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Analyses of Nucleon Interaction with ^{238}U up to 150 MeV Incident Energies Using Coupled-Channels Approach with a Saturated Coupling Scheme Based on Soft-Rotator Nuclear Model Hamiltonian

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Coupled-channels optical model with a saturated coupling built on the wave functions of the soft-rotator nuclear Hamiltonian is applied for the self-consistent analyses of ^{238}U collective nuclear level structure and nucleon interaction with this nuclei. Experimental ^{238}U low-lying level structure, $B(E\lambda)$ γ - transitions and available nucleon (both neutron and proton) interaction data up to 150 MeV incident energies are described simultaneously within less than two experimental errors. Results are recommended to be used for nucleon-induced high energy data evaluation.

KEYWORDS: soft-rotator model, collective level structure, $B(E\lambda)$ γ - transitions, global form optical model parameters, coupled-channels model with 17 coupled levels, relativistic generalization, σ_{tot}, (n,n), (n,n'), (p,p), (p,p'), incident energies up to 150 MeV

I. Introduction

Most of the coupled-channels (CC) optical potentials suggested for actinides are based on potential determined by Lagrange *et al.*,[1)] which was obtained to describe low energy ^{238}U experimental data, with some modifications to enhance agreement with available experimental data for higher incident energies, e.g., total cross section from 10 up to 100 MeV.[2)] All these potentials consider ^{238}U and other actinides to be axial rigid rotator, taking into account coupling of ground state (G.S.) rotational band levels only, while it is well-known that, up to $\sim$ 1 MeV excitation energy, actinides exhibit no less than four rotational bands including negative parity one. A recent measurement[3)] of neutron interaction with ^{238}U shows that excitation cross-section of levels other than G.S. ones at 3.51 MeV incident energy may be greater than excitation of the G.S. 4^+ level and about half of G.S. 2^+ level excitation,[4)] so that coupling of such levels cannot be ignored in reliable CC calculations.

Present work is an attempt to overcome this drawback by using a saturated (17 levels) coupling scheme build with a reliable nuclear structure model. Such a comprehensive coupling scheme assures that inclusion of additional levels in the coupling does not change the results of calculations appreciably, so that we can consider optimized optical potential to be the "bare" one, independent of the coupling assumptions.

II. Analysis of Low-Lying ^{238}U Collective Level Structure and Optical model Saturated Coupling Using Soft-Rotator Nuclear Model

The soft rotator model (SRM) was developed as an extension of Davydov-Chaban model,[5)] accounting the non-axial quadrupole, octupole and hexadecapole deformations, and the β_2-, β_3-, and γ-vibrations of the rotating nucleus. and is described elsewhere.[6–8)] Parameters of SRM Hamiltoniam were adjusted to describe experimental low-lying collective levels of ^{238}U. Results are shown in **Fig. 1** below.

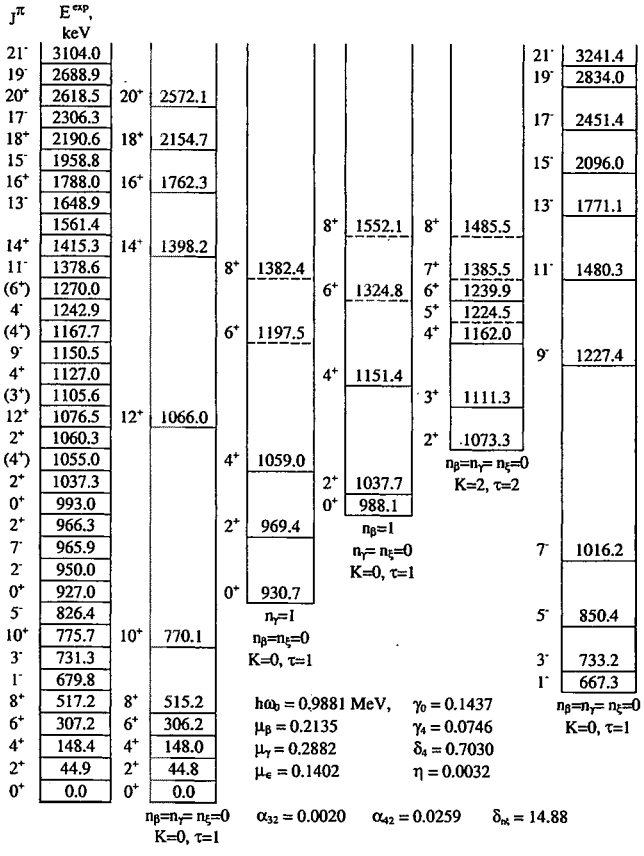

Fig. 1 Comparison of ^{238}U experimental and soft rotator model predicted level schemes

One can see that all the experimental ^{238}U levels can be understood as the members of four positive and $K \simeq 0^-$ negative parity bands at least up to 2.6 MeV excitation energy with accuracy better than 3% in average.

With the achieved quality of levels description we could

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consider SRM nuclear Hamiltonian wave functions reliable enough to be used to built coupling scheme for CC optical model calculations, such coupling was built as described in.[9] We could couple, having necessary nuclear wave functions, all the levels up to 2.6 MeV excitation. Thus we had carried out optical calculations in a saturated coupling concept: in our coupling scheme we keep all the levels except those adding which to coupling scheme changed the results of optical calculations by less than experimental errors. It was checked by preliminary calculations that we need to couple 17 levels: 0^+, 2^+, 4^+, 6^+, 8^+ of G.S. rotational band; 1^-, 3^-, 5^- from $K \simeq 0^-$, $n_{\beta_2} = 0$, $n_\gamma = 0$ band; 0^+, 2^+, 4^+ from $K \simeq 0$, $n_{\beta_2} = 0$, $n_\gamma = 1$ band; 0^+, 2^+, 4^+ from $K \simeq 0$, $n_{\beta_2} = 1$, $n_\gamma = 0$ band and 2^+, 3^+, 4^+ from $K \simeq 2$, $n_{\beta_2} = 0$, $n_\gamma = 0$ band. All these levels were coupled with each other and themselves by optical potential coupling multipoles arising due to deformed nuclear shapes[5,10] in a body fixed system.

$$R(\theta',\varphi') = R_0 \left\{ 1 + \sum_{\lambda=2-4,\mu} \beta_{\lambda\mu} Y_{\lambda\mu}(\theta',\varphi') \right\} \quad (1)$$

All the available experimental proton and neutron optical data up to 150 MeV (see Table 2 of[11]) incident energy was used to adjust optical potential parameters using search option of OPTMAN code.[12] The upper incident energy boundary 150 MeV is comparable with nucleon mass ($\sim$ 1000 MeV), so we used relativistic generalization of non-relativistic Schrödinger equation, following suggestions of Elton[13] and Madland and Sierk.[14] We also used a global optical potential form, zero imaginary part at the Fermi surface, accounting dispersion relationships as proposed by Delaroche *et al.*[15] and high-energy saturation behavior consistent with the Dirac phenomenology.

III. Results and Discussion

It is evident that the total cross section data up to 150 MeV (**Fig. 2**) and nucleon scattering data (**Figs. 3-9**) are described with better accuracy, as comparing with predictions by Young's potential.[2] Moreover, the saturated coupling scheme used gives new results, which are impossible by previous calculations[2] with only three G.S. levels were coupled, as we predict all the significant direct excitations for nucleon interaction with ^{238}U.

For instance last Geel experiments[3] showed that at neutron incident energy of 3.51 MeV, cross section of level excitation with energy losses $E_X = 0.63 - 0.89$ and $0.89 - 1.32$ MeV are 0.056 ± 0.012 and 0.18 ± 0.05 barn, respectively. One can easily check that for such incident energy ^{238}U levels with the quoted excitations are excited mainly through direct mechanism, impact of compound process is less $\sim$ 10 %. So Geel[3] experiments prove that levels from other than ground state bands are excited via direct mechanism. For our coupling scheme for the first $E_X = 0.63 - 0.89$ MeV group these are levels $J^\pi = 1^-, 3^-, 5^-$ of $K \simeq 0^-$ band and for $E_X = 0.89 - 1.32$ MeV - levels of $K \simeq 2^+$ and higher $n_{\beta_2} = 1$ and $n_\gamma = 1$ $K \simeq 0^+$ bands . Our calculated cross section of direct level excitation with energy loss

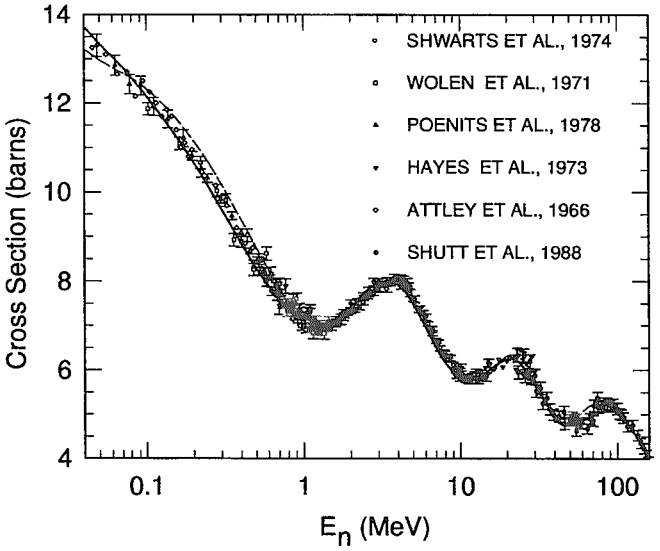

Fig. 2 Neutron total cross section of ^{238}U from 0.05 to 150 MeV
The solid line denotes the result calculated with the optical potential of this work; the broken curve is obtained with Young's potential. Experimental data are shown by various symbols.

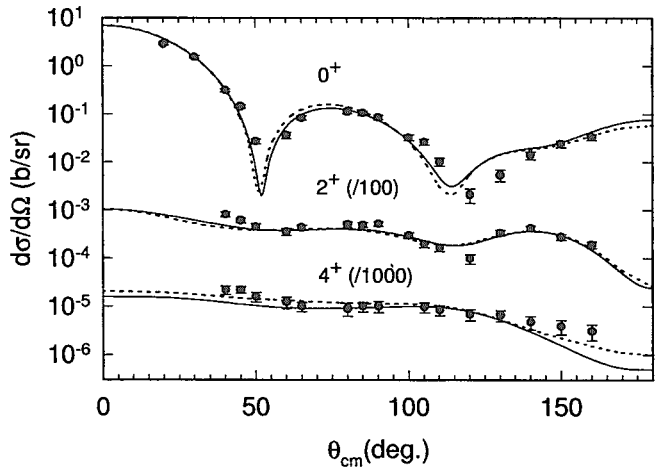

Fig. 3 Neutron elastic and inelastic scattering cross section to the 0^+, 2^+ and 4^+ levels of ^{238}U at 3.4 MeV
The full circles denote experimental data obtained by Haouat *et al.* Meanings of the lines are the same as in Fig. 2.

$E_X = 0.89 - 1.32$ MeV is 0.202 barn and is the sum of $K \simeq 2^+$ band $2^+(1.0603$ MeV$) = 0.10$ barn, $3^+(1.1056$ MeV$) = 0.002$ barn, $4^+(1.1677$ MeV$) = 0.008$ barn level excitations and excitation of six levels from two higher $K \simeq 0^+$ bands, each about 0.02 barn. Calculated cross section of negative parity band level excitation with energy loss $E_X = 0.63 - 0.89$ MeV is $\sim$ 0.04 barn. One can see good agreement of predicted and experimental data, proving, that our predictions for all 17 levels are reliable. Excitation of levels other than G.S. band levels is rather strong, so it cannot be ignored in consistent CC calculations. The good agreement of Young's predictions[2] with experimental data means that his optical potential, although very effective, may be moved from the "real"

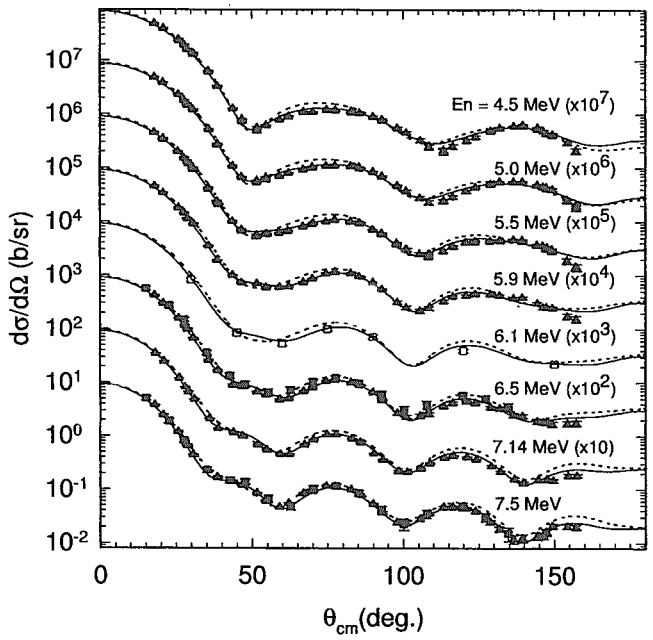

Fig. 4 Neutron scattering cross section for excitation of a sum of 0^+, 2^+, 4^+, 6^+ and 8^+ levels of ^{238}U from 4 to 7 MeV
The closed triangels denote experimental data by Smith and Chiba, the open squares by Baba *et al.*, the closed squares by Kinny *et al.* Meanings of the lines are the same as in Fig. 3.

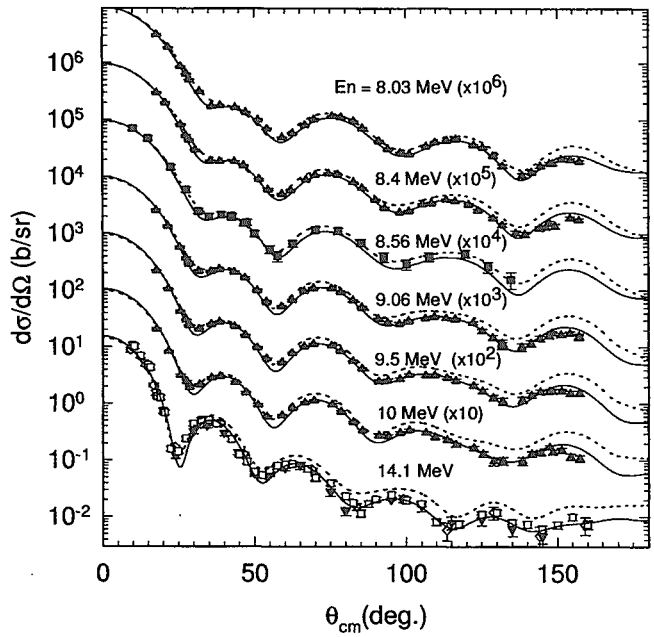

Fig. 5 Same as Fig. 4, but from 8 to 14 MeV
The open diamonds denote experimental data by Hansen *et al*, the closed inverse triangles by Kammerdiener, the open squares by Shen *et al.* Other symbols and lines are the same meanings as Fig. 4.

one to compensate lack of realistic coupling strength.

In the vicinity of 3.5 MeV incident energy, non-axial soft-rotator optical model predicts additional $\sim$ 0.24 barn for the direct scattering cross section on levels other than the ground

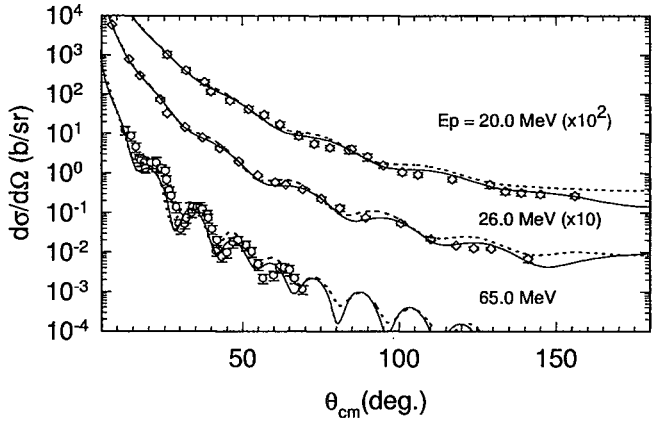

Fig. 6 Proton elastic scattering cross section for ^{238}U from 20 MeV to 65 MeV
The open diamonds denote experimental data by Hansen *et al*, the open circles by Takeuchi *et al.* Meanings of the lines are the same as in Fig. 3.

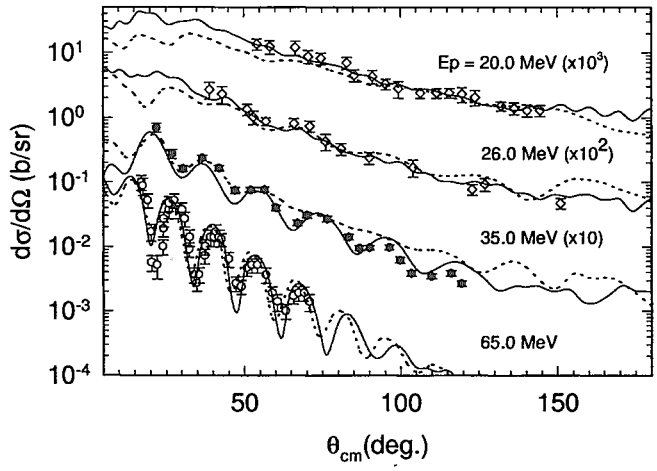

Fig. 7 Proton inelastic scattering cross section to the 1st excited state (2^+) of ^{238}U from 20 to 65 MeV
The closed circles denote experimental data obtained by King *et al.* Meanings of other symbols and lines are the same as in Fig. 6.

state band. Hence, the absorption cross section predicted by the soft-rotator CC approach in the vicinity of 3.5 MeV will be lower than the prediction of the axial rotor CC by this amount, if total and G.S. band level excitations are described with the same quality. Such difference in absorption cross section predicted by both models decreases with the growth of neutron incident energy, as cross section of level excitation from other bands decreases with the energy and is $\sim$ 0.05 barn for neutron incident energy $\sim$ 14 MeV.

Experimental ^{238}U B(Eλ) γ -transition probabilities are also predicted with reasonable accuracy by SRM (for details see:[7]). Calculated B(E2; 0_1^+(G.S.) $\rightarrow$ 2_1^+(0.0449MeV)) transition probability is equal $11.2e^2b^2$, while experimental value is $11.7\pm0.8e^2b^2$, calculated B(E4; 0_1^+(G.S.) $\rightarrow$ 4_1^+(0.1484MeV)) is $0.54e^2b^4$, while measured value is $0.69\pm0.37e^2b^4$. Calculated probabilities for interband

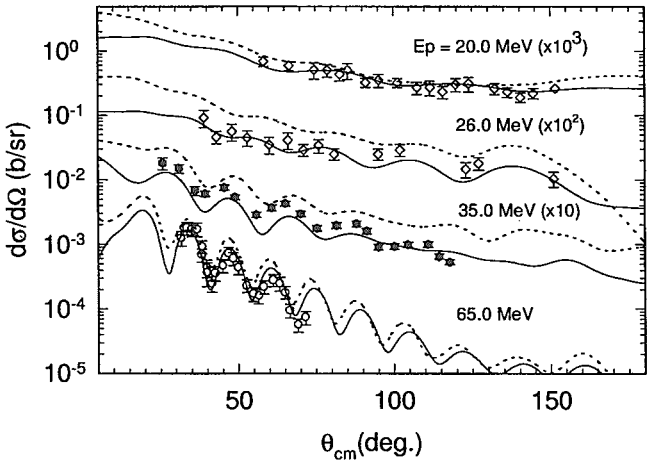

Fig. 8 Proton inelastic scattering cross section to the 2nd excited state (4^+) of ^{238}U from 20 to 65 MeV
Meanings of the symbols and lines are the same as in Fig. 7.

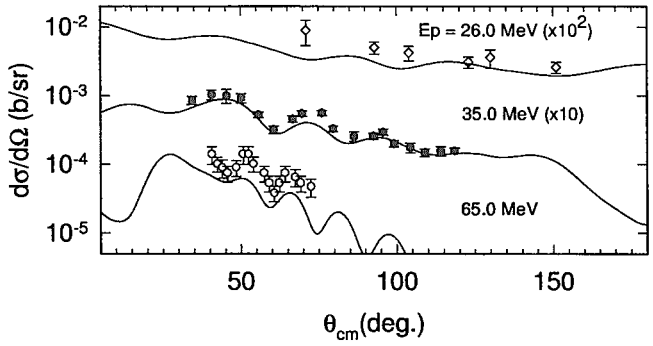

Fig. 9 Proton inelastic scattering cross section to the 3rd excited state (6^+) of ^{238}U from 20 to 65 MeV
Meanings of the symbols and lines are the same as in Fig. 7.

transitions B(E3; 0_1^+(G.S.MeV) $\rightarrow$ 3_1^-(0.7313MeV)) and B(E2; 0_1^+(G.S.) $\rightarrow$ 2_3^+(1.0373MeV)) are $0.79e^2b^3$ and $0.025e^2b^2$, while experimental values are $0.54\pm0.06e^2b^3$ and $0.037\pm0.015e^2b^2$consequently.

IV. Conclusion

CC calculations with coupling built on SRM Hamiltonian allow to describe all the ^{238}U experimental optical data consistently with ^{238}U nuclear structure and B(Eλ) γ -transition probabilities, predicting excitation of all the levels significantly excited by direct process. In addition to the neutron scattering data, we used proton scattering data which, contrary to neutron data, is available for resolved levels and up to much higher incident energies. Along with the saturated coupling used, this makes our predictions much more reliable, while the consistent prediction for the 17 levels most significantly excited by direct mechanism allows to recommend these results to be used for ^{238}U high energy file evaluation.

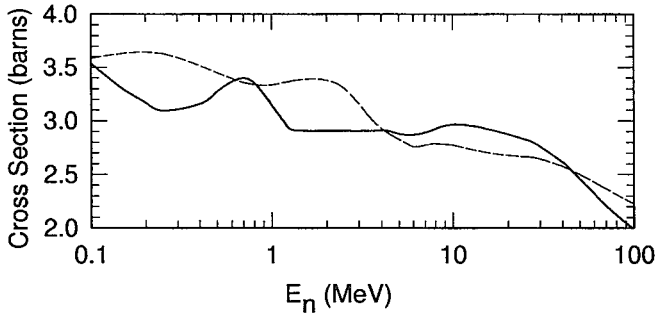

Fig. 10 Neutron absorption cross section of ^{238}U, defined as a difference between the total and direct scattering cross section
Meanings of lines are the same as in Fig. 2.

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