RELATIVE CROSS SECTIONS OF THE (n,p) AND (n,α) REACTIONS ON ELEMENTS WITH SEVERAL STABLE ISOTOPES

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THE available literature data on the cross sections of (n,p) and (n,α) reactions with 14 Mev neutrons are in general not in satisfactory agreement with the theoretical conceptions of these processes. Taking account of this circumstance, and owing to the importance of a correct interpretation of the mechanism of the (n,p) and (n,α) reactions for the explanation of the structure of atomic nuclei, an attempt was undertaken to establish an empirical law for the cross sections of these reactions as functions on the fundamental characteristics of the nucleus, by analysis of the data in the literature and by experiment.

It appears reasonable to expect that some sort of regularity must exist here and that its observation will contribute at least to the systematization of the knowledge of nuclear reactions, and possibly also to their explanation.

Even in a superficial examination of the data in the literature, it is striking that the cross sections for the (n,p) and (n,α) reactions in a series of stable isotopes of one element, decrease as a rule with increasing atomic weight of the isotope. In almost all cases this decrease is by approximately a factor of two. Such a primitive rule contradicts in general the modern ideas about the mechanism of nuclear reactions and, possibly precisely by virtue of its apparent theoretical inconsistency, it has not been taken into consideration.

With the aim of checking this rule and rendering it more precise, a series of experiments were set up to determine the relative cross sections of (n,p) and (n,α) reactions on elements with several stable isotopes, using 14-Mev neutrons. The cross sections were determined by the activation method.

In contrast to the majority of analogous works cited in the literature, the reaction products were analyzed here radiochemically, thus guaranteeing good reliability of the results obtained.

Preliminary results of the first experiments have been communicated earlier.[1] Data on new measurements and revised earlier data are presented below.

1. Relative cross sections of (n,p) reactions were measured for entire series of stable isotopes of nine elements. The following relative cross sections were obtained:

$$\sigma\,\mathrm{Ca}^{42} : \sigma\,\mathrm{Ca}^{44} = 1 : (0.24 \pm 0.02),\quad \sigma\,\mathrm{Ti}^{48} : \sigma\,\mathrm{Ti}^{49} = 1 : (0.55 \pm 0.15),$$
$$\sigma\,\mathrm{Zn}^{64} : \sigma\,\mathrm{Zn}^{66} : \sigma\,\mathrm{Zn}^{67} = 1 : (0.36 \pm 0.02) : (0.23 \pm 0.03),$$
$$\sigma\,\mathrm{Ga}^{69} : \sigma\,\mathrm{Ga}^{71} = 1 : (0.50 \pm 0.05),$$
$$\sigma\,\mathrm{Ge}^{70} : \sigma\,\mathrm{Ge}^{72} : \sigma\,\mathrm{Ge}^{73} : \sigma\,\mathrm{Ge}^{74} = 1 : (0.39 \pm 0.02) : (0.24 \pm 0.02) : (0.13 \pm 0.03),$$
$$\sigma\,\mathrm{Sr}^{86} : \sigma\,\mathrm{Sr}^{88} = 1 : (0.46 \pm 0.04),$$
$$\sigma\,\mathrm{Zr}^{90} : \sigma\,\mathrm{Zr}^{91} : \sigma\,\mathrm{Zr}^{92} : \sigma\,\mathrm{Zr}^{94} = 1 : (0.74 \pm 0.05) : (0.46 \pm 0.04) : (0.20 \pm 0.02),$$
$$\sigma\,\mathrm{Cd}^{106} : \sigma\,\mathrm{Cd}^{111} : \sigma\,\mathrm{Cd}^{112} : \sigma\,\mathrm{Cd}^{113} = (5 \pm 1) : 1 : (0.71 \pm 0.03) : (0.52 \pm 0.02),$$
$$\sigma\,\mathrm{Ce}^{140} : \sigma\,\mathrm{Ce}^{142} = 1 : (0.60 \pm 0.15).$$

The analogous ratios for four pairs of other isotopes, taken from data in the literature,[2,3] are presented below:

$$\sigma\,\mathrm{Mg}^{24} : \sigma\,\mathrm{Mg}^{25} = 1 : (0.23 \pm 0.10),\quad \sigma\,\mathrm{Si}^{28} : \sigma\,\mathrm{Si}^{29} = 1 : (0.46 \pm 0.17),$$
$$\sigma\,\mathrm{S}^{32} : \sigma\,\mathrm{S}^{34} = 1 : (0.23 \pm 0.10),\quad \sigma\,\mathrm{Fe}^{56} : \sigma\,\mathrm{Fe}^{57} = 1 : (\sim 0.5).$$

From the data presented it follows that the cross sections of (n,p) reactions on elements with several stable isotopes decrease sharply with increasing weight of the isotopes, i.e., with decreasing "relative concentration Z/A" of protons in the nucleus. This decrease is monotonic: in all cases the cross section is cut approximately in half upon reduction of Z/A by the equal amount $\Delta(Z/A) = 0.009$. Hence it is natural to suppose that this rule reflects a more general regularity, which relates the probability of emission of a proton from an excited nucleus, $\alpha_p = \Gamma_p/\Sigma\Gamma_i$, with the concentration of protons in the nucleus. An argument in favor of such a supposition is also the fact that similar relations are observed in many cases, at close excitation energies, for the cross sections of (γ, p) reactions[4] and for the quantities Γ_p/Γ_n, calculated by comparison of the cross sections of the (p, pn) and (p, 2n) reactions.[5]

The available experimental data on the absolute cross sections $(\sigma_{n,p})$ of (n,p) reactions and the cross sections (σ_c) for inelastic scattering of 14-Mev neutrons are very incomplete and insufficiently precise for a reliable check of the proposed hypothesis. The qualitative analysis of the data, however, favors this hypothesis, for with few exceptions, the values of $\alpha_p = \sigma_{n,p}/\sigma_c$, estimated from these data, decrease monotonically with decrease of Z/A [more precisely Z/(A + 1)] and the function $\alpha[Z/(A+1)]$ is close to a straight line on a semi-logarithmic scale.

2. Relative cross sections of (n, α) reactions were measured for four pairs of isotopes. The ratios obtained are presented below; the first ratio was calculated from the data of Paul and Clarke:[2]

$$\sigma Cl^{35} : \sigma Cl^{37} = 1 : (0.27 \pm 0.15), \quad \sigma Ge^{72} : \sigma Ge^{74} = 1 : (0.47 \pm 0.04),$$
$$\sigma Rb^{85} : \sigma Rb^{87} = 1 : (0.39 \pm 0.02), \quad \sigma Zr^{94} : \sigma Zr^{96} = 1 : (0.50 \pm 0.05),$$
$$\sigma Cd^{112} : \sigma Cd^{114} = 1 : (0.50 \pm 0.03).$$

As is seen from these data, the cross sections of the (n, α) reactions, like the cross sections of the (n,p) reactions, decrease with increasing weight of the isotope.

3. In the course of the work, several reactions not previously observed were realized, and some new information on radioactive isotopes — the products of these reactions — was obtained:

(a) As a result of the radiochemical study of the products of the reactions Ga (n,p) and Ge (n,α), the existence of the isomer Zn^{71*}, earlier obtained by an (n,γ) reaction from enriched Zn^{70} without chemical identification,[6] was corroborated. The half-life was traced several times in the course of 20 — 25 hours and was found to be 3.92 ± 0.05 hr instead of 3 hr as indicated in Ref. 6. It was found that the isomers Zn^{71*} (3.9 hr) and Zn^{71} (2.3 min) are formed through an (n,p) reaction on Ga^{71} in the ratio 2:3 and through an (n,α) reaction on Ge^{74} in the ratio 1:3. It is interesting that also another pair of isomers of zinc — Zn^{69*} (13.8 hr) and Zn^{69} (52.5 min), is formed with very close ratios (2:4 and 1:1) by the reactions Ga^{69} (n,p) and Ge^{72} (n,α).

(b) As a result of radiochemical analysis of the products of the Ge (n,p) reactions, the existence of the isotope Ga^{74} with T = (8.0 ± 0.5) min (Ref. 7) was confirmed.

(c) The half-life of Br^{84}, which is obtained by the reaction Rb^{87} (n,α), was found to be noticeably different from the value accepted in the literature on the basis of the analysis of bromine activities from fission products [(25.5 ± 0.5) min instead of 31 — 32 min].

(d) As a result of radiochemical analysis of the products of the Zr (n,α) reactions, the existence of Sr^{93} with T = (7 ± 0.5) min was confirmed. By means of absorption measurements, the maximum β-ray energy of Sr^{93} was found to be (3 ± 0.3) Mev.

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