α Continuous Spectra Following K and L Autoionization During α Decay of ^{210}Po

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The α spectra emitted during K and L ionization following α decay of ^{210}Po are investigated in a coincidence experiment with x rays. We present the first observation of α continuous spectra emitted by radioactive samples. The probabilities of this phenomenon and the shape of the α spectra are discussed in the scope of an α collision with zero impact parameter.

What happens during the change of the atomic cloud accompanying nuclear decay is a problem which has been investigated by nuclear physicists for a very long time. During the rearrangement of the atomic cloud, internal ionization processes may occur. This phenomenon, the probability of which is very small, has been extensively studied, especially in the case of β decay.[1] Concerning α autoionization the x-ray emission following α decay was first discovered by Curie and Joliot in 1931,[2] but the first theory of this process was not given until 1941 by Migdal[3] and refined later by Levinger[4,5] and Rubinson.[6]

The rate of change of the nuclear charge, i.e., the velocity of the outgoing nuclear particle, is a very important point in the theory of this process. When the outgoing particle is moving slowly in comparison to the velocity of the atomic electrons, as in the case of α decay, the process may be considered as adiabatic and can be treated in the adiabatic limit of time-dependent perturbation theory. In the case of a fast outgoing particle, as in β decay, for example, the change of the nuclear charge is sudden and the probability of an ionization during the decay is then approximately given by the imperfect overlap of the wave functions of initial and final states, i.e., in the sudden-approximation limit of time-dependent perturbation. In the case of α decay of ^{210}Po, the velocity of the α particle is low relative to those of inner-shell electrons, but fast for the outer-shell electrons. Therefore, the probability of α autoionization for the K and L shells is exceedingly small as might be expected in the adiabatic approximation. However, there has been a very large discrepancy between experimental values of the probabilities and the theoretical predictions. This problem has only been resolved at the beginning of this year,[7] as discussed below.

Let us now consider the energetics of this autoionization process. The energy of the electron ejected during α autoionization may be derived, in a simple way, from the original theory of Migdal. The electron spectrum is expected to be continuous and to decrease in probability very rapidly, following an $E^{-9/2}$ rule. The mean energy of this continuous spectrum is lower than the binding energy of the ejected electron in the atom. It is then very low in energy and too near the electron background to be observed experimentally. The energy of the α particle is then modified and becomes $E_\alpha = E_\alpha{}^n - B_K - E_e$, in the case of K ionization, where $E_\alpha{}^n$ is the energy of the α particle when the final state is neutral, B_K the binding energy of the K electron, and E_e the kinetic energy of the ejected electron. Thus we can expect to observe a continuous α spectrum with a maximum energy of $E_\alpha{}^n - B_K$ which is symmetric in shape with the electron spectrum (Fig. 1). This situation is quite similar to that of the electron shake-off spectra but with a faster decrease of the energy spectrum. (In the case of shake-off spectra the decrease in energy is assumed to follow an $E^{-7/2}$ rule.) We present in this paper the first observation of these continuous α spectra in the case of K ionization as well as in the case of L ionization.

The principle of our experiment is to observe the α spectra emitted in coincidence with the K or L rays which follow the rearrangement of the autoionized atom. The α spectra were studied with a Si surface-barrier detector of 14-keV resolution at 5 MeV, and the x-ray spectra, with a Ge(Li) or Si(Li) detector [Ge(Li) in the case of K rays, the energy of which is of the order of 70 keV, and Si(Li) for the study of L rays]. We used a 1-μCi sample of ^{210}Po prepared by autodeposition on a silver foil of 6 μm thickness, set between the two detectors, in a vacuum chamber closed by a beryllium window.

We present in Fig. 2 the experimental spectrum observed in coincidence with K x rays. This

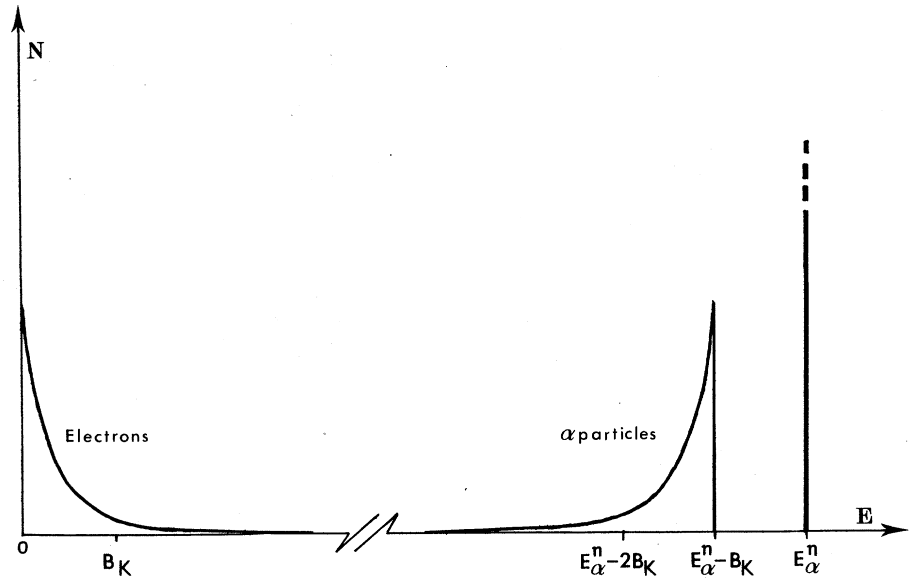

FIG. 1. Theoretical shapes of a continuous α spectrum following K autoionization.

spectrum was obtained in a two-month exposure. One observes in this figure an α continuous spectrum, the maximum energy of which is $E_\alpha{}^n - B_K$ and which decreases rapidly with decreasing α energy. The probability of K autoionization deduced from this experiment is $(2\pm0.5)\times10^{-6}$. In Fig. 3 one can observe the spectrum in coincidence with all L x-rays emitted. The probability deduced from this experiment, corrected by the

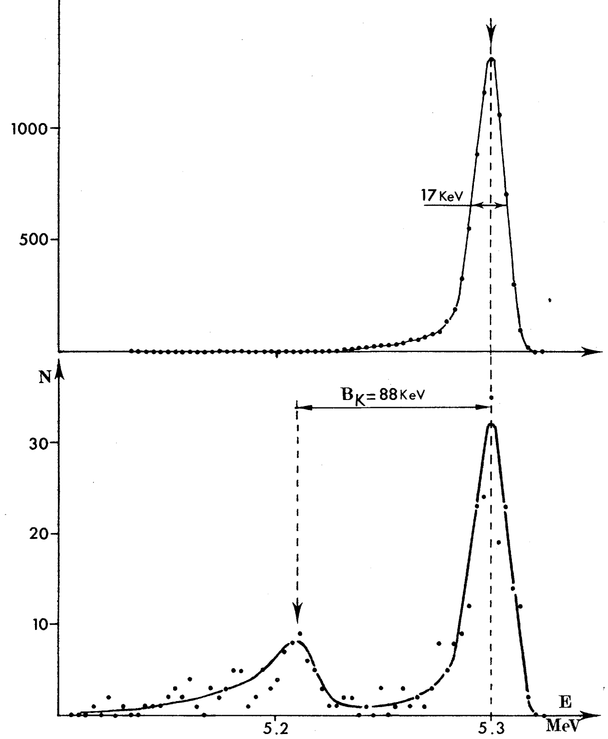

FIG. 2. Experimental α spectrum in coincidence with K x rays of Pb. Upper curve, direct α spectrum; lower curve, coincidence α spectrum. The peak at 5.3 MeV is a chance coincidence peak (for Pb, $B_K = 88$ keV).

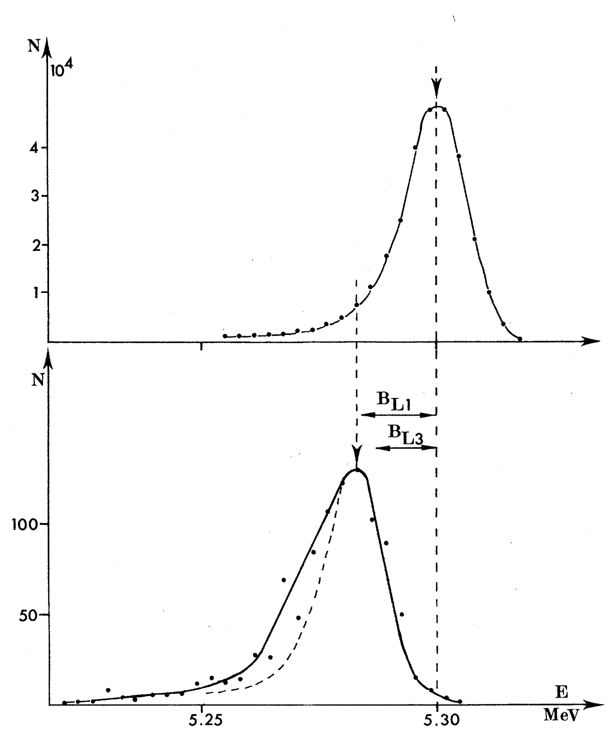

FIG. 3. Experimental α spectrum in coincidence with L x rays of Pb. Upper curve, direct α spectrum; lower curve, coincidence α spectrum.

values of fluorescence yield, Coster-Kronig probabilities, and intensity ratios of the L lines, is $(3.2 \pm 0.8) \times 10^{-4}$. The duration of this experiment was only one week.

The probabilities we obtained are in good accordance with the previous measurements for both K and L autoionization (for the K shell, the previous measurements gave 1.5×10^{-6}, 2×10^{-6}, 1.6×10^{-6}, and 1.5×10^{-6},[8-11] and for the L shell, 2.2×10^{-4}, 2.93×10^{-4}, and 4×10^{-4} [10,11,1]).

Our values, as well as the previous ones, are in large disagreement with the calculations of Migdal, Levinger, and Rubinson, which lead to an order of magnitude of 2×10^{-7} for the internal-ionization probability for the K shell, and with that of Ciochetti[12] ($P_K = 8.7 \times 10^{-7}$). We therefore had tentatively computed the probability in the scope of collision theory.

In fact, α autoionization may be considered as a collision process due to the Coulombic interaction between the moving α particle and an atomic cloud which is still nearly that of Po. The autoionization process during α decay is, in fact, the only case of collision with purely zero impact parameter which can be studied experimentally. Therefore, there are two important differences between autoionization and an ordinary collision of an α particle with a Pb atom. Firstly, the collision originates in the center-of-mass reference frame and the recoil energy is lower (~100 keV); secondly, the α particle travels exclusively from the center of the atom to infinity. Following the calculation of Hansteen and Mosebekk[13] in the semiclassical approximation to the theory of collisions and interpolating their results, one deduces at zero impact parameter a value of the probability of 4×10^{-7} for the K shell, which is of the same order of magnitude as in the previous calculations based on time-dependent perturbation of Migdal, Levinger, and Rubinson.

Very recently, and during the writing of the present paper, Hansen[7] reported the first calculation which agrees well with experimental results, perhaps resolving a problem which has existed for 30 years. Hansen, using the new binary-encounter approximation of collision theory,[14] has taken into account two refinements with respect to the previous theories: relativistic effects and the variation of the kinetic energy of the α particle in the vicinity of the nucleus, i.e., in the region where the probability of collision is largest. He found for the K shell a probability of 1.96×10^{-6}, which agrees very well with all previous experimental values and with our own measurement. Also for L-shell ionization his calculation, after all corrections for fluorescence yields etc. have been made, fits with the experimental values (Hansen predicts 2.3×10^{-4}).

The shape of the α continuous spectrum is not given in Hansen's paper. In view of the importance of the effects taken into account in his calculation, it is not too meaningful to compare the shape of our experimental spectrum for K-shell ejection with the previous prediction given by Migdal's theory. It may be noticed, however, that the predicted $E^{-9/2}$ shape of the electron spectrum is not very far from the shape we observe.

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