Matter under unusual conditions

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What is curiosity – driven research and why do we support it?

Vannevar Bush *Science The Endless Frontier* (1945)

“Science is the pacemaker of technological progress ... New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science “

- Magnetic Resonance Imaging
- Positron Emission Tomography
- Laser applications
- GPS
- Nano Technology
“... The teams at Bell Labs that invented the laser, transistor and solar cell were not seeking profits. They were seeking understanding. Yet in the process they created not only new products but entirely new — and lucrative — industries.” - John Gertner in NYT 2/26/12

Very Hot

Plasma of the Solar Corona  $T > 10^6$ K

Magnetically confined laboratory Plasmas

Hot Fusion, Energy Source for the Future?

ITER
Diagnostics for Temperature and Density

At very high temperatures electrons of the heavier elements (impurities) are stripped from the atoms and they form highly charged ions. The ions are effective in radiating energy (X-rays) that can lead to instabilities. They can also be used as a diagnostic for plasma conditions.
Excitation of highly charged ions by proton and electron beams

Developed first code for full quantum mechanical treatment

FIG. 7. The $\beta$ parameter as a function of the electron density for the ions (a) Ar$^{17+}$, (b) S$^{17+}$, (c) Mg$^{15+}$, (d) C$^{17+}$, (e) He$^+$.

The temperature of the plasma corresponds to the values of $\theta=\kappa T_z^{-2} (\text{a.u.})$ of 0.025, 0.05, 0.1, 0.2, 0.4, and 0.8.
transfer cross sections in collisions of hydrogen with heavier ions over a range of charge states down to relative collision energies of around 1 eV/amu [4,5]. Advances in, and availability of, computing machines have allowed increasingly sophisticated, fully quantum, calculations of the cross sections for electron capture in collisions at this energy range [3]. Because of their predominant abundance in astrophysical and tokamak plasmas, most attention has focused on electron capture in systems involving collisions of H and He with heavier ions.

Trajectory effects have been known to lead to isotope effects in K-vacancy production in ion–atom collisions [6] and in differential cross sections in charge exchange and formation of negative ions [7]. In recent merged-beams experiments, H and D were used interchangeably as a means for relative velocity selection, to decrease angular scattering and improve angular collection of products [4,5]. At collision energies ≳1 eV/amu it is generally believed that the replacement of the hydrogen target with its isotopic counterpart does not affect the total charge transfer cross sections at collision energies much higher than previously thought. Although this effect has not been fully discussed in the literature [12,13], we demonstrate here, using a full quantum calculation of electron capture for the process

\[ N^4+(2s) + H(D) \rightarrow N^3(3s) + H^+(D^+) \]  

the reality of this isotope effect. We show that the kinematic isotope effect is significant for capture into the N^3(3p) state at collision energies on the order of 10 eV/amu, well within the range available in merged-beams experiments. We provide a physical explanation for this effect and, using the semiclassical Landau-Zener-Szabo-Straub (LZS) model, we make estimates for other systems. The LZS calculations suggest that this effect is significant in other, highly charged, collision systems at energies approaching 1 keV/amu.

In general, for a given interaction potential, scattering solutions to the Schrödinger equation may be formulated

\[ N^4+(2s) + H(D) \rightarrow N^3(3s) + H^+(D^+) \]  

1. INTRODUCTION

Collisions of He^+ ions and neutral hydrogen atoms are important in a wide range of astrophysical environments. The He^+ ions may be removed by radiative charge transfer

\[ He^+ + H \rightarrow He + H^+ \]  

for direct and radiative processes which occur in the collisions of He^+ with H at energies up to 100 eV and we present the rate coefficients of the processes (2) and (3) for temperatures up to 1000 K.

II. THEORY

A. Nonradiative charge transfer

State- and isotope-dependent charge transfer of N^4+ with atomic hydrogen in astrophysical and fusion plasmas

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Received 19 November 1996

Abstract. State- and target–isotope-dependent cross sections for electron capture on collisions of N^4+ (2s) with H(1s), D(1s), and T(1s) are presented (for the energy range 0.01–5000 eV amu^{-1}). Results are given for capture via radial coupling into the N^3+ 2s^2 S, 2s2p^5 P^o, 2s2p^5 D, 2s2p^5 F^o, 2s^2 D^o, and 2p^3 3P states and are obtained through a close-coupled, quantum-mechanical, molecular-orbital method. Fully ab initio molecular data determined with the spin-coupled valence bond method are incorporated. Rate coefficients for temperatures between 1000 and 10^9 K are also presented. Applications to astrophysical environments and laboratory plasmas are addressed. The importance of state-dependent parameters for the modeling of neutral emission lines and for fusion plasma impurity diagnostics and the potential significance of isotope effects in tokamak edge region of a tokamak device are briefly discussed.
Very Dense

NIF

Fusion via inertial compression of the isotopes of Hydrogen

The first stars.
Collapsing gas of Hydrogen
TABLE I. Cross sections in units of $a_0^2$ for various values of the Debye length $\Lambda$ and collision energy $E$. [The values in parentheses are obtained using the potential (3), whereas the rest of the entries are obtained using potential (2).]

<table>
<thead>
<tr>
<th>$E$ (a.u.)</th>
<th>$\Lambda = 1a_0$</th>
<th>$\Lambda = 10a_0$</th>
<th>$\Lambda = 50a_0$</th>
<th>$\Lambda = 100a_0$</th>
<th>$\Lambda = \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>$2.64 \times 10^{-1}$ 2.53</td>
<td>(2.52) 6.70</td>
<td>$9.5 \times 10^{-1}$</td>
<td>$2.92 \times 10^{-1}$</td>
<td>$2.8 \times 10^{-2}$</td>
</tr>
<tr>
<td>7.5</td>
<td>(1.00) 1.65</td>
<td>(14.6) 15.7</td>
<td>36.2</td>
<td>41.6</td>
<td>46.6</td>
</tr>
<tr>
<td>10.0</td>
<td>(1.07) 1.50</td>
<td>(13.5) 13.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36.0</td>
<td>$7.18 \times 10^{-1}$ 7.55$\times 10^{-1}$</td>
<td>(5.58) 5.62</td>
<td>12.4</td>
<td>15.1</td>
<td>19.5</td>
</tr>
<tr>
<td>100.0</td>
<td>$4.33 \times 10^{-1}$ 4.53$\times 10^{-1}$</td>
<td>(2.61) 2.28</td>
<td>5.25</td>
<td>6.18</td>
<td>9.01</td>
</tr>
</tbody>
</table>

PHYSICAL REVIEW A

VOLUME 37, NUMBER 7

APRIL 1, 1988

Plasma screening effects on proton-impact excitation of Ar$^{17+}$

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(Received 1 June 1987)

Quantal calculations of the proton-impact excitation of the $n=2$ fine-structure levels of Ar$^{17+}$ in a dense plasma are carried out and compared to recent semiclassical impact-parameter calculations. The agreement is satisfactory and confirms the usefulness of the semiclassical approximation. The sensitivity of the cross sections to the form of the screening potentials is also investigated.

In a recent paper, Scheibner et al.\textsuperscript{1} investigated the effects of plasma screening on the cross section for the impact excitation by proton impact of the $n=2$ fine-structure levels in hydrogen-like ions using a semiclassical method. They adopted for the screened proton-electron interaction the potential

where $Z$ is the nuclear charge of the ion. We\textsuperscript{2} examined the case of the impact excitation of Ar$^{17+}$ using a quantum-mechanical method with the same proton-electron interaction potential (1), but with a proton-ion interaction potential which at large $R$ has the form
Density effects of hyperfine shift in Hydrogen

\[ \omega - \omega_0 = (\rho_{22} - \rho_{44}) < \lambda_0 \nu > n_H \]
Anticipating antihydrogen


The first atoms of antihydrogen were made at CERN more than five years ago, but no one has yet cracked the difficult task of cooling such antitom atoms sufficiently to allow them to be trapped and studied. Recently, the ATRAP collaboration, working at CERN’s new Antiproton Decelerator, reported the use of positrons to cool antiprotons — a first step on the road to cold antihydrogen (see *Phys. Lett. B* **507**, 1-6; 2001). By accumulating positrons and antiprotons in adjacent Penning traps and then allowing them to mix in a nested trap, the ATRAP group has the ingredients of antihydrogen — cold and interacting with each other — but further inducements will be needed to produce antitom atoms from the mixture.

If cold antihydrogen gas could be formed in this or another way, one would want to cool it still further in order to do high-precision spectroscopy. One way of doing this would be to introduce another gas, such as ultracold, spin-polarized hydrogen, into the trap to cool the antihydrogen by elastic collisions. For such a technique to work, the cross-section for inelastic collisions, most of which would lead to destruction of the antihydrogen atoms, must not be too large.

As Bernard Zygelman and colleagues describe in a paper in the May issue of *Physical Review A*, the dominant loss channel for antihydrogen atoms is believed to be the rearrangement reaction $H + \bar{H} \rightarrow \bar{p} \bar{\mu} + e^+ e^-$, which limits the cooling of $\bar{H}$ by $H$ atoms to temperatures above about 0.1 K. In the new paper, Zygelman et al. consider a different kind of inelastic collision: the formation of a ‘quasibound’ molecule $H \bar{H}$ by radiative association of $H$ and $\bar{H}$.

Although the reaction $H + \bar{H} \rightarrow H\bar{H} + h\nu$ has too small a cross-section to affect the cooling of the $\bar{H}$ gas, it has some other interesting consequences. The energy of association is emitted at frequencies ranging from hard X-ray to microwave, depending on the quasibound state that results. The authors show that this radiation can be distinguished from that emitted when protons and antiprotons associate, and should accordingly be a useful diagnostic for the presence of antihydrogen atoms in a trap. As the $H\bar{H}$ ground state has an electric dipole moment, it may even be possible to detect dipole radiation from transitions between different quasibound states.
Ultra-Cold

Fundamental understanding – Exotic Quantum Phenomena
  e.g. Bose-Einstein Condensation ...

Applications – Quantum Computing

Atom Laser

Proposal to develop magnetic lens for neutral atoms


Geometric magnetism

B. Zygelman in Geometric Phases in Physics,
  ed. A. Shapere & F. Wilczek

The Atom Laser

A brief commentary by Wolfgang Ketterle
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Recent work at MIT has realized an atom laser. In this note, the concept and properties of an atom laser are discussed, and also the techniques which were necessary to demonstrate the atom laser.

What is an atom laser?

An atom laser is analogous to an optical laser, but it emits matter waves instead of electromagnetic waves. Its output is a coherent matter wave, a beam of atoms which can be focused to a pinpoint or can be collimated to travel large distances without spreading. The beam is coherent, which means, for instance, that atom laser beams can interfere with each other. Compared to an ordinary beam of atoms, the beam of an atom laser is extremely bright. One can describe laser-like atoms as atoms "marching in lockstep". Although there is no rigorous definition for the atom laser (or, for that matter, an optical laser), all people agree that brightness and coherence are the essential features.
Our most vital calling:
Education and training of the next generation of scientists and engineers,

Quotes from *Rising Above the Gathering Storm*: NAS Report (2007)

**PERSPECTIVES**

• “If you can solve the education problem, you don’t have to do anything else. If you don’t solve it, nothing else is going to matter all that much.”
  —Alan Greenspan, outgoing Federal Reserve Board chairman pg. 42

• “We go where the smart people are. Now our business operations are two-thirds in the U.S. and one-third overseas. But that ratio will flip over the next ten years.”
  —Intel Corporation spokesman Howard High pg. 43

• “If we don’t step up to the challenge of finding and supporting the best teachers, we’ll undermine everything else we are trying to do to improve our schools.”
  —Louis V. Gerstner, Jr., Former Chairman, IBM 44

• “If you want good manufacturing jobs, one thing you could do is graduate more engineers. We had more sports exercise majors graduate than electrical engineering grads last year.”
  —Jeffrey R. Immelt, Chairman and Chief Executive Office, General Electric 45

• “If I take the revenue in January and look again in December of that year 90% of my December revenue comes from products which were not there in January.”
  —Craig Barrett, Chairman of Intel Corporation 46

• “When I compare our high schools to what I see when I’m traveling abroad, I am terrified for our workforce of tomorrow.”
  —Bill Gates, Chairman and Chief Software Architect of Microsoft Corporation 47

• “Where once nations measured their strength by the size of their armies and arsenals, in the world of the future knowledge will matter most.”
  —President Bill Clinton 48

• “Science and technology have never been more essential to the defense of the nation and the health of our economy.”
  —President George W. Bush 49