NOTIZEN

Empirical Evidence for Shell Effects in (n,p)- and (n,α)-Reaction Cross Sections Induced by 14 MeV Neutrons

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Cross section values for (n,p)- and (n,α)-reactions have been analysed as functions of the proton and neutron numbers of the target nuclei. When these numbers equal or approach those of a closed shell structure, the cross section values tend to increase. Far from closed shells the cross sections are small.

Introduction

Fast 14 MeV neutrons induce (n,2n)-, (n,p)- and (n,α)-reactions in the whole mass region. Of these types of reactions, the (n,p)- and (n,α)-reactions have been objects of great interest. It can be shown that both reactions have large cross section maxima in the mass-number region $A \sim 30-50$. For both heavier and lighter nuclei the cross sections decrease. In addition to these gross-structure features of the reaction cross section, there still remains the unsolved problem of the possible shell effects affecting the cross sections.

Several workers indicate the existence of shell effects [1–4] for (n,p)- and (n,α)-reactions. Chatterjee [1, 2] examined the (n,α)-reaction cross sections and found cross-section minima at proton shell closure positions of the residual nuclear charge. From the cross-section data available for (n,p)- reactions Chatterjee [3] further concluded the existence of proton shell and subshell effects and pairing effects. Recently, Cuzzocrea, Perillo and Notarrigo [4] made a comprehensive review of the data available on (n,p)- and (n,α)-reaction cross sections. Their analysis of these data shows that the evaporation model can be used to explain the data when shell effects are included in the excitation energy.

Findings contradictory to the above-mentioned observations are also reported [5, 6]. Gardner and Rosenblum [5] re-investigated cross sections for (n,p)-reactions in the Z-region $6 \leqq Z \leqq 50$, but could not find any support for the hypothesis that true shell effects exist. Qaim [6] recently analysed (n,p)- and (n,α)-reaction cross sections as functions of Z_R, i. e. the charge of the residual nuclei. No abrupt changes in the cross sections were observed.

Havlik [7] measured (n,p)-, (n,α)- and (n,2n)-reaction cross sections for several nuclei and found a dependence of $\sigma_{n,p}$ and $\sigma_{n,\alpha}$ [i. e. the cross sections for (n,p)- and (n,α)-reactions respectively] on $(N-Z)^2$ and on the neutron excess as it appears in the term $(N-Z)/A$ or $(N-Z+1)/(A+1)$.

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Recently Angeli et al. [8, 9] made a search for trends in total neutron cross sections. The total neutron cross sections could be approximated by the "black nucleus" formula. It was found out that the ratio of the experimental cross section value to the theoretical prediction had a $A^{1/3}$-dependence. However, a good agreement was noted between the results of the experiments and the theoretical predictions for medium and heavy mass nuclei, and if systematic trends in total neutron cross sections exist, they amount to only a few percents.

The earlier investigations have generally treated cross-section data as functions of either A, Z, N, Z_R or N_R, i. e. the nucleon numbers in the target nucleus and the residual nucleus. Occasionally only the most abundant isotopes are considered.

In our opinion, however, a great deal of information may also be obtainable from the cross section data for less abundant isotopes. We therefore made an empirical survey of all the data on (n,p)- and (n,α)-reaction cross sections. We also plotted the cross sections as functions of Z and N simultaneously.

Results

In the present study we plotted the cross sections of the (n,p)- and (n,α)-reactions as functions of Z and N, i. e. the proton and neutron numbers of the target nucleus. The two operations were carried out simultaneously, and the result is shown in Figure 1. The experimental data were mainly taken from the review of Cuzzocrea et al. [4]. It can be seen from this review that single measurements have fairly large error limits, and that in cases where several measurements of the same cross sections have been performed the results often differ greatly from each other. As compared with the results by Cuzzocrea et al. [4], a few slight modifications have been made in the present study. For ^{43}Ca in the (n,p)-reaction cross section we used the value $\sigma = 101$ mb, obtained as a mean value of the measurements reported [10–12].

The cross section values given by Havlik [7] show good agreement with the mean values reported by Cuzzocrea et al. For the (n,p)-reaction on ^{158}Gd we included the value $\sigma = 2.6 \pm 0.6$, as measured by Havlik. All the values have been plotted in Fig. 1 without error limits.

The gross-structure features of the cross sections are easily distinguishable. Generally the cross sections for (n,p)-reactions are much greater than those for (n,α)-reactions. For both kinds of reactions broad cross section maxima can be observed in the mass region $A \cong 30-60$, corresponding to the maxima reported by Qaim [6]. In Fig. 1 we have further indicated the nucleon numbers 8, 20, 28, 50, 82 and 126 with heavy lines. It can be seen that the cross-section values increase in the vicinity of these lines. In (n,p)-reactions we observe the maximum value $\sigma = 451 \pm 38$ mb for $Z = 20$

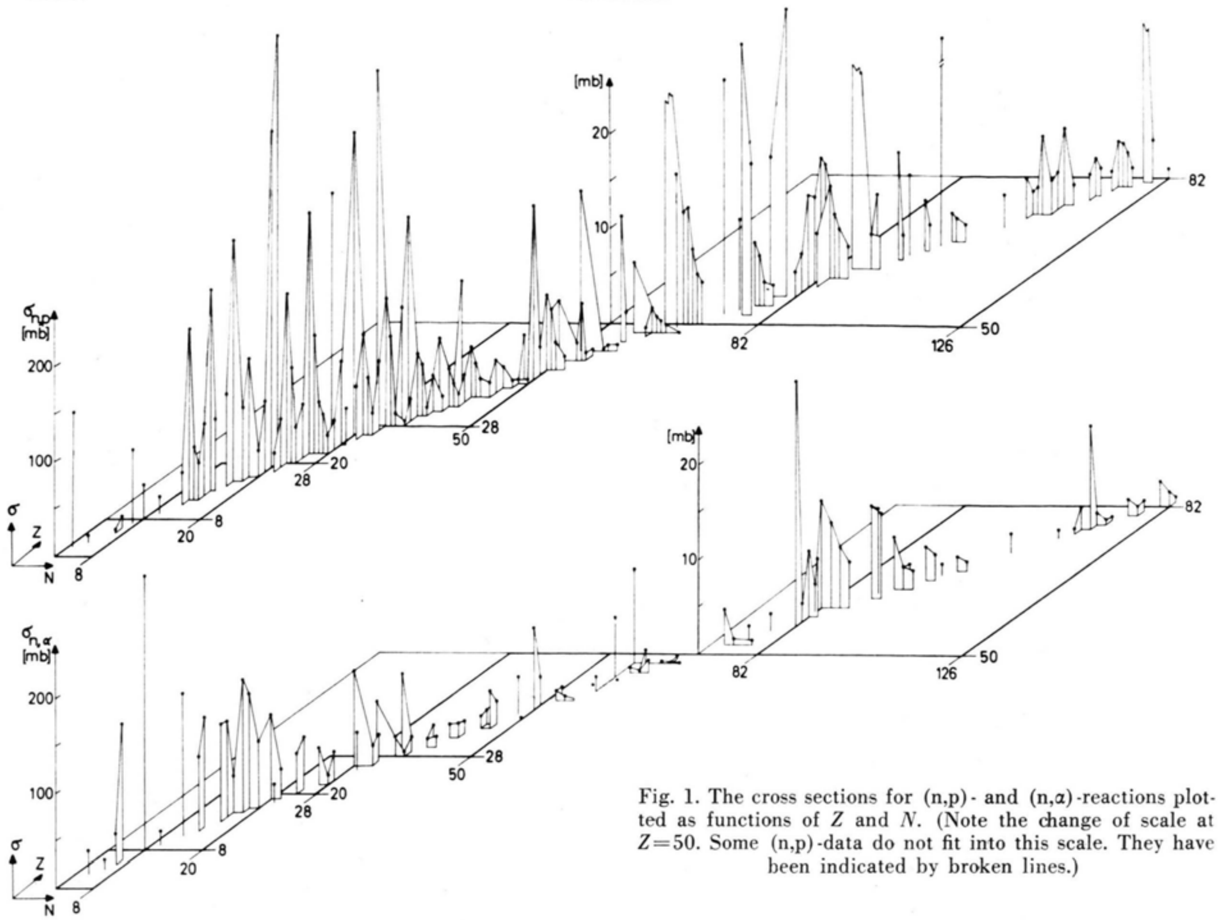

Fig. 1. The cross sections for (n,p)- and (n,α)-reactions plotted as functions of Z and N. (Note the change of scale at $Z=50$. Some (n,p)-data do not fit into this scale. They have been indicated by broken lines.)

and $N=20$, and for ^{58}Ni ($Z=28$, $N=30$) we have the mean value $\sigma=374.7\pm21.7$ mb; both values are higher than the neighbouring values. When $N\cong50$ a rise occurs in the cross section data, and the same phenomenon occurs when $Z\cong50$, $N\cong82$ and $Z\cong82$, $N\cong126$. Between these maxima there is a tendency for smaller values. Generally these occur when the Z, N numbers deviate from the magic numbers. In these regions, however, there also occur a few cross-section values which are not in accordance with the above mentioned rule. Whether these exceptions are true or only due to the statistics of the measurements cannot be stated without further investigations. They do not, however, observe the general trend.

What has been said above of the (n,p)-reactions also applies to the (n,α)-reactions. When Z and/or N of the target nucleus equals or approaches a magic number, there is a rise in the cross section values. This is apparent in the case of ^{16}O with $\sigma=290\pm25$ mb, which is much higher than the neighbouring values. At $Z\cong20$ and $N\cong20$ there is an increase in the σ-values. The same is true of the $Z\cong28$ and $N\cong28$ nuclei. As the nucleon number approaches $Z\cong50$ and 82, and $N\cong50$, 82 and 126, a rise can again be observed in the cross section values. Far from closed proton or neutron shells there is a tendency to minima. This can be seen to happen in the case of nuclei having neutron numbers $28<N<50$ and $50<N<82$. Although there are values which are not in accordance with this rule, they are few and do not completely outrule the above-mentioned statement.

Thus, by analysing simultaneously cross section values for (n,p)- and (n,α)-reactions induced by $\cong$14 MeV neutrons as functions of the proton and neutron numbers of the target nuclei, we have noted the general trend that the cross section values increase as the proton and/or neutron numbers equal or approach closed shells.

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