Title

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K-shell ionization and double-ionization of Au atoms with 1.33 MeV photons

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Abstract. At relativistic energies, the cross section for the atomic photoelectric effect drops off as does the cross section for liberating any bound electron through Compton scattering. However, when the photon energy exceeds twice the rest mass of the electron, ionization may proceed via electron-positron pair creation. We used 1.33 MeV photons impinging on Au thin foils to study double K-shell ionization and vacuum-assisted photoionization. The preliminary results yield a ratio of vacuum-assisted photoionization and pair creation of $2\text{x}10^{-3}$, a value that is substantially higher than the ratio of photo double ionization to single photoionization that is found to be $0.5\text{-}1\text{x}10^{-4}$. Because of the difficulties and large error bars associated with the small cross sections additional measurements are needed to minimize systematic errors.

Inner-shell photoionization of an atom or an ion is one of the most basic processes in atomic collisions. Ionization may proceed through the photoelectric effect or through Compton scattering (1-2). At MeV photon energies and beyond, the cross sections associated with both processes decrease almost linearly with increasing photon energy (3-5). When the photon energy exceeds twice the rest mass of the electron, the negative-energy continuum will play an additional important role; photoionization of, say, the K-shell can now proceed through a new channel in which the excess of energy is taken by one of the negative-energy continuum electrons (6). The final result is the creation of the K-vacancy along with an electron-positron pair.

In the relativistic regime, an atom can be described as a many-body system containing Z electrons occupying discrete bound states, Z being the atomic charge number and, in the Dirac picture of the hole theory, an infinite number of electrons occupying the negative-energy continuum (7). The removal of the inner-shell electron through this process (called here “vacuum-assisted photoionization”) will result in the creation of two vacancies, one in the inner-shell and the other in the negative-energy sea. This means that, from a theoretical point-of-view, vacuum-assisted photoionization can also be viewed as a double-ionization with a single photon. However, compared to the well-known photo double ionization (8-10), the situation is made somewhat more complicated by the presence of an extra lepton, the positron. The positron reflects the creation of a vacancy in the negative-energy continuum, and this vacancy can interact in the post-collision with the inner-shell electron.

Two different mechanisms contribute to vacuum-assisted photoionization. In the first, the photon converts into an electron-positron pair in the field of the nucleus and, subsequently, the bound electron (of the inner-shell) is ionized through an electron-electron or positron-electron encounter. In the second mechanism, the electron-positron pair is produced in the field of the inner-shell electron, that, in the process, takes enough recoil to be freed from the atom or the ion. If E_B denotes the binding energy of the inner-shell electrons, vacuum-assisted photoionization occurs with a threshold of $\omega_{thr} = 2mc^2 + E_B$ for the first mechanism and $\omega_{thr} = 4mc^2 + E_B$ for the second mechanism, m being the rest mass of the electron.

Figure 1 shows the cross sections for creation of a K-vacancy for Pb. The details of the calculation can be found in ref. (6).

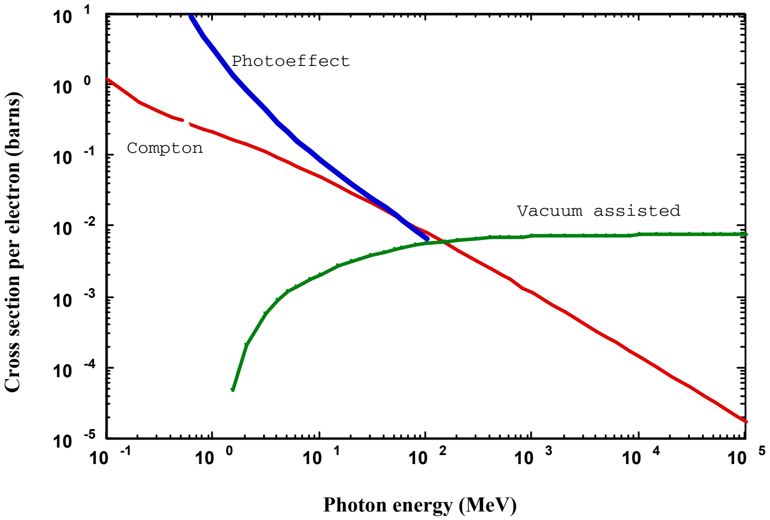

Figure 1

Figure 1: Cross section for creation of a K-shell vacancy for Pb (Z=82) for different photoionization processes as a function of the photon energy. The dashed-dotted line corresponds to the Compton effect and the dotted line to the photoelectric. Vacuum-assisted photoionization cross section is shown in a solid line.

The cross section for the creation of a K-vacancy by photons with energies below few MeV is dominated by the photoelectric effect contribution. However, with increasing photon energy, the photoelectric effect cross section decreases as a high negative power of the photon energy, and then, above about 10 MeV, as the inverse of the photon energy. In contrast, the contribution from vacuum-assisted photoionization increases with increasing photon energy, starting from a threshold of approximately 1

MeV. At high energies the photoionization cross section saturates at 7.5 mb per electron, a value that is due entirely to the contribution of vacuum-assisted photoionization.

We set up a first experiment to study this process at an intense Cobalt Source at the Lawrence Berkeley National Laboratory (LBNL). The 1500 Curies ^{60}Co source emits two gammas at 1.17 MeV and 1.33 MeV, respectively. These energies are below the threshold for pair creation in the field of the inner-shell electron. Thus, the study reported in this paper focuses on the first mechanism, namely, pair creation in the field of the nucleus, with subsequent inner-shell ionization through electron-electron and electron-positron interaction. The photon energy of 1.33 MeV is very close to threshold, and its corresponding cross section is two orders of magnitude smaller than the cross section at saturation. Most of the contribution to photoionization comes from the photoelectric effect and Compton scattering, making the experiment difficult. The measurement of vacuum-assisted photoionization would have been somewhat easier at higher energies (above 100 MeV), but there are very few high energy photon facilities where such experiments can be undertaken.

A beam of 2×10^8 photons/second is produced through a 6-mm diameter collimator in a 25-cm thick lead shielding enclosing the source. We estimate the number of photons in the beam by measuring the rate of single K-shell vacancies created in a 3 mg/cm^2 Au target and comparing to tabulated values for the cross section.

A signature of single K-shell ionization is given by the detection of a K_α or K_β photon emitted when a K-vacancy is filled. A signature of vacuum-assisted photoionization is given by the simultaneous detection of a K-vacancy and of a positron emitted. The positron is detected through its annihilation in a thin, low-Z foil set immediately downstream from the Au target. Two (7.5-cm diameter and 7.5-cm thick) NaI crystal detectors are set on opposite sides of the target to detect the 511-keV photons emitted back-to-back , characteristic of positron annihilation. The experiment is complicated by two backgrounds: First, a two-step process where the pair creation occurs on one atom and the K-shell vacancy on a different atom. The other false event can be simulated by two separate photons striking the target within the time window of the coincidence, one creating an electron positron pair and the other creating a K-vacancy. We set the coincidence window to 50 ns to minimize the latter. One of the difficulties of the experiment is to balance the need of a thick target for statistics and a thin target to minimize the two-step background. Unfortunately, because of the low (5%) geometrical detection efficiency of the germanium detectors, such an ideal target thickness is hard to achieve. To make our way around this problem, we perform a target-thickness-dependent measurement of vacuum assisted photoionization. A two-step process should vary as the square of the target thickness instead of linearly. Thus, a ratio of vacuum-assisted photoionization to pair creation should become independent of the target thickness for very thin targets.

Figure 2 shows the ratio of “vacuum-assisted photoionization” to pair production. A fit to the data yields a value of 2×10^{-3}, a value that is a factor of two to five larger than the theoretical value given in ref. (6). This preliminary number constitutes the first attempt to observe this new ionization process and measure its cross section relative to the pair creation cross section, which is well known at these energies. Because of the inherent difficulties associated with the small cross sections additional measurements are needed to minimize systematic errors. A series of follow up experiments to refine the measurement and make a more meaningfull comparison to theory are ongoing at the Lawrence Berkeley National Laboratory and also in planning at the European Synchrotron Radiation Facility (ESRF).

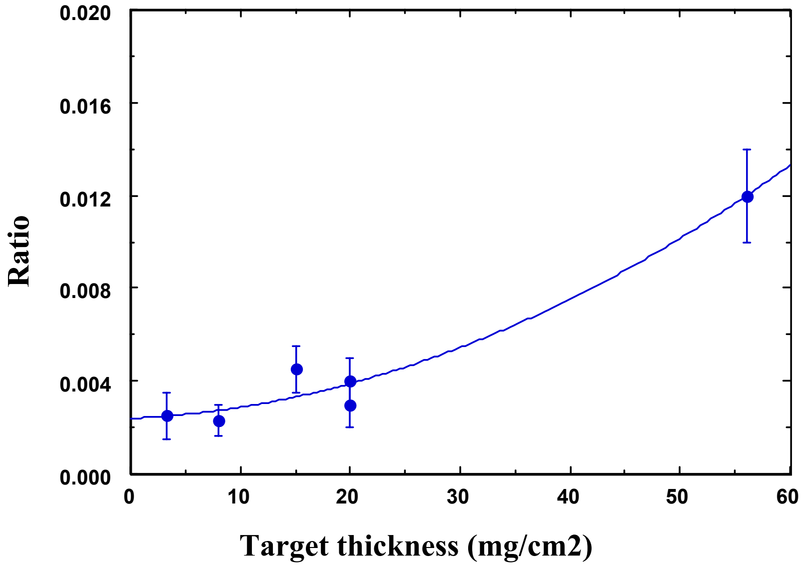

Figure 2

Figure 2: Ratio of the coincidence of "vacuum-assisted photoionization" cross section to the pair creation cross section as a function of the Au target thickness. The solid curve represents a least-square fit to the data used to extrapolate to vanishing thickness.

We used the same experimental set up to measure the ratio of double K-vacancy to single K-vacancy creation in Au. Because of the low count rate, we used a similar target dependent measurement of the ratio of double ionization to single ionization. Using an extrapolation to very thin targets, we obtain a value of 0.5-1 x 10^{-4} for the ratio. This low value is at the limit of sensitivity of our current set up, and should be considered as an upper limit. This sensitivity could be improved by an order of magnitude by requiring a better timing between the germanium detector signals. The theoretical relativistic limit given in ref. (9) and ref. (10) differ by a factor of approximately two and are 0.54 x 10^{-4} and 0.94 x 10^{-4}, respectively.

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REFERENCES

1. Lagarde P., Wuilleumier F. J., and Briand J. P., Special issue of J. Phys. (Paris) Colloq. 48, C9-48 (1987)
2. Drake G., *Atomic, Molecular and Optical Handbook*, AIP, Woodsbury, NY; see section written by Bernd Crasemann, 701 (1996).
3. Heitler W., *The Quantum Theory of Radiation*, Dover, New York, (1984).
4. Pratt R. H., Akiva Ron, and Tseng H. K., Rev. Mod. Phys. **45**, 273 (1973).
5. Hubbell J. H., Gimm H. A., and Overbo I., J. Phys. Ref. Data **9**, 1023 (1980).
6. Ionescu D. C., Sorensen A. H., and Belkacem A., Phys. Rev. A 59, 3527 (1999).
7. Greiner W., Muller B., and Rafelski J., Quantum Electrodynamics of Strong Fields, Springer-Verlag, Berlin, 1985.
8. McGuire J. H. et al., J. Phys. B **28** 913 (1995).
9. Mikhailov A. I., and Mihkailov I. A., JETP **87**, 833 (1998).
10. Drukarev E. G., and Karpeshin F. F., J. Phys. B **9**, 399 (1976).