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PRE-EQUILIBRIUM COLLECTIVE REACTIONS IN THE CONTINUUM[1]

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We show that pre-equlibrium inelastic scattering reactions to the continuum contain substantial collective components in addition to the multistep direct and multistep compound reactions. These collective cross-sections are calculated using the experimental data for low-lying collective excitations supplemented where necessary by the giant multipole resonances evaluated using the energy-weighted sum rule. The MSC and MSD cross-sections are evaluated by the Feshbach-Kerman-Koonin theory using a consistent set of parameters determined by analyses of (p, xn) reactions, that have practically no collective components. The results are compared with high-resolution neutron inelastic scattering data and prove able to account for the absolute magnitude of the cross-sections and also their detailed structure.

1. Introduction

Nuclear reactions to the continuum are successfully described by statistical multistep quantum-mechanical theories that give the cross-section as an incoherent superposition of single-particle excitations. Feshbach, Kerman and Koonin [1] (FKK) identified the multistep direct (MSD) and multistep compound (MSC) pre-equilibrium mechanisms that are followed by the statistical decay of the fully equilibrated compound nucleus (CN). Collective excitations were considered to be important only for the reactions to the lowest 2^+ and 3^- states; these are often resolved experimentally and can be calculated by quantum-mechanical theories [2]. This procedure may be satisfactory for the strong isoscalar-quadrupole excitations for some vibrational nuclei and for the

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strongly deformed nuclei in which 70% to 95% of the non-energy-weighted strength is in the few low-energy excited levels [3]. However the octupole electric giant resonance is centered at the excitation energy of $\sim 30A^{-1/3}$ and may be fragmented into many well separated states around that energy [4] so much of the collective strength will be spread over the continuum region [3, 4]. This is also supported by recent analyses of light-ion reactions based on realistic RPA calculations [5]. Including therefore the cross-sections for populating only the two lowest collective states implies that the remaining collective strength is included in the MSD cross-sections by adjusting the strength of the effective nucleon-nucleon interaction. The calculations then yield unphysical values for the parameters in the MSD calculations and the cross-sections cannot reproduce the high energy-resolution experimental spectra. The experimental data of [6] for example, for inelastic scattering of 14.1 MeV neutrons by a range of nuclei show peaks in the continuum at energies much larger than the lowest 3^- and 2^+ states and these cannot be accounted for by the MSD and MSC cross-sections but only by higher collective excitations or multipole resonances.

In this work we calculate the collective contributions to the continuum for the inelastic scattering of 14 MeV neutrons by a range of nuclei and compare the results with the high-resolution data of [6]. A brief summary of the multistep direct and multistep compound formalism is given in sect. 2 and in sect. 3 the cross-sections of the collective reactions are described. The calculations are compared with the experimental data in sect. 4 and our conclusions are given in sect. 5.

2. The Statistical Theory of Multistep Direct and Multistep Compound Reactions

The FKK theory for both the MSD and MSC processes has been extensively described [7, 8, 9] so here we give a brief account of the formulae we use to calculate the cross-sections without details of the derivations.

The FKK cross-section for multistep direct emission in the continuum can be written as an incoherent sum of a one-step term and multi-step terms. The multi-step terms can be expressed as a convolution of one-step cross-sections highlighting the simplicity of the theory. The one-step cross-sections are decomposed into the contributing transferred angular momenta L

$$\frac{d^2\sigma^{(1)}(\vec{k}_f,\vec{k}_i)}{dU\,d\Omega} = \sum_L \omega_{1p1h}(U)\, R_2(L) \left\langle \left[\frac{d\sigma}{d\Omega}\right]^{DW} \right\rangle_L , \tag{1}$$

where ω_{1p1h} is the level density given by [10] and $[d\sigma/d\Omega]_L^{DW}$ is the DWBA reduced cross-section. The angular momentum distribution is

$$R_2(L) = \frac{(2L+1)}{\sqrt{\pi(2\sigma_2)^3}} \exp\left[-\frac{(L+\frac{1}{2})^2}{2\sigma_2^2}\right], \tag{2}$$

where σ_2 is the spin cut-off parameter for $n = 2$ excitons and in general depends on the average number of excitons [11].

The original FKK theory for the MSC cross-sections has been modified to allow for transitions between the continuum (P-chain) and the quasi-bound states (Q-chain) after the first step which have been found to be important at 14.1 MeV [12, 13]. We use the formalism introduced by [12] which uses a phase-space model to determine the reduction of the incident flux into the MSC process (Q-chain) from

$$R = \frac{\omega^B(2p,1h,U)}{\omega(2p,1h,U)}, \tag{3}$$

where ω^B and ω are the state densities of the Q- and (Q+P)-states respectively. This approach reproduces the experimentally observed partitioning of the incident flux into P and Q-chain terms and is a simplification of the more sophisticated gradual absorption model [14, 15] which has also been derived theoretically in [16].

3. The Collective Model of Multistep Direct Reactions

The collective cross-sections are evaluated by a macroscopic collective model. The radial form factor for a certain shape oscillation is obtained by deforming the optical potential, and its magnitude is determined by an overall strength factor or deformation parameter.

The differential cross-section for an isoscalar transition of multipolarity ℓ has the form [17]

$$\left.\frac{d\sigma_n}{d\Omega}\right._{one-phonon} = \beta_\ell^2(n) \left[\frac{d\sigma_n(\theta)}{d\Omega}\right]_\ell^{DW(macr)} , \tag{4}$$

where $[d\sigma(\theta)/d\Omega]_\ell$ is the reduced macroscopic DWBA cross-section calculated with the radial form factor for zero spin and isospin, and β_ℓ is the deformation parameter- a measure of the strength of the ℓ-multipole excitation. The ℓ-multipolarity of an excited state is determined from the shapes of the angular distributions, and β_ℓ is adjusted to give the magnitude of the experimental distributions. This procedure is followed for low-lying discrete states. For giant resonances, however, the β_ℓ parameters are usually obtained by exhausting the energy-weighted sum-rule [18] which for isoscalar transitions has the form

$$\begin{aligned} S_{EW}^\ell &= \left(\frac{\hbar^2 A}{8\pi m}\right) 3\ell R^{2\ell-2} \\ &= \sum_n \hbar\omega_\ell(n)\beta_\ell^2(n) \left(\frac{3A}{4\pi}\right)^2 \frac{R^{2\ell}}{(2\ell+1)} \end{aligned} \tag{5}$$

where $\hbar\omega_\ell(n)$ is the excitation energy of a given state n with spin ℓ, A is the atomic mass number of the target nucleus and m the nucleon mass. In the above equation we have assumed a uniform distribution of the target nucleons.

The differential cross-sections calculated by (4) are extended to the continuum by a summation over the individual states including the giant resonances and are spread over energy according to a gaussian with a width appropriate to the experimental energy resolution, giving

$$\frac{d^2\sigma}{dE d\Omega} = \sum_{n,\ell} \beta_\ell^2(n) \left[\frac{d\sigma_n}{d\Omega}\right]_\ell^{DW} f_\ell[\hbar\omega_\ell(n), \Gamma], \qquad (6)$$

where f_ℓ is the energy distribution function mentioned above with width Γ. For the giant resonances a Lorentzian distribution with width $\Gamma = 5$ MeV is used.

Second-order effects, namely two-phonon excitations, are very weak, by an order of magnitude compared with the one-phonon excitations, so we neglect them.

4. Calculations and Results

The cross-sections for the inelastic scattering of 14.1 MeV neutrons by ^{56}Fe, ^{58}Ni, ^{90}Zr, ^{93}Nb, ^{208}Pb and ^{209}Bi have been calculated and compared with the experimental data of [6]; a complete description of the calculations and the results is given in [19].

The MSD cross-sections were calculated using DWUCK4 [20] to obtain the reduced DWBA cross-sections with a Yukawa effective nucleon-nucleon potential of range $1fm$. The three parameters: the strength $V_0 = 28\pm3.5$ MeV [21] of the effective interaction, the single-particle level density $g = A/13$ and the spin cut-off parameter $\sigma_2^2 = 0.28 \times 2 \times A^{2/3}$ [11] were established in separate analyses of (p, xn) reactions which are free of the strong isoscalar collective excitations [22]. Thus the calculations are free of adjustable parameters, and any shortfall compared to the data indicates the presence of collective excitations in the continuum.

The MSC cross-sections were calculated with the state density of [23] and the spin cut-off parameter of the spin distribution given in [11], $\sigma_n^2 = 0.24nA^{2/3}$, for the intermediate number of excitons n involved in the MSC configurations. The calculations were carried out with the MSC5X code [12].

After the first three MSC stages we assume that the energy of the projectile has been shared statistically among so many nucleons that the compound nucleus can be considered as equilibrated. Emission from the compound nucleus stage is calculated by the Hauser-Feshbach [24] theory using the STAPRE-H code [25, 26]. The contribution from the remaining reactions such as the $(n,p),(n,\alpha),(n,2n),(n,pn),(n,\alpha n)$ are also included in this code.

At low incident energies the cross-sections for inelastic nucleon scattering favours collective isoscalar transitions by a factor of 9 over transitions with $s = 1$ and/or $t = 1$. Based on this we include only the isoscalar electric vibrations in our analysis as described in sect. 3. These were calculated by (6) using the code DWUCK4 with a macroscopic collective form factor for all the multipolarities ℓ that have been measured and for which values of the deformation parameters β_ℓ have been well determined. The giant dipole (GDR), quadrupole (GQR), low-energy octupole (LEOR) and high-energy octupole (HEOR) resonances have been taken to have excitation energies given by the empirical formulae $\sim 82A^{-1/3}, \sim 63A^{-1/3}, \sim 31A^{-1/3}$ and $\sim 103A^{-1/3}$ respectively [4]. Their deformation strengths were subsequently estimated by exhausting the corresponding

energy-weighted sum-rule (5) along with the contributions from the low-lying excited states of the same multipolarity. We find that at the incident energy of 14.1 MeV the GDR, GQR and the HEOR contribute by an insignificant amount at even the highest excitation energies , so we neglect them, whereas the LEOR contributes substantially to the preequilibrium energy region and is included in the analysis. Furthermore, for all nuclei except ^{58}Ni we assume that the octupole EWSR is exhausted by the low-lying 3^- states and the LEOR, so that our estimates of the LEOR cross-sections are upper limits. For ^{58}Ni we use the results of [27] where the LEOR is not observed as a strong excitation of a giant resonance type, but as a superposition of discrete collective states with energies ranging from 6 to 10 MeV that exhaust up to 17% of the EWSR.

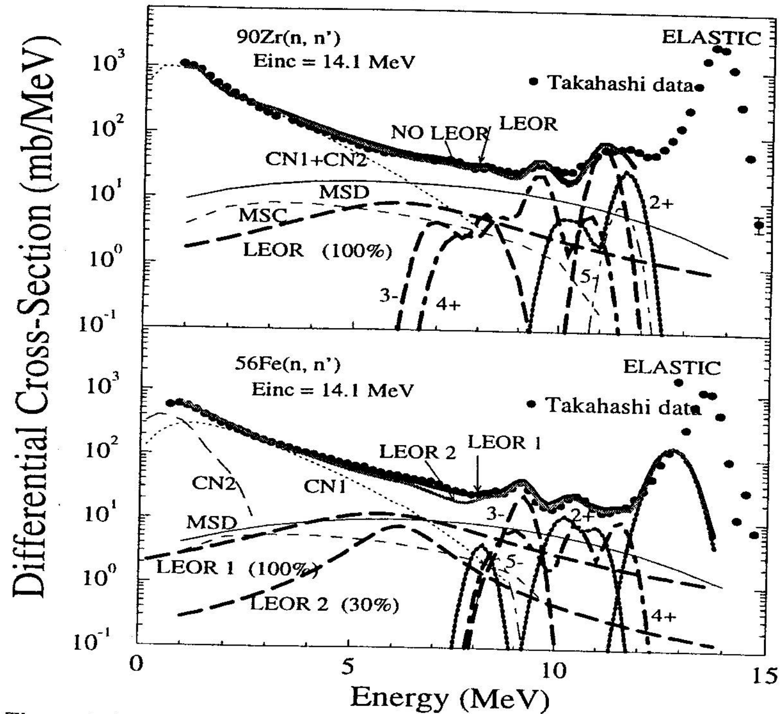

Fig. 1. The angle-integrated energy spectra of neutrons inelastically scattered from ^{90}Zr and ^{56}Fe at 14.1 MeV [6] compared with MSD (thin solid curve), MSC (thin dashed curve), CN (thin dotted curve), secondary compound nucleon emission (CN2) (thin long-dashed curve) and collective cross-sections that include the 2^+ (thick dotted curve), 3^- (thick long-dashed curve), 4^+ (thick dot-dashed curve), 5^- (thin dot-dashed curve) states and the LEOR (thick long dashed curve) assuming 100% and 30% exhaustion of the EWSR respectively. The thick full curve is the incoherent sum of all these cross-sections.

The main sources for estimates of the excited collective states and corresponding deformation parameters are measurements of proton and alpha-inelastic scattering. The

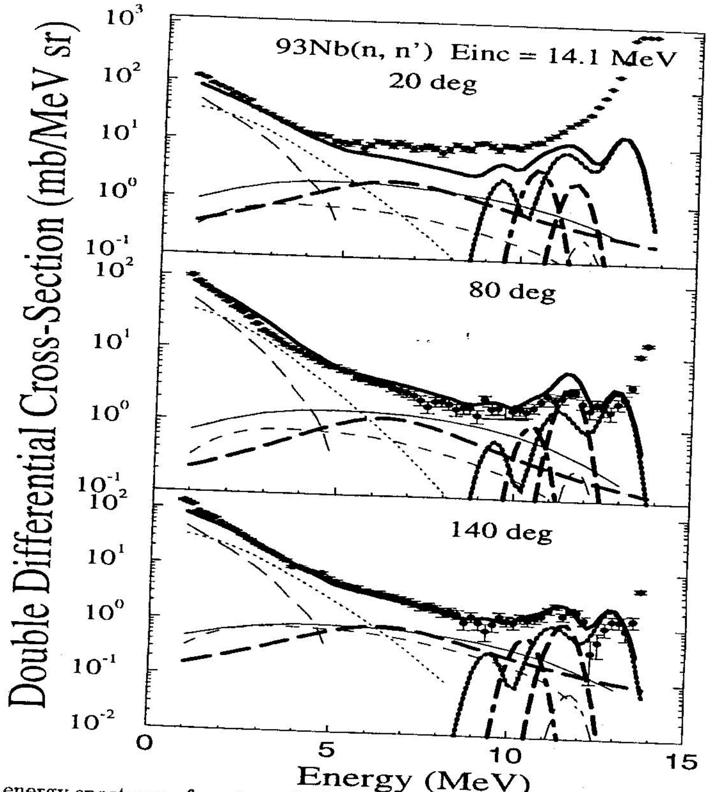

Fig. 2. The energy spectrum of neutrons inelastically scattered from ^{93}Nb at 14.1 MeV at three angles 20°, 80° and 140° [6] compared with MSD (thin solid curve), MSC (thin dashed curve), CN (thin dotted curve), secondary compound nucleon emission (CN2) (thin long-dashed curve) and collective cross-sections that include the 2^+ (thick dotted curve), 3^- (thick long-dashed curve), 4^+ (thick dot-dashed curve), 5− (thin dot-dashed curve) states and the LEOR (thick long dashed curve). The thick full curve is the incoherent sum of all these cross-sections.

excitations and corresponding deformation strengths included in our analysis together with the estimates of the strengths and widths of the distributions of the giant resonances are presented in [19].

The incoherent sums of all these contributions are compared with the angle-integrated experimental cross-sections in Fig. 1 for ^{56}Fe and ^{90}Zr and with some energy distributions at 20°, 80° and 140° for ^{93}Nb in Fig. 2. The calculated cross-sections give an overall good description of the data and are able to account for the detailed structure in the higher outgoing energy region.

The strength of the LEOR for ^{56}Fe, ^{90}Zr, ^{93}Nb, ^{208}Pb and ^{209}Bi, which was calculated by depleting all the EWSR with the lower energy octupole strength and low-lying excitations only, includes the higher energy octupole resonance strength and also the

strengths of all the non-collective single-particle transitions of $\ell = 3$ multipolarity and natural parity. The latter transitions are described by the MSD reaction theory and are therefore included in the MSD cross-sections as well. The total cross-sections thus include the cross-sections for these transitions twice and as a result flux is not conserved.

The problem of double-counting can be overcome by assuming that the strengths of the LEOR and low-lying collective excitations exhaust ≈ 30% of the EWSR. According to [28] nuclei with 66≤A≤200 show a broad resonance located at $30A^{-1/3}$ MeV with a width Γ ≈2 MeV exhausting from 7 to 23% of the EWSR. Together with the low-lying $\ell = 3^-$ collective states this bump identified as the LEOR would exhaust ≈ 30-35% of the EWSR. Other observations show that for some nuclei about 15 to 17% of the octupole strength is located in clusters of states or well separated states around and below $30A^{-1/3}$ MeV which is the energy location of the LEOR [29] as in the case of ^{58}Ni [27]. With these considerations the estimates of the LEOR strength for ^{56}Fe is reduced and the total cross-sections underestimate the experimental cross-sections in the 6 to 10 MeV excitation energy region. For the other three nuclei almost over 30% of the EWSR is already exhausted by the low-lying collective excitations implying that the low energy octupole strength is distributed among individual states and does not appear as a giant resonance. The effects of these corrections for ^{56}Fe and ^{90}Zr are shown in Fig. 1.

5. Conclusions

The excitation of the collective vibrations of different multipolarity as derived from nuclear structure studies was found responsible for all the structure in the cross sections of the (n,xn) reaction on the vibrational target nuclei measured in experiments of high energy resolution. The distinction between the MSD reactions limited to incoherent particle-hole excitations and the coherent collective reactions exciting primarily one-phonon states gives a consistent description of (n, xn) and (p, xn) reactions and provides a practicable method for calculating the cross-sections for excitation of the collective states including the giant resonances in the continuum region, using the macroscopic DWBA model [18]. The absolute values of the collective cross-sections are well determined by normalising using the measured deformation parameters.

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