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Swelling of Nuclear Fuel in Nuclear Reactors

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Abstract

An attempt was made by inelastic scattering of nucleons on nuclei to elucidate the reasons for the excitation of nuclei in nuclear chain reactions, as well as the deformation of nuclei and the swelling of atoms. The proposed distorted-wave theory of multiple scattering of nucleons by nuclei is applied. When studying the properties of excited nuclei, the connections of the quadrupole vibrations of the nuclear surface with the motion of nucleons by the corresponding dipole and quadrupole giant resonances were taken into account. The energies spent on the excitation of giant dipole and quadrupole resonances with the corresponding energies and excitation widths, as well as on the vibrations of the nuclear surface, are determined. For a certain time, being in an excited state, the nucleus deforms and increases its size and the size of the atom, that is, its swelling.

Keywords: Scattering of Nucleons, Excitation of Nuclei, Swelling of Nuclei and Atoms, Nuclear Reactors, Nuclear Fuel

Introduction

It is known that nuclear fuels are used in nuclear reactors to carry out a controlled chain nuclear fission reaction. For this purpose, the widespread use of metallic uranium as a nuclear fuel, especially at temperatures above 500 ° C, is hampered by its swelling [1]. In a nuclear reaction after nuclear fission, two fission fragments are formed, the total volume of which is greater than the volume of a uranium atom with the simultaneous release of several neutrons, which in turn can cause fission of the next nuclei. Such fission occurs when a neutron enters the nucleus of an atom of the initial substance. Due to the change in the volume of atoms in the process of fission, uranium and other nuclear fuels begin to swell [2-4].

Method

In order to clarify the reason for the excitations of nuclei, on the basis of quantum mechanics, in nuclear chain reactions, as well as the deformation of nuclei and the swelling of atoms, adhering to the well-known Bohr hypothesis about the independence of the decay of a compound nucleus from the method of its formation, we will consider the process of the appearance of highly excited states in target nuclei by scattering of nucleons.

The nature of highly excited states, giant resonances - monopole, dipole, quadruple, octuple and other resonances, which reflect more complex forms of coherent nuclear motion in the cross sections of nuclear reactions, which was explained within the framework of the semi classical hydrodynamic model of nuclei, was based on the concept of a single oscillation frequency of all neutrons nucleus relative to all of its protons in the interaction with the incident nucleon [5].

The nuclear reaction that occurs during inelastic scattering of nucleons of intermediate energies goes through the stage of formation of a “compound nucleus”. The strong interaction between the colliding nucleus and nucleons leads to the fact that very soon after the collision, the incident nucleon transfers a significant part of its energy to other nucleons of the nucleus. As a result of such a redistribution of energy, initially concentrated on one nucleon, not a single nucleon of the nucleus will have sufficient energy to overcome the action of the nuclear forces of attraction and leave the nucleus. This is the reason for the long lifetime of quasistationary states of excited nuclei. After some time, when, due to fluctuations, sufficient energy is concentrated on one of the nucleons (or on several nucleons), the compound nucleus will decay and possibly corresponding to different reaction channels [6].

In order to study this process, we write twice the differential cross section for inelastic scattering of nucleons, taking into account the width of the nuclear excitation energy, in the form of the Breit – Wigner formula [7].

$$\frac{d^2\sigma}{d\Omega dE_f} = \left(\frac{d\sigma}{d\Omega}\right)_{NA} \frac{1}{E_i^{1/2} E_f^{1/2}} \frac{1}{2} \sum_{L=0}^{\infty} \frac{|F_L(q)|^2}{2L+1} \frac{\Gamma_L^2/4}{(E_x - E_L)^2 + \Gamma_L^2/4} \qquad (1)$$

here, E_f and E_f are the kinetic energies of the incident and scattered particles, $\left(\frac{d\sigma}{d\Omega}\right)_{NA}$ is the nucleon-nucleon scattering cross section, in all nucleons of the nucleus. The momentum of the transfer of a nucleon to the nucleus by the target in this case takes the form

$$|\mathbf{q}| = |\mathbf{k}_i - \mathbf{k}_f| = \sqrt{k_i^2 + k_f^2 - 2k_i k_f \cos\vartheta} = \left(\frac{2m}{\hbar^2}\right)^{1/2} \sqrt{E_i + E_f - 2E_i^{1/2} E_f^{1/2} \cos\vartheta} \qquad (2)$$

When studying the emerging giant resonances by inelastic scattering of nucleons, it is necessary to take into account the connection between oscillations of the nuclear surface and the motion of nucleons by the corresponding giant multipole resonances. Analysis of the structure of the low-energy spectra of spherical vibrational nuclei shows that the vibrations of the nuclear surface have a rather large amplitude and almost harmonic surface vibrations of the quadruple type [5]. Moreover, the value is of the order of $1MeV$, while the energies of highly excited states of giant multipole resonances are greater than $15MeV$. This means that at each moment of time, the oscillations corresponding to giant resonances occur, as it were, with a fixed shape of the nuclear surface. Therefore, in the dynamic collective model, it is necessary to take into account the interactions of giant resonance vibrations of nucleons with vibrations of the surface of the nucleus.

Results

The results obtained on the basis of theoretical calculations using the expression of the double differential cross section (1) for nucleons with energy MeV in comparison with the experimental and theoretical data calculated by the Glauber approximation method using the near Fermi gas model are shown in Fig.1.

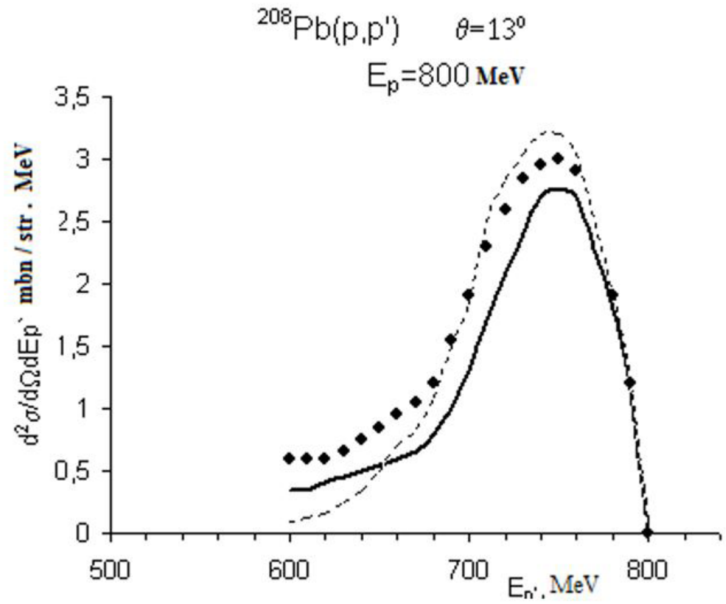

Figure 1: Dependence of the double differential cross section at an incident proton energy of 800*MeV*, the scattering angle for a nucleus on the energy of scattered protons. The solid line is the results obtained, the dots are the experimental data [8] and the dotted line are the results obtained by the Glauber approximation method based on the Fermi gas model [9]

From a comparison of the theoretical double cross section, depending on the energy of scattered protons, with experimental data [8], at the scattering angle, it follows that the energy loss of incident nucleons is ~ 45*MeV*. This energy is spent on the excitation of giant dipole and quadruple resonances with the corresponding energies and excitation widths: $\hbar\Omega_1 = 13{,}18\ MeV$ and $\Gamma_1 = 2{,}3\,MeV$; $\hbar\Omega_2 = 21{,}18\ MeV$ and $\Gamma_2 = 4{,}1\,MeV$, as well as on the vibration of the nuclear surface with energy - $\hbar\omega_2 = 4{,}09\ MeV$ and width $\Gamma_{\lambda=2} = 0{,}23MeV$ [9].

Thus, after determining the excitation energies of giant multipole resonances and the energy losses of scattering protons, one can begin to study the differential cross sections for the scattering angles. The angular dependences of the analyzing power are highly oscillating curves, the shape of which is largely determined by all nuclear parameters.

The differential scattering cross section has the following form [10]:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{NA} \frac{E_f^{1/2}}{E_i^{1/2}} \sum_{L=0}^{\infty} \frac{|F_L(q)|^2}{2L+1} \frac{\Gamma_L^2/4}{(E_x - E_L)^2 + \Gamma_L^2/4} \qquad (3)$$

The obtained results of calculations in dependence of the differential cross section on the angle of scattering of nucleons on the nucleus at 800*MeV* for dipole ($L = 1$) and quadruple ($L = 2$) giant resonances, as well as quadruple ($\lambda = 2$) vibration of the nuclear surface are presented in comparison with experimental data and theoretical calculations obtained in a distorted-wave Born approximation in Fig.2

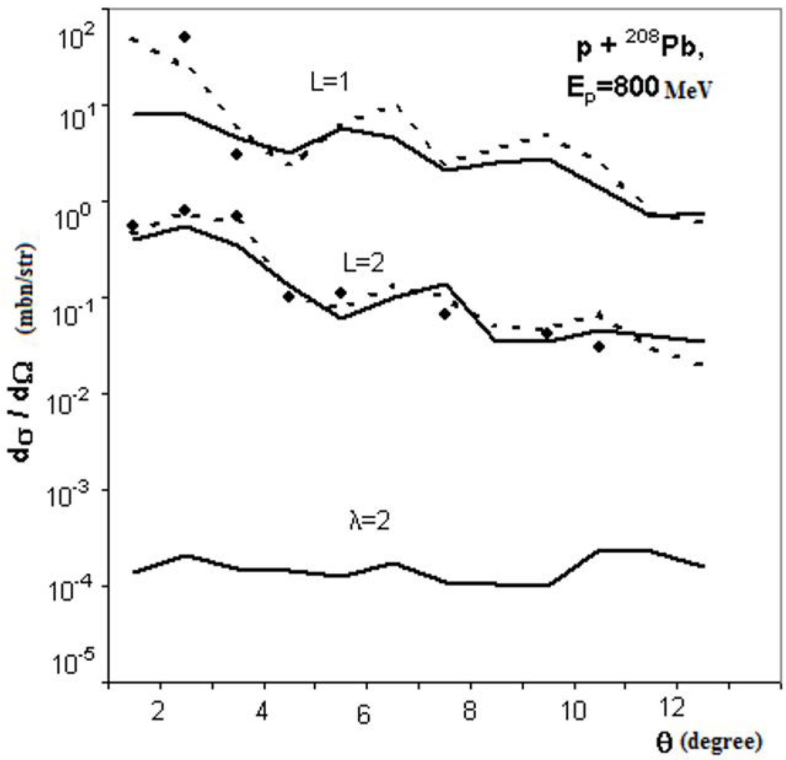

Figure 2: Dependence of the differential cross section on the angle of scattering of protons on the nucleus at $E_i = 800\ MeV$ for dipole $(L = 1)$ and quadruple $(L = 2)$ giant resonances, as well as quadruple $(\lambda = 2)$ vibration of the nuclear surface. The solid line is the results obtained, the dots are the experimental data [8] and the dashed line denotes the results of the work calculated in the distorted-wave Born approximation [12]

The parameter characterizing the root-mean-square deformation of the excited nucleus is determined using the expression

$$\beta = \sqrt{<0\left|\sum_{\mu}\alpha^*_{2\mu}\alpha_{2\mu}\right|0>} = \sqrt{\frac{5\hbar\varpi_2}{2C_2^{vib}}}, \qquad (4)$$

for which, at the value of the stiffness parameter $C_2^{vib} = 224\,MeV$, we have $\beta = 0{,}205$.

Note that due to the lack of experimental work on the scattering of nucleons by radioactive nuclei, the calculations were performed for a lead nucleus.

Discussion

Thus, we can come to the conclusion that the excitation energy is spent on the excitation of giant dipole and quadrupole resonances with the corresponding energies and widths, as well as the surface excitation of the nucleus, which is in excited states for a certain time. At the same time, the core, being deformed, increases its size. This leads to an increase in the size of the atom, that is, its swelling, ultimately, and to the swelling of nuclear fuel.

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