THE (γ, p) AND (γ, n) REACTIONS IN MOLYBDENUM*

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Measurements have been made of the cross sections for some of the (γ, p) and (γ, n) reactions in molybdenum using the technique of residual activation analysis. The gross structure of these cross sections is compared with previous measurements and the results are interpreted as evidence for the isospin splitting of the giant dipole resonance in medium weight nuclei.

The results of the present work are shown in Figure 1 together with other measurements (Duffield, Hsiao, and Sloth 1950; Ferrero *et al.* 1957; Mutsuro *et al.* 1959; Costa *et al.* 1965). No special effort was taken in the present experiment to define the peak positions accurately and the results from other laboratories which are shown in these figures have been adjusted in energy and (with the exception of the ^{100}Mo (γ, p) cross section) normalized to the peak cross sections measured in the present work.

Fallieros, Goulard, and Venter (1965) and Morinaga (1965) have suggested that the observed appearance of the peak in the (γ, p) cross section at a higher energy than that of the (γ, n) cross section in medium and heavy nuclei arises from an isospin splitting of the giant dipole resonance. This interpretation has been applied to recent measurements for zirconium (Fallieros, Goulard, and Venter 1965; Balashov and Yadrovsky 1966; Berman *et al.* 1967). Owing to the action of the isospin selection rules and the Coulomb barrier, it is expected in the simple picture of isospin splitting of the dipole states that the T-lower ($T_<$) states should decay by neutron emission and the T-upper ($T_>$) states by proton emission, thus leading to (γ, n) and (γ, p) cross sections with single resonances peaked at about 15 and 20 MeV respectively. Macfarlane (1966) shows that when the (γ, p) reaction is identified with the photo-absorption to the higher ($T_>$) dipole states and the neutrons are emitted entirely from the decay of the lower ($T_<$) dipole states the expected ratio of the two cross sections is $(T_> - T_<)/T_<$.

The molybdenum (γ, n) and (γ, p) cross sections as shown in Figure 1 indeed show the main resonances to lie at the energies predicted by the isospin splitting theory. To compare the ratio of the experimental (γ, p) and (γ, n) cross sections with the theoretical prediction, the results shown in Figures 1(b) and 1(c) can be used to determine the integrated cross sections for the (γ, n) and (γ, p) reactions in ^{100}Mo. The cross section shown in Figure 1(b) is the sum of the ^{100}Mo (γ, n) and (γ, p) reactions; the measurement of the cross section for the (γ, n) reaction by Duffield, Hsiao, and

* Manuscript received July 15, 1968.

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Sloth (1950) suggests that the cross section above about 18 MeV arises entirely from the (γ, p) reaction. Making this assumption the integrated cross section for the ^{100}Mo (γ, n) reaction is found to be 1000 MeV mb and from the results of Ferrero *et al.* (1957) shown in Figure 1(*c*) the integrated cross section for the ^{100}Mo (γ, p) reaction is 100 MeV mb, so that the ratio of the photoproton to photoneutron cross section is 10%. Since for ^{100}Mo $T_{>} = 9$ and $T_{<} = 8$, the above theory would predict a ratio of the two cross sections of 12·5%, which is in fair agreement with the experimental result.

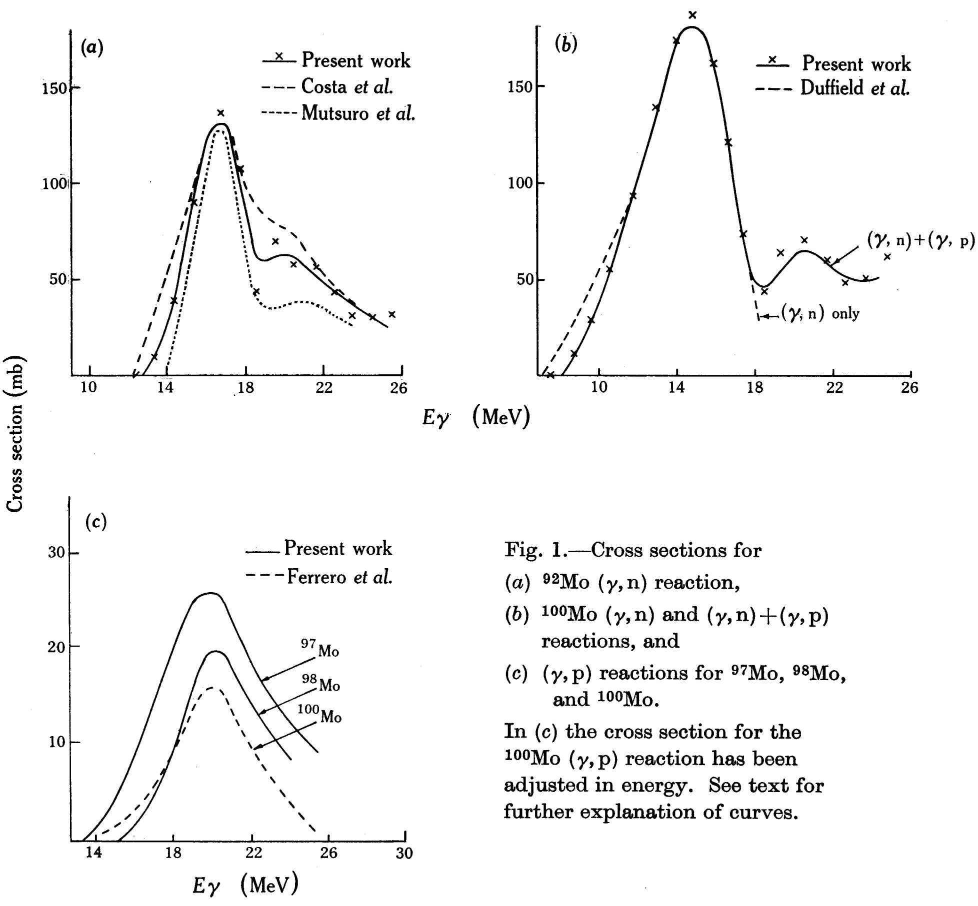

Fig. 1.—Cross sections for
(*a*) ^{92}Mo (γ, n) reaction,
(*b*) ^{100}Mo (γ, n) and $(\gamma, n)+(\gamma, p)$ reactions, and
(*c*) (γ, p) reactions for ^{97}Mo, ^{98}Mo, and ^{100}Mo.
In (*c*) the cross section for the ^{100}Mo (γ, p) reaction has been adjusted in energy. See text for further explanation of curves.

The simple picture of isospin splitting of the giant dipole states seems to successfully predict some of the important features of the cross sections; however, as shown in Figure 1(*a*), the ^{92}Mo (γ, n) cross section has a subsidiary peak in the region of 22 MeV (i.e. at the same energy as the peak in the (γ, p) cross sections). This peak appears not only in the present work but is seen also in the previous measurements shown in Figure 1(*a*).

Three possible reasons have been suggested (Spicer 1968) for the appearance of a peak in the (γ, n) cross section in the energy region of the (γ, p) giant resonance. Firstly, it could arise from isospin mixing in the dipole states, which would allow decay by neutron emission of the higher dipole state ($T_{>} = 5$ for ^{92}Mo), through its $T_{<} = 4$ impurity, to low lying states of ^{91}Mo. A second explanation is that the 22 MeV peak in the ^{92}Mo (γ, n) cross section is a component of the electric quadrupole giant resonance. The third possible explanation is that the ^{92}Mo (γ, n) reaction may proceed through the upper dipole states leaving the residual nucleus ^{91}Mo in its higher excited state; in particular those states that have $T = \frac{9}{2}$ for which the process is not forbidden by the isospin selection rules.

The measured (γ, p) and (γ, n) cross sections indicate that the maximum of the subsidiary peak in the (γ, n) cross section and the peak value of the (γ, p) cross section are approximately the same. It would thus appear that, if the observed cross section in the subsidiary peak of the (γ, n) reaction were attributed to neutron emission from the upper dipole states to low lying states of ^{91}Mo, essentially complete mixing of the isospin states would be required; or, in other words, that isospin is not a good quantum number for the dipole states. Also, measurements of the angular distributions of photoprotons from the ^{92}Mo (γ, p) reaction by Butler and Almy (1953) using 22·5 MeV bremsstrahlung showed that the protons were strongly anisotropic at all energies with a symmetry of the angular distribution about 90°, indicating that the photo-absorption in this energy region is electric dipole in character.

This evidence seems to rule out the first two possible mechanisms and it remains to examine the suggestion that the upper dipole states of ^{92}Mo decay by neutron emission to $T = \frac{9}{2}$ states in ^{91}Mo.

Costa *et al.* (1965) have measured the ^{92}Mo (γ, n) reaction leading to the isomeric state in ^{91}Mo. Their results show that although about 30% of the (γ, n) yield in the energy region between 15 and 20 MeV does not lead to the isomeric state, almost all the (γ, n) decay in the peak near 22 MeV leads to ^{91}Mo^{m}. This indicates that the neutron emission from photon absorption in the region of the main peak leads to different states in the residual nucleus than the decay corresponding to the subsidiary peak. Further, the measurement of the ^{100}Mo (γ, n) cross section by Duffield, Hsiao, and Sloth (1950), shown in Figure 1(*b*), indicates that there is no secondary photoneutron resonance in the case of the ^{100}Mo isotope in the region near 22 MeV. Calculation of the energies involved shows that, whereas there is energy available for decay of the ^{92}Mo dipole states by neutron emission to $T = \frac{9}{2}$ states in ^{91}Mo, this process is certainly not energetically possible for ^{100}Mo decay to the $T = \frac{17}{2}$ states of ^{99}Mo.

It is concluded that the isospin splitting of the giant dipole resonance states is observed in the photodisintegration of molybdenum and that the subsidiary photoneutron resonance in the ^{92}Mo (γ, n) reaction arises from decay by neutron emission of the upper dipole states in ^{92}Mo to $T = \frac{9}{2}$ states in ^{91}Mo. Further experiments with this element and in particular an investigation of the energy spectra for neutrons emitted from the (γ, n) reactions in ^{92}Mo and ^{100}Mo could provide valuable evidence to test these conclusions.

Financial assistance from a CSIRO Post-graduate Studentship held during the course of this work is gratefully acknowledged.

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