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Non-destructive Diagnostics of Antihydrogen by the Characteristic Spectra of Microwave Ionization

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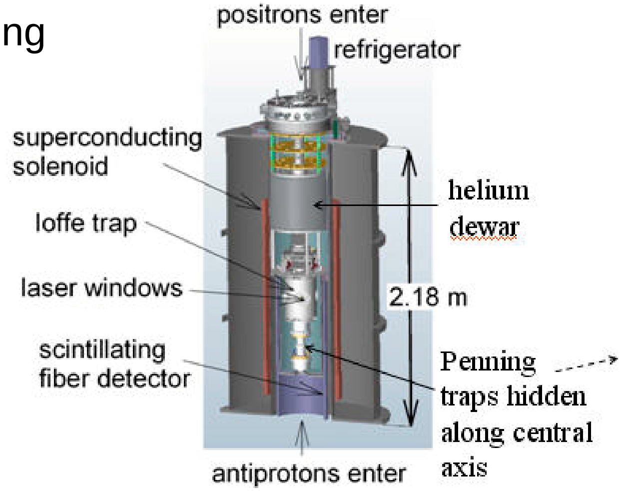
Introduction

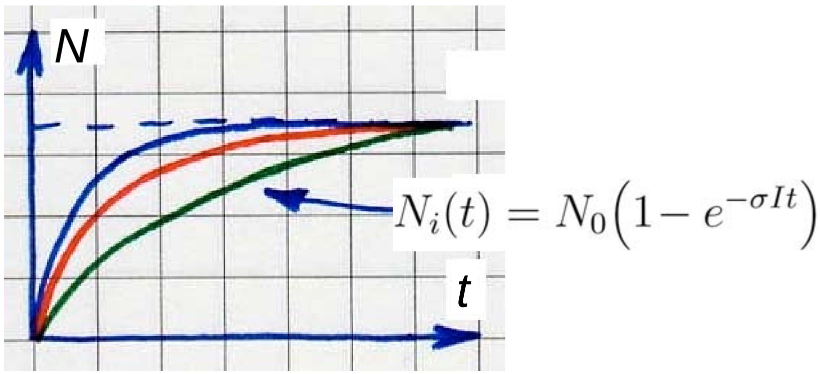
- The high-precision spectroscopy of antihydrogen is commonly considered as a powerful tool for testing the fundamental laws of nature.
- However, the main experimental obstacle is that the antihydrogen atoms are usually formed by the three-body recombination as a complex mixture of the highly-excited (Rydberg) states. Therefore, dealing with the Rydberg states becomes of crucial importance.
- Moreover, the purely “atomic” properties of antihydrogen can be quite interesting by themselves, because they enable us to study some phenomena that are hardly detectable in the ordinary matter:
  - **o** one such example is the magnetically-stimulated diffusion of antihydrogen [Yu.V. Dumin. *Phys. Rev. Lett.*, v.110, p.033004 (2013)].

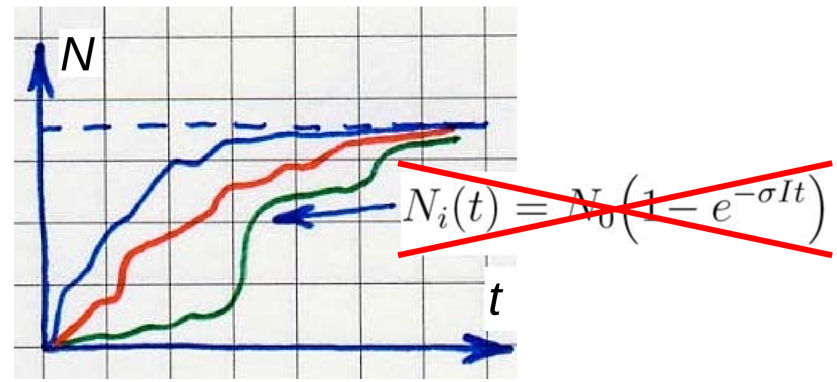
- The standard method of diagnostics of the Rydberg atoms, including the antihydrogen, is their ionization by a DC electric field with an increasing amplitude.
  - **o** Unfortunately, such a procedure results in the complete destruction of the Rydberg sample.
  - **o** This is not a serious problem in the experiments with ordinary matter, but becomes extremely expensive for antimatter.
- An alternative method for diagnostics of the Rydberg states can be **irradiation by microwaves**, which **destroys only a fraction of the Rydberg sample.**



Basic properties of the microwave ionization

- Since the microwave ionization represents a **correlated** absorption of a large number of photons, it cannot be characterized by a single universal parameter, such as the cross section σ.
- As a result, there is no universal dependence of the number of ionized atoms on time.



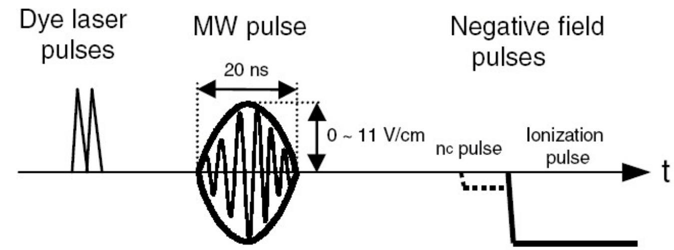


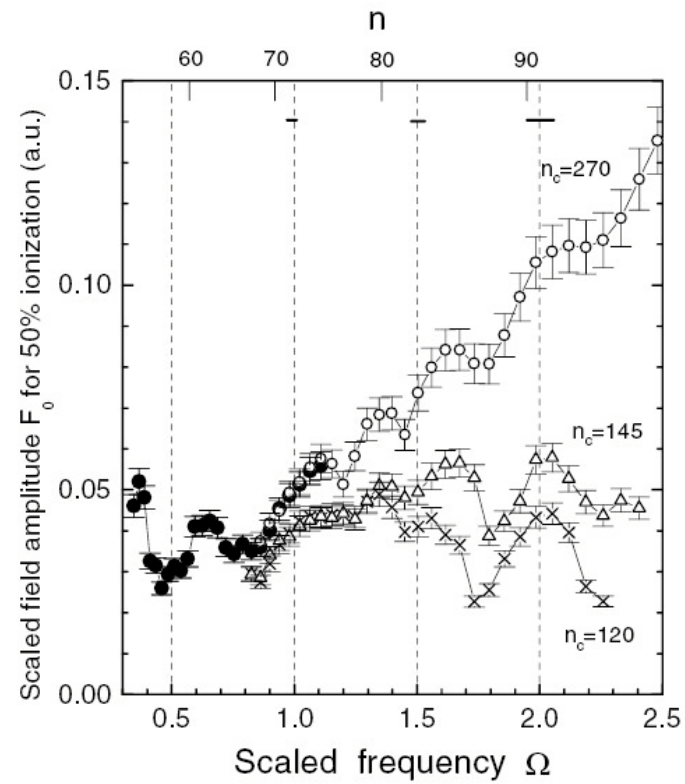
  - The correlated absorption usually develops faster than in the uncorrelated case, but then the process slows down.

- Since it is impossible to define σ(ω), the efficiency of microwave ionization as function of frequency can be described by different ways, *e.g.*:
  - by the number of atoms ionized by the irradiation with a given frequency and intensity, *N*(ω, *I*), or
  - by the intensity of radiation required to ionize the specified number (*e.g.*, 50%) of atoms, *I*(ω, *N*).
- The fist definition is straightforward and preferable for theoretical description, while the second definition is often more convenient for the experimental measurements.

Previous experimental studies

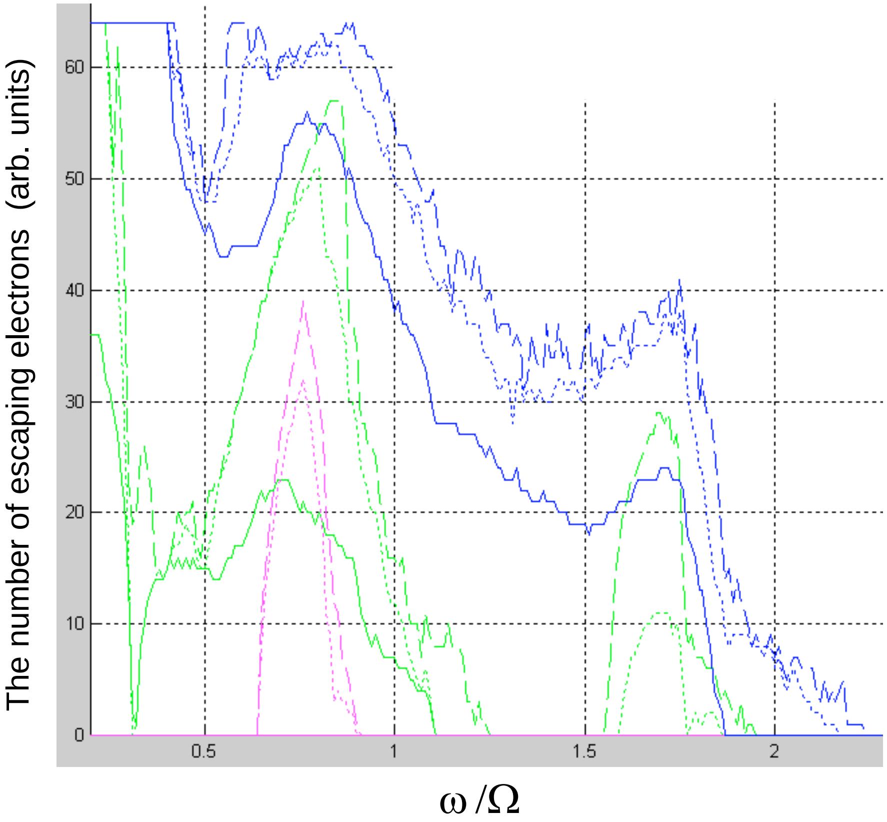
- The most important hint to the existence of the characteristic peaks in the microwave ionization spectra was given by the experiment [H. Maeda & T. Gallagher. *Phys. Rev. Lett.*, v.93, p.193002 (2004)].
  - The well-expressed peaks are observed in the case of “artificially reduced” ionization threshold, *i.e.*, when the atom is excited to quasi-continuum and then ultimately ionized by the external electric field.
  - The artificially-reduced threshold should naturally take place in the positron–antiproton plasma (from which the antihydrogen atoms are formed) just due to the interparticle Coulomb’s fields (sometimes also called “stray” fields).
- However, there is a principal difference between the two setups:
  - The Rydberg atoms produced by laser excitation have **very small angular momenta ($l \ll n$)**, *i.e.*, their electronic orbits are strongly elliptical or “linear”.
  - The Rydberg atoms formed by the three-body recombination in plasmas have **large angular momenta ($l \approx n$)**, *i.e.*, their electronic orbits are approximately “circular”.





- **Will the characteristic peaks of microwave ionization survive in the case of large angular momenta?**

Simulated spectra of microwave ionization for the circular Rydberg states



Amplitude of the external field (in atomic units):

magenta curve – $E_0 = 0.025$,

green curve – $E_0 = 0.05$,

blue curve – $E_0 = 0.1$

Pulse duration of the external field:

solid curve – $\Delta t = 4\pi$,

dotted curve – $\Delta t = 8\pi$,

dashed curve – $\Delta t = 12\pi$

$R_{\text{lim}} = 1.5$,

ω – frequency of the external field,

Ω – Keplerian frequency of the electron

- Under appropriate choice of parameters (first of all, the amplitude of the microwave field), **it is possible to obtain very sharp peaks in the ionization spectrum**, either at the frequency of the main harmonic or subharmonics.
  - It is interesting that the main peak takes place at $\omega \approx 0.75\,\Omega$ rather than $\omega = \Omega$ (as would be expected for small perturbations).
- The spectrum turns out to be relatively insensitive to the pulse duration (for the sufficiently long pulses) and to the value of the artificially-reduced threshold.

Conclusions

1. The microwave ionization may be a reasonable alternative to the DC field ionization for diagnostics of the antihydrogen Rydberg states, **because it destroys only a fraction of the original (anti-)atomic sample.**

2. A crucial role in the formation of the characteristic spectra is played by the “stray” electric fields.

- The characteristic spectra were overlooked in the previous theoretical calculations just because of the ignorance of the stray fields.

3. The characteristic spectra may be interesting not only in the context of diagnostics but also by themselves, as a fundamental atomic-physics phenomenon.