Exotic atoms

Antiprotons tickle nuclei

from C.J. Batty

WITH a few exceptions, atomic physics (concerning the orbitals of particles about the nucleus) and nuclear physics (concerning nuclear excitations) rarely meet. But in the experiment of W. Kanert *et al.* (*Phys. Rev. Lett.* **56,** 2368; 1986) they have clearly met head on, with the X-ray transitions of antiprotonic atoms interacting resonantly with nuclear excitations.

Kanert and his colleagues used antiprotons from the low energy antiproton ring at CERN, near Geneva, to generate 'exotic' atoms. In such atoms, one of the electrons is replaced by a heavier, negatively charged particle, such as a muon, pion, kaon or antiproton, and is formed by stopping the particles in suitable target material. Because of the larger mass of the trapped particle, its orbits will be much closer to the central nucleus than those of the remaining electrons. Because there is only one heavy particle, the Pauli exclusion principle is not involved and the full range of classical orbits characterized by the principal quantum number (n) and angular momentum $l (0 \leqslant l \leqslant n-1)$ are available. As a result, the outer electrons can generally be ignored and the exotic atom has many properties closely similar to those of the simple, one-electron hydrogen atom. The exotic atom is initially formed in an excited state of high n and then de-excites by a mixture of Auger (electron emission) and X-ray transitions, with the latter predominating in the latter stages of the cascade. When the so-called classical 'circular' orbits, with $l = n-1$, are strongly populated so that the X-ray transitions are generally of the type $(n, l=n-1) \rightarrow (n-1, l=n-2)$.

In muonic atoms, the muon wavefunction for low n has a considerable overlap with the nucleus. As the energies that would excite the nucleus itself are frequently comparable to the energies of the muonic atom, the nucleus can be excited during the muonic cascade. In the case of negative hadrons like the antiproton, which interact strongly with the nucleus, the hadron will be absorbed by the nucleus while at a relatively high n-value, where most of its wavefunction is far outside the nucleus. The paradoxical result is that in general the probability of nuclear excitation in hadronic exotic atoms is extremely small. However M. Leon (*Nucl. Phys.* **A260,** 461; 1976) pointed out that in certain special cases, where the atomic de-excitation energy is closely matched by a nuclear excitation energy, a resonance condition is satisfied and large nuclear excitation effects may be observed. When this occurs the exotic atom can be considered as being partly in the atomic state (n, l) with the nucleus in its ground state and also partly in the $(n-2, l-2)$ state with the nucleus in an excited spin-parity 2^+ state. Because of the stronger overlap of the $(n-2, l-2)$ atomic wavefunction with the nucleus, absorption of the hadron from this state results in significant induced absorption from the (n, l) atomic state, so reducing the intensity of the $(n, l) \rightarrow (n-1, l-1)$ X-ray. Leon referred to these exceptional cases as 'ticklish nuclei'. Leon predicted that the effect should be strong in antiprotonic atoms of the molybdenum isotopes and it is these which were studied by Kanert *et al.*

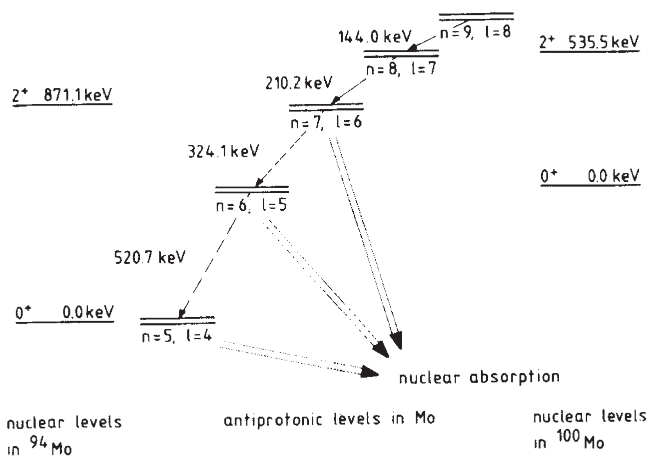

Fig. 1 Nuclear and antiprotonic atom levels in ^{94}Mo and ^{100}Mo. The populations of certain levels diminish rapidly through the absorption of the antiprotons into the nucleus. (From Kanert *et al.*)

Figure 1 shows the nuclear and atomic levels in ^{94}Mo and ^{100}Mo which are relevant to this resonance effect. In the case of ^{94}Mo the spacing between the antiprotonic $(n, l) = (7, 6)$ and $(5, 4)$ levels (844.8 keV) is sufficiently close to the first 2^+ nuclear excitation energy (871.1 keV) to allow mixing of the (7, 6; spin-parity $I^\pi = 0^+$) and (5,4; $I^\pi = 2^+$) atomic-nuclear states. This admixture reduces the $(n = 7) \rightarrow (n = 6)$ X-ray intensity compared with that, for example, in ^{92}Mo where the resonance does not occur. This is precisely what is seen in Fig. 2, where antiprotonic X-ray spectra of five different Mo isotopes measured by Kanert *et al.* are shown. Normalizing the intensity of the $(n = 11) \rightarrow (n = 10)$ X-ray transition, the $7 \rightarrow 6$ transition has a measured intensity of around 11 per cent in ^{94}Mo compared with a value of 40 per cent in ^{92}Mo.

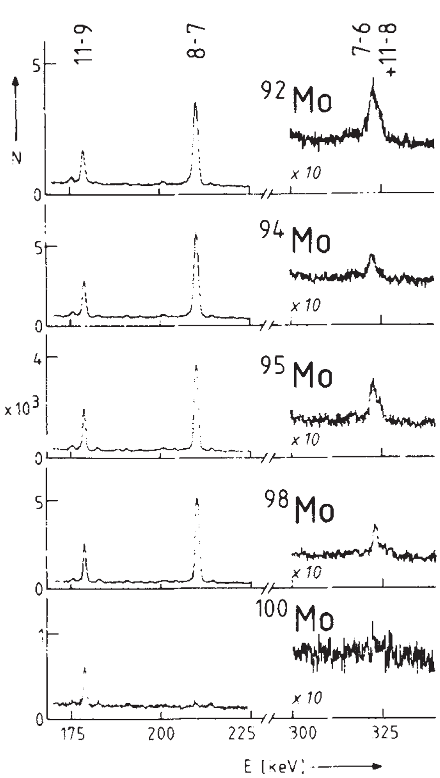

Fig. 2 Antiprotonic atom X-ray spectra for various Mo nuclides: counts per channel (N) versus energy (E). (From Kanert *et al.*)

The effect is seen even more dramatically in ^{100}Mo. Here the spacing between the (8, 7) and (6, 5) atomic levels (534.3 keV) is so close to the first 2^+ nuclear excitation energy (535.5 keV) that there is a very strong coupling between the (8, 7; 0^+) and (6, 5; 2^+) atomic-nuclear states. As a result the $8 \rightarrow 7$ X-ray transition is strongly attenuated (Fig. 2) with an intensity of around 5 per cent in ^{100}Mo compared with 122 per cent in ^{98}Mo where there is no resonance.

Why are these results of particular interest? First, the unique and predicted strong coupling in antiprotonic ^{100}Mo has been observed for the first time; indeed the coupling is so strong that the $9 \rightarrow 8$ X-ray line is also broadened and this too is observed experimentally. Second, in the case of ^{94}Mo the $(n = 5, l = 4)$ level is normally hidden by the very strong absorption from the (6, 5) level that prevents direct X-ray transitions to the (5, 4) level from being seen. This experiment provides information about the characteristics of the (5, 4) level and gives an important test of models of strong interaction effects in antiprotonic atoms. □

C.J. Batty is at the Rutherford Appleton Laboratory, Chilton, Didcot, Oxford OX11 0QX, UK.