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INTERMEDIATE STRUCTURE AND THRESHOLD PHENOMENA

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The Intermediate Structure , evidenced through Microstructures of Neutron Strength Function, is reflected in open reaction channels as fluctuations in excitation function of Nuclear Threshold Effects. The Intermediate State supporting both Neutron Strength Function and Nuclear Threshold Effect is a Micro-Giant Neutron Threshold State.

1. INTRODUCTION

A potential connection between two apparent distinct topics of the Nuclear Reactions Physics, Threshold Phenomena and Intermediate Structure, was firstly stated decades ago, [1], [2]. Subsequently, the Micro-Giant Approach to Nuclear Threshold Effects has been reiterated in other works too, *e.g.* [3], [4]. This Report does approach the subject from perspective of present knowledge.

2. INTERMEDIATE STRUCTURE IN NUCLEAR REACTIONS

The nucleus continuum, explored by means of nuclear reactions, does exhibit a large spectrum of resonant-like structures: sharp narrow resonances, gross resonant structures,intermediate resonant structures. The narrow resonances are associated to Compound Nucleus, the gross-resonant structures to Single Particle Resonances, while the Intermediate Structure to Doorway States.

Intermediate Structures, superposed on a continuum of statistical levels, were evinced in excitation functions of some nuclear reactions; these structures were interpreted as originating in Intermediate (or Doorway) States, see *e.g.* [5]. An Intermediate State is visible experimentally as an Intermediate Structure only if its "Escape Width" $\Gamma^{\uparrow}$ is larger than "Spreading Width" $\Gamma^{\downarrow}$; otherwise it will be spreaded in continuum of statistical levels. The spreading width of the Intermediate State is proportional to probability for dissipating in compound nucleus states, while its escape width is proportional to probability of decay in incident reaction channels.

The Problem of the Intermediate Structure is to understand the nature of the Intermediate State and the mechanism which reduces its coupling to complicated compound nucleus states. A well-known example of Doorway State is the Isobaric Analog Resonance, see [6]. The Isobaric Analog Resonance is a member of an isobar multiplet, energetically shifted at positive energy by coulombian interactions; the Isospin Symmetry prevents the spreading of Isobaric Analog Resonance in complicated compound nucleus states.

Later on, the concept of Intermediate Structure was included by Lane, [7], in that of "Line-Broadening". This approach does assume the existence of a "Special State" which has a large overlap of one (or few) reaction channels, (i.e. large escape width). By "residual forces" the "Special State" is mixed to "ordinary" or continuum states, resulting in "Line-Broadening" phenomenon. Lane considered, [7], there are only five types of Line-Broadening in Nuclear Physics: (1) Single Particle States, (2) usual Doorway States, (3) Isobaric Analog Resonances, (4) Giant Multipole States, (5) Fission Doorway States.

One proves that the Threshold States are an additional example of Line-Broadening in Nuclear Physics.

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3. NEUTRON THRESHOLD STATE

The Threshold State is a special quasistationary state, coincident in energy with threshold, which has a large reduced width ($\cong$Wigner unit γ_W) for decay in the threshold channel, see [8].The reduced width is a measure of single particle character of the level in interior region. The probability of finding a pair of threshold particles out of channel radius is proportional to the threshold channel reduced width; a very large reduced width will result into level "explosion" out of channel radius .

The spatial extension of a state is described by renormalization of its wave function out of channel radius. The "spatial extension" renormalization-factor,[9], is identical to "threshold compression" factor of R- Matrix Theory, [10], $\beta(E)=1/[1+\gamma^2_{\pi n} dS_n/dE]$. Here S_n denotes the shift-factor of threshold channel n and $\gamma_{\pi n}$ is the reduced width for decaying of the Threshold Level π in threshold channel n. The "threshold compression" factor $\beta(E)$ results into changes of the resonant level's energy, $E_\pi \rightarrow \beta E_\pi$, and of the total width, $\Gamma \rightarrow \beta\Gamma$. It is proved, at least in neutron case, that $dS_n/dE>0$ and this results into $\beta<1$. In the limit $\beta \rightarrow 0$, the level is shifted to zero (threshold) energy and the decay width is compressed. A large reduced width $\gamma_{\pi n}$ (order of Wigner unit γ_W) is vital for small values of β-factor. A near-threshold level, having a large reduced width for decay in threshold channel, is shifted towards threshold and its width (including spreading component) is compressed. [If the level is far away from threshold, then $S_n(E)$ does not change very much with energy, $dS_n/dE \cong 0$, or if its reduced width is small $\gamma_{\pi n} \cong 0$, then in both cases $\beta \rightarrow 1$]. The β-factor is essentially smaller than unity only for levels interplaying with threshold, $|E_\pi - E_{thr}| < \Gamma_\pi$, and decaying preferentially in threshold channel, $\gamma_{\pi n} \cong \gamma_W$.

The Threshold State could be described, in a first approximation, as a Single Particle State coincident with threshold; its overlap $\gamma_{\pi n}$ with threshold channel is very large, i.e. it has a large escape width $\Gamma^{\uparrow}_{\pi}$ By residual interactions the Single Particle Resonant State is spread out over compound nucleus actual levels. The group of actual levels, carrying out a substantial fraction of Single Particle State, constitues the Giant Resonance, (Micro-Giant Model of Lane-Thomas-Wigner, for Single Particle Resonance, see [10]).

The Threshold State is highly excited state, embeded in a continuum of statistical levels. The Threshold State has a small overlap to inner compound nucleus states because of its spatial extension, out of channel radius. The Threshold State is decoupled from statistical levels by the "de-enhancement" factor β, resulting in a small spreading width $\Gamma^{\downarrow}_{\pi}$ The Micro-Giant Threshold State is an additional example of "Line-Broadening" in Nuclear Physics. Both the "doorway" nature of the Threshold State as well as the mechanism preventing its spreading in statistical continuum originate in its very large spatial extension, (out of channel radius).

The Micro-Giant Neutron Threshold State is not more described by neutron reduced width but rather by its statistical counterpart, the Neutron Strength Function, (next paragraph). Then the Neutron Threshold State's role in producing significant threshold effects in open competing channels, [11], is approached in terms of Quasi-Resonant Scattering, [12], and of Neutron Strength Function.

4. NEUTRON STRENGTH FUNCTION

A Compound Nucleus Resonance implies, according to Bohr, multinucleon excitations. The first configuration of this developing process corresponds to independent motion of incident nucleon in the self-consistent nuclear potential of the compound system. This motion is described by Independent Particle Models as Shell Model (for negative energies) and Optical Model (for positive energies). The Optical Model does generate a continuum of scattering states, modulated in amplitude by the (Optical Model Shape or) Single Particle Resonances. The single particle motion is followed, in this hierarchy, by processes of higher complexity, culminating with formation of the Compound Nucleus Resonance(s). This path is mediated through residual interactions. The Single Particle Model configuration (Shell Model Bound State at negative energy, or Optical Model Resonance at positive energy) is fragmented through residual interactions into many components, modulating (enhancing) the actual compound nucleus levels and resulting in a Giant Resonance.The (broad) Giant Resonances correspond to each of the single particle states of the compound system when the residual interaction was neglected. The Neutron Giant Resonance Spectroscopy is not more described by Neutron Reduced Width but rather by Neutron Strength Function.

The Strength Function is the mean strength of reduced widths of actual compound nucleus resonances. It is defined as the total value of reduced width $\gamma_{\lambda n}$ of actual λ states per unit energy interval,

$$S_{\lambda n} = < \gamma^2_{\lambda n} \rho_\lambda >$$

where ρ_λ is the density of λ levels. This statistical spectroscopic quantity is defined as the overlap of Single Particle State and compound nucleus states, giving how much the Single Particle State is mixed with actual states of the nucleus. The Strength Function displays maxima whenever a Single Particle state is present. The amplitude modulation of the Strength Function , resembling to a gross-resonant structure, reveals existence of single particle nucleon state in nucleus.

The Giant Resonances are (e.g. neutron) Single Particle Resonances which are split , by residual interactions, into complicated Compound Nucleus states. If single particle fragments (components) are uniformly spread into each other by mixing in more complicated states, then there results a homogenous background and a Breit-Wigner shape of the Strength Function. If the corresponding components are not uniformly spread into each other then there occur fluctuations of the Breit-Wigner line shape, [7]. Fluctuations in excitation function of the Neutron Strength Function, depending on nature of the involved nuclear states, has been predicted for a long time, [13]. According to G.E. Brown, the Intermediate Structure is evidenced as an amplitude modulation of the Strength Function.

5. NEUTRON THRESHOLD STATES AND NUCLEAR THRESHOLD EFFECTS

A Neutron Threshold State π is a neutron single particle state, coincident in energy with threshold, $|E_\pi - E_{thr}| < \Gamma_\pi$, which decays preferentially in neutron channel, $\Gamma_\pi \cong \Gamma_{\pi n}$, ($\Gamma_\pi$ and $\Gamma_{\pi n}$ are the total width, respectively, the partial width for decay in neutron threshold channel). Its reduced width for decay in threshold channel does approach the maximal value of Wigner unit, $\gamma_{\pi n} \cong \gamma_W$. It is expected a Neutron Threshold State will induce significant threshold effects in open competing channels. Indeed, the threshold effects are related to flux transfer to threshold channel and the flux leakage of a resonance is controlled by resonance's reduced width and channel penetration factor.

The flux leakage from a resonance (λ) to reaction channel (n) is described by the partial resonance decay width, $\Gamma_{\lambda n}{}^{1/2} = P_n{}^{1/2} \gamma_{\lambda n}$; i.e. the preformation factor of (n)-particle in (λ) resonance, (particle reduced width $\gamma_{\lambda n}$), and the penetration factor (P_n) of the channel barrier. The reduced width $\gamma_{\lambda n}$ is amplitude of single particle component (n) in the wave function of the resonant state (λ). The resonance total width, $\Gamma_\lambda = \Gamma_{\lambda n} + \Gamma_{\lambda a} + \Gamma_{\lambda b} + ...$, gives the flux leakage in all reaction channels. The threshold effect is directly related to flux absorbed by threshold channel; this results into condition $\Gamma_\lambda \cong \Gamma_{\lambda n}$, i.e the resonance has a large neutron reduced width, approaching its maximal value, $\gamma_{\lambda n} \cong \gamma_W$, (reduced width Wigner unit). The necessary conditions for a significant threshold effect are energy coincidence of the resonance π with neutron threshold,$|E_\pi - E_{thr}| < \Gamma_\pi$, and its preferential decay, $\gamma_{\pi n} \cong \gamma_W$, in neutron threshold channel, [11].

The Multichannel Resonances are either Compound Nucleus Resonances or Coupled Channel Resonances. The Coupled Channel Resonances, (Quasi-Resonant Scattering), originate in Single Particle Resonances: a selective and strong Direct Channel Coupling of a Single Particle Resonance to other competing reaction channels results into a multichannel resonance, [12] .

The Quasi-Resonant Scattering process consists of direct channel-channel ($a \rightarrow n; n \rightarrow b$) transitions, followed or preceded by a Single Channel (n) Resonance (π). This process is experimentally evinced as resonant structures in some reaction channels; complementary competing reaction channels show a monotone energy dependance. The magnitude of the quasiresonant process is proportional both to channel coupling strengths (Γ_{an},Γ_{nb}) and to the reduced width ($\gamma_{\pi n}{}^2$) of the (Neutron) Single Channel Resonance. The last property is subject of this chapter.

A peculiar aspect of a quasi-resonant process comes into play if the ancestral single particle state π is located near n channel threshold. A near-threshold Neutron Single Particle Resonance will induce, via Quasi-Resonant Scattering, a threshold effect in open reaction channels (a,b). A R- Matrix parametrization of the Quasi-Resonant Threshold term, ΔS_{ab}, of S- Matrix formula displays a strong energy dependance of the resonance denominator via neutron threshold channel logarithmic derivative L_n=S_n+iP_n.

$$\Delta S_{ab} = \frac{\Gamma_{an}\gamma_{\pi n}^2\Gamma_{nb}}{E_\pi - E + S_n\gamma_{\pi n}^2 - i(P_n\gamma_{\pi n}^2 + \Gamma')}$$

The Resonant Threshold Structure's total width displays the decay partial widths for threshold channel, ($P_n\gamma_{\pi n}{}^2$), and for complementary open channels Γ'. The non-linear energy dependance of the level-shift term, $S_n\gamma^2{}_{\pi n}$, results into a "threshold compression" factor, $\beta(E)=1/[1+\gamma_{\pi n}{}^2 dS_n/dE]$, [9], [10]. One has to mention that this type of formula has been proposed by Lane, [9], as basis of a phenomenological model for the Deuteron Stripping Threshold Effect, $\alpha/[E_\pi - E + S_n\gamma_{\pi n}{}^2 - i(P_n\gamma_{\pi n}{}^2 + W)]$, where W is spreading width and α parameters are related to (isospin proton-neutron) channels coupling strength.

As mentioned before, the Single Particle State is spread out , by residual interactions, over the actual (compound nucleus) levels. By averaging over actual levels one obtains the result the Quasi-Resonant Threshold effect is proportional to Neutron Strength Function, $<DS_{ab}>\sim<\gamma_{\pi n}{}^2>\sim S_{pn}$. [The only fluctuant quantities are neutron reduced width $\gamma_{\pi n}{}^2$ and total resonance width Γ; the other terms (Γ_{an},Γ_{nb},S_n,P_n) are monotone energy dependent and are not involded in averaging. The averaging method used here is Brown procedure, [13]; one has to avoid a small region at threshold-branch point.] The relation Threshold Effect magnitude - Neutron Strength Function, , α - $<\gamma_{\pi n}{}^2>$, was firstly obtained by another procedure, [1],

$$\alpha_{ab} = \Gamma_{an} < \gamma_{\pi n}^2 > \Gamma_{nb}$$

with Γ_{an} and Γ_{nb} as coupling strengths of the threshold channel n to open ones.

The magnitude of a threshold effect does depend not only on Reaction Mechanism but also on Spectroscopical Amplitude, (i.e. neutron reduced width), of the ancestral quasistationary threshold state. A threshold quasistationary state does act as an amplifier for flux transfer to threshold channel provided state-channel overlap is large, i.e. it has a large reduced width for decay in threshold channel. The Micro-Giant properties of Neutron Threshold States have to be reflected in corresponding threshold effects.

6. INTERMEDIATE STRUCTURE IN NUCLEAR THRESHOLD EFFECTS

The averaged threshold effects, originating in Single Particle Neutron Threshold States, are directly related to Neutron Strength Function, $\alpha\sim S_n$. This relationship does allow to deduce observed characteristics of the Threshold Effect from those of Neutron Strength Function. One can also adopt the inverse procedure, to obtain properties of Neutron Strength Function from experimental parameters of threshold effect.

Let us discuss the structures induced in threshold effects via Neutron Strength Function, [1]. The structures in Neutron Strength Function are related to structure of the nuclear state in compound system, (from exit threshold channel), formed by neutron coupled to residual nucleus state. The system neutron + non-zero spin state can be coupled to various angular momenta. This way, the Shell Model configuration can be fragmented, through the residual interactions, into many components. If these components spread into each other by mixing into more complicated states, then there results a homogenous Breit-Wigner shape for the Neutron Strength Function. For a system neutron + zero spin state of residual nucleus, one can expect less fragments and that the resulting components are not uniformly spread into each other; then there occur fluctuations in the Breit-Wigner line shape of the Neutron Strength Function. G.E. Brown, [13], has predicted fluctuations of the Neutron Strength Function, depending on nature of involved nuclear states: the Intermediate Structures is displayed as microstructures of the Neutron Strength Function.

The specific aspects of the Intermediate Structure in Neutron Strength Functions and Nuclear Threshold Effects are related to "threshold compression" (or non-linearity) of energy scale. The apparent density of near-threshold microstructures (or fluctuations) could increase by an order of magnitude; only disparate microstructures could remain visible experimentally in excitation function of threshold effects.

Assuming this interpretation is correct, one could observe fluctuant threshold anomalies when the residual nucleus state in threshold channel has a simple relative structure (e.g. even-even nuclei). The non-fluctuating type of threshold anomalies, according to this view, should be related to complicated (non-zero spin) states of residual nucleus in threshold channel

A similar interpretation was proposed by Lane, [2], by taking into account the coupling 0^+-2^+ states in residual nucleus. Then one can observe a definite number of structure components in Neutron Strength Function and this should be a global property for all even-even residual nuclei.

The analysis, [1], [2], of experimental data for Deuteron Stripping Threshold Anomaly does support the Intermediate Structure interpretation for fluctuations observed in the excitation function of this threshold effect. The Deuteron Stripping Threshold Anomaly originates in 3-*p* wave neutron threshold state and its structure does reflect that of the 3-*p* wave Neutron Strength Function.

A similar analysis for Isotopic Threshold Effect was not yet performed. In this case all threshold reaction channels have non-zero spins (mirror iso-doublet nuclei) except only one case, (a member of an isospin triplet). A Fourier analysis of these data, [14], does display, in addition to gross-single particle component, (~500 keV), small width compound nucleus structures and fluctuations(~100 keV).

7. CONCLUSIONS

This Report discussed several subjects relating Intermediate Structure and Threshold Phenomena in Nuclear Reactions: (a) Neutron Threshold State as a Doorway (Intermediate) State, (b) Neutron Threshold States and Quasiresonant Threshold Effects, (c) Intermediate Structure in Neutron Strength Function, (d) Evidence for Intermediate Structure in averaged Threshold Effects, via Neutron Strength Function. Indirect information about Neutron Strength Function could be obtained from averaged Threshold Effects, both at positive (above threshold) and negative (below threshold) energies. The mass dependance of Neutron Strength Function determines the mass dependance of the threshold effects magnitude, [15]. The energy dependance of Neutron Strength Function determines the "excitation function" of threshold effect; it does support Intermediate Structure interpretation of Micro-Giant structures observed in threshold effects. One establishes a definite connection between two (apparent distinct) topics, the Threshold Phenomena and Intermediate Structure in Nuclear Reactions. This work is complementary to [15] in studying relationship between Neutron Strength Function and Nuclear Threshold Effects.

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