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
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

I. INTRODUCTION

In modeling $\beta$, various approximations are employed to obtain the collision rates of the fine-structure transition. Among them are the Born approximation with a zero potential, a variational calculation, the Coulomb-Born approximation, and small-numbers methods. In this paper, we carry our fully quantum close-coupling calculations of the proton- and electron-impact excitation rates for transitions within the fine-structure levels of the ions He$^+$, C$^+$, Mg$^{13+}$, Si$^{16+}$, and Ar$^{18+}$. Scaling arguments can be used to predict the fine-structure excitation rate coefficients for the entire range of hydrogen-like ions with nuclear charge $2 \leq Z \leq 18$. In Sec. II we present the scattering formalism. We perform a close-coupling expansion of the scattering amplitude over a set of atomic target states that contain a state from the $n = 2$ manifold. The expansion should be consistent for transition coefficients for values of $n = 2$.

FIG. 7. The $\beta$ parameter as a function of the electron density for the ions (a) Ar$^{17+}$, (b) S$^{14+}$, (c) Mg$^{13+}$, (d) C$^{14+}$, (e) He$^+$. The temperature of the plasma corresponds to the values of $\theta = kT_\text{e}$ (a.u.) of 0.025, 0.05, 0.1, 0.2, 0.4, and 0.8.

Developed first code for full quantum mechanical treatment
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 quantal, 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 quantal calculation of electron capture for the process

\[ \text{N}^4(2s) + \text{H}(D) \rightarrow \text{N}^3(3p) + \text{H}^+(D^+) \quad (1) \]

the reality of this isotope effect. We show that the kinematic isotope effect is significant for capture into the N\(^{3}(3d)\) 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-Stueckelberg (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 parameterized in terms of charge transfer cross sections 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 coefficient of the processes (2) and (3) for temperatures up to 1000 K.

I. 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

\[ \text{He}^+ + \text{H} \rightarrow \text{He} + \text{H}^+ \quad (1) \]

or by recombination.


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

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Abstract. State- and target-isotope-dependent cross sections for electron capture in collisions of N\(^{4+}\) ions with H(1s), D(1s), and T(1s) are presented for the energy range 0.01–5000 eV/amu. Results are given for capture via radial coupling into the N\(^{3+}\) 2p\(^2\) 1S, 2p\(^2\) 1P, 2p\(^2\) 3D, 2p\(^2\) 3F, 2p\(^2\) 3D, and 2p\(^2\) 3F\(^+\)) 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 10 000 K are also presented. Applications to astrophysical environments and laboratory plasmas are addressed. The importance of state-dependent parameters for the modellling of neutral emission lines and for fusion plasma impurity diagnostics and the potential significance of isotope effects to models of the 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 x 10^{-1}) 2.53</td>
<td>(2.52) 6.70</td>
<td>9.5 x 10^{-1}</td>
<td>2.92 x 10^{-1}</td>
<td>2.8 x 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>
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<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 x 10^{-1}) 7.55 x 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 x 10^{-1}) 4.53 x 10^{-1}</td>
<td>(2.61) 2.28</td>
<td>5.25</td>
<td>6.18</td>
<td>9.01</td>
</tr>
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</table>

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

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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 hydrogenlike ions using a semiclassical method. They adopted for the screened proton-electron interaction the potential

$$\sigma(2s_{1/2}-2p_{3/2})$$

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

\[ \omega - \omega_0 = (\rho_{22} - \rho_{44}) < \lambda_0 v > n_H \]
**Exotic Matter**

Fundamental Physics – Test of CPT invariance, Weak Equivalence Principle ...

Applications?
Antiprotons beams for medical research

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**Anticipating antihydrogen**

*Physical Review A 63, 052722 (May 2001)*

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 antiatoms 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 antiatoms 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 $H + \overline{H} \rightarrow p\bar{\mu} + e^+\mu^-$, which limits the cooling of $\overline{H}$ 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 $H\overline{H}$ by radiative association of H and $\overline{H}$.

Although the reaction $H + \overline{H} \rightarrow H + \overline{H}$ has too small a cross-section to affect the cooling of the $\overline{H}$ 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 $H\overline{H}$ ground state has an electric dipole moment, it may even be possible to detect dipole radiation from transitions between different quasibound states.

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**The ATRAP collaboration’s antimatter trap: will it someday trap the $H\overline{H}$ molecule?**

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FAIR, Facility for Antiproton and Ion Research

Höchste Strahlintensität | Brillante Strahlqualität | Höhere Strahlenergie | Höchste Strahlleistung | Effizienter Parallelbetrieb

In den nächsten Jahren wird bei GSI das neue internationale Beschleunigerzentrum FAIR entstehen, eines der größten Forschungsvorhaben weltweit. An FAIR wird eine der art der Vielfalt an Experimenten möglich sein, durch die Physiker aus aller Welt neue Einblicke in den Aufbau der Himmel und die Entwicklung des Universums, vom Urknall bis heute, erwarten.

FAIR wird Antiprotonen- und Ionenstrahlen mit bisher unerreichter Intensität und Qualität liefern. Im Endausbau besteht FAIR aus acht Ringbeschleunigern mit bis zu 1.100 Metern Umfang, zwei Linearbeschleunigern und rund 3,5 Kilometern Strahlführungsrohren. Die bereits existierenden GSI-Beschleuniger dienen als Vorbeschleuniger.
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

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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 step!". 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.
Quotes from *Rising Above the Gathering Storm*: NAS Report (2007)

Our most vital calling: Education and training of the next generation of scientists and engineers,