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X-Ray Emission Following Nuclear Reactions

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We have recorded and analyzed spectra of x rays following proton and α-particle bombardment of heavy atoms. The normal K x rays are accompanied by satellite peaks originating from nuclear reactions. The phenomenon is very intense in α-induced reactions and it is correlated with (α, xn) cross sections; in the case of proton bombardment the intensity of the phenomenon is surprisingly weak. It is presumed that the ionization is due to internal conversion of residual γ rays.

The emission of x-rays following proton and α-particle bombardment has long been investigated by many experimenters and a detailed study of the phenomenon was reported by Merzbacher and Lewis,[1] who calculated the cross section by using the plane-wave Born approximation. Another method of calculation was examined by Garcia,[2] who used the impulse approximation and took into account the distortion of the particle in the Coulomb field. The cross section for x-ray production is dependent on the fluorescence yield ω_K which converts ionization into x-ray cross sections, and this factor is sufficiently well known in the case of heavy elements. Comparisons of theory and recent experimental data were reported at different incident energies.[3,4] The theory can predict the cross sections with an accuracy estimated at 20%, and the general trend of the variations is well reproduced. The theory can then be used for extrapolation of known cross sections.

In addtion to the normal K x-ray emission, different phenomena have recently been investigated: isotopic-shift effects,[5] projectile z dependence of the K cross sections,[4] and satellite emissions.[6] Until now very little attention has been paid to the influence of nuclear reactions on the x-ray production; indeed, nuclear cross sections are many orders of magnitude lower than atomic cross sections. This is not the case for the so-called (α, xn) nuclear reactions which were discovered in the past few years. For instance, the reaction $^{197}\mathrm{Au}(\alpha, xn)$ has a total cross section of 1.67 b for 40-MeV α particles while the computed cross section for x-ray production is 2.1 b. The effect of nuclear reactions of this type is to increase the atomic number Z of the target; if an atomic x-ray is emitted after the reaction, it will correspond to the element of atomic number $Z+2$. Experimental evidence for this phenomenon was reported in α[7] and ^{14}N bombardment.[8]

In this work we investigate the production of K x-rays following the bombardment of heavy- and medium-weight elements with light projectiles. Targets of natural elements (Pb, Au, W, Hg, Ba, and Sn) were bombarded at different energies with $^{+}\mathrm{H}_2$, $^{+}\mathrm{H}$, and $^{++}\mathrm{He}$ from the isochronous cyclotron at Grenoble. The K x rays were detected at 90° from the beam with a 5-mm-thick Ge(Li) detector ($\Delta E = 0.7$ keV at 0.1 MeV) especially designed for minimizing the Compton background from high energy γ rays. The spectra were recorded with a 4-k analyzer and processed with a PDP 9 computer. Self-supported targets of natural elements (10 mg/cm^2) were used. The average beam current was limited to 0.1 nA and the measurements were made in very short periods of time. No appreciable residual activity was observed under these conditions.

A set of typical spectra is shown in Fig. 1; it corresponds to the bombardment of Pb and Au with protons and α particles. The 49-MeV pro-

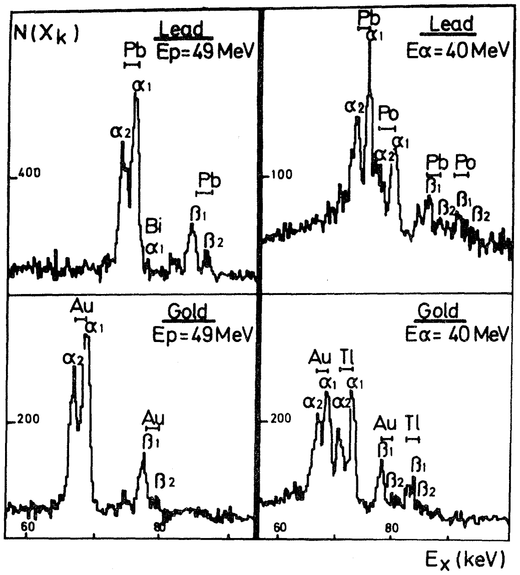

FIG. 1. Comparison between x-ray emission from gold and lead excited by proton and α particles.

ton spectra indicate the presence of normal K x-ray emission, while the spectra recorded during the bombardment of 40-MeV α particles are more complex; the normal K x rays are accompanied by satellites which are identified as characteristic of the element $Z+2$. Even in the case of protons, a very small peak was observed in most spectra; it corresponds to the $K_{\alpha 1}$ x ray from element $Z+1$ (Bi $K_{\alpha 1}$ in the first spectrum of Fig. 1).

Similar observations were made in different atoms; the satellites were present in heavy elements (Pb, W, Hg, etc.) and they were not observable in medium-weight elements such as Ba and Sn. The background is very important; it originates from the Compton effect of γ rays emitted by the target during the bombardment.

In what follows we shall discuss the results obtained with the gold target. The gold nucleus is a pure isotope and the different ^{197}Au(α, xn) cross sections are well known.[9,10] The dominant reactions are strongly dependent on the incident energy; they can be obtained from the data of Ref. 9 and they are given in Table I.

The (α, xn) reaction proceeds mainly by compound-nucleus formation followed by neutron evaporation and γ-ray emission. The average number of γ rays following the α capture and the neutron emission is of the order of 10, so that the rate of production of γ rays is a factor of 10 higher than the (α, xn) cross section itself. In some cases a high-angular-momentum "yrast" level[11] is formed and then a complete rotational band of E_2 transitions is emitted.

The incident particle can also interact with the electron clouds leaving holes in the K shell. Our interest lies in the case where the projectile will give a nuclear reaction. In this case, the signature will be the emission of K x rays from the $Z+2$ atom. We are thus limiting our analysis to the part of the incident beam which has an impact parameter equal to the nuclear radius. If we think in terms of a perturbation theory there are four steps in this experiment: (1) The particle crosses the 1s electron cloud and reaches the nucleus; this distance is of the order of 10^{-10} cm and the average time spent by a 40-MeV α particle will be 5×10^{-20} sec. The perturbation will be essentially a dipole effect,

$$U_1(t) = 2e^2/|\vec{r}_i - \vec{r}(t)|,$$

where $\vec{r}_i$ is the position vector of the ith electron, and $\vec{r}(t)$ is that of the moving projectile. (2) The particle is captured by the nucleus and the sudden change of charge gives rise to a shake-off effect. (3) The excess energy of the nucleus can be transferred to the electrons by internal conversion; the perturbation is then

$$U_2(t) = \sum_j e^2/|\vec{r}_i - \vec{r}_j|,$$

where $\vec{r}_j$ are the coordinates of the $Z+2$ protons. (4) The recoil of the atom may cause the ioniza-

TABLE I. Nuclear cross sections for different ^{197}Au(α, xn) reactions (Ref. 9).

$E\alpha$ (MeV)	Dominant reaction	Cross section of dominant reaction (mb)	Residual nucleus	$\sigma(\alpha, xn)$ total (mb)
30.5	$(\alpha, 2n)$	590	^{199}Tl	803
41.1	$(\alpha, 3n)$	1387	^{198}Tl	1669
49.3	$(\alpha, 4n)$	1290	^{197}Tl	1764

tion of the different shells; the phenomenon is described by the perturbation

$$U(t)=(Z+2)e^2/|\vec{r}_i-\vec{V}t|,$$

where $\vec{V}$ is the speed of the recoil nucleus.

The order of magnitude of each of these different effects is not easy to calculate. Relativistic wave functions should be used in the matrix elements and the lifetime of the compound nucleus is important in the competition between the third and fourth steps. At this stage we are thus restricted to estimations based on experimental evidence.

In order to estimate the cross section for primary K ionization (σ_Z) at 30, 40, and 50 MeV, we have extrapolated the data of Lark[7] by using the Merzbacher theory. The K ionization cross section after nuclear reaction (σ_{Z+2}) is simply obtained from the spectra by measuring the relative intensity of the satellite. The value obtained for σ_{Z+2} is affected by an error of 30% (mostly systematic). In Table II we have reported the magnitude of σ_Z and σ_{Z+2} computed for gold; the value of $\sigma(\alpha, xn)$ is given for comparison and the errors on the later are estimated at 25%. It is seen that σ_{Z+2} and $\sigma(\alpha,xn)$ are not significantly different if we take into account the experimental and systematic errors noted above; the ionization percentage is thus very important when a nuclear reaction occurs.

Spectra resulting from Hg, Pb, and W bombardment were also analyzed, and the conclusions are similar to those discovered in the case of gold. The satellite peaks were also observed in the rare earths but they are much weaker; in the case of Ba and Sn bombarded with 40- and 49-MeV α particles, they completely disappear. Of course, the ratio $\sigma(\alpha,xn)/\sigma_Z$ decreases rapidly with Z and the satellites become difficult to observe in light nuclei because of the background due to bremsstrahlung.

In order to discuss the intensity of the first and second ionization processes, we can compare the phenomenon with natural α emission. The cross section must be of the same order of magnitude since the perturbation matrix elements differ only by the magnitude of the speed, V (a factor of 3), and by the initial wave function [$\Psi_{1s}(Z)$ instead of $\Psi_{1s}(Z+2)$]. In the case of ^{210}Po the K-shell ionization probability is only 2.1×10^{-6}.[12] This is many orders of magnitude lower than the observed effect, and we shall thus ignore the first and second processes in our conclusions. The same considerations are also valid for the fourth effect which is also present in α emission. The third process (internal conversion) seems thus to be responsible for the strong ionization observed. Indeed the internal conversion must be very intense because of the high number of γ rays emitted and the high value of the K-conversion coefficients in heavy elements.

TABLE II. Comparison of nuclear and K ionization cross sections for gold bombarded with α particles.

E_α (MeV)	σ_Z	σ_{Z+2}	$\sigma(\alpha,xn)$
30	0.7	0.4	0.8
40	1.5	1.3	1.67
50	2.5	1.75	1.76

It is important to notice that we did not observe x rays from the element $Z+1$ in the case of α bombardment. This is in accordance with the fact that the (α,xnp) cross sections are an order of magnitude lower than the (α,xn) cross sections.

In the case of proton bombardment, the cross section σ_{Z+1} is very low and difficult to estimate. This is partly because of the higher normal emission rate (a factor of 3 on gold) and partly because of the lower nuclear cross sections (roughly a factor of 2), but this is not sufficient to explain the weakness of the cross section σ_{Z+1}. A possible explanation is that because the proton is carrying less angular momentum, the nature of the compound nucleus is different than in the α capture; the conversion coefficients are very sensitive to the order of multipolarity and energy of γ transitions.

In conclusion, very important satellite peaks were observed in K x ray spectra following α-particle bombardment of heavy elements. It is supposed that they originate from (α,xn) nuclear reactions and that the ionization is due to internal conversion. The cross sections σ_{Z+2} and $\sigma(\alpha,xn)$ are found to be of the same order of magnitude, indicating that the ionization is nearly total. It is then possible to obtain the cross sections for (α,xn) reactions by a simple x-ray measurement; this is particularly important when the residual nuclear is stable and thus impossible to detect by residual radioactivity. The method is presumably applicable to heavy-ion reactions such as $(^{14}\mathrm{N},xn)$, and we have already observed satellite x rays from the bombardment of holmium with 94-MeV ^{14}N ions. In the case of protons the phenomenon is very weak; more data on (p,xn) reactions are needed before explaining this observation.

The production of $Z+2$ Kx rays resulting from ionization before nuclear reaction is a process which is restricted to impact parameters of the order of the nuclear radius; physically, the experiment is equivalent to a collimated beam of a radius of 10^{-12} cm. The ionization could be calculated using relativistic[13] wave functions, and anisotropy in the angular distribution of emitted x rays could be predicted and then measured.

More data on nuclear reactions and ionization cross sections are needed to explore this phenomenon in more detail. However, it has immediate practical consequences in γ-ray spectroscopy, and in sample analysis by fluorescence excited with charged particles, where it is a source of interferences.

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New Spectroscopic Measurements via Exotic Nuclear Rearrangement: The Reaction ^{26}Mg(^{7}Li, ^{8}B)^{25}Ne†

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A 79-MeV ^{7}Li beam and counter-telescope techniques were employed to observe the reaction ^{26}Mg(^{7}Li, ^{8}B)^{25}Ne. The cross section to the ground state was ~ 350 nb/sr at forward angles and its Q value was -22.05 ± 0.10 MeV, corresponding to a ^{25}Ne mass excess of -2.18 ± 0.10 MeV. Five excited states were also observed at 1.65 ± 0.05, 2.03 ± 0.05, 3.25 ± 0.08, 4.05 ± 0.08, and 4.7 ± 0.1 MeV.

Although all of the $T_z = \frac{1}{2}(N-Z) = \frac{5}{2}$ nuclei from ^{11}Li to ^{35}P (except ^{13}Be) are known to be particle stable, many of their masses are not yet accurately known and no data on the positions of their excited states are available.[1] Knowledge of their masses and energy levels is important because it permits the testing of systematic mass relations and the comparison of experimental with theoretical level schemes for nuclei in a region far from stability. Spectroscopic information on such neutron-excess nuclei has been difficult to obtain via "in-beam" reactions since a large isospin transfer is required in the production process. Unusual heavy-ion rearrangement reactions may then be an excellent means of overcoming this restriction. In this spirit, we have investigated the feasibility of using the (^{7}Li, ^{8}B) reaction ($|\Delta T_z| = \frac{3}{2}$) as a prototype for such studies.

By bombarding ^{26}Mg with a 79-MeV ^{7}Li^{2+} beam from the Lawrence Berkeley Laboratory 88-in. cyclotron, we have successfully detected ^{8}B nuclei from the ^{26}Mg(^{7}Li, ^{8}B)^{25}Ne reaction ($Q = \sim -22$ MeV), determining the mass of ^{25}Ne and, for the first time, the level structure of a $T_z = \frac{5}{2}$ nucleus in the very light elements. Reactions yielding ^{8}B nuclei are particularly suitable for the study of neutron-excess isotopes for several reasons. Proton-rich ^{8}B is the lightest, particle-stable $T_z = -1$ nuclide and the fact that both ^{7}B and ^{9}B are proton-unbound simplifies its identification. Further, since all excited states of ^{8}B undergo particle decay, any possible "shadow" problems are eliminated.

This reaction was studied utilizing a lithium