A Comment on “The possible explanation of neutron lifetime beam anomaly” by A. P. Serebrov, et al.

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In a recent manuscript, Serebrov et al. [1] propose that loss of protons due to residual gas interactions in the most recent beam neutron lifetime experiment [2, 3] led to a systematic error that could account for the well known disagreement between the beam method [2–5] and the ultracold neutron storage method [6–13]. In their paper, Serebrov et al. make a simplified model of the vacuum environment of the trap as a vessel with cold walls (the magnet bore) located inside another vessel with warm walls (the outer vacuum system). They assume that residual gas flows from the outer vessel into the inner vessel, remaining in gas phase at thermal equilibrium with the walls in the two vessels. Therefore the molecular density in the inner vessel reaches equilibrium at

\[ n = \frac{P}{k \sqrt{T_1 T_2}} \]

where \( P \) is the vacuum pressure in the outer chamber, \( k \) is the Boltzmann constant, and \( T_1, T_2 \) are the vessel temperatures. Using \( P = 10^{-9} \) mbar as the ion gauge pressure (actually the upper limit as the gauge was under range) and \( T_1 = 300 \) K, \( T_2 = 4 \) K, they obtain \( n = 2.1 \times 10^8 \) cm\(^{-3} \) inside the trap. Later they show that, at such a density, charge exchange by trapped protons with residual gas components such as H\(_2\)O, CH\(_4\), CO, and CO\(_2\) would cause a significant loss during the 10 ms trap period and result in a measured neutron lifetime that is too long. While residual gas interactions should occur at some level, we find this analysis to be flawed because it neglects cryocondensation on the cold bore, a crucial feature of the trap vacuum.

The cold bore of the magnet was a 45 cm long, 12 cm inner diameter stainless steel tube in direct contact with the liquid helium bath. Its operational temperature was about 8 K. At this temperature the condensation coefficients of most gases are close to unity so residual gas will condense on the wall after just a few collisions, rather than remain in the gas phase and reach thermal equilibrium. The bore is effectively a cryopump. According to the theory of cryocondensation (see for example [14, 15]) the partial pressure of each gas component in the bore will reach equilibrium close to its saturation vapor pressure. Figure 1 shows a plot of saturation vapor pressure vs. temperature for a number of common gases. Other than hydrogen, helium, and neon the partial pressure and density of all residual gas components are predicted to be far lower than the estimate in [1], although we note that determining the actual partial pressures of species inside the proton trap is a complicated problem that depends on many factors. There is no reason to expect neon in the vacuum system. One would expect hydrogen of course, and also helium due to its omnipresence in the guide hall atmosphere. Charge exchange with these species would result in trapped hydrogen (monatomic or diatomic) and helium ions that could be detected by the surface barrier detector after the trap is opened.

In summary, we find the analysis of Serebrov et al. [1] to be incorrect due to their neglect of cryocondensation of residual gas on the cold magnet bore that encloses the proton trap in the beam lifetime experiment. More generally, for the past few years we have been actively investigating many systematic effects in the beam neutron lifetime experiment, including those that could be caused by residual gas and other vacuum related phenomena. This is primarily an experimental effort, as the apparatus is very complicated and difficult to model accurately and to useful precision in a simulation or calculation.
Figure 3 expands on Fig. 2 by describing the dependence of boiling-point or sublimation temperature on external pressure for common cryogens. Also noted is the triple point where the cryogen transitions to a solid. This plot also indicates the temperature and pressure where external contaminants, such as water vapor, will begin to condense on cryogenic surfaces such as low-emittance shields and MLI. Preventing such condensation is a critical issue for managing radiant parasitic loads on low-emittance shields and cryogenic surfaces. This topic of emittance degradation from contaminant films is covered later in this chapter in Section 6.4.3.5.

6.2.3 Cooling with Liquid Cryogens

Over the years, many liquid cryogenic systems have been developed, fabricated, and operated in both ground environments and in space. They cover a wide range of cryogen fluids and construction features in terms of stored volume, pressure and temperature limitations, and relative efficiency in terms of the parasitic heat leaks. Many of these systems utilize liquid helium for achieving temperatures between 1.4 K and 4 K or liquid nitrogen for achieving temperatures around 77 K. To achieve temperatures below 4.2 K requires that liquid helium be stored under partial vacuum conditions. At pressures from 10 to 40 torr, temperatures in the range of 1.4 K to 1.8 K are achievable with liquid helium.

6.2.3.1 Engineering Aspects of Liquid Cryogen Systems

Typical Dewar Construction Features. As illustrated in Fig. 4, liquid cryogen systems typically involve a nested storage tank concept whereby the inner tank, which holds the liquid cryogen, is suspended inside an outer vacuum shell with low-conductivity structural supports. These structural supports are typically made of low-conductivity tubes, struts or tension bands in order to achieve high structural efficiency and minimum conductivity between the two tanks. The gap between the two tanks is then evacuated and filled with Multilayer Insulation (MLI). In addition, a high efficiency dewar may also contain one or more strategically placed vapor-cooled shields (VCS) that are cooled by the evaporating cryogen as it vents from the inner tank.

The goal of the gap construction is to prevent gaseous conduction and radiation between the outer and inner tank and to achieve maximum thermal benefit from the evaporating cryogen. Although the heat of vaporization of the cryogen is the primary cooling force in the system, there is also considerable benefit associated with extracting the available heat from the vapor as it rises up in temperature from the cryogen temperature to the external vent temperature. This is accomplished by piping the venting gas through the vapor cooled shields, which serve to intercept much of the radiant energy coming through the MLI layers from the outer tank. The VCS can also be attached to the support struts or plumbing to further reduce conductive heat leaks.

FIG. 1. Saturated vapor pressure of common gases as a function of temperature, from [16].

[1] A. P. Serebrov, et al., arXiv:2003.02092v1 [nucl-ex], (2020).
[2] J. S. Nico, et al., Phys. Rev. C 71, 055502 (2005).
[3] A. T. Yue, et al., Phys. Rev. Lett. 111, 222501 (2013).
[4] P. E. Spivak, JETP 67, 1735 (1988).
[5] J. Byrne, et al., Europhys. Lett. 33, 187 (1996).
[6] B. Mampe, et al., JETP Lett. 57, 82 (1993.)
[7] A. Serebrov, et al., Phys. Lett. B 605, 72 (2005).
[8] A. Pichlmaier, et al., Phys. Lett. B 693, 221 (2010).
[9] A. Steyerl, et al., Phys. Rev. C 85, 065503 (2012).
[10] S. Arzumanov, et al., Phys. Lett. B 745, 79 (2015).
[11] V. F. Ezhov, et al., JETP Lett. 107, 671 (2018).
[12] R. W. Pattie, et al., Science 360, 627 (2018).
[13] A. P. Serebrov, et al., Phys. Rev. C 97, 055503 (2018).
[14] W. G. Baechler, et al., Vacuum 37, 21 (1987).
[15] J. F. O’Hanlon, A User’s Guide to Vacuum Technology, 3/e, pp. 263–285, John Wiley & Sons, USA (2003), ISBN 0-471-27052-0.
[16] R. G. Ross, in Low Temperature Materials and Mechanisms, ed. by Y. Bar-Cohen, pp. 109-181, CRC Press, USA (2019), ISBN 0-367-87134-3.

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