CONTAINMENT OF POSITRONS IN A MIRROR MACHINE*

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A significant fraction of the positrons emitted isotropically from a uniform volume source has been contained in a static magnetic mirror machine for a mean containment time greater than 10 sec; this corresponds to more than 10^{10} cyclotron periods. Aside from its fundamental interest, this is of practical importance in various research fields such as controlled fusion and studies of the Van Allen radiation belt. It may also be of value in the study of the particle which is kept under observation.

The apparatus, which is shown in Fig. 1, consists of a magnetic mirror machine (coaxial 60-in. mean-diameter coils with 64 in. between coil centers) located adjacent to the Livermore cyclotron used to produce Ne^{19}. The radioactive gas is introduced into a 20-in. diameter vacuum tank where it provides a source of positrons and from which it may be rapidly removed by opening a 20-in. diameter valve.[1] This valve isolates the vacuum system from a 32-in. oil diffusion pump (base pressure $\simeq 10^{-7}$ mm Hg). Noble gases which serve as known scattering gases can be introduced in such a manner that their partial pressure is independent of the position of the fast-opening valve. Intermittent evaporation of titanium maintains a relatively small base pressure ($\simeq 10^{-8}$ mm Hg) of an unknown gas when the fast valve is closed, but does not pump on the Ne^{19} or other noble gases. The rate of escape of positrons through one mirror is monitored by a scintillation counter located just outside a thin foil window in the end wall of the vacuum chamber. For the data presented, the 1.5-in. diameter sensitive area of the counter was on axis. Electronic circuitry provides for the time analysis of the pulses which are within a selected range in amplitude, corresponding to a known energy range. The calibration (pulse height vs positron energy) and resolution of the counter are obtained using monoenergetic electrons from a beta-ray spectrometer.

Positrons which are created with their velocity vector in either escape cone leave promptly without reflecting. Those which are not in either escape cone are initially trapped and reflect back and forth until their precessional surfaces intercept the wall because of asymmetries, or until they escape due to nonadiabatic effects or gas scattering. If multiple small-angle scattering is the dominant effect, and the Larmor radius is small relative to the vacuum tank radius, then most of the trapped component escapes via the weaker mirror when the two mirrors are not of

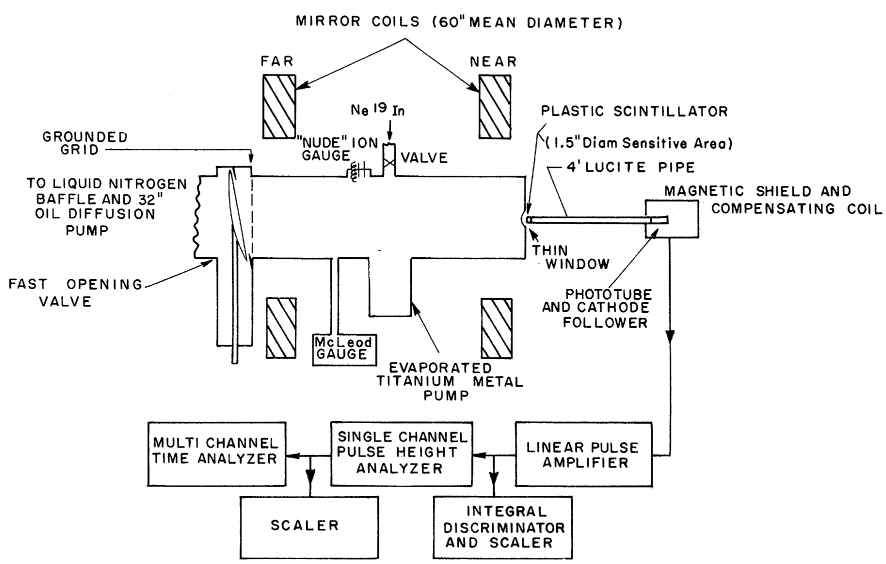

FIG. 1. Schematic diagram of apparatus.

equal strength (i.e., bias $\neq 0$). The bias is defined as $2(I_f - I_n)/(I_f + I_n)$, where I_f and I_n are the currents through the mirror coils, which are far from and near to the counter, respectively. In collecting a set of data at various bias values $(I_f + I_n)$ was held constant.

To start a "fast-empty" run, a valve in the Ne^{19} source line is closed and the trapped positron density ($< 10^4$ cm^{-3}) is allowed to come to equilibrium with the Ne^{19} density. At time zero the large valve (opening time $= 0.04$ sec) is opened and the Ne^{19} diffuses into the pump and is removed with a 0.3-sec e-fold time (measured by observing the counting rate vs time with the field off). Removal of the Ne^{19} causes a sudden decrease of counting rate due to removal of the prompt component, followed by a slower decrease due to the escape of the trapped positrons. Figure 2(a) shows a typical set of data obtained with stable neon added as the scattering gas. The logarithm of the counting rate is plotted versus time for three different pressures of neon. The curves are normalized to have a counting rate of unity at zero time. Following the initial drop there is a region in time which can be fitted by a straight line within the uncertainty set by counting statistics. The time constant, τ, in this region of the curve is taken as a measure of the containment time and the intercept of this straight line at zero time is the fraction of the counting rate at equilibrium which is due to these trapped particles. The observed times are listed in Table I.

The theoretical values in Table I (column 3) are based on the following formula which is derived from gas scattering theory[2]:

$$\tau = \frac{\beta^3 \langle\theta^2\rangle_{av}}{8\pi N_0 (Z^2 + Z) r_0^2 c (1 - \beta^2) \ln(\delta/\Delta)},$$

where $\langle\theta^2\rangle_{av} = 2[\pi/2 - \sin^{-1}(1/\sqrt{R})]^2$, R = maximum field/minimum field (for bias $\neq 0$, the smaller of the two R values is to be used), N_0 = scattering gas density ($atoms/cm^3$), $\delta = 0.1$, $\Delta = [2Z^{4/3}\alpha^2 \times (1 - \beta^2)^{1/2}]/\beta^2$, and the other symbols have their usual meaning. Column 4 of Table I gives the theoretical times after correction for the effects of energy degradation of the beta spectrum and energy resolution of the detection system. The distribution in energy of the trapped particles, $N(E)$, and their leakage rate, $N(E)/\tau(E)$, are computed as functions of time. The counting rate is obtained by integration of the leakage rate over the resolution of the detector. It is assumed that the energy loss is due to interactions with the scattering gas atoms, and that the particles behave adiabatically until they escape and hit the counter because of multiple Coulomb scattering. Values of τ obtained with neon scattering gas pressure as low as 10^{-7} mm Hg scale correctly

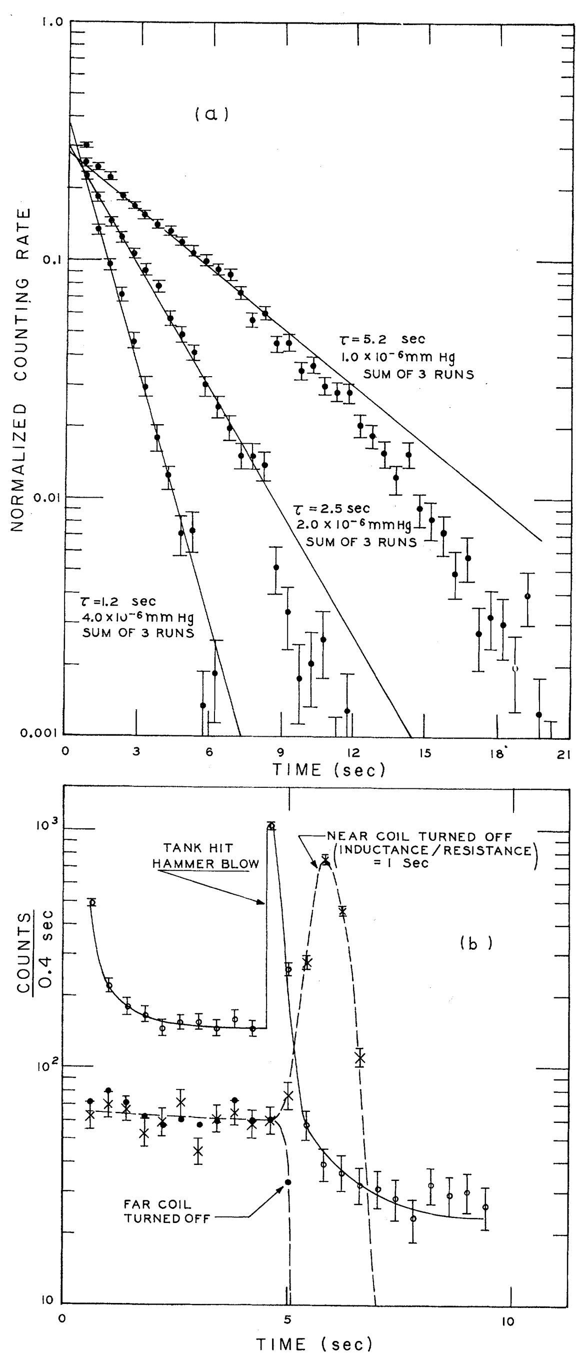

FIG. 2. Counting rate vs time after opening fast valve, for central field of 1300 gauss, zero-bias mirror ratio of 1.8. (a) 1.00 ±0.23 Mev, neon scattering gas, base vacuum 5×10^{-8} mm Hg, bias 13%. (b) 0.50 ±0.15 Mev, bias approx. 1%.

Table I. Observed mean containment times (τ) compared with the predictions of gas scattering theory, for central field of 1300 gauss, bias of +13%, and R equal to 1.68.

Energy setting and resolution (Mev)	Pressure of neon (10^{-6} mm Hg)	τ (sec) Theoretical (single energy)	Theoretical (corrected)	Observed
0.50 ± 0.15	1.0	2.7	5.9	5.4
	2.0	1.4	3.0	2.9
	4.0	0.68	1.5	1.3
1.00 ± 0.23	1.0	7.0	5.0	5.2
	2.0	3.5	2.5	2.5
	4.0	1.7	1.3	1.2

with pressure (within 30%) but require additional corrections for radiation effects.[3] The more rapid dropoff of counting rate observed at long times is expected from the theoretical treatment of the energy loss.

The gas pressure is read on an ion gauge which is calibrated by an expansion technique using a McLeod gauge. Repeated calibrations indicate an uncertainty of ± 5%. Repeated measurements of the containment time yield maximum deviations of ± 10%. The observations in Table I scale correctly with pressure and agree satisfactorily in magnitude with the corrected theoretical values.

Trapped particles may be "dumped" by mechanically shocking the vacuum tank [see Fig. 2(b)]. It is thought that dust falling through the contain-

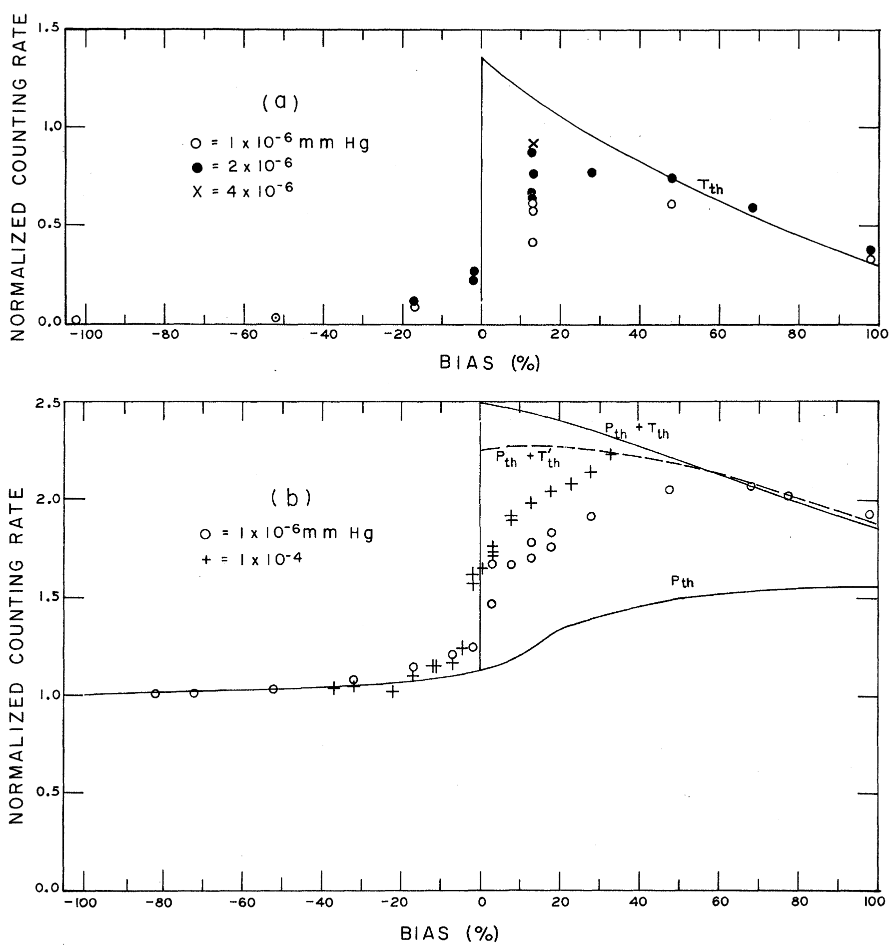

FIG. 3. Theoretical and observed counting rates as a function of bias, for central field of 1300 gauss, zero-bias mirror ratio of 1.8, 1.00 ±0.23 Mev, neon scattering gas. (a) Counting rate due to particles having long mean containment time (corrected for energy loss) compared with theory. (b) Total equilibrium counting rate compared with theory.

ment region causes a large fraction of the trapped positrons to scatter and escape through a mirror. The remaining fraction escapes with the characteristic scattering-out time. Also shown in Fig. 2(b) are the effects of turning off the near or far coil.

The relative counting rate due to positrons which are initially trapped ($T_{\rm th}$) and those which escape promptly ($P_{\rm th}$) (normalized to unity at -100% bias) has been calculated numerically as a function of bias for the steady state, by assuming that all the trapped positrons behave adiabatically and escape from the weaker mirror. In Fig. 3(a) the zero time intercepts of the "fast-empty" curves have been corrected for energy degradation effects and are compared with $T_{\rm th}$. Normalization of these data has been achieved by measuring the total equilibrium counting rate prior to opening the large valve. In an equilibrium experiment, the source gas is held in the closed chamber and the counting rate is measured as a function of bias. In Fig. 3(b) the experimental results are compared with $(P_{\rm th}+T'_{\rm th})$, which is the theoretical total counting rate corrected for energy degradation effects. The different measurements are normalized to the same source-gas density by following each measurement with a measurement of the number of counts received in an accurately timed interval with the magnetic field off. Comparing Figs. 3(a) and 3(b) it is seen that, with the experimental uncertainty, all of the trapped particles escape with the mean containment time predicted by scattering theory. A fraction of the trapped particles is detected on negative bias. This is due to a sudden change in pitch angle, greater than the difference between the two escape angles, during the time it takes for multiple small-angle scattering to accumulate to a large angle.[4] Deviations from the theoretical curve may also be due to small asymmetries since it has been observed that tilting a coil slightly changes the observed bias curve drastically.

The present results agree with the "fast filling" experiment.[5] They also appear to agree with, and extend, the conclusions of an experiment in which ionization currents created by 18-kev electrons in a mirror machine were measured.[6]

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[1]Designed by T. H. Batzer and J. R. Ullman of this laboratory.

[2]G. Gibson and E. J. Lauer, University of California Lawrence Radiation Laboratory Report UCRL-5696 (unpublished).

[3]G. Gibson and E. J. Lauer, Phys. Rev. 117, 1188 (1960).

[4]This may provide a means for observing single scattering events that would normally be masked by the multiple small-angle scattering.

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[6]S. N. Rodionov, Atomnaya Energiya 6, 623 (1959).