Remarks on the Present Status of the Problem of the X-Ray Deficiency in μ-Mesonic Atoms

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The K and L x-ray yields from μ-mesonic atoms were recently remeasured by the Chicago group. These results show better agreement with the theoretical predictions than previous measurements, but some discrepancy still persists. It is shown that the problem really reduces to a striking incompatibility between the observed high K_α and low L yields in low Z elements (carbon to oxygen). Furthermore, one can show, with the help of theoretical and experimental arguments, that the Auger effect cannot make up for this difference. The crucial problem is, therefore: How is the $2p$ state in carbon and other light elements populated?

SINCE the problem of the "missing x rays" in the low-energy region (mainly light elements) has recently received much attention[1–7] and since it may have also some importance in the K^--mesonic x ray yields,[8] it seems to be worthwhile to make a few comments on this subject.

Recently, the Chicago group[9] has repeated the old experiment of Stearns and Stearns[10] and has measured again the μ-mesonic x ray yields in the light elements. A comparison between the experimental results of the Chicago group[9] and our detailed cascade calculation[6] of the μ-meson capture process is shown in Fig. 1. In the same figure, we present also the old experimental results of reference 10 (the errors on each point, which are about 10%, are omitted). The absolute yields of reference 10 are normalized to cascade C^{IV} at ^{8}O (K lines) and ^{14}Si (L lines) where C^{IV} is the "modified statistical" distribution (see reference 6).

The main motivation for repeating the Stearns experiment was the suspicion that in the old experiment the loss of soft quanta was responsible for the discrepancy between theory and experiment. Thus, special care was taken in order to assure 100% efficiency in the detection of quanta of all energies.[9] Indeed, the absolute x-ray yields (number of quanta per stopping meson) observed by the Chicago group, in the region where discrepancy between experiment and theory[7] occurred previously, are significantly higher than those of Stearns and Stearns.[10] However, in the light elements (see Fig. 1), namely, in the K lines of Li and L lines of C, N, and O (the quantum energy for all of these lines is below 40 keV), a significant discrepancy between theory and experiment is still present.

It is remarked in reference 9 that perhaps a different initial meson distribution, similar to the one proposed recently by Mann and Rose,[11] could explain the discrepancy. This question has been discussed by us in detail.[6,7] We have tried several initial distributions, for both μ mesons[6] and π mesons,[7] and it was shown that only cascade C^{IV} [where the initial population of the $n=14$ level is proportional to $(2l+1)e^{al}$, with $a=0.2$] reproduced the experimental results satisfactorily. It gives agreement with the absolute yields above the discrepancy region and with the relative yields (K_α/all K and L_α/all L) for practically all the elements which were studied. This can also be seen from Fig. 1, where we give, for comparison, the results of C^{III} [statistical $\sim(2l+1)$ distribution] and C^{II} (homogeneous distribution at $n=14$). Unfortunately, the measured relative yields are not precise and one cannot say whether the specific shape predicted by the theory is indeed observed. Some recent accurate measurements[12] of the ratio K_α/all K in the region of heavier elements (see Fig. 1) agree very well with our cascade C^{IV} calculations and disagree with C^{III} and C^{II}. The results of cascade calculations based upon the initial capture distribution suggested by Mann and Rose[11] (Δ in Fig. 1) also disagree with the experimental data (this distribution was criticized on theoretical grounds by Day *et al.*[13]).

Finally, we would like to point out that there is a serious inconsistency among the following 3 pieces of experimental evidence: the low yield of Auger electrons associated with μ captures[14] in C, N, and O, and the observed[9] x-ray yields of the K and L lines in the same elements. That this paradox has nothing to do with the

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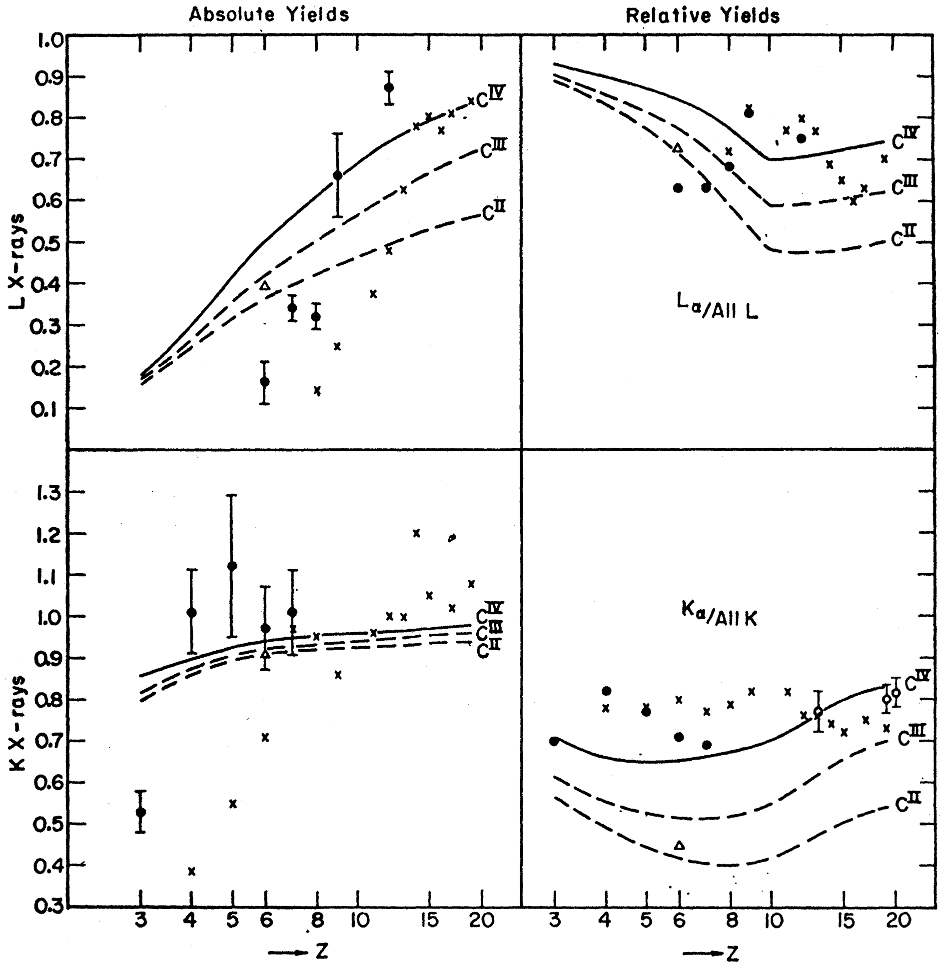

FIG. 1. Absolute and relative yields of x rays in μ-mesonic atoms. The broken and full lines are our cascade calculations with initial distributions C^{II}, C^{III}, and C^{IV} (see text and reference 6). The triangle is the result of a calculation done with the help of the initial distribution of Mann and Rose (reference 11). The black dots are the experimental results of the Chicago group (reference 9) and the crosses the older measurements of Stearns and Stearns (reference 10).

assumed initial meson population can be best demonstrated by the following example. For 1000 μ^- mesons stopped in carbon, for instance, the Chicago group has observed 690 K_α x rays, so that 690 muons must have reached the $2p$ state. On the other hand, in the same experiment, the total L yield in carbon was determined to be only 16%. Now, according to our calculations,[6] about 6% of all muons pass through the $2s$ state. Even if we neglect these and assume that all L x rays are produced by muons which go to $2p$, we arrive at the conclusion that only 160 muons reach the $2p$ state by radiative transitions, so that about 530 mesons must reach this state by radiationless processes. Only Auger transitions from $3s$ and $3d$ can contribute significantly, because the Auger transitions from higher levels into $2p$ have very small branching ratios: the $4s-2p$, $4d-2p$, $5s-2p$, and $5d-2p$ Auger transitions have relative probabilities of 1.5, 2.5, 0.1, and 0.3%, respectively. The ratio of the calculated Auger transition probability to radiation is, for both $3s-2p$ and $3d-2p$, about 27/73. The experiment, on the other hand would require a ratio of 530/160, or about 9 times more than the calculated value. Even if we take into account the experimental errors and assume that the K_α yield was *overestimated* by 10%, and the L yield *underestimated* by 30%, there would still remain a discrepancy of a factor 5.

The above argument shows that it is impossible to construct the cascade backwards, starting from the observed K and L x-ray yields and assuming the calculated radiative and Auger transition rates to be correct. This argument is, therefore, free from any uncertainties about the details of the cascade in the higher levels or the initial population. Similar discrepancies occur also in nitrogen and oxygen.

It seems very hard to put the blame of this paradox on the calculations of the radiative and Auger transition rates, which involve only straightforward quantum electrodynamics. It is true that the predicted Auger yields for particular transitions have not been checked against experiment. However, there is a fair agreement between the theoretical predictions for μ, π, and K mesonic atoms[6-8] and experimental observations,[14,15,8] as far as the total Auger yields and energy spectra in

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nuclear emulsions are concerned. Such discrepancies as exist, namely, too low experimental rates of low-energy electrons, can be explained by observational difficulties and besides point in the wrong direction. Therefore, an increase of the Auger rates by almost an order of magnitude would be impossible to reconcile with the experimental facts.

There is another possibility which we have to consider, namely, that a substantial fraction of the muons is captured directly from the continuum into the $2p$ state. Such an explanation is faced by two difficulties. Theoretically, the fraction of all muons which undergo this direct transition from the continuum to $2p$ in carbon (by Auger effect *and* radiation) is, according to Mann and Rose,[11] 0.39%, whereas more than 50.0% would be needed for the Auger contribution alone in order to balance the population of the $2p$ state. From the experimental point of view, we may refer to Pevsner's experiment on Auger electrons emitted by the capture of muons in the light elements of nuclear emulsion. It is true that, strictly speaking, this experiment refers to Auger electrons in the energy range from 30 to 200 keV, whereas the lower limit of the energy of electrons from the transition continuum-$2p$ in carbon is 25 keV. It is, however, estimated, conservatively, that due to the bad energy resolution characteristic of experiments of this type, at least 20% of these electrons should have been counted. Assuming again that the direct transition from continuum to $2p$ takes place in 50% of all captures in carbon and normalizing to the total number of captures in Pevsner's experiment, we arrive at 85 events, as compared to a total number of 2 actually seen.

Let us summarize: The observed K_α and L radiative yields in carbon (and also nitrogen and oxygen) require the $2p$ state to be populated, to a large extent, by radiationless transitions. The required rate disagrees, by about one order of magnitude, with all we know, theoretically and experimentally, about the Auger transitions. Thus, the "missing x ray" problem really reduces to the question: How is the $2p$ state in, for instance, carbon populated? There seems to be no obvious answer to this question. On the other hand, one cannot completely exclude the possibility that, in spite of all the precautions taken, some unknown experimental effect might have reduced the measured L yields.[16] It seems that a clue to the solution of this problem could be obtained from a measurement of the higher x rays in coincidence with K_α.

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