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## Evidence of decrease of potential energy in nonsequential double ionization above threshold for electron impact excitation

To cite this article: Zhangjin Chen and C D Lin 2014 *J. Phys.: Conf. Ser.* **488** 032042

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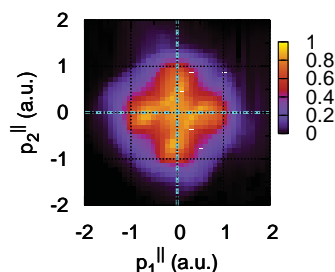
Zhangjin Chen<sup>\*1</sup> and C D Lin<sup>†2</sup>,

<sup>\*</sup>Department of Physics, College of Science, Shantou University, Shantou, Guangdong 515063, China

<sup>†</sup>Department of Physics, Kansas State University, Manhattan, Kansas 66506-2604, USA

**Synopsis** We study the CEP (carrier envelope phase) dependent correlated electron momentum distributions for nonsequential double ionization of Ar in near-single-cycle short pulses at the intensity of  $3.0 \times 10^{14}$  W/cm<sup>2</sup> with a central wavelength of 750 nm measured by Bergues *et al* [Nat. Comm. **3**, 813 (2012)]. A kinematical analysis on the constraints for the correlated electron momenta reveals that the excitation potentials of the parent ion Ar<sup>+</sup> are reduced at the instant of scattering.

Recently, the measurements of the correlated electron momentum distributions (CEMD) for nonsequential double ionization (NSDI) of Ar with near-single-cycle, 4 fs laser pulses at the peak intensity of  $3.0 \times 10^{14}$  W/cm<sup>2</sup> with a central wavelength of 750 nm have been carried out by Bergues *et al* [1] using the CEP tagging method. While the CEP-resolved spectra enables one to trace the correlated emission of the two electrons on sub-femtosecond timescales in the NSDI processes, the cross-shaped structure observed in the CEP averaged CEMD (see Fig. 1) provides a clear evidence of changes of the threshold of the single charged ion Ar<sup>+</sup> at the time when the electron impact excitation takes place.



**Figure 1.** Experimental correlated electron momentum distributions along the polarization direction for NSDI of Ar with near-single-cycle, 4 fs laser pulses at the intensity of  $3.0 \times 10^{14}$  W/cm<sup>2</sup> [1].

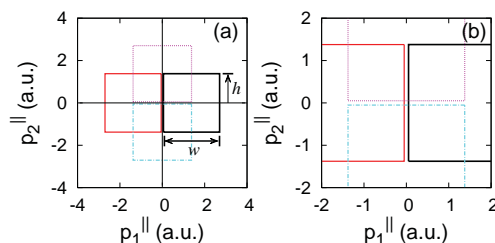
The cross-shaped structure shown in Fig. 1 is mainly attributed to recollision excitation of Ar<sup>+</sup> with subsequent tunneling. According to the kinematical analysis on the constraints for the correlated electron momenta [2], it is the ponderomotive energy  $U_p = A_0^2/4$ , where  $A_0$  is the maximum value of the vector potential, rather than the pulse duration of the laser field that plays crucial role in producing the cross-shaped structure in the CEP-averaged CEMD. Besides,

<sup>1</sup>E-mail: [chenzj@stu.edu.cn](mailto:chenzj@stu.edu.cn)

<sup>2</sup>E-mail: [cdlin@phys.ksu.edu](mailto:cdlin@phys.ksu.edu)

the constraints for the correlated electron momenta are also determined by the excitation potential  $I_p$ .

For electron impact excitation of Ar<sup>+</sup>, the excitation from  $3s^23p^5$  to  $3s^23p^43d$  dominates [3]. In Fig. 2, we show the kinematically allowed region for the correlated electron momenta for recollision excitation of Ar<sup>+</sup> from  $3s^23p^5$  to  $3s^23p^43d$  with subsequent tunneling in NSDI of Ar for the laser parameters used in Ref. [1]. It can be seen that the region with small momenta is not covered leading to a small hole in the center. This clearly indicates that to reproduce the cross-shaped structure, the excitation potential has to be reduced [4].



**Figure 2.** Kinematically allowed region for the correlated electron momenta for recollision excitation in NSDI of Ar with  $w=2\sqrt{2(3.17U_p - I_p)}$  and  $h=A_0$ . (a) The whole region; (b) The zoomed-in region of the central part.

### References

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