EXCITATION OF MEDIUM NUCLEI IN THE CONTINUUM REGION IN INELASTIC SCATTERING OF DEUTERONS

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Experiments on elastic and inelastic scattering of deuterons by ^{12}C, ^{48}Ti, ^{58,64}Ni nuclei at laboratory energy of $37\,MeV$ for angles ranging from $16°$ to $61°$ were carried out on the U-240 isochronous cyclotron of the Institute for Nuclear Research, National Academy of Science of Ukraine. A broad maximum comprising the giant resonance in the spectrum of scattered deuterons for scattering angles less than $21°$ is observed at the nucleus excitation energies ranging from 12 to $30\,MeV$. The observed maximum was theoretically described in diffraction approximation after summing the cross-section over all final nucleus states.

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1. INTRODUCTION

The continuum in the energy spectrum of practically all multi-nucleon nuclei can be exited by various particles (including complex particles).

The excitation of nucleus states in the region of the giant resonance was discovered in inelastic scattering of helions by medium nuclei not long ago [1]. In the spectra of ^{3}He-particles scattered by ^{58}Ni and ^{64}Ni isotopes, an asymmetrical broad maximum corresponding to the excitation energy $U = 16-20\,MeV$ was observed. In this energy domain, monopole as well as dipole and quadrupole resonances can be excited [2, 3, 4]. With the reference to the analysis carried out in [4], the authors of [1] identify the observed asymmetrical maximum as a manifestation of the monopole and dipole resonances. According to [1, 2], the energy of the giant quadrupole resonance excitation corresponds to $16.3\,MeV$ for ^{58}Ni and $15.8\,MeV$ for ^{64}Ni, whereas the energy of the giant quadrupole resonance excitation – $20.7\,MeV$ for ^{58}Ni and $20.0\,MeV$ for ^{64}Ni. Thus the observed asymmetrical maximum at the excitation energy $U = 16 - 20\,MeV$ apparently corresponds to the excitation of both monopole and quadrupole resonances. According to theoretical estimations [3], an excitation of the giant dipole resonance is quite small.

In order to describe the results of our experiments on measurement of the cross-sections in the continuum domain in the inelastic scattering of deuterons by ^{12}C, ^{48}Ti, $^{58,64}Ni$ nuclei, we used the developed theory of a coherent and non-coherent scattering of particles by nuclei as well as the diffractive nucleus model.

2. EXPERIMENTAL RESULTS

Experimental study of inelastic scattering of deuterons by atomic nuclei was carried out on the isochronous cyclotron U-240 of Institute for Nuclear Research, NAS of Ukraine. A beam of deuterium ions with energy $E_d = 37\,MeV$ was transported to the scattering chamber through the beam collimating system.

Beam collimation was carried out with quadrupole lenses and slit diaphragms. "Cutting-off" diaphragm, located behind shielding wall of experimental box, was used to reduce background scattering. Ion beam quality was checked by TV cameras and residual current measurement from the diaphragms.

The target, detectors and part of electronic modules were placed in scattering chamber. Deuterons were registered by two telescopes $\Delta E - E$, consisting of $\Delta E(Si)$ detector with thickness of $150\,\mu m$ and scintillation E detector with thickness of $25\,mm$. Incident beam current was measured by Faraday cup beyond the target. Remote control and observation of collimating system, detectors and target were carried out from the measurement center.

Inclusive spectra were accumulated as described earlier in [5]. Increase of productivity of spectra accumulation was achieved by use of $512\,K$ memory modules in CAMAC standard.

Local network client with CAMAC crate preformed preprocessing of experimental information and recorded in to the network drive. After that, it became accessible at any point of local network.

In the experiment, targets from carbon, titanium and nickel isotopes were used. To carry out energy

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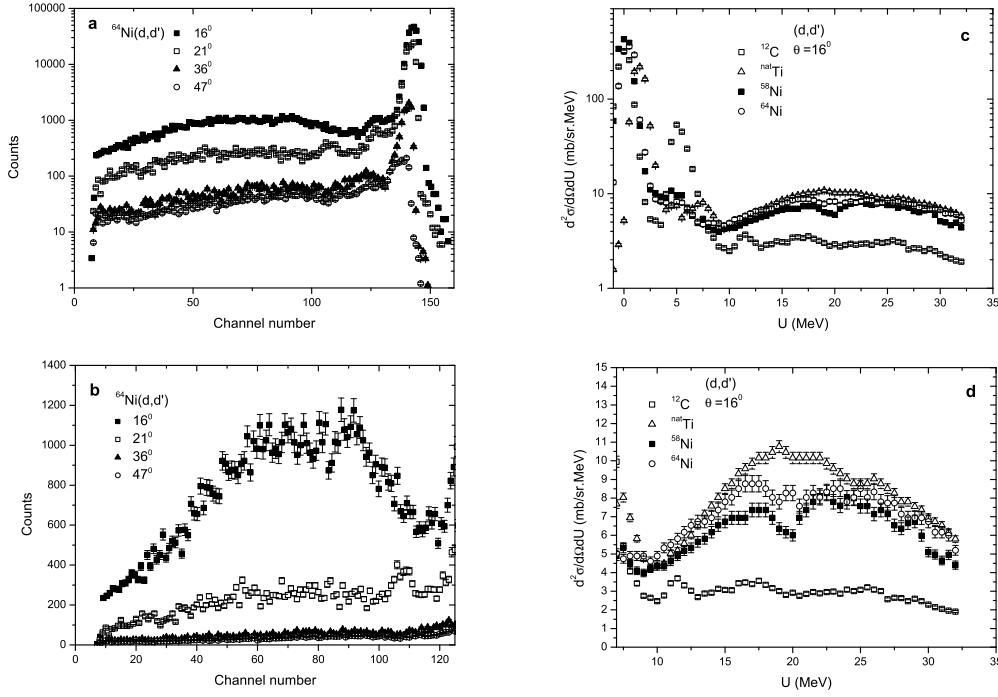*Series:* Nuclear Physics Investigations (48), p.13-17.

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Fig.1. *Experimental data:*
a, b – scattering of deuterons by ^{64}Ni *at 16°, 21°, 36° and 47°;*
c, d – cross-sections of the deuteron scattering by ^{12}C, ^{48}Ti, *and* $^{58,64}Ni$ *at 16°*

calibration, additional measurements on target from polyethylene enriched with deuterium were done. All targets were self-supported foils, thicknesses and enrichment of which are stated in the table.

Target characteristics

Element	Thickness, mg/cm^2	Enrichment, %
^{12}C	4,5	98,9
^{48}Ti	7,48	Nat. (73,8)
^{58}Ni	9,37	99,5
^{64}Ni	8,48	91,0

Inclusive spectra of deuterons on targets ^{12}C, ^{48}Ti, and $^{58,64}Ni$ in wide energy range at scattering angles $16° \leq \theta \leq 61°$ were measured. Statistical error of measurements was 3% for ^{12}C, ^{48}Ti nuclei and 5% – for nickel isotopes. Energy calibration of spectra was carried out by elastic scattering of deuterons, measured on CD_2 target, on deuterium and carbon nuclei.

In Fig.1,a, experimental spectra, obtained on ^{64}Ni nucleus at angles $\theta = 16°, 21°, 36°$ and $47°$ in all energy measurement range are given; and in Fig.1,b – in the range of high excitation energies. Spectra, given in Fig.1, are typical for all investigated nuclei and are characterized by drastic decrease of cross-section in the region of continuum with increase of scattering angle. At angle $\theta = 21°$, cross-section decreases by about 5 times compared to the cross-section at angle $\theta = 16°$. Appearance of wide maximum in the region of high excitation energies is a characteristic feature of spectra at small angles.

With increase of scattering angle, maximum becomes less evident. In the spectra of deuterons at angles $\theta = 36°$ and $47°$, structural peculiarities are no longer observed.

Analysis of inclusive spectra of deuterons on targets ^{12}C, ^{48}Ti, and $^{58,64}Ni$ at scattering angles of $16° \leq \theta \leq 61°$ has shown that it is expedient to investigate excitation of high states only at scattering angles $\theta < 21°$. Therefore, later on, we will pay major attention to analysis of energy spectra, obtained at angle $\theta = 16°$.

In Fig.1,c, energy spectra of deuterons, measured at scattering angle $\theta = 16°$ on ^{12}C, ^{48}Ti, and $^{58,64}Ni$ nuclei in wide excitation energy range (beginning from $5\,MeV$) are shown; and in Fig.1, d – these spectra in the region of continuum. As it is seen from Fig.1, for all nuclei investigated, increase of cross-section in continuum is observed. For nuclei with medium atomic weight, increase of cross-section in continuum may be characterized as "structured maximum", width and position of which practically do not change in the given range of atomic masses. Region of continuum is separated with "dip" from the field of excitation of discrete states.

In spectrum of deuterons, inelastically scattered on titanium nuclei, structural peculiarities are feebly marked. Only increase of cross-section at excitation energies of $\sim 16 - 20\,MeV$ and $\sim 26\,MeV$ could be noted. Maximum has slight slope both to the range of low excitation energies and to the range of high energies. On nickel isotopes, structural peculiarities in the range of excitation energies of $\sim 16 - 18\,MeV$ and $\sim 22 - 26\,MeV$ are mani-

fested more evidently. "Structured maximum" is bifurcated. Essential discrepancy in cross-sections between titanium and nickel isotopes is observed in the range of excitation energies $17 - 23\,MeV$. The difference is about $20 - 25\%$. One of the reasons of discrepancy can be more drastic angle dependence of cross-sections on nickel isotopes, than on titanium. Measurements on titanium and nickel isotopes were carried out at different values of parameters of deuteron beam, therefore, we consider the experimental data as preliminary results.

Another peculiarity of observed energy spectra is discrepancy in values of cross-sections on nickel isotopes in the range of excitation energies $15 - 20\,MeV$. Cross-sections in this energy range on ^{64}Ni are by 15% more than on ^{58}Ni. In this case, difference in cross-sections is not related to experimental accuracy and is a consequence of isotopic difference.

In energy spectrum of inelastically scattered deuterons on ^{12}C nucleus, decrease of excitation cross-section of high states is observed. Nevertheless, in spite of evident increase of cross-section in continuum, maximums are observed in the range of excitation energies $\sim 16 - 18\,MeV$ and $\sim 24 - 26\,MeV$. It is possible that their origin has common nature with increase of cross-section on nuclei with medium atomic weight, being observed in the same region.

Narrow maximum at excitation energies of $\sim 11\,MeV$ apparently belongs to the excitation of group of discrete states.

3. THEORETICAL ANALYSIS

Differential cross-section for inelastic deuteron scattering per unit spatial angle and unit final deuteron energy E'_d in nonrelativistic approximation after summing over all final nucleus states in diffraction approximation [6, 7] can be written in the following form:

$$\frac{d\sigma}{dE'_d d\Omega_d} = \sqrt{\frac{E'_d}{E_d}} \frac{1}{D} \left| f_d\left(\vec{q}\right) \right|^2 N_1, \quad \vec{q} = \vec{k}_d - \vec{k}'_d, \quad (1)$$

where $D \equiv D(U)$ is the distance between neighboring nucleus levels with excitation energy $U = E_d - E'_d$ (Landau formulae was used to find D); $f_d(\vec{q})$ is an amplitude of quasielastic scattering of deuteron by a single nucleon of a nucleus; $\vec{k}_d$ and $\vec{k}'_d$ are initial and final deuteron momenta respectively; N_1 is an effective number of nucleons, which scatter incoming deuterons, at the periphery of target nucleus ($N_1 \ll A$, where A is the nucleus mass number). The cross-section (1) is written in the approximation of smallness of the nucleon-nucleon interaction radius as compared with the size of scattering nucleus, neglecting the contribution of multiple scattering and correlations between nucleons in the target nucleus. Formulae (1) is the generalization of the corresponding expression for the cross-section given in [6, 7].

By choosing the Gaussian expressions for deuteron wave function

$$\varphi_d\left(r\right) = N_s e^{-\frac{1}{2}\mu r^2}, \quad N_s = \left(\frac{\mu}{\pi}\right)^{\frac{3}{4}},$$

$$\mu = 0.143\,\mathrm{fm}^{-2} \qquad (2)$$

and nucleon-nucleon profile functions

$$\omega_N\left(\rho_N\right) = ae^{-b^2\rho_N^2}, \quad N = n, p \qquad (3)$$

(ρ_N is an impact NN parameter), the amplitude $f_d(\vec{q})$ in (1) can be expressed in explicit form:

$$f_d\left(\vec{q}\right) = ik_d \frac{\pi^{\frac{3}{2}}a}{b^2\sqrt{\mu}} N_s^2 \left\{ \frac{1}{\mu} \exp\left[-\left(\frac{1}{16\mu} + \frac{1}{4b^2} \right) q^2 \right] - \right.$$

$$\left. - \frac{a}{4\left(\frac{1}{2}b^2 + \mu\right)} \exp\left(-\frac{q^2}{8b^2} \right) \right\}. \qquad (4)$$

It follows from (4) that the total cross-section of deuteron-nucleon interaction has the following form:

$$\sigma_d = \frac{4\pi}{k_d} \mathrm{Im} f_d(0) =$$

$$= \frac{\pi^{\frac{5}{2}} N_s^2}{b^2\sqrt{\mu}} \left[\frac{4\mathrm{Re}a}{\mu} + \frac{(\mathrm{Im}a)^2 - (\mathrm{Re}a)^2}{\frac{1}{2}b^2 + \mu} \right]. \qquad (5)$$

For multi-nucleon spherical nucleus with radius R and constant nucleon density $\rho(\vec{r}) = \rho_0 = \frac{3A}{4\pi R^3}$ for the N_1 in (1) we can obtain the following expression:

$$N_1 = \frac{\pi}{\rho_0^2\sigma_d^3} \left[1 - \left(2\rho_0^2\sigma_d^2 R^2 + 2\rho_0\sigma_d R + 1 \right) \times \right.$$

$$\left. \times \exp\left(-2\rho_0\sigma_d R \right) \right]. \qquad (6)$$

Parameters of NN-interaction a and b, entering (3) - (5), are taken from [8, 9, 10], where they were obtained from experimental data:

$$\mathrm{Re}\,a = 2.65, \quad \mathrm{Im}\,a = -1.95, \quad b^2 = 0.30\,\mathrm{fm}^{-2}. \quad (7)$$

In order to find the total cross-section σ_t of interaction between deuterons and target nuclei, we use the optical theorem and stepped nucleon-nucleus profile functions

$$\omega_n(\rho) = \omega_p(\rho) = \theta(R - \rho), \qquad (8)$$

where $\theta(R - \rho)$ is the Heaviside function. In this case

$$\sigma_t = 2\pi R^2 \left\{ 1 + \exp\left(-2\mu R^2 \right) \times \right.$$

$$\left. \times \left[I_0\left(2\mu R^2 \right) + I_1\left(2\mu R^2 \right) \right] \right\}, \qquad (9)$$

where $I_0(2\mu R^2)$ and $I_1(2\mu R^2)$ are modified Bessel functions [11]. In our case, the total cross-section σ_t in barns equals to 0.7, 1.6, 1.8, 1.9 for ^{12}C, ^{48}Ti, $^{58,64}Ni$ respectively.

Since theoretical cross-section was summed over all final nucleus states, it can not describe all details of the cross-section in the range of observed broad maximum at excitation energies $12 - 30\,MeV$. However, at small scattering angles of deuterons in our experiment, for ^{12}C and especially for $^{58,64}Ni$, the two-hump fine structure of the broad maximum (see Fig.1) can be observed. It could correspond to the excitation of the quadrupole giant resonance at lower
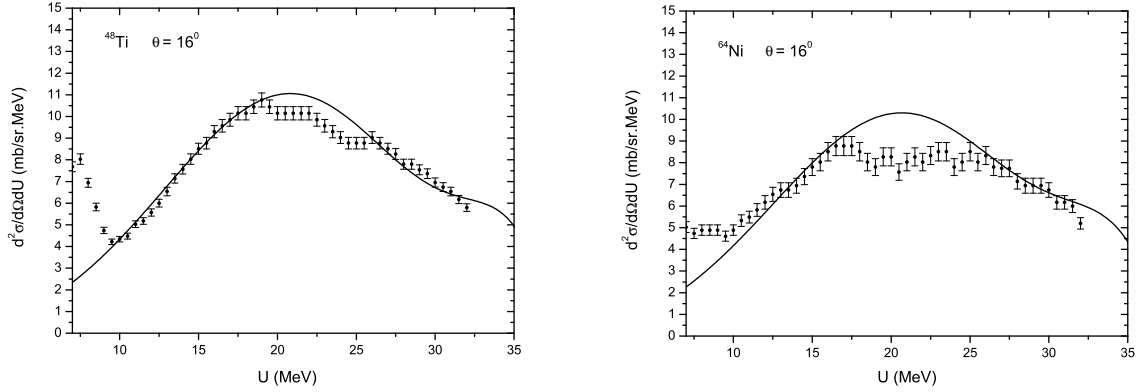
Fig.2. *a – calculated cross-section vs. excitation energy for* ^{48}Ti *at* $16°$*; b – the same for* ^{64}Ni *at* $16°$

energies, and the dipole giant resonance at higher energies [12]. It is also possible that the first of two humps is related to the energy transfer to the peripheral nucleons of a nucleus, whereas the second hump – to nucleons of the internal 1s-shell.

The cross-section of the processes with excitation of discrete nucleus levels (between the elastic scattering peak and the broad maximum) with energy U was calculated according to the following formulae:

$$\frac{d\sigma_u}{dE'_d d\Omega_d} = \sqrt{\frac{E'_d}{E_d}} \left| f_d \left(\vec{k}_d - \vec{k}'_d \right) \right|^2 \delta \left(E_d - E'_d - U \right),$$

(10)

where δ-function was replaced by the finite multiplier

$$\delta_\Delta \left(E_d - E'_d - U \right) = \frac{1}{\sqrt{\pi\Delta^2}} \times$$

$$\times \exp\left(-\frac{1}{\Delta^2} \left(E_d - E'_d - U \right)^2 \right)$$

(11)

(the parameter Δ defines errors in measuring the energy). The same formulas (10) and (11) were used to calculate the cross-section of elastic deuteron scattering (at $U = 0$).

The results of our calculations of the cross-section (1) for ^{48}Ti and ^{64}Ni nuclei in the region of the continuum are presented in Fig.2. We have reached quite good agreement of our calculations with the experimental data in the whole region of continuum except its central part (around $20\,MeV$). The discrepancy in that region is rather significant for ^{64}Ni (see Fig.2,b), because of the two-hump structure of the maximum. Though the data for ^{48}Ti do not show the same structure of the maximum (see Fig.2,a), we believe that the same physical effects as for ^{64}Ni contribute here.

4. CONCLUSIONS

In this work we have studied experimentally the scattering of deuterons by ^{12}C, ^{48}Ti, $^{58,64}Ni$ nuclei and found the existence of the continuum region in

the differential cross-sections at angle $\theta < 21°$. Experimental data show that the broad maximum of the cross-section in the continuum region has fine structure. For ^{12}C and $^{58,64}Ni$ this structure has a shape of two humps.

We believe that the fine structure of the broad maximum is related to the excitation of the giant resonances in the target nuclei. As it was explained above, our preliminary formulae do not take the effects, leading to the hump-like structure of the maximum, into account. Nevertheless, the formulae allow us to describe the data in all but central parts of the continuum quite well. We plan to take the contributions of the giant resonances into account in our further work. This will allow us to improve our description of the fine structure of the broad maximum.

Our experimental and theoretical study of the fine structure of the deuteron-nucleus cross-section in the continuum region will be continued in the future.

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ВОЗБУЖДЕНИЕ СРЕДНИХ ЯДЕР В ОБЛАСТИ КОНТИНУУМА ПРИ НЕУПРУГОМ РАССЕЯНИИ ДЕЙТРОНОВ

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Выполнены эксперименты по упругому и неупругому рассеянию дейтронов ядрами ^{12}C, ^{48}Ti, ^{58,64}Ni при энергии 37 МэВ на углы от 16° до 61° на изохронном циклотроне У-240 Института ядерных исследований НАН Украины. В энергетическом спектре рассеянных дейтронов для углов рассеяния меньше 21° наблюдается широкий максимум при энергиях возбуждения ядер от 12 до 30 МэВ, включающий в себя максимум гигантского резонанса. Широкий максимум был описан теоретически в дифракционном приближении после суммирования сечения по всем конечным ядерным состояниям.

ЗБУДЖЕННЯ СЕРЕДНІХ ЯДЕР В ОБЛАСТІ КОНТИНУУМА ПРИ НЕПРУЖНОМУ РОЗСІЯННІ ДЕЙТРОНІВ

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Виконано експерименти з пружного та непружного розсіяння дейтронів ядрами ^{12}C, ^{48}Ti, ^{58,64}Ni при енергії 37 МеВ на кути від 16° до 61° на ізохронному циклотроні У-240 Інституту ядерних досліджень НАН України. В енергетичному спектрі розсіяних дейтронів для кутів розсіяння менше 21° спостерігається широкий максимум при енергіях збудження ядер від 12 до 30 МеВ, який включає в себе максимум гігантського резонансу. Широкий максимум було описано теоретично в дифракційному наближенні після підсумовування перерізу за всіма кінцевими ядерними станами.