Correlation of Intermediate Energy Proton- and Neutron-Induced Fission Cross Sections in the Lead-Bismuth Region

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Abstract. Neutron- and proton-induced fission cross-sections of the lead isotopes $^{204,206-208}$Pb and $^{205}$Tl in the intermediate energy region have been measured at the Svedberg Laboratory in Uppsala, Sweden. Average fissions of the composite nuclei and the dependence on the nucleon energy and the parameter $Z^2/A$ were determined. On this basis, the correlation between the proton- and neutron-induced fission cross sections has been established in the atomic mass region $A \sim 200$ and for nucleon energies above 50 MeV, where shell effects do not play a very significant role. The correlation is discussed in the frame of results from calculations by the code TALYS.

INTRODUCTION

A first comparison of the ($p,f$) and ($n,f$) reaction cross-sections (as well as the ($\gamma,f$) reaction cross-section) in the intermediate energy region has been undertaken in this work [1]. In this and succeeding works (see, e.g., [2] and references therein) it was found that at incident nucleon energies of 150-200 MeV the value of the ($p,f$)/($n,f$) reaction cross-section ratio for nuclei from $^{244}$Am to $^{181}$Ta is higher than 1, increases with the decrease of the parameter $Z^2/A$ of the target nucleus, and reaches a value of about 5 and higher. From the beginning, the effect was ascribed to the increase of the charge ($Z$), and therefore of the parameter $Z^2/A$ of the fissioning nucleus by the incident proton [1,3]. However, some works published recently both confirm this explanation [4] and attribute the effect to a possible influence of the isovector term of the nucleon-nucleus optical potential [5].

The present work is devoted to a further experimental and theoretical study of the correlation between proton and neutron cross sections in the lead-bismuth region, which is of great importance for applied and fundamental research.

FISSION CROSS-SECTION MEASUREMENTS AND RESULTS

The neutron- and proton-induced fission cross-sections of $^{204,206-208}$Pb and $^{205}$Tl have been measured at the accelerator of The Svedberg Laboratory, Uppsala, Sweden, at nucleon energies up to 180 MeV [6], with the use of the thin-film breakdown counter (TFBC) technique. The experimental technique and data processing were described in detail in [2,6], and part of the results were presented in [2]. In the present paper all results and the analysis performed using calculations by the code TALYS [7] are under consideration. The results for protons and neutrons are shown in Fig. 1. The experimental errors of our measurements are about 10%. The curves are the best fits calculated using the following expression:

$$\sigma_f(E_n) = P_1 \cdot \exp\left(-\left(P_2 / E_n\right)^{P_3}\right),$$

where $E_n$ is the incident nucleon energy and $P_1$, $P_2$, and $P_3$ are fitting parameters depending on the target nuclide. The presented results for neutrons systematically disagree with some results obtained with the use of other techniques [8].
FIGURE 1. Proton- (left panel) and neutron-induced (right panel) fission cross-sections of nuclei in the lead region. Filled symbols are results of the present work, open symbols are results of other authors. Curves are the best fits.

The possible reason for the disagreement (about 20%) is that systematical errors declared by the authors are too optimistic. Thus, a value of 20% seems to be a more realistic estimation of the uncertainty of the up-to-date experimental results.

FISSILITY AND ITS DEPENDENCE ON NUCLEON ENERGY AND NUCLEON COMPOSITION OF COMPOSITE NUCLEI

To take into account the difference between reaction cross sections for protons and neutrons, the fission cross sections were divided by the corresponding reaction cross sections, and the obtained ratios were considered as the average fissions, \( F = \sigma_f/\sigma_r \), of the nuclei. The reaction cross sections, parameterized in accordance to Barashenkov [8], are shown in Fig. 2.

FIGURE 2. Reaction cross-sections for \(^{208}\text{Pb}\) induced by neutrons and protons in the intermediate energy region.

It is seen that in the energy region 50-200 MeV (the region of lower energies is not considered because of the influence of shell effects) the reaction cross sections for neutrons and protons are close,
though the proton cross section is systematically lower than the neutron one by about 10%. This value does not exceed the experimental errors of the fission cross sections, but from the physics point of view the consideration in terms of fissility looks preferable. In Fig. 3 the dependences of the values $P_f$ on the parameter $Z^2/A$ of composite nuclei for reactions with protons and neutrons are presented for different projectile energies. It is seen from the figure that the dependences are of the same character – the lines in semi-logarithmic scale – the slope of which decreases with the increase of the projectile energy. It means that the $(n,f)$ and $(p,f)$ cross sections (with the accuracy of the factor $\sigma_{np}/\sigma_{nn}$) for the reactions passing through the same composite nuclei have to be of the same magnitude.

In Fig. 4 parameterizations of the fission cross sections are presented for the reactions $^{209}$Bi+n and $^{208}$Pb+p, and $^{206}$Pb+n, $^{208}$Pb+n, and $^{205}$Tl+p. It is seen from the figure that the fission cross section of the $^{209}$Bi+n and $^{208}$Pb+p reactions, passing through similar composite nuclei (with $Z=83$, $A=210$, and $Z=83$, $A=209$, respectively), are close, moreover in the case of $^{209}$Bi+n, corresponding to a value of $A$ which is larger by 1, the fission cross section is somewhat lower. The value, by which the cross section becomes lower, corresponds within the experimental uncertainties to the data shown in Fig. 3. It is seen also that in accordance with the conclusion on fissility the value of the cross section for $^{205}$Tl+p ($Z=82$, $A=206$) lies between the ones for $^{204}$Pb+n ($Z=82$, $A=205$) and $^{206}$Pb+n ($Z=82$, $A=207$). Moreover, one can observe that at low energies the fission cross section of $^{205}$Tl+p resembles the result for $^{206}$Pb+n, while at high energies the $^{205}$Tl+p curve approaches the $^{206}$Pb+n result. This can be explained by the impact of direct and pre-equilibrium processes on the population of the evaporation chain, and hence on the population of the fissioning systems.

**FIGURE 3.** Average fissilities vs. the parameter $Z^2/A$ of the composite nucleus. The lines are parameterizations.

**FIGURE 4.** The $^{208}$Pb(p,f), $^{209}$Bi(n,f), $^{205}$Tl(p,f), and $^{206}$Pb(n,f) cross sections.

**ANALYSIS OF CALCULATIONS PERFORMED WITH THE CODE TALYS**

Experimental results, pointing to an equality of the fissilities in reactions induced by protons and neutrons in the intermediate energy region, similar to the situation at low energies (below 20 MeV) where a compound nucleus is formed with high probability, seem to be unexpected. At incident nucleon energies around 20 MeV, direct processes (intranuclear cascade and preequilibrium emission) start to come into play, preceding a slower fission process. The sharing of nucleons and excitation energy of the target nucleus are taken away during the direct processes. As a result, a wide set of intermediate nuclei with different charges, masses, and excitation energies appears, which, reaching thermal balance, undergo fission, contributing to the fission cross section measured experimentally. The capacity of TALYS allows one to calculate the composition of intermediate equilibrium (compound) nuclei and their individual contributions into the observed fission cross section.

In Fig. 5 dependences of average charge, mass, fissility parameter, $Z^2/A$, and excitation energy of the
fissioning nucleus vs. incident nucleon energy are shown for two of the considered reactions: $^{209}$Bi+n and $^{208}$Pb+p. It is seen that changes with the energy are significant. It is also seen that the changes for both reactions are similar (differences in nucleon composition occur only at the end of the energy region, at $E_{\text{proj}}$ above 150 MeV). This is what leads to the closeness of the cross sections observed experimentally.

![Diagram showing average charge, mass, and parameter $Z^2/A$ vs. projectile energy for $^{209}$Bi+n and $^{208}$Pb+p reactions.](image)

**FIGURE 5.** Average charge, mass, the parameter $Z^2/A$ of the intermediate nuclei vs. projectile energy for the reactions $^{209}$Bi+n and $^{208}$Pb+p calculated by the code TALYS.

### CONCLUSION

Equality of neutron- and proton-induced fission cross sections for composite nuclei, characterized by the same parameter $Z^2/A$, is found within experimental errors. With regard to the calculations performed with TALYS, this fact may be explained by similar changes in the nucleon composition and excitation energy in these two types of reactions, which take place in direct processes preceding fission. It seems to be interesting to compare also other characteristics of fissioning nuclei, for example charge and mass distributions of fission fragments.

### REFERENCES

9. V.S. Barashenkov and V.D. Toneev, “Interaction of high energy particle and nuclei with atomic nuclei,” Atomizdat, Moscow (1972) [in Russian].