

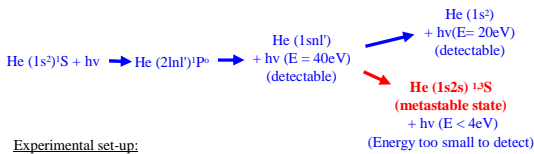
Detailed Measurements of the Fluorescent Photon and Metastable Atom Yield Resulting from the Radiative Decay of Helium Doubly Excited States

J. G. Lambourne¹, F. Penent¹, P. Lablanquie², R.I. Hall¹, M. Ahmad¹, M. Zitnik³, K. Bučar³, J. Harries⁴, D. K. Waterhouse⁵, P. Hammond⁵, S. Stranges^{6, 8}, M. Alagia⁷, M. Coreno^{7, 8}, M. Ferianis⁹, R. Richter⁹

¹DIAM, Université P & M Curie, 75252 Paris Cedex 05, France.
²LURE, Centre Universitaire Paris-sud, Bâtiment 209D, BP 34, 91898 Orsay, France.
³J. Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia.
⁴KEK-PF, Tsukuba, Ibaraki 305-0801, Japan.
⁵Department of Physics, University of Western Australia, Perth, WA6009, Australia.
⁶Dipartimento di Chimica, Università di Roma La Sapienza, 00185 Rome, Italy.
⁷IMP-CNR, c/o Gas Phase Beamline, Laboratorio Elettra, I-34012, Italy.
⁸INFN Unita' Laboratorio TASC, Area Science Park, I-34012 Trieste, Italy
⁹Sincrotrone Trieste, I-340 12, Trieste, Italy.

Principle of the experiment:

We have studied the **photo-ion** double-excitation of Helium atoms below the second ionization threshold. Until recently, only the **autoionization** channel was considered for the decay of these states since they are imbedded in the $\text{He}^+ + e^-$ continuum [1-4]. In the present experiment [5], we detect the VUV **fluorescence** of $\text{He}(2n1)$ states [6,7] and the **metastable** $\text{He}(1s2s)^1S$ atoms [6,8] produced by subsequent cascade decays. The processes, in competition with **autoionization**, are the following:



Experimental set-up:

The apparatus for the current experiment is shown in Figure 1. The photon beam from the synchrotron (Elettra, Gas Phase Beamline 6.2L [9]) crosses the effusive Helium beam at right angle. Three detectors are used each composed of three MCPs. A set of two polarized avoid detection of charged particles (electrons and ions). Only neutral particles (UV photons: $h\nu > 10$ eV and metastable Helium atoms) can be detected. Due to the directivity of the excited atom beam, metastable atoms are selectively detected on the MCP in front of the needle while the other two MCPs detect only photons.

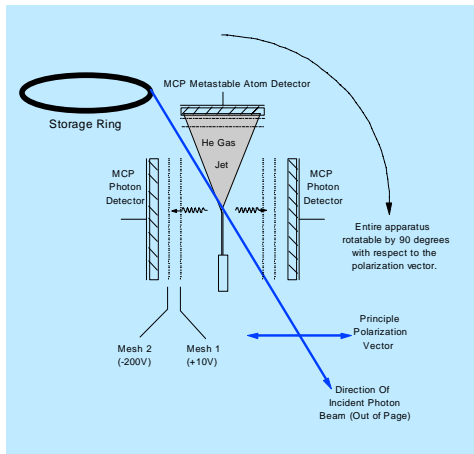


Figure 1: Experimental apparatus.

Figure 2 shows the yield of **photo-ions**, **VUV photons** and **metastable atoms** as a function of photon energy. If spin-orbit interaction is neglected, only three $^1P^o$ series can be excited: $(sp,2n+)$, $(sp,2n-)$, and $(2pn)$ (written in Cooper notation [10]). The first series, $(sp,2n+)$ $^1P^o$ decays predominantly by **autoionization** as can be seen by the large resonances in photo-ion yield.

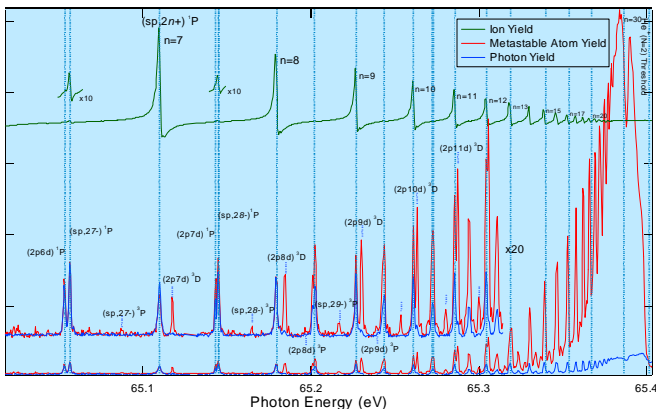


Figure 2: Yields of VUV photons, metastable helium atoms and helium ions below the $\text{He}(N=2)$ ionization threshold. The $(sp,2n+)^1P^o$ series is strongly dominant in the ion signal, however the three $^1P^o$ series have similar intensities in the photon and metastable atom yields. **Three additional series**, identified as the $(2pn)$ $^1D^o$, $(sp,2n-)^1P^o$ and $(2pn)$ $^1P^o$ are visible in the metastable atom signal [5].

When **relativistic effects** [11] (essentially spin-orbit interaction of the inner $2p$ electron: $2p_{3/2} - 2p_{1/2} = 0.726$ meV) are considered **seven $J=1$ states** [12] can be excited by one photon absorption from the ground state [5,13]:

$$\begin{aligned} &3^1P^o_1 : (sp, 2n+), (sp, 2n-), \text{ and } (2pn) \\ &3^1P^o_2 : (sp, 2n+), (sp, 2n-), \text{ and } (2pn) \\ &1^1D^o_2 : (2pn) \end{aligned}$$

Once **triplet states** are excited, they can decay by **fluorescence** or **autoionisation**. A typical fluorescence decay pathway is shown for each series in Figure 3. Following the fluorescent decay of a $^1P^o$ doubly excited state there is approximately 2% probability of arriving in the metastable $(1s2s)^1S$ state [13,14,15]. For **triplet states** the decay cascade always ends with the $(1s2s)^1S$ metastable state [5]. The detection of metastable atoms is hence very sensitive to **triplet states**. This is demonstrated by the enhanced size of **triplet peaks** in **metastable atom yield**.

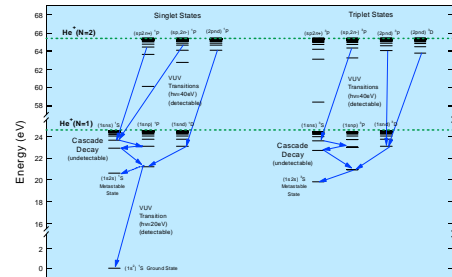


Figure 3: Typical decay pathways for the six observed series.

Time Resolved Measurements:

The radiative decay of $2pn$ doubly excited states proceeds via a $2p$ to $1s$ transition of the inner electron. Two recent independent theoretical papers [13,15] have made the surprising prediction that the radiative decay rates of $2pn$ states are **slower** than the radiative decay rate of the He^+2p ion state ($\tau = 99.717 \pm 0.075$ ps [16]).

A qualitative explanation for this behaviour is that the core electron is an **admixture of $2s$ and $2p$** wavefunctions due to a dynamical linear Stark effect resulting from the field of the outer electron [13]. The degree of stabilisation is also highly series dependent, reflecting the importance of electron correlation effects in an accurate description of these states [13,15].

For the $(2pn)$ $^1P^o$ series **fluorescence is already dominant over ionisation** for the first $n=3$ member [7]. This allows the stabilisation of the $(2p3d)$ $^1P^o$ state to be examined experimentally via a lifetime measurement.

Figure 4 shows the resulting timing spectra fitted by appropriate functions. The lifetime of the $(2p3d)$ $^1P^o$ state is visibly longer than that of the He^+2p ion state. The fit reproduces the lifetime of the He^+2p ion state and gives a value of 190 ± 30 ps for the $(2p3d)$ $^1P^o$ state. Similar measurements for the $(2p4d)$ $^1P^o$ and $(2p5d)$ $^1P^o$ states shows their lifetimes increase with n as predicted by theory [13,15].

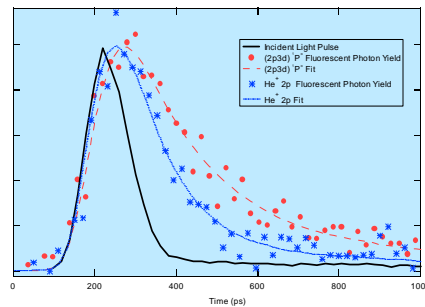


Figure 4: Time resolved measurement of the VUV photon yield from the $(2p3d)$ $^1P^o$ doubly excited state and the He^+2p ion state. The incident light pulse, broadened by the jitter of the detection electronics, is also shown.

References:

- [1] R. P. Madden and K. Codling, Phys. Rev. Lett. **10**, 516 (1963)
- [2] Domke *et al.*, Phys. Rev. Lett. **69**, 1171 (1992)
- [3] K. Schultz *et al.*, Phys. Rev. Lett. **77**, 3086 (1996)
- [4] J.M. Rost *et al.*, J. Phys.B **30**, 4663 (1997)
- [5] F. Penent *et al.*, Phys. Rev. Lett. **86**, 2758 (2001)
- [6] M.K. Odling-Smee *et al.*, Phys. Rev. Lett. **84**, 2598 (2000)
- [7] J.E. Rubensson *et al.*, Phys. Rev. Lett. **83**, 947 (1999)
- [8] E. Sokell *et al.*, J. Phys. B **29**, L863 (1996)
- [9] K. Prince *et al.*, Synchrotron Radiat. **5**, 565 (1998)
- [10] J.W. Cooper, U. Fano, and F. Prats, Phys. Rev. Lett. **10**, 157 (1963)
- [11] T.W. Gorczyca *et al.*, Phys. Rev. Lett. **85**, 1202 (2000)
- [12] L. Lipsky *et al.*, Atomic Data & Nuclear Data Tables **20**, 127 (1977)
- [13] M. Zitnik *et al.*, Phys. Rev. A, **65**, 032520 (2002)
- [14] C. E. Theodosios, Atomic Data & Nuclear Data Tables **36**, 97 (1987)
- [15] C. Liu *et al.*, Phys. Rev. A, **64**, 010501 (2001)
- [16] G. W. F. Drake *et al.*, Phys. Rev. A, **46**, 113 (1992)