Boosting sensitivity of ton-scale rare event search experiments via improved thermal shielding of cryostats

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Introduction

In ton-scale rare event search experiments, such as neutrinoless double beta decay $0\nu\beta\beta$ and dark matter, cryostat systems and cryogenic liquids present key challenges such as thermal instability, radiation shielding deficiencies, leaks, boil-off, cryogen purity, material fatigue, and the need for large-scale infrastructure, etc [1]. Experimentalists worldwide are investing significant R&D efforts into designing cryostats to address these challenges, which is essential for ensuring the safe, stable, and reliable performance of detectors [2, 3].

The present work addresses the critical issue of thermal instability, emphasizing the importance of maintaining a stable temperature of cryogenic liquids. Maintaining thermal stability minimizes thermal noise and reduces cryogenic liquid evaporation by controlling the ambient heat load from the outer hot wall (with temperature T_1) to the inner cold wall (T_2) of the cryostat. We investigate the impact of the dominant radiation heat load $q^{1\rightarrow 2}$, comparing the performance of no insulation, single-layer insulation, & multilayer insulation (MLI) between the hot and cold wall boundaries in protecting the cryostat's cold wall from environmental heat transfer (see Top panel of Fig. 1).

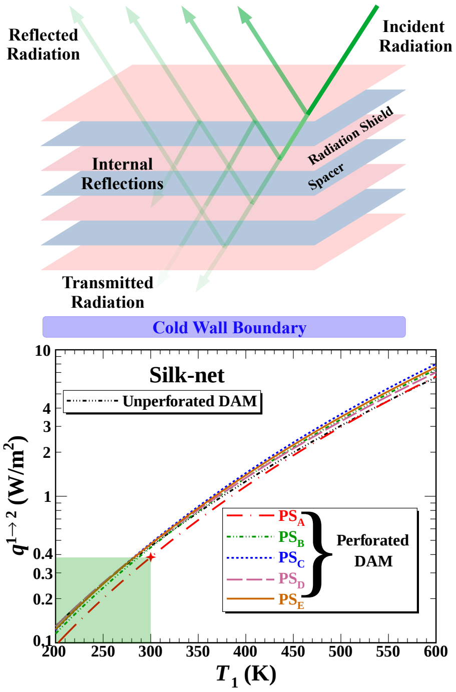

FIG. 1: (Top) Schematic representation of radiation heat transfer in a parallel plate configuration, forming the basis for heat load analysis with MLI. (Bottom) Effect of MLI on total heat load reduction, comparing perforated (PS_A, PS_B, PS_C, PS_D, PS_E) [4] and unperforated radiation shields (e.g., double aluminized mylar (DAM) with Silk-net), with T_1, while T_2 stabilized at 77.4 K (liquid N_2 temperature).

Methodological framework

The success of rare event detection experiments hinges on the radiopurity of every component involved. The MLI technique significantly reduces heat transfer to cryogenic liquids housed within cryostats, and further improvements can be achieved using perforated materials of ideal dimensions (refer to Fig. 1, bottom panel) [5]. However, commonly used

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MLI materials like double Aluminized Mylar (DAM) with silk-net, glass tissue, and Dacron, etc. [6] often fail to meet strict radiopurity standards. Therefore, introducing multiple layers may not be particularly effective until optimized, as layer count, density, and spacing, alongside the development of theoretical/empirical models, depend significantly on the material's physical and mechanical properties, which must meet the stringent radiopurity criteria for such experiments. Consequently, the primary objective of this study is to assess the effect of inserting a single intermediate layer between the hot and cold boundaries, with findings that may guide the integration of additional layers in cryostats for rare event searches in the future. For detailed mathematical expressions of heat load exchange $q^{1\to2}$, refer to Ref. [5].

Results and discussion

To assess the potential of MLI, we investigated the effects of inserting a single intermediate layer between the hot and cold boundaries of the GERDA [7] and KamLAND-ZEN [8] cryostats, considering both spherical and cylindrical geometries with equivalent volumes. The pronounced effect of T_1 on $q^{1\to2}$ is strongly highlighted in the top panel of Fig. 2, with observed reductions of 59.1%, 87.1%, and 97.4% in both spherical and cylindrical geometries as T_1 decreases to 400 K, 300 K, and 200 K, respectively, relative to T_1=500 K, while maintaining emissivity of intermediate layer ε_3 and T_2=4.15 K (liquid He) constant. Introducing a single intermediate layer yields reductions in $q^{1\to2}$ by 89%, 57%, 43%, and 3.9% for both geometries, corresponding to ε_3 values of 0.01, 0.06, 0.10, and 1.0, respectively, when compared to the no-layer configuration.

Cryogenic liquid evaporation rates (E_R) are closely correlated with the magnitude of the $q^{1\to2}$ (see bottom panel of Fig. 2). This technique results in an average savings of over 40% of cryogenic liquid in both spherical and cylindrical geometries when the single layer is located close to the hot (near R_1), and over 50% when it is situated near the cold (near R_2) wall boundary.

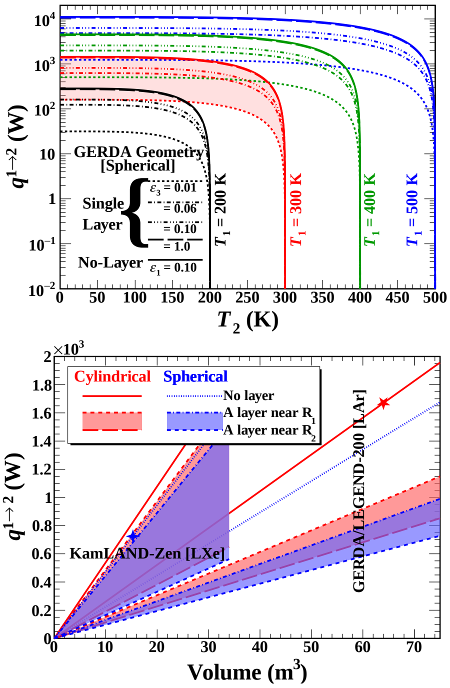

FIG. 2: (Top) Effect of a single layer insertion on $q^{1\to2}$ between hot and cold wall boundary of GERDA experiment's spherical cryostat. (Bottom) Impact of optimal intermediate layer positioning near R_1 and R_2 on $q^{1\to2}$.

References

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