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IN NEUTRON SCATTERING BY NIOBIUM

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Collective Reactions to the Continuum in Neutron Scattering by Niobium

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Abstract

The preequilibrium cross sections for the direct excitation of collective states, including giant resonances, in the continuum region, are calculated and combined with the multistep direct, multistep compound and compound nucleus cross sections to give a complete analysis of neutron scattering by niobium. These collective cross sections we calculated in the framework of DWBA. A good description of neutron emission spectra and angular distributions has been obtained at incident energies 14.1 MeV, 20 MeV and 25.7 MeV.

I. INTRODUCTION

In the first semiclassical models of preequilibrium nuclear reactions they are considered as a homogeneous reaction mechanism, though the question arose whether to treat the collective enhancement of the reaction cross sections inclusively, in the framework of a preequilibrium model or as separate, additive collective contributions [1]. The formulation of the quantum-mechanical, statistical theories did not answer this question but Feshbach, Kerman and Koonin [2] (FKK) have emphasized for the first time the distinctly different features of the multistep direct reactions (MSD) on one hand, and of the preequilibrium compound ones, called multistep compound reactions (MSC), on the other. This distinction, followed by the contemporary quantal theories of preequilibrium reactions [3, 4] locates the direct excitation of the collective degrees of freedom in the continuum, as a reaction that occurs in parallel with the MSD reactions. However the collective reactions were not considered as a separate reaction mechanism and any collective effects in the continuum were masked by adjusting the parameter of the MSD reaction [5, 6]. Simultaneous analyses of nucleon inelastic scattering and charge-exchange reactions in terms of the MSD, MSC and the Hauser-Feshbach (H-F) compound nucleus reaction models, completed in the case of inelastic scattering by the cross sections due to excitation of the first collective 2^+ and 3^- states [7], showed that a good description of both types of reactions is possible, but only at the expense of inconsistent parametrisation of the MSD reaction [8]. The physically meaningful parameters that bring the calculated cross sections of the (p, xn) reactions into agreement with experiment [9] provide MSD cross sections that are too low to fit the experimental (n, xn) reaction data. This is because inelastic neutron scattering is strongly

enhanced due to excitation of the isoscalar giant resonances in the continuum region, whereas the charge-exchange reactions are subject only to the isovector excitations, which are weaker by almost an order of magnitude and/or well concentrated in energy, like the isobaric analogue state. The isovector, collective excitations are thus either clearly distinguished from the underlying smooth cross sections under investigation or are less significant.

The purpose of the present paper is to calculate for the first time the collective cross sections in the continuum and thus to give a description of neutron emission from ^{93}Nb at incident neutron energies of 14.1 MeV, 20 MeV and 25.7 MeV that combines incoherently the three different preequilibrium reaction mechanisms, namely the MSC reactions, the MSD reactions and the direct reactions that excite collective states including the giant resonances. This goal was achieved by using the macroscopic, collective model [10] in the framework of DWBA for the excitation of the vibrational states of different multiplicities. In these calculations the energy-weighted sum-rules were used to assign appropriate collective strengths (deformation parameters) to the giant-resonance states provided the deformation parameters of the low-lying collective levels have been experimentally determined. The MSD and the preequilibrium MSC reaction cross sections were calculated according to the FKK theory which has been modified in order to account for the gradual absorption [11] of the projectile flux, a phenomenon accompanying MSD reactions [12, 13].

The FKK theory has been described in [14] and the references contained therein as well as in a recent review article [15]. Here, in Sec. II, we describe only the modification due to gradual absorption into the quasibound states involved in the successive stages of the MSC reaction. In Sec. III the cross sections of the direct reactions are described and in Sec. IV the calculations are discussed and the results are compared with experimental cross sections for the (n, xn) reaction on niobium. Our conclusions are in Sec. V.

II. THE MULTISTEP COMPOUND REACTION CROSS SECTION

The optical model absorption cross section accounts for all the flux removed from the elastic channel. However the removed flux feeds not only the compound states of the MSC reaction chain, gradually from the continuum [11, 13], but also the direct inelastic reactions that do not contribute to absorption. Thus to calculate the MSC reaction cross sections the optical model absorption has to be reduced by the direct inelastic reactions. The latter divide into the MSD reactions which include the incoherent, particle-hole excitations and the coherent ones that result in excitation of collective vibrations of the nucleus as a whole. The sum of the cross sections of these reactions can be evaluated both theoretically and experimentally [5, 11]. Let us call the fraction of the optical model absorption cross section due to these reactions $(1-R)$, so that R is the fraction that feeds the MSC reaction chain. The gradual absorption splits R according to the partial R_M 's that describe feeding of separate reaction stages M [11]. Thus the absorption cross section to be used in the MSC cross section formulae is [6, 11]

$$\sigma_{abs} = \pi \lambda^2 \sum_M R_M \sum_{J^\pi} \sum_{j=|J-I|}^{J+I} \frac{(2J+1)}{(2j+1)(2I+1)} T_j = \pi \lambda^2 \sum_M R_M \sum_{J^\pi} \sum_{j=|J-I|}^{J+I} \frac{(2J+1)}{(2j+1)(2I+1)} 2\pi \frac{\langle \Gamma_{MJ^\pi}^j \rangle}{\langle D_{MJ^\pi} \rangle}, \quad (1)$$

where i, I, J, j are the spins of the projectile, the target nucleus, the composite nucleus and the total angular momentum of the projectile, respectively. The symbol J^π is used to indicate that parity is

conserved in all angular momentum couplings. The partial-wave transmission coefficients T_j come from the standard optical model and the R_M 's are determined by the recurrence formula given by Marcinkowski *et al* [11].

$$R_M = (R - R_1 - R_2 - \dots - R_{M-1}) \frac{\rho_{(M+1)p,Mh}^B}{\rho_{(M+1)p,Mh}}. \quad (2)$$

with $R_0 = 0$. Equation (2) was obtained from a phase-space model, considering the densities of the unrestricted $(M+1)p, Mh$ states $\rho_{(M+1)p,Mh}$, given by Ericson [16], and the densities of the restricted bound-particle-hole states derived by Oblozinsky [17],

$$\rho_{(M+1)p,Mh}^B(U) = \frac{g^{2M+1}}{(M+1)!M!(2M)!} \sum_{k=0}^{M+1} (-1)^k \binom{M+1}{k} \theta(U - kB)(U - kB)^{2M}. \quad (3)$$

Recently Arbanas *et al* [13] provided a quantum-mechanical justification for the presence of gradual absorption described by Eq. (2). In Equation (3) the number of excited particles and holes (excitons) is $n = 2M+1$ and $g = A/13 \text{ MeV}^{-1}$ is the average single-particle state density. U and B are the excitation energy of the final nucleus and the binding energy of the particle exciton to be emitted, respectively. The spin distribution of the particle-hole states $R_n(S)$ is

$$R_n(S) = \frac{(2S+1)}{2(2\pi)^{1/2}\sigma_n^3} \exp\left[\frac{-(S+\frac{1}{2})^2}{2\sigma_n^2}\right]. \quad (4)$$

The spin cut-off parameter σ_n depends on the number of excitons n through the relation $\sigma_n^2 = CnA^{2/3}$, where C is determined by the average value of n [18].

The absorption cross section given by equation (1) is expressed in terms of the partial strength functions $2\pi\langle\Gamma_{MJ\pi}^j\rangle/\langle D_{MJ\pi}\rangle$ for passing by the $2p, 1h$ doorway states (see Eq. (1) in [6]), in a series of DWBA transitions, on the way from the entrance channel to the quasibound $(M+1)p, Mh$ states formed at the $M > 1$ reaction stages. These transitions reduce the preequilibrium MSC cross section in favour of the compound nucleus cross section since damping towards the compound nucleus is increasingly stronger than emission from the quasibound states formed at the successive reaction stages.

III. THE MULTISTEP DIRECT REACTION CROSS SECTIONS

The cross section for the incoherent MSD excitation is a sum over contributions from collisions inside the nucleus of the projectile, which loses energy and direction by creating successive particle-hole pairs. At the incident energies considered in the analysis of Sec. IV only the first and possibly the second step contribute appreciably since the third collision adds less than 1% of the cross section.

According to FKK the microscopic DWBA angular distributions to all allowed, final $1p1h$ states of the shell model when averaged over energy contribute incoherently to the one-step cross section,

$$\frac{d^2\sigma}{dU \cdot d\Omega_{one-step}} = \sum_{\ell} \rho_{1,1}(U) R_2(\ell) \left\langle \left[\frac{d\sigma(\theta)}{d\Omega} \right]_{\ell}^{DW(micr)} \right\rangle. \quad (5)$$

The summation in (5) runs over the transferred orbital angular momenta ℓ and $[d\sigma(\theta)/d\Omega]_\ell$ is the reduced DWBA cross section calculated with a microscopic two-particle form factor (hole treated as a particle).

The formula for calculating the two-step cross section in the framework of the FKK theory is given in [19]. This formula can be easily extended to more than two reaction steps by using the convolution structure over the single steps characteristic of the FKK multistep cross sections. In the computational versions one usually assumes that the final states are those of the particle-hole pair just created, independent of the reaction stage spectators. This assumption which is analogous to the Brink-Axel hypothesis in photoabsorption reactions, ensures that only $\rho_{1,1}$ enters the multistep formulae. This two exciton state density is that given by [16], but its spin distribution $R_2(\ell)$ is given by Eq. (4).

The coherent excitations that result in collective surface vibrations of the nucleus are described by simple macroscopic models [20] in the framework of DWBA. Comparison of the shapes of the angular distributions allows one to obtain the orbital angular momentum transfer ℓ that determines the multipolarity of the strongest isoscalar, electric vibrations, including the giant resonance states in the continuum. The collective cross sections are calculated with the radial form factors derived by deforming the optical model potentials of radius R . For the isoscalar, electric term we have [10].

$$f_{00}(r) = -R \left[\frac{\partial U_0}{\partial R} \right]. \quad (6)$$

with U_0 being the phenomenological, complex optical potential obtained from analysis of elastic scattering data.

In case of the isovector, electric dipole resonance U_0 in Eq. (6) is replaced by the symmetry potential U_1 , which is assumed to have the same shape as the main U_0 term. This prescription corresponds to the Goldhaber-Teller form factor, which is an alternative to that of Steinwedel-Jensen [10].

The magnitudes of the cross sections to the low-energy vibrational states are then determined in terms of the phenomenological effective deformation parameters β_ℓ , which allow one to deduce also the measure of the collective strength $\beta_{\ell-GR}$ that remains in the giant resonance states in the continuum, by depletion of the energy-weighted sum rule (EWSR) which for $\ell > 2$ reads (for the sum rules for the breathing and dipole mode see [10]).

$$\sum_i (\epsilon_i - \epsilon_0) \beta_\ell^2(0 \rightarrow i) = \frac{h^2}{6\pi A m R^2} \ell(2\ell + 1). \quad (7)$$

The summation in Eq. (7) runs over the excited ℓ -phonon states i having energies ϵ_i . Here m is the mass of a nucleon. Knowing the energies of the collective levels and the corresponding deformation parameters β_ℓ is sufficient to evaluate from Eq.(7) the collective strength of the isoscalar, electric, giant resonance state of multipolarity ℓ in the continuum.

In the absence of spin-orbit coupling in the distorted waves the differential cross section for an isoscalar, electric, one-phonon vibration in inelastic scattering is

$$\frac{d\sigma}{d\Omega_{one-phonon}} = (\beta_\ell)^2 \left[\frac{d\sigma(\theta)}{d\Omega} \right]_\ell^{DW(macr)}. \quad (8)$$

Here β_l is to be replaced by β_{l-GR} in case of a giant resonance state. In Eq. (8) $[d\sigma(\theta)/d\Omega]_l$ is the reduced DWBA cross section calculated using the macroscopic form factor $f_{00}(r)$ of Eq. (6).

The case of ^{93}Nb we consider in Sec. IV is for the weak-coupling model, in which the final states are treated as though they consisted of a valence, odd proton unchanged and with the ground state angular momentum $I=\frac{9}{2}^+$, coupled to a single ℓ -phonon of collective motion. In this model the valence part is purely a spectator in the transition. Instead of identifying all members of the weak-coupling multiplet $|I-\ell| \leq S \leq I+\ell$, both experimentally and in the calculations it is practicable to calculate the cross sections for excitation of the one-phonon states in the even-even core ^{92}Zr , for which the deformation parameters of the low-energy collective levels have been experimentally determined (see Table I). The spread of the members of the weak-coupling multiplet in ^{93}Nb can be then accounted for by assuming a realistic spreading width that in conjunction with the experimental energy resolution will broaden the natural collective width of the one-phonon state.

While the integral contribution of the incoherent particle-hole MSD reactions rises with incident energy, the faster the higher the multiplicity of the direct two-body interactions, it decreases for phonon excitations. The ratio of the two-phonon to one-phonon excitations is approximately 0.1 at incident energies lower than 30 MeV and the two-phonon cross section can be easily evaluated by the method of [7].

IV. CALCULATIONS AND RESULTS

In this analysis we describe theoretically the experimental cross sections of neutron-induced neutron emission on ^{93}Nb measured at Ohio University for incident energies 25.7 MeV [21] and 20 MeV [22] as well as the data obtained by Pavlik *et al* [23] at 14.1 MeV. All these data exhibit clear preequilibrium, direct contributions which are also subject to strong collective enhancement in the continuum region. It is thus a new task to develop a practicable model for describing these collective effects.

The cross section for the incoherent MSD excitation of particle-hole pairs is given by the FKK formulae (5) (and formula (15) in [19]). The reduced angular distributions of emitted neutrons in (5) were calculated using the DWUCK-4 code [24] with microscopic two-particle form factor. Distorted waves were obtained from global optical potential [25].

The MSD cross section of formula (5) depends via the form factor on the strength V_0 of the Yukawa effective interaction of 1 fm range, acting on the bound-state wavefunctions of a real Woods-Saxon potential, as well as on the average single-particle state density g and the cut-off parameter σ^2 of its spin distribution $R_2(\ell)$. Therefore it was important to assume in the present analysis the physically meaningful values of these parameters $V_0=28$ MeV, $g=A/13$ MeV $^{-1}$ and $\sigma_2^2 = 0.28 \times 2A^{2/3}$, which have proved successful and are justified by an extensive analysis of charge-exchange reactions that are free of the strong isoscalar collective excitations [9].

In order to keep the MSD computations within reasonable limits, we took into account only a limited range of transferred orbital angular momenta ℓ . For each value of ℓ from 0 to 9 (from 0 to 5 in case of the second reaction stage) all $1p1h$ configurations in the final nucleus allowed by angular momentum selection rules and energy conservation were chosen in accord with the shell model of Seeger [26]. Both neutron and proton particle-hole pairs contribute to neutron scattering. In order to obtain smooth neutron spectra averaging was applied over $1p1h$ states contained in 5 MeV energy intervals, centered in the middle of the experimental outgoing energy bins.

The cross sections for excitation of the isoscalar electric vibrations of different multipolarity given by formula (8) were calculated using the code DWUCK-4 with the macroscopic form factor (6). The calculations were performed for the giant resonance states in addition to all final low-energy levels of ^{92}Zr for which the deformation parameters given in Table I have been determined [27, 28]. The $\mathcal{J}_{I-GR}$ parameters characteristic of the giant resonances were then evaluated by depletion of the EWSR of Eq. (7) from its 100%-strength by the collective strengths of the low-energy one-phonon states of given multipolarity. The energies of the giant resonances were taken from [29]. The strength of the isovector GDR has been obtained using the dipole EWSR from [10].

The cross sections for the excitation of the giant resonances were then spread according to the Lorentzian function with a typical width of $\Gamma=5$ MeV. The cross sections for the low-energy phonon states were also broadened in order to account for the spreading of the spectroscopic strength adopted from the weak-coupling model for odd-mass nuclei and for the limited energy resolution in the experiments. The main contribution to the width of the effective distributions of these cross sections comes from the energy resolution of the neutron t.o.f. facility and from the outgoing-energy bins assumed in the experimental data reduction procedure, since the spreading of the weak-coupling multiplet is only 270 keV. The resulting width was $\Gamma=1.7$ MeV in case of the Ohio University data and $\Gamma=1.1$ MeV in case of the data of [23]. The calculated MSD emission spectra and the summed spectra of neutrons emitted after direct excitation of the collective states are shown in Figs. 1 to 3 and some of the angular distributions in Fig. 4.

The incoherent MSD emission spectra of neutrons and protons as well as the collective direct spectra of neutrons were summed, integrated over outgoing energy and divided by the standard optical-model absorption cross section in order to obtain $(1-R)$. In this case R denotes the fraction of the incident flux feeding the quasibound states of the MSC reaction chain that enters formula (2). The values of R obtained were 0.82, 0.72 and 0.59 at bombarding energies 14.1, 20 and 25.7 MeV, respectively.

The preequilibrium MSC calculations were performed according to the FKK cross section formula (Eq. (1) in [6]) with gradual absorption determined by Eqs. (1) and (2). The MSC contributions to the cross section were truncated so that emissions from stages greater than third were included in the compound nucleus cross section calculated according to the H-F theory. The bound-particle-hole state densities given by Eqs. (3) and (4) were used with the spin cut-off parameter $\sigma_n^2 = 0.24nA^{2/3}$, appropriate to the intermediate numbers of excitons ($\bar{n}=5$) involved in the MSC reactions [18].

For consistency with the H-F calculations $g = 6a/\pi^2$ was used in (3). The H-F cross sections were calculated with the compound nucleus level density formulae and pairing energy shifts Δ given by [30]. The level density parameters a and nuclear temperatures T were taken from the systematics [31] and the empirically determined spin distribution cut-off parameter $\sigma^2 = 0.146A^{2/3}[a(U - \Delta)]^{1/2}$ was used for the fully equilibrated compound nucleus. In the MSC model only nucleon emission is described, but in the H-F calculations the emission of alpha particles was also taken into account. The optical potentials for neutrons, protons and alpha particles were obtained from [25, 32, 33]. Emission of γ -rays in the H-F formalism was calculated by combining single-particle and phenomenological giant resonance strength functions for E1, E2, and M1 transitions. The MSC and the related H-F calculations have been made with the extended version of the EMPIRE code [34].

The results of calculations are compared with experimental neutron emission spectra in Figs. 1 to 3 and with some of the measured angular distributions in Fig. 4. The overall agreement between theory and experiment is very good even at the high outgoing energies where direct collective processes dominate. It is worth emphasizing that the adequate account of all the low-energy collective

levels has removed the difficulties in describing the very end of the measured spectra where the method of [7] failed to account for all the collective strength [5, 6]. Of the giant resonances the most important here is the octupole giant resonance because it is concentrated at low energies (see LEOR in Table I). The experimental angular distributions are well reproduced over all the outgoing energy range as shown in Fig. 4. Comparison of the summed cross section for direct excitation of the collective modes with the cross sections for the incoherent MSD reactions and the MSC reactions in Table II shows clearly that the collective excitation does not make just a small correction to the two latter reaction mechanisms introduced by [2]. Thus one has to recognize that excitation of collective vibrations in nuclei including those in the continuum region is a third preequilibrium reaction mechanism, comparable in strength with the incoherent MSD reactions, though not as strong as indicated by some recent RPA analyses, which tend to ascribe practically all the direct cross section to collective excitations [35]. When comparing our cross sections for excitation of the collective modes with those obtained in [35] one should bear in mind that our absolute cross sections are well established owing to the phenomenological normalization of the macroscopic DWBA model via the effective deformation parameters.

We emphasise that all the calculations have been made without parameter adjustment. The slight dependence of the effective interaction strength V_0 on the bombarding energy [14] is insignificant in the present analysis since the incident energy range studied here is too narrow to reveal any changes in V_0 .

V. CONCLUSIONS

We have shown that the preequilibrium, multistep direct reactions consist of two distinctly different reaction mechanisms, which involve either incoherent particle-hole excitations on one hand, and the coherent collective excitations including giant resonances in the continuum region, on the other. The former reactions are to be identified with the MSD reactions of FKK. The collective excitations were known from spectroscopic studies of the low-energy vibrational levels of transitional nuclei in nucleon scattering and the macroscopic model describing them in the framework of DWBA was formulated quite early [20]. Nevertheless these reactions were not viewed as a competitive reaction mechanism which contributes throughout the scattered nucleon spectrum. Usually the collective cross sections in the continuum were masked by parameter adjustment within the semiclassical models of preequilibrium emission or within the MSD theory of FKK [5, 11, 36].

We have found the incoherent and the coherent direct excitations to be of comparable strength as shown in Table II. The clear distinction between the two mechanisms removes the inconsistency in the parameterisation of the MSD cross sections when applied simultaneously to nucleon scattering and to nucleon charge-exchange reactions [8, 9]. This result includes the neglect of collective enhancement of the continuous spectra from charge-exchange reactions. One has to be aware however that the isovector collective excitations, though much weaker than the isoscalar ones, do contribute to charge-exchange reactions and can be evaluated within the model applied provided the empirical data (effective deformation parameters) on their strength distribution are available.

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TABLE I. Energies and deformation parameters of one-phonon states and giant resonances in ^{92}Zr [27, 28].

$\omega_i \hbar$ (MeV)	ℓ^π	β_i
0.93	2^+	0.13
1.85	2^+	0.05
2.07	5^-	0.05
2.30	3^-	0.18
2.49	2^+	0.08
2.90	2^+	0.07
3.39	4^+	0.11
4.43	2^+	0.06
$36A^{-1/3}$	3^- (LEOR)	0.29
$62A^{-1/3}$	2^+ (GQR)	0.13
$77A^{-1/3}$	1^- (GDR)	0.07

TABLE II. Cross-sections (mb) of reactions contributing to neutron scattering by ^{93}Nb .

Reaction	Energy (MeV)		
	14.1	20.0	25.7
MSD	122	241	320
MSC	104	83	61
Collective	214	228	233
CN	1226	1052	760

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FIG. 1. Comparison of the measured angle-integrated c.m. cross sections for neutron emission from ^{93}Nb bombarded with 14.1 MeV neutrons [23], with calculated preequilibrium-MSC, incoherent MSD and coherent, collective (COLL) cross sections together with the cross sections for evaporation of primary CN1 and secondary CN2 neutrons and for (n, pn) CP2 evaporation from the compound nucleus. The collective cross section is a sum of the cross sections for population of the excited levels and the giant resonances listed in Table I. The thick solid line is the sum of all partial cross sections.

FIG. 2. The same as in Fig. 1 but at bombarding neutron energy 20 MeV [22]. The cross section labelled CN3 corresponds to evaporation of tertiary neutrons.

FIG. 3. The same as in Figs. 1 and 2 but at bombarding neutron energy 25.7 MeV [21].

FIG. 4. Comparison of the measured c.m. angular distributions of neutrons emitted from ^{93}Nb bombarded with neutrons of energies 14.1 MeV, 20 MeV and 25.7 MeV. The outgoing energy bins are given. The thick solid lines are sums of all partial cross sections (see Figs. 1 to 3). The strong partial cross sections are also shown (thin solid lines). The collective cross sections are labeled by the orbital angular momentum and parity transferred in the transition or by reference to the giant resonance.