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Measurement of the spectral shape for the two-photon decay in heliumlike gold

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Abstract

Progress on a measurement of the spectral distribution of the two-photon decay of the 1s2s $^1S_0$ level in the strong central fields of heavy heliumlike ions is reported. A measurement of the exact shape of the continuous spectrum of the two-photon decay in heavy heliumlike ions provides a sensitive test of the details of the complete structure of a heliumlike system. In our experiment at GSI, a beam of 106.6 MeV/u Au^{77+} ions was excited by a thin Aluminum foil and the subsequent decays were observed in an array of Ge(i) detectors. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

In this contribution we are dealing with the phenomenon of two-photon decay as a second order process in strong electromagnetic fields. In this process a transition between two quantum levels occurs via simultaneous emission of two photons. The energies of the individual photons form a continuous symmetric distribution with a maximum at half the transition energy. The theory to describe the two-photon decay (2E1) of metastable states was first developed by Maria Göppert-Mayer [1,2] nearly 70 years ago.

In atomic systems two-photon decay was first observed in 1965 by Lipeles et al. [3] in the He^+ ion. Since that time 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. [4]. Measurements of the spectral distribution attributed to the 2E1 decay provide additional information on the details of the two-photon transition probabilities and go beyond the lifetime measurements

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which only test those probabilities summed over all continuum photon energies. The first dedicated measurements to determine the spectral distribution of the 2E1 photons were performed by Lipeles et al. [3] and O'Connell et al. [5] for the very light systems of He^+ and H, respectively. Unfortunately, there is little information available on the spectral distribution of the 2E1 decay in few-electron systems, like H- and He-like ions, in the medium-Z regime. Such simple atomic systems are well suited for detailed tests of the theoretical description of the 2E1 decay. Up to now, there are only three measurements of the spectral shape performed in He-like Ge [6], Kr [4,7] and Ni [8] which show, within the accuracy achieved, a reasonable agreement between experiment and theoretical prediction.

In heliumlike ions (Fig. 1) 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 (singlet) ^1P states contribute significantly to that sum. Beyond $Z = 18$, relativistic effects, in particular the two-photon branches via (triplet) ^3P states, have to be taken into account. Such fully relativistic calculations have been performed very recently by Derevianko and Johnson [9]. The calculations show a strong dependence of the two-photon energy distribution on the atomic number Z, which is caused by the competing influences of electron–electron correlation and relativistic effects on the wave functions. Therefore, there is a need to confirm these theoretical predictions in very heavy systems.

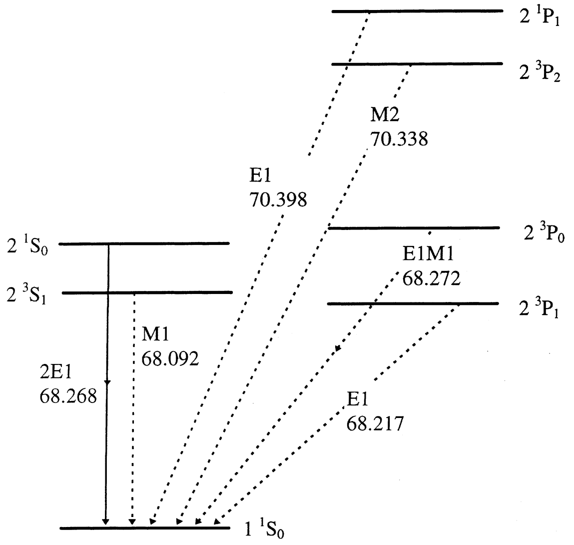

Fig. 1. Level scheme of heliumlike gold including important decay modes. All energies in keV.

With a precise measurement of the spectral shape one can test the theoretical predictions for the whole atomic system, because both energy levels and wave functions for a complete set of intermediate states have to be known. Because these predictions are found in a model with certain prerequisites, we therefore can test our understanding of the physical problem. In this contribution we report the first experiment aimed at a determination of the spectral shape for the continuum radiation from the two-photon decay of the 1s2s $^1S_0$ level in heliumlike gold. This study extends our earlier work [4,6–8] to the higher-Z regime in order to provide evidence for the predicted Z dependence of the 2E1 decay.

2. Experiment

In the experiment a 106.6 MeV/u beam of Au ions (momentum spread $dp/p = 10^{-3}$) with a charge state 63+ was provided by the heavy ion synchrotron SIS at GSI in Darmstadt. About 10^8 ions per second were extracted over a period of 9 s within a duty cycle of 11 s. After the beam was stripped in a 20 mg/cm^2 Al foil (energy loss 3.4 MeV/u) the 77+ charge state (about 60% of the total beam intensity) was magnetically separated and directed to our target chamber. The spot size of the beam was about 5 mm × 5 mm as observed on a fluorescent screen.

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 [10]. Photon–photon coincidences associated with the decay were registered by two Ge(i) X-ray detectors, each at 60° from the beam axis (Fig. 2). 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 × 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. The detector geometry was optimized for photons in the projectile system with an opening angle of 180°, where the angular distribution has its maximum [1,11].

Standard coincidence electronics were used for data acquisition. The preamplifier outputs of the detectors were directed to both fast and slow amplifiers to give timing and energy signals for each detector. Shaping times of 50 ns and 2 μs were used as a compromise between resolution and rate for the fast and slow amplifiers, respectively. In the experiment, a valid event was defined when timing pulses from two detectors arrived within 1 μs of each other. These events started the readout of our data acquisition system. All measured parameters were written to tape and accumulated with an online data analysis program simultaneously. The total data collection time was 35 h.

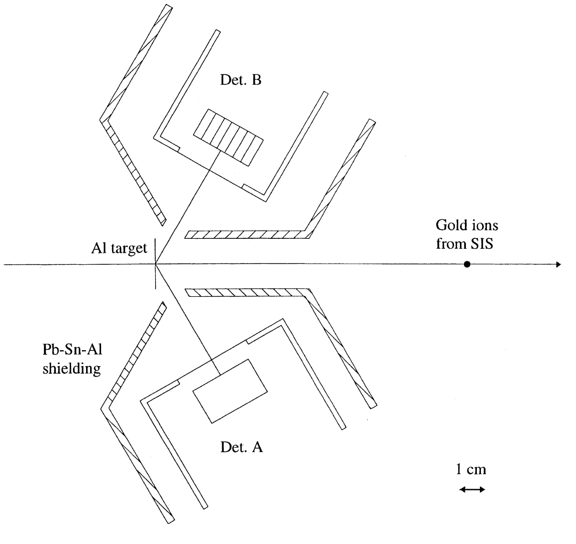

Fig. 2. Experimental setup at the target area.

Precise determination of the efficiency of the experimental setup as a function of photon energy was very crucial in this experiment. Especially, in the low-energy range this efficiency is strongly dependent on the ability of low amplitude pulses to trigger the discriminators. This part of the efficiency dependence was determined by simultaneous recording of X-rays from standard radioactive sources and signals from an electronic pulser. The ratio of pulser counts to the counts of the reference X-ray lines represents the efficiency of triggering our data acquisition system. In addition, the efficiency of the detectors to absorb a photon in the germanium crystal plays an important role over the whole energy range of the experiment (5 to 90 keV). The intrinsic efficiency of the detectors was determined relative to the high-energy domain (>100 keV), where the determination could be done very precisely. The procedure applied followed the method of Campbell and McGhee [12]. In a series of measurements performed just after the experiment, we collected energy spectra for several radioactive sources (Am-241, Cd-109, Co-57), where the intensity ratio of X-ray lines to a reference γ-ray line was obtained. Comparing these ratios to the corresponding ratios from Ref. [12], which are unaffected by any absorption process, the intrinsic efficiency of each detector (detector stripe) was determined.

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 different conditions on the accumulated time spectra. Subtraction of a “random” spectrum from the corresponding “prompt” spectrum yields the two-dimensional energy spectrum for true coincidences. 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). An example of such a two-dimensional spectrum registered in detector A and segment 4 of detector B is shown in Fig. 3. With this method some blending between the 2E1

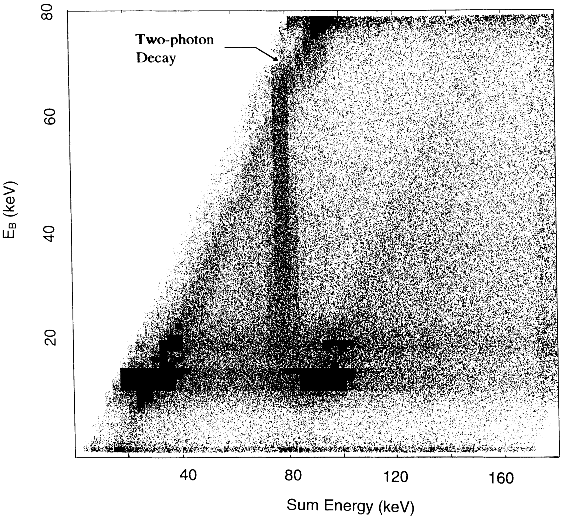

Fig. 3. Sum energy ($E_A + E_B$) vs the energy of one detector E_B for true coincidences between detector A and segment 4 of detector B.

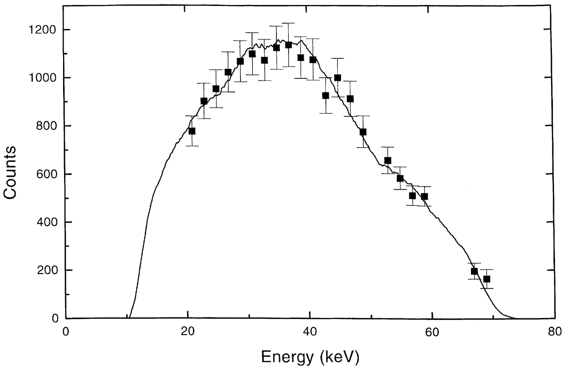

Fig. 4. Experimental data points obtained from fitting the two-photon peaks in the cuts of the sum-energy spectra (Fig. 3) as discussed in the text. The solid curve represents the Monte Carlo simulation based on the theoretical 2E1 energy distribution for heliumlike gold calculated by Derevianko and Johnson [9].

events and other true coincidences can be avoided. The advantage of this particular presentation for further data analysis is discussed in Ref. [4].

For the shown case, the 2E1 transitions form a vertical line at a sum-energy of 78 keV in the laboratory system which is shifted with respect to the CM system energy of 68 keV (Fig. 1) due to the Lorentz transformation. The other continuous structures in Fig. 3 are due to additional true coincidences between cascade events of populated higher states and one of the 2E1 decay photons. For further analysis this two-dimensional plot was divided into horizotal 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.

In Fig. 4 the experimental result of detector A and B (only segment 4) are compared with a Monte Carlo simulation. The modelling of this simulation is based on the theoretical 2E1 energy distribution for He-like gold [9], the angular distribution of the 2E1 decay as proposed in Refs. [1,11] and all relevant experimental factors like detector geometry and efficiencies, beam parameters and, finally, Doppler corrections to the X-ray energies. Hence this simulation allows to compare directly the theoretical predicted 2E1 energy distribution with our measurement.

Good agreement between the experimental data and the preliminary Monte Carlo simulation based on theoretical predictions of Derevianko and Johnson could be found for the measured case of heliumlike gold. But our data analysis is still in progress. In order to improve the significance, we want to add all combinations of detector A with the seven segments of detector B. This should allow us to confirm the relativistic corrections to the spectral shape of the two-photon decay in strong central fields.

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