Photo-Effects in Middle-Weight Nuclei

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The statistical model is applied to (γ,p) and (γ,n) processes induced by Li γ-rays. It is shown that the assumption of a particular regularity for the residual nuclear states that can arise from the compound nucleus gives results that are in good agreement with recent experiments by Hirzel and Wäffler.

THE results of relative measurements of the total cross sections for (γ,p) processes induced by Li γ-rays (17.3 Mev) in several light- and middle-weight nuclei have recently been reported by Hirzel and Wäffler.[1] Although their experimental technique was not adapted to the measurement of (γ,p) and (γ,n) processes for the same parent nucleus, they were able to estimate the cross-section ratio $\sigma(\gamma,p)/\sigma(\gamma,n)$ by interpolation of $\sigma(\gamma,n)$ values for neighboring isotopes. For light nuclei (Mg, Al, Si) they found that the cross sections fluctuate considerably and that the ratios are of order unity. For middle-weight nuclei ($Z=30$ to 50) the fluctuations become less pronounced as Z increases, and the cross-section ratios show a general decrease from about 0.05 at $Z=30$ to about 0.02 at $Z=50$.

The observed ratios are 100 to 1000 times larger than those obtained from a straightforward application of the statistical theory of nuclei,[2] which should provide an adequate description in the range of Z from 30 to 50. The small values of the theoretical ratio arise from a combination of two factors. 1. The Coulomb potential barrier surrounding the compound nucleus formed by absorption of a γ-quantum makes the escape of a proton less probable than the escape of a neutron with the same energy. 2. The rapid increase in the density of energy levels of the two residual nuclei with increasing excitation energy favors the emission of low energy protons and neutrons, for which the barrier effect is most pronounced. It is apparent that any theoretical consideration that increases the number of high energy nucleons that are available for emission also increases the cross-section ratio, and thus reduces the discrepancy between theory and experiment.

It might seem at first that the direct absorption of a quantum by a single proton would give a sufficient number of high energy protons to account for the experimental cross-section ratio.[3] The computed cross section for electric dipole transitions of this type is of the observed order of magnitude if the absorbing proton is weakly coupled to the other nucleons, as is the case with an electron in the corresponding atomic situation. Actually, however, the coupling between particles in a nucleus is so strong that the initial and final wave functions of the other nucleons are different, and the dipole matrix element for a single proton is reduced considerably. This effect accounts for the suppression of dipole with respect to quadrupole transitions in nuclei. Strong coupling implies that radiative transitions involve the nucleus as a whole (liquid drop model), so that the small separation of nuclear charge and mass centers results in small dipole matrix elements.

An alternative explanation of the experimental results, which seems more likely to represent the quite complex processes that actually take place, is based on the statistical model but takes account of the difference in character of the compound nuclei formed by fast nucleon impact and by absorption of a γ-quantum. In the first case the kinetic and binding energy of the incident nucleon is rapidly shared among all particles of the nucleus because of the strong coupling between each particle and its neighbors. This results in a compound nucleus whose state is a superposition of many modes of oscillation of the

[1] O. Hirzel and H. Wäffler, Helv. Phys. Acta **20**, 374 (1947); the writer is indebted to Professor H. H. Staub for informing him of these results prior to publication.

[2] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472, 935 (1940).

[3] V. F. Weisskopf, private communication.

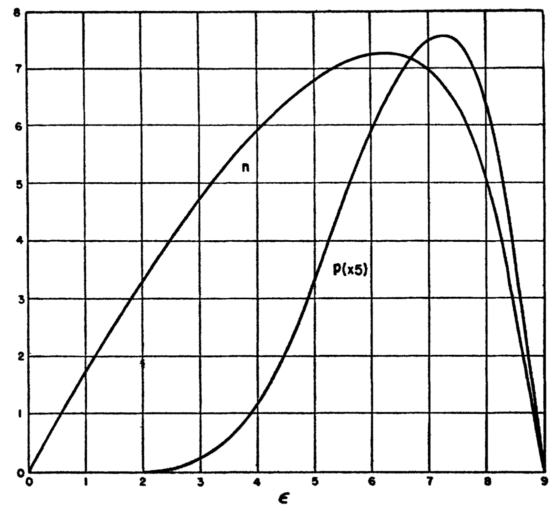

FIG. 1. Relative energy distributions for protons and neutrons when $Z=30$; the ordinates of the proton curve have been multiplied by 5.

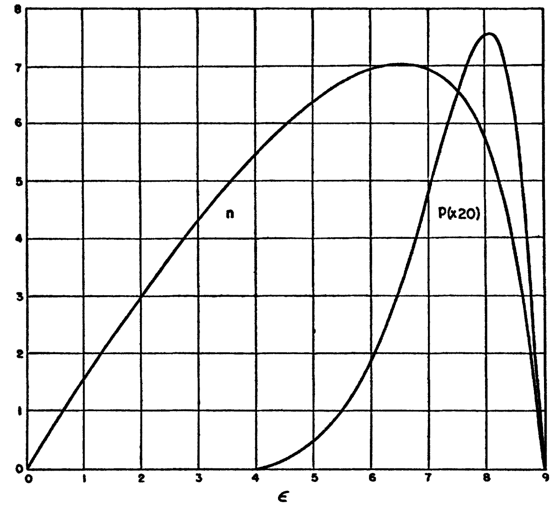

FIG. 2. Relative energy distributions for protons and neutrons when $Z=50$; the ordinates of the proton curve have been multiplied by 20.

nucleus as a whole. In the second case, the electromagnetic field of the incident radiation varies slowly over the nucleus ($\lambda\!\!\!^{-}=11\times10^{-13}$ cm for the Li γ-ray), so that all of the protons are acted on by similar forces. This results in a compound nucleus that can be described by a very small number of modes of oscillation.

The high degree of regularity of the compound states formed by γ-ray absorption will be reflected to some extent in the states of the residual nuclei that result from the subsequent emission of a proton or a neutron. This can be seen from a consideration of the reverse process, in which a proton or neutron is absorbed by the residual nucleus to form the compound nucleus. It is clear that only a small fraction of all possible states of the residual nucleus in a given energy range can absorb a proton or a neutron to form such a compound state. If then the density of *regular* energy levels of the residual nuclei (those levels that can result from the compound state by proton or neutron emission) increases less rapidly with increasing excitation energy than the density of all energy levels, relatively more high energy nucleons will be emitted.

The regular level density can be estimated on the basis of the statistical model.[4,5] The total level density is assumed to be proportional to $\exp[2(E/a)^{\frac{1}{2}}]$, where E is the excitation energy of the nucleus in Mev and $a\approx 20/A$ Mev for a nucleus of mass number A.[2] This can be shown to be equivalent to the assumption that the frequencies of the modes of oscillation of the nucleus are distributed with constant average spacing a/h.[5] It is plausible to define a regular state as one that can be represented as a superposition of a very small number of modes of oscillation. In particular, if only one mode contributes to each regular level, a simple expression for the regular level density can be obtained. For this purpose, the mode frequencies are assumed to be equally spaced, so that the first mode has energy levels (disregarding the zero point energy) a, $2a$, $3a$, $\cdots$, the second mode has energy levels $2a$, $4a$, $6a$, $\cdots$, and the nth mode has energy levels na, $2na$, $3na$, $\cdots$. Then for an interval E to $E+\Delta E$ of excitation energy, where E and ΔE are large in comparison with a, the number of regular levels is approximately

$$\frac{\Delta E}{a}+\frac{\Delta E}{2a}+\cdots=\sum_{n=1}^{E/a}\frac{\Delta E}{na}\cong\frac{\Delta E}{a}\ln\left(\frac{E+a}{a}\right).$$

Thus the regular level density is proportional to $\ln(E/a)$, and increases much less rapidly with increasing E than the total level density. Similar expressions can easily be obtained for other assumptions concerning the total level density.

[4] H. A. Bethe, Phys. Rev. **50**, 332 (1936).
[5] V. F. Weisskopf, Phys. Rev. **52**, 295 (1937).

The ratio $\sigma(\gamma,p)/\sigma(\gamma,n)$ can now be calculated from Eq. (19) of the paper of Weisskopf and Ewing:[2]

$$\sigma(\gamma,p) \propto \int_0^{\epsilon_0} \epsilon S_p(\epsilon)\xi_p \ln\left(\frac{\epsilon_0-\epsilon+a}{a}\right)d\epsilon,$$

$$\sigma(\gamma,n) \propto \int_0^{\epsilon_0} \epsilon S_n(\epsilon)\xi_n \ln\left(\frac{\epsilon_0-\epsilon+a}{a}\right)d\epsilon.$$

The integrands give the relative numbers of protons and neutrons that are emitted with energy ϵ (in Mev), where the maximum energy ϵ_0 is the difference between the γ-ray energy and the binding energy of a nucleon. For the energy range under consideration, the sticking probabilities, ξ_p and ξ_n, are taken to be unity, and the cross section for neutron capture, $S_n(\epsilon)$, is taken to be the nuclear area. The proton capture cross section, $S_p(\epsilon)$, can be found from Fig. 1 of reference 2. The dependence of ϵ_0 and the residual nuclear level densities on the oddness or evenness of Z and A will be ignored here.

The relative energy distributions computed in this way for the emitted protons and neutrons are shown in Fig. 1 for $Z=30$ ($a=0.30$ Mev) and in Fig. 2 for $Z=50$ ($a=0.17$ Mev); it is assumed that $\epsilon_0=9$ Mev. The cross-section ratios can be found from the areas under the curves:

$$\frac{\sigma(\gamma,p)}{\sigma(\gamma,n)}=\begin{cases}0.124, & Z=30,\\ 0.020, & Z=50.\end{cases}$$

These values are in good agreement with the experimental results,[1] but indicate a somewhat more marked dependence of cross-section ratio on Z than is observed. This suggests that the statistical model is inadequate for the smaller group of Z values covered by the experiments, especially since rather large fluctuations are observed there. Experiments on the energy distributions of protons and neutrons emitted by the same compound nucleus would be helpful in clarifying the nature of the processes that take place.

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Note on the Stability of Systems Containing a Light Positive Particle

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It is of interest to consider the dynamic stability of atomic or molecular systems which contain a positron, e.g., e^+Cl^-. This paper examines what information about this stability can be obtained without elaborate calculations, (a) from experimental data descriptive of hydrides and of the hydrogen molecule or molecular ion, and (b) from existing calculations of the energy of light polyelectrons. The procedure (a) suffices to guarantee stability only when the positron is replaced by a positive meson which has a mass of the order of twenty-electron masses or more. The second procedure allows a certain lowering of these approximate minimum mass values, in a special case to a few electron masses. The various numerical results are obtained very easily. They indicate that negative atomic ions can have a positive positron affinity.

I. INTRODUCTION

RECENTLY Wheeler[1] envisaged the existence of short-lived atomic or molecular systems which contain a positron, e.g., e^+Cl^-. At present, even the question of the dynamic stability of such systems remains unanswered.

In a quantitative investigation of this stability the approximate methods of atomic or molecular theory do not seem well adapted. In the first place, the electric charge of the positron has the opposite sign of that of an atomic electron. Secondly, the adiabatic approximation, which is justified in the case of ordinary molecules (Born-Oppenheimer), cannot be expected

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[1] J. A. Wheeler, Ann. N. Y. Acad. Sci. **48**, 219 (1946).