_{13}$ in a broad class of SUSY seesaw scenarios, with different possibilities for the mixing in the neutrino sector. We have also incorporated in our analysis the requirement of generating a successful baryon asymmetry of the Universe (BAU) via thermal leptogenesis [4]. In particular, we have shown that various of the $l_j \rightarrow l_i \gamma$ and $l_j \rightarrow 3l_i$ ($i \neq j$) channels indeed offer interesting expectations regarding the sensitivity to $\theta_{13}$. This sensitivity to $\theta_{13}$ had been previously pointed out [3, 5], for some specific seesaw cases.

Ultimately, and as shown in [1], the impact of a potential $\theta_{13}$ measurement on the LFV branching ratios, together with the current and future experimental bounds (measurements) on the latter ratios, may lead to a better knowledge (determination) of the heavy neutrino parameters.

2. LFV within the SUSY Seesaw

The leptonic superpotential containing the relevant terms to describe a type-I SUSY seesaw is given by

$$W = N^c Y_e L H_2 + E^c Y_l L H_1 + \frac{1}{2} N^c m_N N^c,$$

where $N^c$ is the additional superfield that contains the right-handed neutrinos and their scalar partners, $Y_{l,l_e}$ are the lepton Yukawa couplings and $m_N$ is Majorana mass. Henceforth we will assume that we are in a basis where $Y_{l}$ and $m_{M}$ are diagonal in flavour space. After EW symmetry breaking, the full $6 \times 6$ neutrino mass matrix is given in terms of the $3 \times 3$ Majorana mass matrix $m_N$, and the $3 \times 3$ Dirac mass matrix $m_D = Y_{\nu} v_2$, where $Y_{\nu}$ denotes the neutrino Yukawa couplings and $v_2$ are the vacuum expectation values of the neutral Higgs scalars, with $v_1(2) = v \cos(\sin) \beta$ ($v = 174$ GeV).

In the seesaw limit, $v \ll m_N$, we obtain the seesaw equation for the light neutrino mass matrix $m_\nu = \frac{-m_D^T m^{-1}_D m_D}{v^2}$. The diagonalisation of the full neutrino mass matrix leads to the six physical Majorana states: three light $\nu_i$ and three heavy states $N_i$. Their masses are given by $m_\nu = U^T_{\text{MNS}} m_\nu U_{\text{MNS}} = (m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$ and $m_D = (m_{N_1}, m_{N_2}, m_{N_3})$. We use the standard parameterisation for the Maki-Nakagawa-Sakata unitary matrix $U_{\text{MNS}}$ [6], in terms of three mixing angles $\theta_{13}, \theta_{23}$, and $\theta_{13}$, and three CP violating phases, $\delta, \phi_1$, and $\phi_2$.

Following the parameterisation proposed in [6], the solution to the seesaw equation can be written as

$$m_D = i \sqrt{m_\nu^\text{diag}} R \sqrt{m_\nu^\text{diag}} U^T_{\text{MNS}},$$

(1)
where $R$ is a generic complex orthogonal $3 \times 3$ matrix, defined by three complex angles $\theta_i$. This parameterisation allows to accommodate the experimental data, while leaving room for extra neutrino mixings, in addition to those in $U_{\text{MNS}}$. It further shows how large Yukawa couplings $Y_{\nu} \sim \mathcal{O}(1)$ can be obtained by choosing large entries in $m^{\text{diag}}_{\nu}$.

In our analysis, we have considered scenarios of hierarchical heavy and light neutrinos, $m_{N_i} \ll m_{N_j} \ll m_{N_k}$, and $m_{\nu_i} \ll m_{\nu_2} \ll m_{\nu_3}$, with $m^2 = \Delta m^2_{\text{sol}} + m_{\nu_1}^2$ and $m^2_{\nu_2} = \Delta m^2_{\text{atm}} + m_{\nu_2}^2$. Regarding the numerical estimates, we have used $\Delta m^2_{\text{sol}} = 8 \times 10^{-5}\text{eV}^2$, $\Delta m^2_{\text{atm}} = 2.5 \times 10^{-3}\text{eV}^2$, $\theta_{12} = 30^\circ$, $\theta_{23} = 45^\circ$, $\theta_{13} \lesssim 10^\circ$. For simplicity we have further set $\delta = \phi_1 = \phi_2 = 0$.

Within the context of the Constrained Minimal Supersymmetric Standard Model (CMSSM), universality of the soft SUSY breaking parameters is imposed at a high-energy scale $M_X$, which we choose to be the $SU(2) - U(1)$ gauge unification scale ($M_X \approx 2 \times 10^{16}\text{ GeV}$). Instead of scanning over the full CMSSM parameter space (generated by $M_{1/2}$, $M_0$, $A_0$, $\tan \beta$, $\text{sign}(\mu)$), we considered specific choices for the latter parameters, given by some of the “Snowmass Points and Slopes” (SPS) cases defined in Table I.

Table I: Values of $M_{1/2}$, $M_0$, $A_0$, $\tan \beta$, and $\text{sign}(\mu)$ for the SPS points considered in the analysis.

<table>
<thead>
<tr>
<th>SPS</th>
<th>$M_{1/2}$ (GeV)</th>
<th>$M_0$ (GeV)</th>
<th>$A_0$ (GeV)</th>
<th>$\tan \beta$</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>250</td>
<td>100</td>
<td>-100</td>
<td>10</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>1b</td>
<td>400</td>
<td>200</td>
<td>0</td>
<td>30</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>1450</td>
<td>0</td>
<td>10</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>3</td>
<td>400</td>
<td>90</td>
<td>0</td>
<td>10</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>400</td>
<td>0</td>
<td>50</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>150</td>
<td>-1000</td>
<td>5</td>
<td>&gt; 0</td>
</tr>
</tbody>
</table>

Regarding our computation of the LFV observables [1], it is important to stress the following points:

- It is a full one-loop computation of the branching ratios (BRs), i.e., we include all contributing one-loop diagrams with the SUSY particles flowing in the loops. For the case of $l_j \to l_i \gamma$, the analytical formulae can be found in [6, 10]. Regarding the $l_j \to 3l_i$ decays, the complete set of diagrams (including photon-penguin, Z-penguin, Higgs-penguin and box diagrams) and formulae are given in [6].

- The computation is performed in the physical basis for all SUSY particles entering in the loops. In other words, we do not use the Mass Insertion Approximation (MIA).

- To obtain the low-energy parameters of the model the full renormalisation group equations (RGEs), including relevant terms and equations for the neutrinos and sneutrinos, are firstly run down from $M_X$ to $m_N$. At the seesaw scale (in particular at $m_{N_3}$), we impose the boundary condition of Eq. (1). After the decoupling of the heavy neutrinos and sneutrinos, the new RGEs are then run down from $m_{N_i}$ to the EW scale, at which the observables are computed. More concretely, we do not use the Leading Log Approximation (LLog), but rather numerically solve the full one-loop RGEs.

- The numerical implementation of the above procedure is achieved by means of the public Fortran code SPheno2.2 [11], which has been adapted in order to fully incorporate the righthanded neutrino (and sneutrino) sectors, as well as the full lepton flavour structure [6].

- The SPheno code has been further enlarged by additional subroutines that compute the LFV branching ratios for all the $l_i \to l_j \gamma$ and $l_i \to 3l_j$ channels [6]. We have also included subroutines [1] to implement the requirement of successful baryogenesis (which we define as having $n_B/n_\gamma \in [10^{-10}, 10^{-9}]$) via thermal leptogenesis in the presence of upper bounds on the reheating temperature, and to ensure compatibility with present bounds on lepton electric dipole moments (EDMs): $\text{EDM}_{e\mu\tau} \lesssim (6.9 \times 10^{-28}, 3.7 \times 10^{-19}, 4.5 \times 10^{-17})$ e.cm [12].

In what follows we present our main results for the case of hierarchical heavy neutrinos. We also include a comparison with present bounds on LFV rates [13–16, 17] and their future sensitivities [18–21, 22] collected in Table II.

Table II: Present bounds and future sensitivities for the LFV processes.

<table>
<thead>
<tr>
<th>LFV process</th>
<th>Present bound</th>
<th>Future sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}(\mu \to e \gamma)$</td>
<td>$1.2 \times 10^{-11}$</td>
<td>$1.3 \times 10^{-13}$</td>
</tr>
<tr>
<td>$\text{BR}(\tau \to e \gamma)$</td>
<td>$1.1 \times 10^{-7}$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>$\text{BR}(\tau \to \mu \gamma)$</td>
<td>$6.8 \times 10^{-8}$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>$\text{BR}(\mu \to 3e)$</td>
<td>$1.0 \times 10^{-12}$</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>$\text{BR}(\tau \to 3e)$</td>
<td>$2.0 \times 10^{-7}$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>$\text{BR}(\tau \to 3\mu)$</td>
<td>$1.9 \times 10^{-7}$</td>
<td>$10^{-8}$</td>
</tr>
</tbody>
</table>

3. Results and Discussion

Here we focus on the sensitivity of the BRs to $\theta_{13}$, and on the dependence on other relevant parameters, which, for the case of hierarchical heavy neutrinos, are the heaviest mass $m_{N_3}$, $\tan \beta$, $\theta_1$, and $\theta_2$ (using
the $R$ parameterisation of [8]). The other input seesaw parameters $m_{N_1}$, $m_{N_2}$ and $\theta_3$, play a secondary role since the BRs do not strongly depend on them. Finally, we comment on the hints on the SUSY seesaw parameters that can be derived from a measurement of the BRs and $\theta_{13}$.

For $R = 1$, the predictions of the BRs as functions of $\theta_{13}$ in the experimentally allowed range of $0^\circ \leq \theta_{13} \leq 10^\circ$ are illustrated in Fig. 1. In this figure we also include the present and future experimental sensitivities for the channels. We clearly see that the BRs of $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$ are extremely sensitive to $\theta_{13}$, with their predicted rates varying many orders of magnitude along the explored $\theta_{13}$ interval. The BRs of $\tau \rightarrow e\gamma$ and $\tau \rightarrow 3e$ channels are also sensitive to $\theta_{13}$, but experimentally less challenging. The other LFV channels, $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow 3\mu$, are nearly insensitive to this parameter (see [1]). In the case of $\mu \rightarrow e\gamma$ this strong sensitivity was previously pointed out in Ref. [2]. In [3], working within a full RGE approach, it was noticed that $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$ were the channels that, in addition to manifesting a clear $\theta_{13}$ dependency, were the most promising from the experimental detection point of view.

The most important conclusion from Fig. 1 is that, for this choice of parameters, the predicted BRs for both muon decay channels, $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$, are clearly within the present experimental reach for several of the studied SPS points. The most stringent channel is manifestly $\mu \rightarrow e\gamma$ where the predicted BRs for all the SPS points are clearly above the present experimental bound for $\theta_{13} \gtrsim 5^\circ$. With the expected improvement in the experimental sensitivity to this channel, this would happen for $\theta_{13} \gtrsim 1^\circ$.

In addition to the small neutrino mass generation, the seesaw mechanism offers the interesting possibility of baryogenesis via leptogenesis [4]. Thermal leptogenesis is an attractive and minimal mechanism to produce a successful BAU, even compatible with present data, $n_B/n_\gamma \approx (6.10 \pm 0.21) \times 10^{-10}$ [22]. In the supersymmetric version of the seesaw mechanism, it can be successfully implemented provided that the following conditions can be satisfied. Firstly, Big Bang Nucleosynthesis gravitino problems have to be avoided, which is possible, for instance, for sufficiently heavy gravitinos. Since we consider the gravitino mass as a free parameter, this condition can be easily achieved. In any case, further bounds on the reheat temperature, $T_{RH}$, still arise from decays of gravitinos into the lightest supersymmetric particle (LSP). In the case of heavy gravitinos and neutralino LSP masses in the range 100-150 GeV (which is the case of our work), one obtains $T_{RH} \lesssim 2 \times 10^{10}$ GeV. In the presence of these constraints on $T_{RH}$, the favoured region by thermal leptogenesis corresponds to small (but non-vanishing) complex $R$-matrix angles $\theta_i$. For vanishing $U_{\text{MNS}}$ CP phases the constraints on $R$ are basically $|\theta_2|, |\theta_3| \lesssim 1$ rad (mod $\pi$). Thermal leptogenesis also constrains $m_{N_1}$ to be roughly in the range $10^{10}$ GeV, $10 \times T_{RH}$ [see also 23, 24].

In [1] we have explicitly calculated the produced BAU in the presence of upper bounds on the reheating temperature $T_{RH}$. We have furthermore set as “favoured BAU values” those that are within the interval $[10^{-10}, 10^{-9}]$, which contains the WMAP value, and chosen the value of $m_{N_1} = 10^{10}$ GeV in most of our analysis. Similar studies of the constraints from leptogenesis on LFV rates have been done in [25].

For very small values of $m_{\nu_1}$ ($m_{\nu_1} \sim O(10^{-5}$ eV)) a baryon asymmetry in the range $10^{-10}$ to $10^{-9}$ can be obtained for a considerable region of the $|\theta_2|$ parameter space, with the BRs exhibiting a clear sensitivity to the value of $\theta_{13}$ [3]. On the other hand, the situation changes dramatically for larger values of $m_{\nu_1}$.
In Fig. 2 we display the dependence of the most sensitive BR to $\theta_{13}$, BR($\mu \rightarrow e \gamma$), on $|\theta_2|$. We consider two particular values of $\theta_{13}$, $\theta_{13} = 0^\circ$, $5^\circ$ and choose SPS 1a. Motivated from the thermal leptogenesis favoured $\theta_2$-regions [1], we take $0 \lesssim |\theta_2| \lesssim \pi/4$, with $\arg \theta_2 = \{\pi/8, \pi/4, 3\pi/8\}$. We choose $m_{\nu_i} = 10^{-3}$ eV, while for the heavy neutrino masses we take $m_N = (10^{10}$, $10^{11}$, $10^{14}$) GeV.

While for smaller values of $|\theta_2|$ the branching ratio displays a clear sensitivity to having $\theta_{13}$ equal or different from zero (a separation larger than two orders of magnitude for $|\theta_2| \lesssim 0.05$), the effect of $\theta_{13}$ is diluted for increasing values of $|\theta_2|$. For $|\theta_2| \gtrsim 0.3$ the BR($\mu \rightarrow e \gamma$) associated with $\theta_{13} = 5^\circ$ can be even smaller than for $\theta_{13} = 0^\circ$. This implies that in this case, a potential measurement of BR($\mu \rightarrow e \gamma$) would not be sensitive to $\theta_{13}$. Similar results were obtained for $\theta_3$, but for shortness are not shown here.

Concerning the EDMs, which are clearly non-vanishing in the presence of complex $\theta_i$, we have checked that all the predicted values for the electron, muon and tau EDMs are well below the experimental bounds.

We now consider the dependence of BR($\mu \rightarrow e \gamma$) on $m_{N_3}$. As displayed in Fig. 3 there is a strong sensitivity of the BRs to $m_{N_3}$. In fact, the BRs vary by as much as six orders of magnitude in the explored range of $5 \times 10^{11}$ GeV $\lesssim m_{N_3} \lesssim 5 \times 10^{14}$ GeV. Notice also that for the largest values of $m_{N_3}$ considered, the predicted rates for $\mu \rightarrow e \gamma$ enter into the present experimental reach. Although not shown here, it is also worth mentioning that by comparing our full results with the LLog predictions, we found that the LLog approximation dramatically fails in some cases. Similar effects were also noticed in [26, 27].

Regarding the tan$\beta$ dependence of the BRs we obtained that the BR grow as tan$^2\beta$. In fact, the hierarchy of the BR predictions for the several SPS points (as already manifest in Fig. 1) is dictated by the corresponding tan$\beta$ value, with a secondary role being played by the given SUSY spectra. We found the following generic hierarchy: $BR_{SPS4} > BR_{SPS1b} \gtrsim BR_{SPS1a} > BR_{SPS3} \gtrsim BR_{SPS2} > BR_{SPS5}$.

Let us now address the question of whether a joint measurement of the BRs and $\theta_{13}$ can shed some light on experimentally unreachable parameters, like $m_{N_3}$. The expected improvement in the experimental sensitivity to the LFV ratios supports the possibility that a BR could be measured in the future, thus providing the first experimental evidence for new physics, even before its discovery at the LHC. The prospects are especially encouraging regarding $\mu \rightarrow e \gamma$, where the experimental sensitivity will improve by at least two orders of magnitude. Moreover, and given the impressive effort on experimental neutrino physics, a measurement of $\theta_{13}$ will likely also occur in the future.

Given that, as previously emphasised, $\mu \rightarrow e \gamma$ is very sensitive to $\theta_{13}$, whereas this is not the case for BR($\tau \rightarrow \mu \gamma$), and that both BRs display the same approximate behaviour with $m_{N_3}$ and tan$\beta$, we have studied the correlation between these two observables. This optimises the impact of a $\theta_{13}$ measurement, since it allows to minimise the uncertainty introduced from
not knowing tan β and \( m_{N_{1}} \), and at the same time offers a better illustration of the uncertainty associated with the \( R \)-matrix angles. In this case, the correlation of the BRs with respect to \( m_{N_{3}} \) means that, for a fixed set of parameters, varying \( m_{N_{3}} \) implies that the predicted point (BR(\( \tau \rightarrow \mu \gamma \)), BR(\( \mu \rightarrow e \gamma \))) moves along a line with approximately constant slope in the BR(\( \tau \rightarrow \mu \gamma \))-BR(\( \mu \rightarrow e \gamma \)) plane. On the other hand, varying \( \theta_{13} \) leads to a displacement of the point along the vertical axis.

In Fig. 4 we illustrate this correlation for SPS 1a, choosing distinct values of the heaviest neutrino mass, and scanning over the BAU-enabling \( R \)-matrix angles (setting \( \theta_{3} \) to zero) as

\[
\begin{align*}
0 \lesssim |\theta_{1}| & \lesssim \pi/4, \\
-\pi/4 \lesssim \text{arg} \theta_{1} & \lesssim \pi/4, \\
0 \lesssim |\theta_{2}| & \lesssim \pi/4, \\
0 \lesssim \text{arg} \theta_{2} & \lesssim \pi/4, \\
\theta_{3} & = 0,
\end{align*}
\]

(2)

We considered the following values, \( \theta_{13} = 1^\circ, 3^\circ, 5^\circ \) and \( 10^\circ \), and only included in the plot the BR predictions which allow for a favourable BAU. Other SPS points have also been considered but they are not shown here for brevity (see [3]). We clearly observe in Fig. 4 that for a fixed value of \( m_{N_{3}} \), and for a given value of \( \theta_{13} \), the dispersion arising from a \( \theta_{1} \) and \( \theta_{2} \) variation produces a small area rather than a point in the BR(\( \tau \rightarrow \mu \gamma \))-BR(\( \mu \rightarrow e \gamma \)) plane.

The dispersion along the BR(\( \tau \rightarrow \mu \gamma \)) axis is of approximately one order of magnitude for all \( \theta_{13} \). In contrast, the dispersion along the BR(\( \mu \rightarrow e \gamma \)) axis increases with decreasing \( \theta_{13} \), ranging from an order of magnitude for \( \theta_{13} = 10^\circ \), to over three orders of magnitude for the case of small \( \theta_{13} \) (1\(^\circ\)). From Fig. 4 we can also infer that other choices of \( m_{N_{3}} \) (for \( \theta_{13} \in [1^\circ, 10^\circ] \)) would lead to BR predictions which would roughly lie within the diagonal lines depicted in the plot. Comparing these predictions for the shaded areas along the expected diagonal “corridor”, with the allowed experimental region, allows to conclude about the impact of a \( \theta_{13} \) measurement on the allowed/excluded \( m_{N_{3}} \) values.

The most important conclusion from Fig. 4 is that for SPS 1a, and for the parameter space defined in Eq. (2), an hypothetical \( \theta_{13} \) measurement larger than \( 1^\circ \), together with the present experimental bound on the BR(\( \mu \rightarrow e \gamma \)), will have the impact of excluding values of \( m_{N_{3}} \gtrsim 10^{14} \) GeV. Moreover, with the planned MEG sensitivity, the same \( \theta_{13} \) measurement can further constrain \( m_{N_{3}} \gtrsim 3 \times 10^{12} \) GeV. The impact of any other \( \theta_{13} \) measurement can be analogously extracted from Fig. 4.

As a final comment let us add that, remarkably, within a particular SUSY scenario and scanning over specific \( \theta_{1} \) and \( \theta_{2} \) BAU-enabling ranges for various values of \( \theta_{13} \), the comparison of the theoretical predictions for BR(\( \mu \rightarrow e \gamma \)) and BR(\( \tau \rightarrow \mu \gamma \)) with the present experimental bounds allows to set \( \theta_{13} \)-dependent upper bounds on \( m_{N_{3}} \). Together with the indirect lower bound arising from leptogenesis considerations, this clearly provides interesting hints on the value of the seesaw parameter \( m_{N_{3}} \). With the planned future sensitivities, these bounds would further improve by approximately one order of magnitude.

Ultimately, a joint measurement of the LFV branching ratios, \( \theta_{13} \) and the sparticle spectrum would be a powerful tool for shedding some light on otherwise unreachable SUSY seesaw parameters. It is clear from all this study that the interplay between LFV processes and future improvement in neutrino data is challenging for the searches of new physics.
Acknowledgments

A. M. Teixeira is grateful to A. Abada for her help in preparing this presentation. This work has been supported by the French ANR project PHYS@COL&COS.

References