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Measurement of the Spectral Distribution for the Two-Photon Decay of the 1s2s $^1S_0$ level in Heliumlike Gold

Dedicated to Prof. Dr. Karl-Heinz Schartner on the occasion of his 60th birthday

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Abstract

A first measurement of the spectral distribution of the two-photon decay of the 1s2s $^1S_0$ level in heliumlike gold is reported. This study extends our earlier work for heliumlike krypton and nickel to higher atomic numbers Z into the fully relativistic regime. The measured spectral shape of the two-photon decay differs from that observed at intermediate Z but is in agreement with the results of a recent fully relativistic calculation of Derevianko and Johnson.

1. Introduction

The phenomenon of two-photon decay was discussed theoretically beginning with Maria Göppert-Mayer [1] nearly 70 years ago. In this process a transition between two quantum levels occurs via simultaneous emission of two photons with a continuous energy distribution.

In heliumlike ions the 1s2s $^1S_0$ state can only decay to the $1s^2\ ^1S_0$ ground state by the emission of two photons (2E1) due to the conservation of angular momentum. To calculate the probability for such a transition summing over all bound and continuum states of the system is required. For light ions with an atomic number $Z < 18$ only ^1P states contribute significantly to that sum. Beyond $Z = 18$, relativistic effects, in particular the two-photon branches via ^3P states, have to be taken into account. Such fully relativistic calculations have been performed recently by Derevianko and Johnson [2]. The calculations show a strong dependence of the two-photon energy distribution on the atomic number Z (Fig. 1), which is caused by the competing influences of electron-electron correlation and relativistic effects on the wave functions. Therefore, there is a need to verify these theoretical predictions in very heavy systems. In this contribution we describe an experiment to study the two-photon energy distribution in He-like gold.

Since 1965 many lifetime measurements have been performed for the two-photon emitting states in ions of the isoelectronic series of hydrogen (atomic number $Z = 1 - 47$) and helium ($Z = 2 - 41$); for a short review see e.g. Ali *et al.* [3]. Despite of the high precision these lifetime measurements can only test the 2E1 decay probability summed over all continuum photon energies, whereas a measurement of the spectral distribution provides additional information on the details of the decay mode. Up to now there is only information available on the spectral distribution of the 2E1 decay in few-electron systems in the medium-Z regime (He-like Ge [4], Kr [3,5] and Ni [6]). All these experiments show, within the accuracy achieved, reasonable agreement with theoretical prediction.

2. Experiment

In the experiment a 106.6 MeV/u beam of Au ions with a charge state 63+ was provided by the heavy ion synchrotron SIS at GSI in Darmstadt. After the beam was stripped in a 20 mg/cm^2 Al foil the heliumlike charge state 77+ (about 60 percent of the total beam intensity) was magnetically separated and directed to our target chamber.

The 1s2s $^1S_0$ initial state for the 2E1 decay was prepared by excitation of the ions by a 100 μg/cm^2 Al target. Under these experimental conditions a cross section of 140 barn for excitation into the desired initial state can be expected [7]. Photon-photon coincidences associated with the decay were

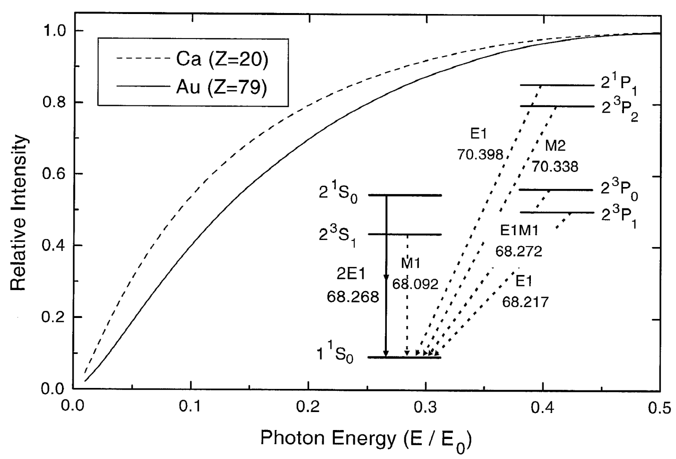

Fig. 1. Spectral distributions for two-photon decay as a function of E/E_0 for different atomic numbers Z. Inset includes the level scheme of heliumlike gold including important decay modes (all energies in keV).

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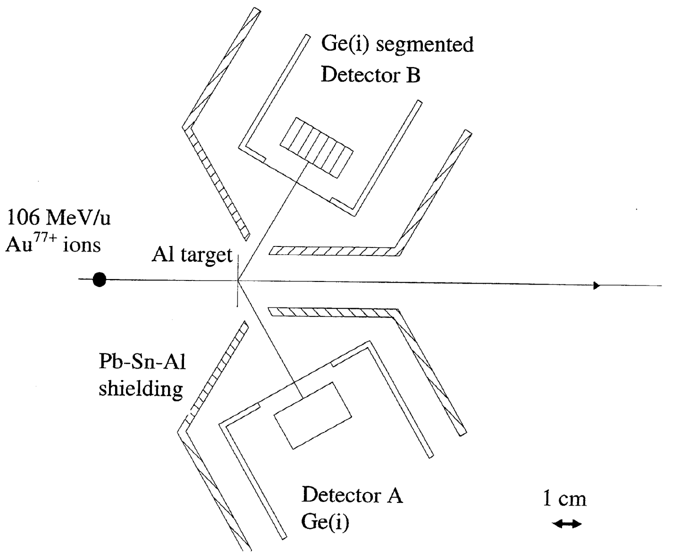

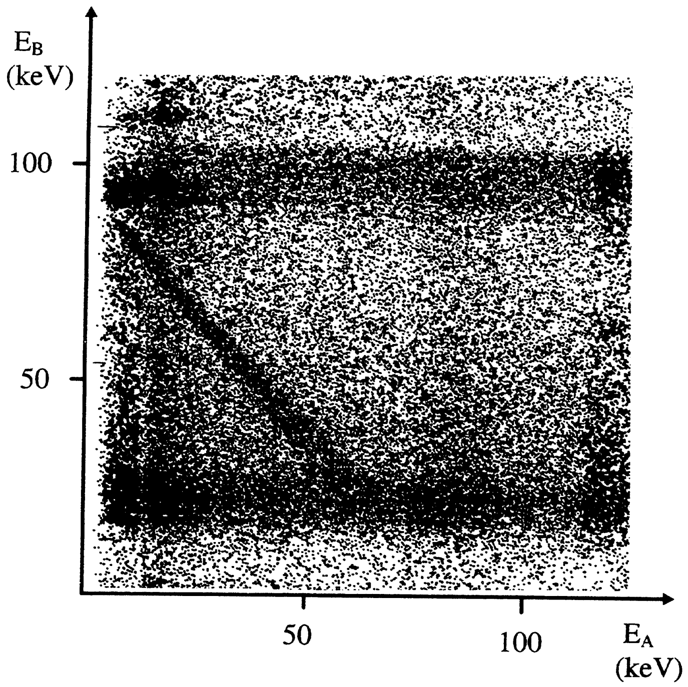

Fig. 2. (a) Experimental setup at the target area. (b) Energy E_A vs. the energy E_B for true coincidences between detector A and segment 6 of detector B. Note the diagonal stripe corresponds to a constant sum energy (2E1 decay branch!).

registered by two Ge(i) X-ray detectors, each at 60 degrees from the beam axis (Fig. 2a). The detector geometry was optimized for the registration of photons emitted in the projectile system with an opening angle of 180 degree, where the angular distribution has its maximum [1]. 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. 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 separate the 2E1 decay from other background processes a standard slow/fast coincidence technique was used for data acquisition.

For the measurement of the continuous energy distribution of the two photons a precise calibration of the coincidence efficiency of the experimental setup as a function of photon energy was performed. Moreover, the intrinsic efficiency of the detectors was determined relative to the high-energy domain (>100 keV) applying the method of Campbell and McGhee [8].

3. Results

The off-line analysis of two-dimensional energy spectra (E_A vs. E_B, where E_A and E_B denote the X-ray energy registered in detector A and B, respectively) was carried out using appropiate condition windows on the accumulated time spectra. Subtraction of a "random" spectrum from the corresponding "prompt" spectrum yields the two-dimensional energy spectrum for true coincidences (Fig. 2b). The final analysis procedure, however, was based on two-dimensional plots where the sum-energy (E_A + E_B) was presented versus the energy in one of the segments in detector B (E_B). The procedure for data analysis is discussed in Ref. [3].

For further analysis this two-dimensional plot was divided into horizontal slices with 2-keV-wide windows set on E_B which were finally projected onto the sum-energy axis. The 2E1 peak area was obtained with a least-squares fitting routine for each slice separately.

The experimental results of each combination of detector A and segments of B are compared with a Monte Carlo simulation. The modelling of this simulation is based on the theoretical 2E1 energy distribution for He-like gold [2], the angular distribution of the 2E1 decay as proposed in Ref. [1] with $1 + \cos^2(\theta)$ distribution for the opening angle θ between the two photons [9] and all relevant experimental factors like detector geometry and efficiencies, beam parameters and, finally, Doppler corrections to the X-ray energies.

Good agreement between the experimental data and the preliminary Monte Carlo simulation based on theoretical predictions of Derevianko and Johnson is found. In order to improve the significance of the experimental data, one

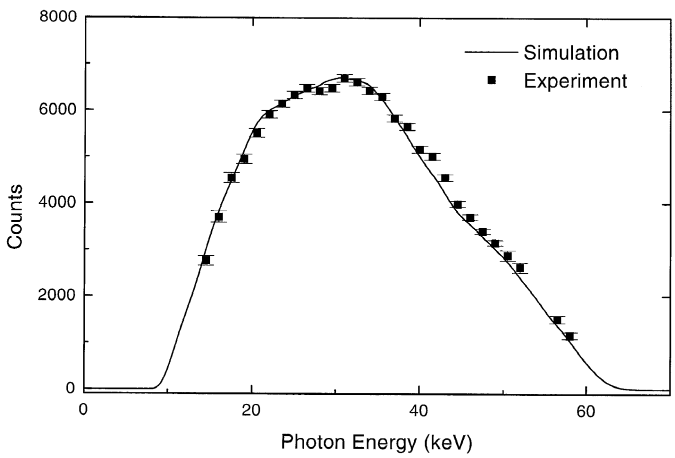

Fig. 3. Experimental data points obtained after summing up all detector combinations. The curve represents the Monte Carlo simulation based on the theoretical 2E1 energy distribution for heliumlike gold calculated by Derevianko and Johnson [2].

can combine all combinations of detector A with the seven segments of detector B. Because the transition energy of the two-photon decay measured in the laboratory system depends on the detection angle (Doppler effect) a direct combination of all experimental 2E1 distributions cannot be performed. By using a transformation from the laboratory to the emitter system (Doppler correction of photon energies and solid angles of the detectors) the desired combination becomes feasible. The result is shown in Fig. 3 which demonstrates good agreement between theory and experiment.

In conclusion, we have made the first observation of two-photon decay in a very high-Z heliumlike ion. The spectral distribution of the 2E1 spectrum has been measured and good agreement with the fully relativistic calculation of Derevianko and Johnson has been found.

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