Gabrielse *et al.* Reply: ATRAP's field ionization method [1,2] provides the only probe of the internal properties of observed antihydrogen ($\overline{\rm H}$) atoms to date. $\overline{\rm H}$ are produced in a nested Penning trap [3] during e^+ cooling of $\overline{p}$ [4]. The probability $P(F, F_{\rm max})$ per $\overline{p}$ of detecting an $\overline{\rm H}$ that is ionized by electric fields between F and $F_{\rm max}$ is measured without background, and displayed as the normalized ratio $R = P(F, F_{\rm max})/P(F_1, F_2)$ [points in Fig. 1(a)].

Three body $\overline{\rm H}$ formation, $\overline{p} + e^+ + e^+ \to \overline{\rm H} + e^+$ is expected to be the highest rate $\overline{\rm H}$ production mechanism at low temperatures [3], even for strong magnetic fields and finite e^+ plasmas [5]. As long anticipated, the initially observed $\overline{\rm H}$ are highly magnetized and excited Rydberg atoms—sometimes called guiding center atoms [5]—whose ionization some of us recently studied [6].

The Comment [7] approximates a simulation by others [5] and claims good agreement [dotted red in Fig. 1(a)] with our measured R [points in Fig. 1(a)]. We very much like this conclusion, but it seems instead that incorrect fields and an inadequate approximation conspire to give the appearance of good agreement.

The most pronounced features of R, that $R \sim 1$ and that R decreases with increasing F, are true by construction for comparable field ranges $(F, F_{\rm max})$ and (F_1, F_2)—even if the probabilities are completely wrong. Only the rate at which R changes with F tests the agreement between the measured R and the simulation. This agreement is not so encouraging when we use correct experimental parameters with the approximation of the Comment [red dashes in Fig. 1(a)]. Reference [2] explicitly states the correct average fields: $F_1 = 35$ V/cm, $F_2 = 140$ V/cm, and $F_{\rm max} = 150$ V/cm; values in the Comment are from a figure that pertains only on the trap axis. The correct positron density is $1.5 \times 10^7/{\rm cm}^3$, and a better constant relating the $\overline{\rm H}$ binding energy to the ionization field is $\alpha = 0.5$ [6].

The Comment's approximation [red in Fig. 1(c)] actually differs from the numerical simulation points [squares in Fig. 1(c)] by more than an order of magnitude [Fig. 1(c)]. Integrating instead an interpolation of the simulation [blue in Fig. 1(c)] thus changes the probabilities by more than an order of magnitude [Fig. 1(b)]. R's definition ensures that it changes much less; the agreement of simulation and measurement improves [blue dashes in Fig. 1(a)].

The calculated and measured probabilities P differ by many orders of magnitude [Fig. 1(b)]. The experimental calibration comes from an example (720 observed $\overline{\rm H}$ for 2×10^5 $\overline{p}$ in Refs. [1,2]). The difference would be even bigger if all produced (rather than all detected) $\overline{\rm H}$ were plotted because of the small detection solid angle $\sim 4\pi/250$.

With so many orders of magnitude involved, it is not possible to tell if the difference is entirely due to a feature of $\overline{\rm H}$ production [2] in a nested Penning trap [3]—that the $\overline{p}$ make many passes through the e^+ plasma. A weakly bound $\overline{\rm H}$ formed is field ionized as it exits the e^+ plasma, leaving the $\overline{p}$ to make a more deeply bound $\overline{\rm H}$ on a subsequent pass through the e^+. Such stripping gives more time for e^+ to cool $\overline{p}$, so thinner plasmas and higher trapping fields may produce colder $\overline{\rm H}$.

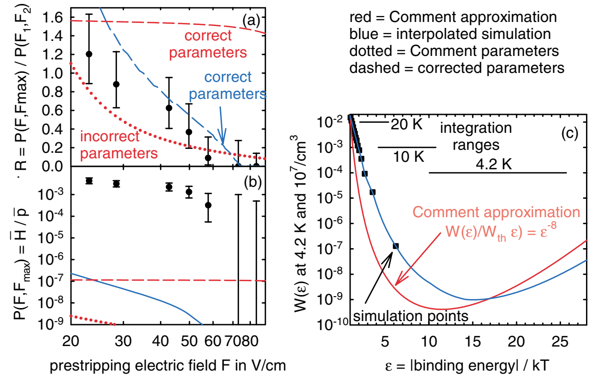

FIG. 1 (color). The ratio (a), probability (b), and probability density (c) relevant to the ATRAP $\overline{\rm H}$ distribution (filled circles) and the numerical simulation (squares), with a key.

Comparisons of theory and simulation are premature in that they rely upon extrapolations that go well beyond the simulation values available. The integration ranges for $P(F, F_{\rm max}) = \int_{\epsilon_1}^{\epsilon_2} W(\epsilon)\, d\epsilon$ for various e^+ temperatures are horizontal lines in Fig. 1(c). For 4.2 K, the integration is entirely extrapolation, even as the probability density W changes so rapidly that the result will likely be sensitive to the statistical inaccuracy of the simulation points.

In summary, there is not yet convincing agreement between our $\overline{\rm H}$ distribution data and numerical simulations, though more accurate simulations over a wider energy range may make this possible. Other work suggests these must incorporate $\overline{\rm H}$ center-of-mass motion [6] and diffusion drag collisions [8].

G. Gabrielse *et al.* (ATRAP Collaboration)*
Department of Physics
Harvard University
Cambridge, Massachusetts 02138, USA

Received 4 November 2003; published 9 April 2004
DOI: 10.1103/PhysRevLett.92.149304
PACS numbers: 36.10.–k

*For a complete list of authors, see Ref. [1].

[1] G. Gabrielse *et al.*, Phys. Rev. Lett. **89**, 213401 (2002).
[2] G. Gabrielse *et al.*, Phys. Rev. Lett. **89**, 233401 (2002).
[3] G. Gabrielse, S. L. Rolston, L. Haarsma, and W. Kells, Phys. Lett. A **129**, 38 (1988).
[4] G. Gabrielse *et al.*, Phys. Lett. B **507**, 1 (2001).
[5] M. Glinsky and T. O'Neil, Phys. Fluids B **3**, 1279 (1991).
[6] D. Vrinceanu *et al.*, Phys. Rev. Lett. **92**, 133402 (2004).
[7] C. F. Driscoll, preceding Comment, Phys. Rev. Lett. **92**, 149303 (2004).
[8] P. O. Fedichev, Phys. Lett. A **226**, 289 (1997).

