The Two-Photon Continuum Observed in Decay of the $1s2s\ ^1S_0$ Level in Heavy Helium-like Ions

H.W. Schäffer[1] , P.H. Mokler[1], S. Cheng[2], L.J. Curtis[2], R.W. Dunford[3], E.P. Kanter[3], C. Kozhuharov[1], A. Krämer[1], A.E. Livingston[4], T. Ludziejewski[1], H.-Th. Prinz[1], P. Rymuza[5], L. Sarkadi[6], Th. Stöhlker[1], P. Swiat[7], and A. Warczak[7]

[1] GSI, Darmstadt, Germany; [2] University of Toledo, USA;
[3] ANL, Argonne, USA; [4] University of Notre Dame, USA;
[5] INS, Swierk, Poland; [6] Inst. of Nuclear Research, Debrecen, Hungary;
[7] Inst. of Physics, University Cracow, Poland

The phenomenon of two-photon decay was discussed theoretically beginning with Maria Göppert-Mayer [1] nearly 70 years ago. In the simple H- and He-like atomic systems the $2s\ ^2S_{1/2}$ and the $1s2s\ ^1S_0$ levels, respectively, decay via two-photon emission. To calculate the probability for such a transition summing over all virtual intermediate (bound and continuum) states is required. Therefore the entire structure of the atom/ion has to be understood. In hydrogenlike ions the wave functions can be calculated analytically by solving the Dirac equation. Heliumlike ions are the simplest multi-electron systems and one has to use variational methods to determine the atomic structure. As the simplest multi-electron systems, they are an ideal testing ground for our understanding of electron-electron correlation in many-body systems and of relativistic effects in heavy systems.

The most accurate non-relativistic calculation was performed by Drake [2] for atomic numbers up to $Z = 36$ (krypton). Fully relativistic calculations have been performed recently by Derevianko and Johnson [3]. The calculations show a strong dependence of the two-photon energy distribution on the atomic number Z.

We are pursuing a joint effort between Argonne National Laboratory and GSI to test these calculations for the full range of nuclear charge Z. Experiments are being done both at intermediate Z (in Kr^{34+} and in Ni^{26+}) and at high Z (in Au^{77+}) to measure the spectral distribution of photons from the two-photon decay of the $1s2s\ ^1S_0$ level in heliumlike ions. Measurement of the spectral distribution provides more information than a lifetime measurement which determines the transition probability already summed over the spectral distribution. Also, spectral distribution measurements allow the study of two-photon transition probabilities to be extended to very high Z where the lifetime of the initial state becomes too short to measure with standard techniques.

In related work we have also studied the two-photon decay mode of inner shell vacancy states in neutral atoms. Here the first detailed determination of the dependence of the transition probability on the opening angle between the two photons has been made for the case of silver. For the 2s - 1s two-photon transition in Ag an intensity ratio $I(180^o)/I(90^o)$ of 1.90 ± 0.27 was found in agreement with the theoretical value of 2.0. This experiment was done at GSI where the inner-shell vacancy was produced by nuclear electron capture using a Cd radioactive source.

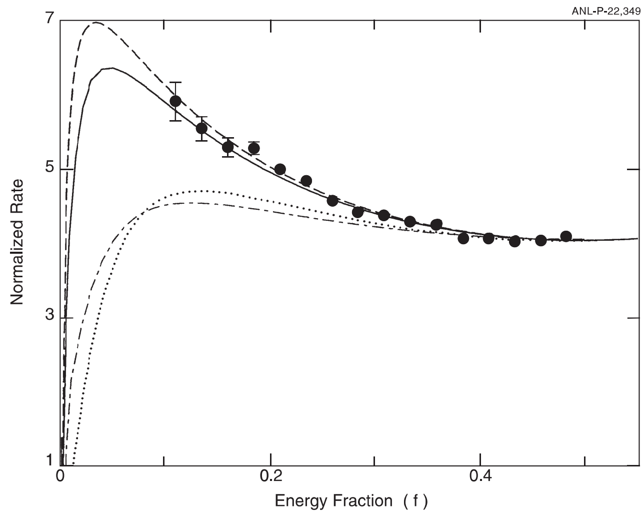

Figure 1: Comparison of theory and experiment for two-photon decay in heliumlike Ni. (Full line, relativistic calculation for Ni [3]; dashed line, non-relativistic calc. for Ni [2]; dashed-dotted line, relativistic calc. for Au [3]; dotted line, calc. for He [3]).

The most recent experiment at Argonne was a measurement of the spectral distribution of the 2E1 decay of the $1s2s\ ^1S_0$ level in He-like Ni [4]. This was an improvement on earlier measurements done both at GSI in Ge and Kr [5, 6] and at Argonne in Kr [7]. The main improvement was to measure the spectral shapes in both H-like and He-like Ni in the same run, switching between the two species several times during the run. Since the continuum shape for H-like nickel is known precisely, the data for H-like nickel was used to calibrate the spectral efficiency of the Si(Li) detectors used to detect the coincident photons. This technique allowed us to eliminate the largest uncertainty in the former experiments.

The results of the Ni experiment are shown in Fig. 1, which is a plot of the He-like spectral distribution vs photon energy (f) in units of the transition energy. The data were divided by the phase space factor f(1-f) which makes it proportional to the second order matrix element for two-photon decay [4]. We employ the symmetry of the curves about the midpoint of the distribution and plot only the low energy photon of each coincident pair. The data are given by the solid dots with error bars. The solid line is the theoretical distribution of Derevianko and Johnson [3] and the dashed line is the nonrelativistic result of Drake [2]. The dot-dashed line is the relativistic result for Au (Z=79) and the dotted line is the same for He (Z=2) [3]. There is a qualitative difference between the shape for He-like Au and He-like Ni and the data clearly follow the predicted shape for Ni.

In the GSI experiment [8], a beam of 106 MeV/u Au ions with a charge state 77+ was provided by the heavy ion synchrotron SIS at GSI in Darmstadt. The $1s2s\ ^1S_0$ initial state for the 2E1 decay was prepared by excitation of the ions in a 100 μg/cm^2 Al target. Photon-photon coincidences associated with the 2E1 decay were registered by two Ge(i) x-ray detectors, each at 60 degrees from the beam axis. One of these detectors has a nominal size of 500 mm^2 (Det. A), whereas the other one (Det. B) consists of 7 independent segments (stripes) of the size 3.5 mm by 25 mm. The characterization of these detectors is described in Ref. [9]. This particular setup allowed us to investigate the 2E1 decay in 7 independent combinations of Det. A and Det. B and to reduce significantly the Doppler broadening of the spectra taking into account the relativistic Lorentz transformation.

In order to account for experimental details, such as detection geometry, beam velocity and the angular distribution of the decay radiation a Monte Carlo simulation was developed to model our experiment. This simulation is based on the theoretical 2E1 energy distribution for He-like gold [3], the angular distribution of the 2E1 decay [1], i.e. the $1 + \cos^2(\theta)$ distribution for the opening angle θ between the two photons, and all relevant experimental factors.

Using the Monte Carlo simulation to remove the detector efficiency we obtain the result shown in Fig. 2 which shows the spectral distribution of the 2E1 decay in heliumlike gold. The photon energy is given in units of the transition energy. As for the nickel result, the data are normalized by a factor of $f(1-f)$ and so it is proportional to the second order matrix element for two-photon decay up to a multiplicative constant. The solid line is the theoretical distribution of Ref. [3] for heliumlike gold, the dashed line is the theoretical result for heliumlike nickel. Our experimental data are given by solid squares with statistical (inner bars) and systematical errors (outer bars). Our data is in good agreement with the theoretical prediction for heliumlike gold. Especially for the most asymmetric energy sharing of the photons there is a clear separation of our data to the theoretical curve for heliumlike nickel.

Comparison of the data for He-like Ni and He-like gold indicates a clear difference between the continuum shape for these two species. In particular, the data in Fig. 1 show a marked increase towards the lowest energy, whereas the Au data is much flatter in this region. Our results indicate good agreement with the calculations and provide the first evidence for a dependence of the shape of two-photon decay on nuclear charge. To provide a more definitive test of the relativistic corrections, the experiments must be improved. One possibility is to extend the data for both experiments to lower photon energy. In the case of Ni, this will require the use of windowless Si(Li) detectors, while in the case of the Au experiment, it is possible to push the data to lower energies by improvements to the electronics.

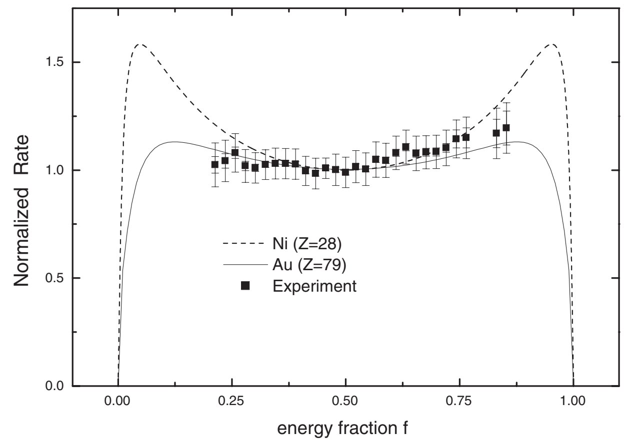

Figure 2: Normalized rate of the two-photon decay as a function of the photon energy f (in units of the transition energy). Our experimental data is compared to the theoretical prediction of Ref. [3] for heliumlike nickel ($Z = 28$) and gold ($Z = 79$). See text for explanation.

References

1. M. Göppert-Mayer, Ann. Phys. **9** (1931) 273
2. G.W.F. Drake, Phys. Rev. A **34** (1986) 2871
3. A. Derevianko and W.R. Johnson, Phys. Rev. A **56** (1997) 1288
4. H.W. Schäffer et al., Phys. Rev. A **59** (1999) 245
5. P.H. Mokler et al., Phys. Rev. Lett. **65** (1990) 3108
6. Th. Stöhlker et al., Z. Phys. D **21** (1991) S233
7. R. Ali et al., Phys. Rev. A **55** (1997) 994
8. H.W. Schäffer et al., Phys. Lett. A **260** (1999) 489
9. H.W. Schäffer et al., Nucl. Instr. Meth. B **146** (1998) 62