Report of the Work Done

Major Research Project **MAJOR-PHYS-2013-12281**

UGC-MRP project titled as **"Phenomenological Studies on the Role of Neutrinos in Astrophysics and Cosmology".**

Principal Investigator: Prof. B.C Chauhan

Brief Objective:

The research in the neutrino physics has now entered into the precision era. The issues like determination of the absolute mass scale, structure of mass matrix, determination of mass hierarchy, quadrant of Δm_{23}^2, nature of neutrinos (Dirac or Majorana) and CP violation phases are expected to be settled in the future endeavours. Our objective was to join forces or work in close contact with the main stream scientific community to help resolving CP-violation and the existence sterile neutrinos mainly on the following lines:

1. The observation of non-zero value of θ_{13}^{PMNS} strongly motivates the investigation of an underlying flavour symmetry, QLC and measurement of the Dirac-type CP-violation which is totally unconstrained at present. Plan to study the implication of the non-zero value of θ_{13}^{PMNS} in a QLC model.

2. To obtain the constraints for θ_{23}^{PMNS} mixing angle of neutrinos with neutrino mass hierarchy. The sterile neutrino parameters using 3+1 scenario in the QLC model for quarks and leptons will also be investigated. Investigate the role of neutrinos/ sterile neutrinos as a potential candidate for Dark Matter studies.

3. To investigate the additional CP phases in the neutrino mass matrix that can generate baryon asymmetry of universe (BAU) through the mechanism of leptogenesis. Introducing the right-handed current part in the neutrino mixing matrix, and using the data from neutrino experiments and other several related experiments to constrain the parameters of V+A admixture would also be investigated.

Work done: (Annual Basis)

1. **Year-1**
   - ✓ There was a huge uncertainty about the implementation of the project. The project was submitted through online in September 2013, and after scrutiny the official notification of selection came out in October 2015. Thereafter, the funds were actually released in March 2016, however on paper the project was officially implemented by the UGC from back date i.e. from 1st July 2015.
   - ✓ In fact, we had already initiated working on the plan proposed and studied the implication of the non-zero value of θ_{13}^{PMNS} in a QLC model. We got quite constrained predictions for θ_{23}^{PMNS} mixing angle of neutrinos, which is less than 45° at 3σ level and work was published in JHEP.

2. **Year-2**
   - ✓ In the mean time the role of neutrinos as Dark Matter was also investigated, and work was published.

- ✓ The existence of sterile neutrino in the low energy solar neutrino measurement by using our model, which assume two active and one sterile neutrino (2+1) was investigated in the light of recent results from KamLAND.
- ✓ We further study the bound on sterile neutrino component in a model independent way, present in the solar neutrino flux.
- ✓ QLC model based predictions for θ_{23}^{PMNS} with neutrino mass hierarchy was also investigated.

3. **Year-3**
   - ✓ Investigated the sterile neutrino parameters using 3+1 scenario in our QLC model.
   - ✓ Also obtained constraints on the sterile neutrino components present in the light of global solar neutrino data.
   - ✓ Investigated dark matter density profiles for various galaxies including the Milky way and investigated the constrains on energy density of neutrinos.

Publications: 18

1. Light Sterile Neutrinos and Dark Sector of Universe; **B.C. Chauhan;** Proc. International Conf. on Recent Trends in Basic and Applied Sciences, 2015, p3; ISSN: 2395-3373.
2. Quark-Lepton Complementarity(QLC) Predictions for θ_{23}^{pmns} and CP Violation; Gazal Sharma and **B.C. Chauhan**, JHEP 1607 (2016) 075, arXiv: 1511.02143 [hep-ph].
3. Dark Matter and Neutrinos, Gazal Sharma, Anu and **B.C. Chauhan**, Physics Education, Volume 32, Number 4, Article Number: 7, (Sep.-Dec.2016).
4. Physics and Phenomenology of Dark Matter; Gazal Sharma, **B.C. Chauhan** and Debasish Majumdar; Physics in New Dimensions, p69, Bharti Publications (2017); ISBN- 978-81-933475-7-7.
5. Physics of Neutrinos: The Elusive Particles; Govind Singh, **B.C. Chauhan** and Debasish Majumdar; Physics in New Dimensions, p33, Bharti Publications (2017); ISBN- 978-81-933475-7-7.
6. Quark-lepton Complementarity Model based predictions for θ_{23}^{PMNS} with Neutrino Mass Hierarchy, Gazal Sharma, Shankita Bhardwaj, **B.C. Chauhan** and Surender Verma, XXII DAE-HEP Symp. Springer Proc. in Physics **203** [Part of Springer Nature], Ch.57, (2018) 251.
7. Search for Sterile Neutrino Signal in the ^{7}Be Solar Neutrino Measurement with KamLAND, Ashish Sharma, Govind Singh, Gazal Sharma, Shankita Bhardwaj, Surender Verma and **B.C. Chauhan**, XXII DAE-HEP Symp. Springer Proc. in Physics **203** [Part of Springer Nature], Ch.12 (2018) 59.
8. Bounds on Sterile Neutrino Component in the Solar Neutrino Flux, Govind Singh, Ashish Sharma, Gazal Sharma, Shankita Bhardwaj, Surender Verma and **B.C. Chauhan**, XXII DAE-HEP Symp. Springer Proc. in Physics **203** [Part of Springer Nature], Ch.170 (2018) 713.

9. Probing CP Violation in Neutrino Oscillation Experiments and Leptonic Unitarity Quadrangle, Surender Verma, **B.C. Chauhan,** Shankita Bhardwaj and Gazal Sharma, XXII DAE-HEP Symp. Springer Proc. in Physics **203** [Part of Springer Nature], Ch. 58 (2018) 257.
10. Investigating the existence of Sterile Neutrino parameters with QLC in 3+1 scenario; Gazal Sharma, Ankush and **B.C. Chauhan**, Proc. XXXII Annual IAPT National Convention & National Symposium on Recent Trends in Physics at Different Scales (2017).
11. Role of Neutrinos as Dark Matter**; B.C. Chauhan**, National Conference on Recent Trends in Experimental and Theoretical Physics, Proc. (NCRTETP - 2017).
12. Investigating the presence of Sterile Neutrinos in light of Quark-Lepton Unification; Gazal Sharma, Shankita Bhardwaj, Ankush, **B.C. Chauhan** and Surender Verma, Proc. HP Science Congress (2017).
13. Non-Unitary and C P Violation effects in Neutrino Oscillation Experiments, Gazal Sharma, Shankita Bhardwaj, **B.C. Chauhan** and Surender Verma, Proc. HP Science Congress (2017).
14. Investigating the sterile neutrino parameters with QLC in 3 + 1 scenario, Gazal Sharma and **B.C. Chauhan;** Submitted for publication in PRD.
15. Chi-Square Analysis and bounds on Sterile Neutrino Component in the Solar Neutrino Flux, Ankush, Rishu Verma, Gazal Sharma and **B.C. Chauhan**, Proc. Conference on Science: Emerging Scenario and Future Challenges(SESFC-2018).
16. A Model for Estimating the Unexplained Matter, Kumar Anshuman and **B.C. Chauhan**, Proc. Conference on Science: Emerging Scenario and Future Challenges (SESFC-2018).
17. Neutrino: A Potential Candidate for Dark Matter! Rishu Verma, Ankush, Gazal Sharma, and **B.C. Chauhan,** Proc. 3rd Himachal Pradesh Science Congress, 2018, IIT Mandi (HP).
18. Investigating Sterile Neutrino Flux in the Solar Neutrino Data, Ankush, Rishu Verma, Gazal Sharma and **B.C. Chauhan**, Submitted for publication in PRD.

Was as per the plan:

The work was as per plan, and more focussed in the first QLC part of the proposal and there were emerging quite interesting results.

Difficulties in Implementation:

To execute any Project following basic requirements are to be met:

1. **Funds:** The Project was officially started 1st July 2015 however the amount of 1st instalment was received on dated 18th March 2016 (9 Months late).
2. **Equipments and Literature:** The purchase of equipments and books completed **after about 14 Months**. In such a situation the online material was a great support.
3. **Project Fellow:**
    - Due to delay in release of funds the appointment of the project fellow was delayed.

- The process of appointing the Project Fellow started on 06-01-2016 and completed on 27-06-2016.
- The 1st, 2nd and 3rd in selection merit didn't join; altogether the process was delayed by ~ 12 Months (1 year).
- The Project Fellow (Mr. Ashish Sharma) joined on 27-06-2016.
- After getting fully trained the Fellow got opportunity to join **Gran Sasso Science Institute, Italy**. The Fellow Mr. Ashish Sharma left the position in the project on 16-08-2017and joined the institute in Italy.
- A new process for the selection of Project Fellow was initiated on 14-08-2017.
- The new Project Fellow (Mr. Ankush) joined on 01-09-2017.
- During training the fellow got chance to get enrolled in PhD on Nov. 2017.
- The fellow completed his course work for PhD in June 2018. In such a situation it took significant amount of time to train him to the level required for research.

4. **Focussed temperament:** Our University is newly established. Being amongst the few senior faculty members, am holding a number of administrative responsibilities. Therefore, the lack of man power lead excess teaching load and other official work distracted the research temperament and definitely hampered the research progress.

Part of Project Not Completed:
The Baryon Asymmetry of universe (BAU) through the mechanism of Leptogenesis and the role of $0\nu\beta\beta$-decay and possible signature of V+A currents are yet to be investigated.

Reasons:

- Delay in release of funds affected purchase of equipments, books, appointment of project fellow.
- After training the Fellow got opportunity to join an international level institute for PhD, but affected the progress of research project deeply.
- It took further 6 months more to get appointed another Fellow for the project. The new fellow took ample time to get trained to meet the requirements of the research work.

Any Other relevant Info:
The Project Fellow (Mr. Ashish Sharma) got **Best Poster Award** in the DAE Symposium held in Delhi University. He got finally selected for PhD in **Gran Sasso Science Institute, Italy**.

To complete the remaining part of the proposal I had requested the UGC to extend the time of project time for at least six months (e-mail enclosed), but didn't receive any response.

The budget is almost utilized i.e. 92%. However, due to delay in the appointment of Project Fellow the fellowship on only 22 months out of 36 months (3 years) could be utilized. As such the net utilized amount of grant goes down by 8 %.

I believe, now onwards my line of research is not going to divert much. Therefore, I have planned to complete this in near future and UGC Grant will be acknowledged in all the related work publications.

Summary of Findings (500 words)

No. of publications: 18

In the light of recent experimental results on θ_{13}^{PMNS}, we re-investigated the complementarity between the quark and lepton mixing matrices, popularly known as `Quark-Lepton Complementarity' (QLC). We obtained predictions for most unsettled lepton mixing angle θ_{23}^{PMNS} and CP violating phase invariants J, S_1 and S_2. Using the QLC model we obtain quite constrained limits for $sin^2\theta_{23}^{PMNS} = 0.4235_{-0.0043}^{+0.0032}$ that is narrower to the existing ones. We also obtain the constrained limits for the three CP violating phase invariants J, S_1 and S_2:as J < 0.0315, $S_1 < 0.12$ and $S_2 = 0.08$, respectively. The J invariant describes all CP breaking observables in neutrino oscillations and the other two CP invariants and S_1 and S_2 are related to Majorana phases.

Further, we use the QLC model, where the non-trivial relation between U_{PMNS} and U_{CKM} mixing matrix is taken as the phase mismatch between quark and leptons, via ψ the diagonal matrix. After following the model procedure, the central values obtained for θ_{23}^{PMNS} are $44.24°$ and $47.16°$ for normal (NH) and inverted (IH) neutrino mass hierarchies respectively. It has been noticed that the precise values of θ_{23}^{PMNS} thus obtained for the two cases, NH and IH are about 2σ and 3σ away from our previously obtained result, which can give a strong hint for the hierarchy of neutrino masses. As such, in future the better precision of θ_{23}^{PMNS} can settle the issue of the neutrino mass hierarchy. Our results have been recently verified by the Noνa experiment.

The recent advancements in the sector of Dark Matter leads to the proposal of many more particles in freeze-out and freeze-in scenarios that can be Dark Matter Candidates like Strongly Interacting Massive Particles (SIMP) and Feebly Interacting Massive Particles (FIMP), responsible for Baryon Asymmetry of Universe (BAU). Understanding of CP violation can help us to understand the Baryogenesis and Leptogenesis in the universe, which remains unsolved till date.

Beyond Standard Mode the neutrinos are massive and there can exist sterile neutrinos, which are proposed to be the potential candidate for Dark Matter. We studied the role of neutrinos as candidate for Dark Matter and also obtained bounds on energy density of neutrinos. We also investigated the density profiles of Dark Matter Halo for various spiral galaxies using a proposed fluid model.

In the QLC model, we investigated 3+1 model constraints on sterile neutrinos, with 4 x 4 unitary matrix U_{PMNS4}, for 4 generation quarks and leptons. We performed model based analysis using latest global data and determine bounds on the sterile neutrino parameter i.e. the neutrino mixing angles. Monte carlo simulations are performed to estimate the texture of V_{C4} (the correlation matrix) followed by the calculation of U_{PMNS4}. The sterile neutrino mixing angles are assumed to be freely varying between (0- 2π) and obtained results, which are consistent with the data available from various experiments, like NovA, MINOS, SuperK, Ice Cube-DeepCore. And further we analytically obtain approximately similar ranges for various neutrino mixing parameters $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$.

In another work we investigated the non-unitarity and CP-Violation effects in Neutrino Oscillation Experiments, here we focused on $\nu_\mu \rightarrow \nu_\tau$ channel to study the non-unitary neutrino mixing. We have discussed the formalism of minimal unitary violation (MUV) scheme for parameterising the non-unitary neutrino mixing matrix and to obtain the general expression for oscillation probability for $\nu_\mu \rightarrow \nu_\tau$ oscillation to non-unitary parameters $|\rho_{\mu\tau}|$ and $\omega_{\mu\tau}$ with normal and inverted hierarchical neutrino masses.

We investigated the sterile neutrino signal solar neutrino flux including low energy solar neutrino measurement from experiments like, KamLAND and BOREXINO. We performed model independent global data analysis and obtained constraints on the sterile neutrino component in solar neutrino flux better than the previous existing in literature.

Bounds on sterile neutrino component in present in the Solar Neutrino Flux for various cases studied at 1σ are: $\varphi_{sterile} \leq 0.11\, X\, 10^6 \quad cm^{-2}s^{-1}$ For SNO-III; $\varphi_{sterile} \leq 0.95\, X\, 10^6\ cm^{-2}s^{-1}$For SK Combined, $\varphi_{sterile} \leq 1.93\, X\, 10^6 \quad cm^{-2}s^{-1}$ For KamLAND: $\varphi_{sterile} \leq 1.06\, X\, 10^6 \quad cm^{-2}s^{-1}$ For Borexino (3MeV); $\varphi_{sterile} \leq 1.64\, X\, 10^6 \quad cm^{-2}s^{-1}$ For Borexino (5MeV); and $\varphi_{sterile} \leq 0.62\ X\, 10^6\ cm^{-2}s^{-1}$ For φ^{ES} Overlap.

Contribution to the Society:

The contribution of project to society is not direct, but has a consequence of knowledge enhancement of the humanity towards understanding nature. This work is related to the fundamental research; therefore the technological applications to the welfare of humanity to be seen in the years to come in direct or indirect ways.

Principal Investigator