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Dedicated to Professor Valentin I. Vlad's 70$^{\rm th}$ Anniversary

ON P-WAVE THRESHOLD PHENOMENA IN NUCLEAR AND BARYONIC REACTIONS

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Abstract. Two p-wave threshold phenomena related either to Quasinuclear Baryon States or to Neutron Threshold State are discussed in parallel approaches.

The p-wave threshold phenomenon in Low Energy Nuclear Physics originates in Neutron Threshold State and to its Direct Interaction Coupling to open observed channels. The Neutron Threshold State is approached in terms of "threshold channel compression factor", representing the wave function spatial extension out of nucleus radius and renormalization of decay width.

The Quasinuclear Baryon-Antibaryon States are near-threshold states, spatially extended out of annihilation channel radius. The present discussion of Quasinuclear Baryon-Antibaryon States is based on their similar properties to Neutron Threshold States. The spatial extension of Quasinuclear State and its Direct Coupling to complementary symmetry-channels prevent the disintegration into annihilation channels. The isospin-symmetry coupling of $p-$wave quasinuclear $\Lambda\bar{\Lambda}$ to proton-antiproton $(p,\bar{p})$ open reaction channels, results into Coupled Channel Resonance which should manifest in the threshold behaviour of both $(p,\bar{p})$ and $(p\bar{p}\to\Lambda\bar{\Lambda})$ reactions.

1. INTRODUCTION

The Wigner-Breit-Baz Cusp Theory, [1–3], predicts s-wave nuclear threshold effects due to neutron opening channel. S-wave threshold effects were observed in some reactions on light nuclei; however they cannot be interpreted as evidence for a genuine threshold cusp, see [5]. On other side, p-wave threshold effects have been observed in some Low Energy Nuclear Reactions, [6–8, 39], becoming subject of many experimental and theoretical investigations, (see [30] and references therein). The spectroscopic aspects of p-wave threshold effects (relation to Neutron Strength Function) have been recently discussed, [9].

The Threshold Physics field appears to be more rich in phenomena than in schematic descriptions. Understanding of the physical aspects of the p-wave threshold effect should be of interest not only in Low Energy Nuclear Physics, see [5], but also in the other Quantum Scattering fields as Atomic Collisions, see [10], and High Energy Physics, see [11].

The p- wave threshold phenomenon in Low Energy Nuclear Physics is related to Neutron Threshold State and to its Direct Interaction Coupling to open observed channels, [21]. Spectroscopic aspects of the threshold effect, both with respect to magnitude and microstructure, are discussed in terms of the Strength Function (statistical spectroscopic factor) of the Neutron Threshold State [30]. The Neutron Threshold State is related to R-Matrix "compression factor", representing both threshold channel renormalization of spectroscopic factor as well as the wave function spatial extension out of nucleus radius.

The Quasinuclear Baryon-Antibaryon States are distinguishable from usual Quark-Model States by weak-binding energies and relative larger rms radius; they coexist with (without spreading into) annihilation channels. The Quasinuclear Baryon-Antibaryon States were formally approached in terms of the Coupled Channel Model taking into account both baryon-antibaryon channels as well as the annihilation ones, [11]. The Quasinuclear Baryon-Antibaryon $p-$ wave states, (*e.g.* $\Lambda\bar{\Lambda}$), [11], are spatially extended states, out of annihilation radius. The present approach to Quasinuclear Baryon-Antibaryon States is based on their similar properties to Neutron Threshold States. The threshold channel renormalization of Quasinuclear State decay width implies its non-dissolution in annihilation channels. The Direct Coupling of Quasinuclear State channel to complementary symmetry-channels is another source for compression of the decay width, [21]. The two mechanisms, Quasinuclear Baryon State spatial extension (via threshold compression) and direct channels couplings (*via* direct compression) prevent the state dissolution into annihilation channels. The Quasinuclear Baryon-Antibaryon $p-$ wave states are coupled by isospin symmetry to proton-antiproton $(p,\bar{p})$ open reaction channels, resulting in Quasiresonant Scattering, [21]. In last part of the work one discusses, in terms of R-Matrix and of symmetry multiplets, the threshold behaviour of both $(p,\bar{p})$ and $(p\bar{p} \to \Lambda\bar{\Lambda})$ reactions.

2. LANE MODEL FOR P-WAVE THRESHOLD EFFECTS

A deuteron stripping threshold effect in Low-Energy Nuclear Physics was evinced both in cross-section [6] and polarization [7] experiments. The main experimental characteristics of this threshold effect were systematized by Lane [17]: (1) the threshold effect in $A(d,p_0)B_0$ stripping reactions is not related to lowest $A(d,n_0)C_0$ neutron threshold but rather to the threshold of neutron analogue channel $A(d,\bar{n})T^{-}B$, (T-isospin operator), (2) it manifests as a dip (reversed resonant shape) in cross-section excitation functions, the typical dip half-width is 1 MeV, and (3) the strength of the threshold effect is dependent on mass number of residual (or target) nuclei, the maximal strength is for $A \sim 90$ mass nuclei.

The first experimental observation, [6], was considered as evidence for isospin coupling of exit proton $(p + B)$ and analogue neutron $(\bar{n} + T^{-}B)$ channels. This experimental fact was basis for the Coupled Channel Born Approximation Model, [12]. The threshold effect mass dependence was related to the computational remark, [13], on the dominance near zero-energy of the $p-$wave neutron transmission factor for $A \sim 90$ mass nuclei. Both Shell Model and Optical Model calculations, *e.g.* [25, 37], predict the $3-p$ wave neutron single particle state near zero-energy for $A \sim 90$ mass nuclei. The last remark is basis for the Lane's Model, [17], for deuteron stripping threshold effect with $A \sim 90$ mass nuclei. One should mention that that the Wigner-Breit-Baz theory, [4], for genuine cusp threshold effect cannot account for deuteron stripping threshold effect, [14–16].

The Lane Model, [17], is based on existence of zero-energy neutron $3-p$ wave single particle resonance, specific to $A \sim 90$ mass nuclei, as well as on isospin coupling of underlying neutron threshold channel to the observed proton channel. The $3-p$ wave neutron single particle resonance is parametrized in R-Matrix terms, $1/[E_{\pi} - E - L_n \gamma^2_{\pi n} - iW]$, with E_{π} neutron resonance energy, $E_{\pi} \sim 0$, $\gamma^2_{\pi n}$- neutron reduced width, $L_n = S_n + iP_n$ - $p-$ wave neutron channel logarithmic derivative, (S_n - shift factor, P_n - penetration factor), W- spreading width. (The spreading width is a measure of mixing of single particle state with complicated actual states; its order of magnitude is 10 MeV). The total resonance width $i\Gamma_{\pi}$ comprises both natural decay width $i\Gamma_{\pi n}$ $=iP_n\gamma^2_{\pi n}$ and spreading width iW. The threshold feature of the Lane Model is the strong energy dependence near threshold of the neutron channel logarithmic derivative; it implies a non-linearity of the energy scale for resonance denominator. The L_n energy dependence results into distortion of the resonance's shape, *esp* for s- and p- waves. In the Thomas approximation, [18], $S_n = S_n(0) + ES'_n(0)$, ($'$ - energy derivative), the near-zero energy or threshold neutron single particle resonance becomes $1/[\bar{E_{\pi}} - E - i(\bar{\Gamma}_{\pi n} + \bar{W}]$ with threshold channel renormalization of level energy $\bar{E_{\pi}} = \beta_{\pi n}(0)(E_{\pi} - S_n(0)\gamma^2_{\pi n})$ and of the total width $\bar{\Gamma}_{\pi n} + \bar{W} = \beta_{\pi n}(0)(\Gamma_{\pi n} + W)$. The compression factor $\beta_{\pi n}(0) = 1/[1 + \gamma^2_{\pi n} S'_n(0)]$ is subunitary because, at least in neutron case, the slope of the shift factor is positive. Its minimal value is attained just or near the threshold. Far-away from threshold, $S_n \sim const$, the compression factor plays no more role $\beta_{\pi n} \sim 1$. Observe also that small value of compression factor requires a big value of neutron reduced width *i.e.* the single particle characteristic of the π neutron threshold state. The resonance's energy E_{π} is shifted to threshold $E_{\pi} \to E_{\pi} - S_n(0)\gamma^2_{\pi n} < E_{\pi}$. Both level energies $\bar{E_{\pi}} = \beta_{\pi n}(E_{\pi} - S_n(0)\gamma^2_{\pi n}) < (E_{\pi} - S_n(0)\gamma^2_{\pi n})$ and width $\bar{W} = \beta_{\pi n}(0)W$ are compressed.

The neutron single particle threshold state does induce by isospin coupling a threshold effect in open competing proton threshold channel. The threshold state from neutron channel $n+T^{-}B$ is reflected in analogue open proton channel $p+B$ as an additional term of the S- matrix element of (d,p) reaction

$$S_{dp} = S^0_{dp} + \frac{\alpha}{E_\pi - E - -i(\bar{\Gamma}_{\pi n} + \bar{W})}$$

The background (stripping) reaction is described by the S^0_{dp} term. The α parameter was devised by Lane as isospin coupling strength. Later on, [19], the parameter α was related to neutron strength function $\alpha \sim < \gamma^2_{\pi n} >$. The neutron strength function $< \gamma^2_{\pi n} >$ is a statistical (energy averaged $<>$) spectroscopic factor; it measures the overlap of the neutron single particle state to the actual (complicated) states of the nucleus. The strength function will display maxima whenever a single particle state is present. The $3p_{3/2}$ wave neutron strength function attains its maximal value for $A \sim 90$ mass nuclei.

A theory of threshold phenomena, [24], based on Reduced Collision/Scattering S Matrix (or on Reduced R/K Matrix, [23],) does establish a relation between threshold effect ΔS_{dp} and reaction mechanism of threshold reactions $S_{\bar{n}\bar{n}}, S_{\bar{n}p}, S_{d\bar{n}}$

$$S_{dp} = S^0_{dp} + \Delta S_{dp} = S^0_{dp} + S_{d\bar{n}} \frac{1}{1+S_{\bar{n}\bar{n}}} S_{\bar{n}p}$$

Here S^0_{dp} is Scattering S-Matrix element of the (d,p) reaction uncoupled to neutron threshold channel; anyway the $DWBA$ for the stripping reactions does not take into account the opening of other competing reaction channels. Based on this approach two conditions for a $p-$ wave threshold effect were established, [21, 30, 32], : (1) a p-wave neutron single particle resonance coincident with threshold, and (2) direct reaction transitions between threshold channel $\bar{n}$ and competing open channels, d and p. For different theoretical approaches to Threshold Phenomena see reviews [4, 5, 26, 30].

Let us do explicitly the two conditions in framework of R-Matrix Theory. In this theory, usually, one considers only compound system multichannel resonances described by poles of all R- Matrix elements. The single particle resonances are described, in this theory, by a perturbative approach developed by Bloch, see [18]. By perturbative residual interactions, the single (-channel) -particle resonance of independent particles system is subject to transitions to actual states of compound system and to couplings to other reaction channels. The R- Matrix becomes a series of resonant terms collected, with statistical assumptions, in a Single Particle Resonance formula. The total width comprises, in addition to natural decay width, an additional spreading component related to flux lose into actual states and the other reaction channels. By using Bloch's procedure for describing single particle resonances in R-Matrix Theory, [18], and by implementing it into Reduced S-Matrix one obtains, in second-order perturbation theory,

$$\Delta S_{dp} = \mathcal{P}_{dn}^{1/2} \frac{\gamma_{\pi n}^2}{E_\pi - E - \Delta_{\pi n} + i(\Gamma_{\pi n} + G_{\pi n})} \mathcal{P}_{np}^{1/2}$$
$$\mathcal{P}_{dn}^{1/2} = \Sigma_b P_d^{1/2} (S_N^0 + 1)_{db} R_{bb}^0 V_{bn}$$
$$G_{\pi n} = (E_\pi - E)^2/(P_n \gamma_{\pi n}^2)$$
$$-\Delta_{\pi n} + i\Gamma_{\pi n} = -\gamma_{\pi n}^2 \Sigma_{ab} (P_a^{1/2} R_{aa}^0 V_{an}, (S_N^0 + 1)_{ab} P_b^{1/2} R_{bb}^0 V_{bn}),$$

with $\mathcal{P}_{dn}$ and $\mathcal{P}_{np}$ - generalized penetration factors, S_N^0 -the Scattering Matrix of N open reaction channels $(a,b = 1,2,,....,N)$ uncoupled to threshold channel n, R_{aa}^0 - R-Matrix element describing uncoupled (independent) open channel a, V_{an} - the direct transition between open channel a and threshold one n, $R_{nn}^0-$the neutron single channel R-Matrix element, (neutron single particle resonance π), $R_{nn}^0 = \gamma_{\pi n}\gamma_{\pi n}/(E_\pi - E)$, and $\gamma_{\pi n}^2$- neutron reduced width. The width $\Gamma_{\pi n}$ is positive due to unitarity of S_N^0 - Scattering Matrix. The additional width term $G_{\pi n}$ does increase the "escape width", thus enforcing the doorway aspects of the neutron threshold state. (If applied to s-wave case, one obtains a very broad effect, mixing up with background, while Lane formula does predict a very strong s-wave threshold effect. One has to remark, however, the artificial aspect of this term, resulting from exact coincidence of neutron single particle state with threshold.) Anyway, this description displays explicit the role played by Direct Interaction Coupling of resonance threshold channel to open observed ones. This approach explains the absence of threshold effect in other open competing reaction channels which are not coupled by direct transitions (like d and p channels did) to neutron threshold channel. The direct transitions from deuteron and proton channels mean that the generalized penetrations factors $\mathcal{P}_{dn}$ and $\mathcal{P}_{np}$ consist only of one term (in the sum), $\mathcal{P}_{dn}^{1/2} = P_d^{1/2}(S_N^0 + 1)_{dd} R_{dd}^0 V_{dn}$. The direct transitions in deuteron stripping (d,p) reactions manifest near closed shells via a big neutron spectroscopic factor (order of magnitude $\sim$ unity). A small neutron spectroscopic factor signifies, [31], multistep transitions rather than a direct one; this happens for non-closed shell nuclei (as *e.g.* $A \sim 110$ mass nuclei). The deuteron stripping threshold effect with $A \sim 110$ mass nuclei is smaller (as compared to that with $A \sim 90$ ones), see [30], in spite the $3p_{1/2}$ neutron strength function (localized at this mass area) is rather large. The only one condition (either (1) or (2)) is not sufficient for a sizeable threshold effect.

3. ON ISOSPIN RELATED THRESHOLD PHENOMENA AND ISOTOPIC THRESHOLD EFFECT

The theory of threshold phenomena, [24], results into necessary conditions for threshold effects; they are related both to reaction mechanisms (direct transitions to or from threshold channel) and to spectroscopy of threshold channel state. In this and next chapter we approach the two conditions.

The direct transitions between threshold and open channel implies to a large overlap of their wave functions; it is either one-step stripping reaction (a large (d,p) spectroscopic factor) or the reaction channels related to a symmetry constraint, like isospin (analogue proton and neutron channels). We meet the first variant in deuteron stripping threshold effect; the second variant one meets, for example, in proton scattering $p+A$ on target nucleus A belonging to mirror nuclei (an isospin doublet). In last case not only exit channels $p+A$ and $n+T^{-}A$ but also the input channel (proton on target) are subjects of two isospin doublets. An example of such phenomenon is Isotopic Threshold Effect. The Isotopic Threshold Effect is neutron-threshold anomaly of proton elastic scattering on mirror light-medium nuclei ($A \sim 30$), $[8,39,40]$; it originates in a $p-$wave neutron single particle state coincident with threshold (specific to $A \sim 30$ nuclei) and in isospin coupling of proton and neutron charge-exchange channels.

It is related to quasi-resonant scattering (coupled channel resonances) at neutron zero-energy. A quasi-resonant scattering process consists from (1) a single particle resonance in the neutron channel, and (2) direct selective coupling of the neutron channel to the observed proton one. The first condition does select the mass region, while the second does select the reaction channel. A single particle resonance/state, located at a given energy, is a global property of a whole mass region; for example the $2-p$ wave neutron zero-energy single particle resonance is specific for $A \sim 30$ mass nuclei, see *e.g.* [37]. The neutron single particle resonance is coupled selectively, by isospin interaction, only to a given (analogue proton) channel. The two coupled analogue channels are proton scattering and neutron charge-exchange reaction on mirror nuclei.

The possible proton induced reactions, satisfying to above two conditions, can be, for example, illustrated by the proton elastic scattering and (proton, neutron) charge exchange reaction on ${}^{27}_{13}\mathrm{Al}_{14}$ target nucleus, [8]. The two reaction channels ${}^{1}_{1}\mathrm{p}_{0} + {}^{27}_{13}\mathrm{Al}_{14}$ and ${}^{1}_{0}\mathrm{n}_{1} + {}^{27}_{14}\mathrm{Si}_{13}$ are coupled by isospin interaction $\mathbf{t}.\mathbf{T}$, because the two nuclei ${}^{27}_{13}\mathrm{Al}_{14}$ and ${}^{27}_{14}\mathrm{Si}_{13}$ are mirror nuclei (isotopic doublet, $T=1/2$), see *e.g.* [38]; also the proton and neutron are members of the nucleon (isodoublet, $t=1/2$). The $2-p$ wave neutron single particle resonance, appearing at zero-energy for $A \sim 30$ mass nuclei, does induce by isospin coupling a quasiresonant structure in the proton (analogue) channel. The $2-p$ wave neutron single particle state at zero-energy is a global property of $A \sim 30$ mass nuclei; consequently, one can expect the same threshold effect with other nuclei in this mass region.

The threshold effect, based on isospin coupling of proton and neutron channels, could, in principle, manifest also in proton reactions on other isospin multiplets, (*e.g.* isobaric triplets, $T=1$) from same $A \sim 30$ mass area.

This threshold effect related to isospin coupling of only exit proton and neutron channels could manifest in direct transfer reactions as deuteron stripping. The stripping reaction $^{30}\mathrm{Si(d,p)}^{31}\mathrm{Si}$ was studied with polarized beam, by providing experimental evidence for a threshold anomaly both in cross-section and analysing power data, [39].

The Leningrad State University work [40], based on experimental data existing in literature, has extended this study to other isospin coupled reactions. They found evidence for this anomaly in other proton reactions on $A \sim 30$ and named it "Isotopic Threshold Effect".

One can summarize main physical aspects of the Isotopic Threshold Effect: isospin coupling of neutron threshold channel to mirror proton one (reaction dynamics), ancestral source of anomaly in zero-energy neutron $p-$wave single particle state (nuclear structure aspect).

4. ON NEUTRON THRESHOLD STATE

Theories of threshold effects, [17, 24], evince the primordial role of the "neutron threshold state" in producing threshold effects in open competing reaction channels. The threshold states have some peculiar properties to be discussed in the following. The threshold state is a special quasistationary state, coincident in energy with threshold, which has a large reduced width ($\simeq$ Wigner unit γ_W) for decay in threshold channel, [33]. 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, [33]. The spatial extension of a state is described by renormalization of its wave function out of channel radius a to the outer turning point a_t, [17, 18],

$$\beta(E) = \frac{\int_0^a |u(r)|^2 dr}{\int_0^a |u(r)|^2 dr + |u(a)/f(a)|^2 \int_a^{a_t} |f(r)|^2 dr} \leq 1,$$

where $u(r)$ is radial wave function of the level and $f(r)$ is the channel wave function which for large r becomes e^{ikr} (for $E > 0$) or e^{-kr} (for $E < 0$), $|E| = \hbar^2 k^2/2m$. The "spatial extension" renormalization factor, [17], is identical to "threshold compression" factor of R- Matrix Theory, [18], $\beta(E) = 1/[1 + \gamma_n^2 dS_n/dE]$; S_n denotes the shift-factor of threshold channel n and $\gamma_{\pi n}$ is the reduced width of the threshold state π for decaying in threshold channel n.

For positive energy the shift-function S_n should be replaced by logarithmic derivative L_n, as it is implied by the normalization condition for Gamow-Siegert state, $e.g.$ [27], $\int_0^a u(r)^2 dr + u(a)^2 dL_n/dE = 1$. The two terms represent, [18], the volume $\int_0^a u(r)^2 dr$ and channel $\int_a^\infty u^2 dr = u(a)^2 dL_n/dE$ probabilities integrals for a Siegert state, see [45]. The $\beta(E)$ factor is just wave function normalization on inner configuration space, $\beta(E) = \int_0^a u(r)^2 dr$.

The "threshold compression" factor $\beta(E)$ results into changes of resonant level energy, $E_\pi \to \beta E_\pi$, and of the total width,$\Gamma_\pi \to \beta\Gamma_\pi$. A near-threshold level, with a large reduced width for decay in threshold channel, is shifted towards threshold and its width (including spreading component) is compressed; in the limit $\beta \to 0$, the level is shifted just to zero (threshold) energy. The β-factor is essentially smaller than unity only for levels interplaying with threshold, $|E_\pi - E_{nthr}| < \Gamma_\pi$, and decaying preferentially in threshold channel, $\gamma_{\pi n} \simeq \gamma_W$; these two conditions define the threshold state.

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 $\Gamma_\pi^\uparrow$. 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, constitutes the 'giant resonance', (Micro-Giant Model of Lane-Thomas-Wigner for single particle resonance, see [18]). According to G.E. Brown, [20, 29], the single particle state could be coupled selectively to some Intermediate States; consequently, its strength function will exhibit some Intermediate Structures.

The threshold state is highly excited state, embedded in a continuum of statistical levels. The nucleus continuum 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 Intermediate or Doorway States. Intermediate structure, superposed on a continuum of statistical levels, is visible experimentally only if the "escape width" $\Gamma_\pi^\uparrow$ is larger than the "spreading width" $\Gamma_\pi^\downarrow$; otherwise it is spread 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 channel. 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, see [34], [22]. Later on, the concept of intermediate structure was included by Lane, [28], in that of "Line-Broadening". This approach does assume the existence of a "special state" which has a large overlap to one (or few) reaction channels, $i.e.$ large escape width. By "residual interactions" the "special state" is mixed to "ordinary" or continuum states, resulting in "Line-Broadening" phenomenon. Lane considered there are only few types of Line-Broadening in Nuclear Physics. The threshold state is an additional example of Line-Broadening; it 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 smaller spreading width $\Gamma_{\pi}^{\downarrow}$, [35]. The Micro-Giant Threshold State is another ”Line-Broadening” phenomenon, [36], in the 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 $< \gamma_{\pi n}^2 >$. The threshold effect, originating in a neutron threshold state is proportional to neutron strength function, $< \Delta S_{dp} > \sim \alpha_{dp} \sim < \gamma_{\pi n}^2 >$. The magnitude of a threshold effect does depend not only on reaction mechanism but also on spectroscopic amplitude of ancestral quasistationary threshold state. A threshold state does act as an amplifier for flux transfer to threshold channel thus enhancing the threshold effect.

5. ON COUPLED CHANNEL RESONANCES

A mechanism which prevents the broadening of the single-channel (bound or resonant) state is ”direct compression” [21]. The resonance width broadens, as a rule, due to its coupling to open channels; this property is specific to Compound Nucleus Resonances. The Coupled Channel Resonance or Quasiresonance originates in a single channel resonance which is reflected in complementary channels due to strong channels couplings. One proves, [41], that the reduced width of single channel resonance $\gamma_{\pi n}^2$ becomes narrower due to the direct coupling to complementary a channels and rescattering in n -channel, $\gamma_{\pi n}^2 \rightarrow \gamma_{\pi n}^2(1 - \Sigma_l |T_{ln}^0|^2)$, ($T^0$- nonresonant component of the transition matrix; l either open a or threshold channel n). The ”direct compression” $(1 - \Sigma_l |T_{ln}^0|^2)$ is due to transition to and from complementary channels a as well as to n- channel rescattering (T_{nn}^0), thus delaying quasiresonance decay, $i.e.$ decreasing its width. This result could be related the ”Channel Coupling Pole”, [26], observed in numerical experiments for multichannel reactions; it does appear for strong channel coupling interaction. It is considered that the channel coupling pole originates in distant poles, (located at infinity in complex energy or wave planes, when channel couplings tend to zero), which are driven to physical region when channel couplings become strong.

The two mechanisms, ”threshold compression” and ”direct compression” do act coherently in narrowing the width of a resonance in multichannel systems, making it discernible in presence of background scattering.

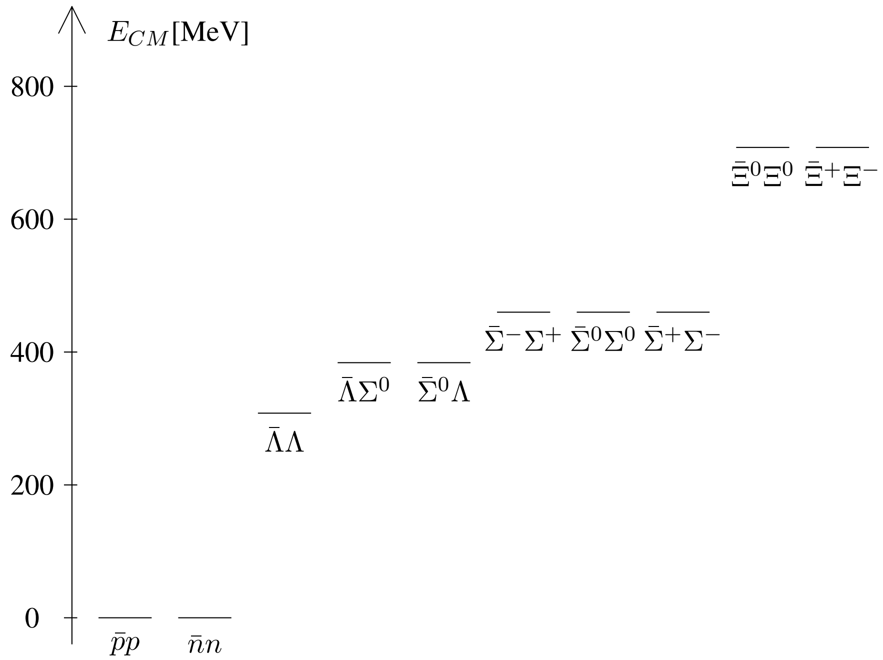

Fig. 1 – The energy of various $Y = 0$, $I_3 = 0$ baryon-antibaryon channels in the centre of mass frame.

6. ON QUASINUCLEAR BARYON STATES

The experimental data on hyperon production process $\bar{p}p \to \bar{\Lambda}\Lambda$ obtained at CERN using LEAR indicate a substantial p-wave contribution which dominates the cross section already at only few MeV above the reaction threshold [47].

Theoretical studies have been carried out employing the traditional meson-exchange picture [50] as well as models based on quark degrees of freedom. It was suggested that the substantial p-wave contribution might be due to the existence of quasi-nuclear states close to the threshold of interest, *e.g.* the $\bar{\Lambda}\Lambda$ threshold [18].

The baryons, B, or antibaryons, $\bar{B}$, with the same spin and parity can be classified in multiplets based on the SU(3) flavour group [51]. In particular, the $1/2^+$ baryon/antibaryon SU(3) octets include isospin $1/2$ nucleons/antinucleons (hypercharge $Y = 1/-1$) and the lowest mass hyperons/antihyperons, the isoscalar, hypercharge $Y = 0$ $\Lambda/\bar{\Lambda}$.

The low energy baryon-antibaryon interaction is similar to the baryon-baryon interaction and, at large separation is dominated by one-meson exchange potentials. This strong $B\bar{B}$ interaction may result in bound states like in the baryon-baryon case (the neutron-proton bound or virtual state in s-wave is the well known example).

These are the quasi-nuclear states. However, the annihilation into mesons could destroy these states as the annihilation cross section, of the order of hundred millibarns, comparable with the proton-antiproton elastic cross section, is much larger than the cross section for hyperon-antihyperon production of the order of tens of microbarns. However, Shapiro [11, 43] advanced the idea that the range of nuclear forces, R, and the characteristic distances involved in annihilation process, R_a, are different, $R \gg R_a$, and this range separation does not destroy the quasinuclear states in spite of the large annihilation cross-section.

The Quasinuclear Baryon States are produced by strong nuclear attraction in $B\bar{B}$ systems, [11, 42, 43]. They are distinguishable from usual quark-model states, weak binding energy and relative large rms radius, and manifest by rather narrow bound states and resonances in the $B\bar{B}$ systems near threshold, [42]. The main difference between BB and $B\bar{B}$ systems physics is presence of the annihilation processes in later case; however the Quasinuclear Baryon States are not destroyed by annihilation forces. The mechanism preventing its spreading in annihilation channels, $i.e.$ a small spatial overlap, was discussed, [11, 43]. Another mechanism originating in strong multichannel coupling was previously mentioned.

We add here a remark concerning the $p\bar{p}$ atom level in relation to Quasinuclear Baryon States. One considers that the experimental observation of "pushing out" of $p\bar{p}$ atomic $1s$ level would be evidence for existence of an $N\bar{N}$ quasinuclear state, [43]. It should be similar to atomic quantum defect of Rydberg states due to inner core. The Rydberg states are "channel states" affected by the inner core one(s). One proves, [44], that the shift of Rydberg level energy is ΔE = $(e^4 m/\hbar^2 n^3)\mu$; $e-$ electric charge, $m-$ reduced mass, $n-$ principal quantum number, $\mu-$ atomic quantum defect. The complex quantum defect is related to Reduced R- Matrix element $\mathcal{R}$ of Rydberg channel, $\mathcal{R} = \tan \pi\mu$, which at its turn is related to complex scattering length, $\mathcal{R} \sim -a$, i.e. $\Delta E \sim -a$, (see [43] for last relation). The Reduced R-Matrix of the Rydberg channel takes into account the states and reaction channels of the inner core, in our case the Quasinuclear Baryon States. The shift and width of the Rydberg level (of the $p\bar{p}$ atom) are proportional to $Re\mu$ and $Im\mu$ respectively, ($Im\mu \sim Im\mathcal{R}$ is always positive).

7. ON R-MATRIX AND BARYON INTERACTION

Despite the fact that R-matrix theory, both at the phenomenological level [18] and at the calculation level [52], is a well established framework to describe the complex many-body nuclear and atomic scattering systems, the properties of the nucleon-nucleon system are not described usually in the R-matrix language: energy of the R-matrix internal eigenstates, their reduced widths, width renormalization.

We are aware of only two approaches in the R-matrix spirit for this system: the description of the nuclear correction to the low energy proton-proton scattering by Breit [53] and the description of the deuteron bound state by Baye [54]. Nevertheless neither works reports reduced widths for the isoscalar deuteron s-wave state or for the isovector nucleon-nucleon s-wave virtual state.

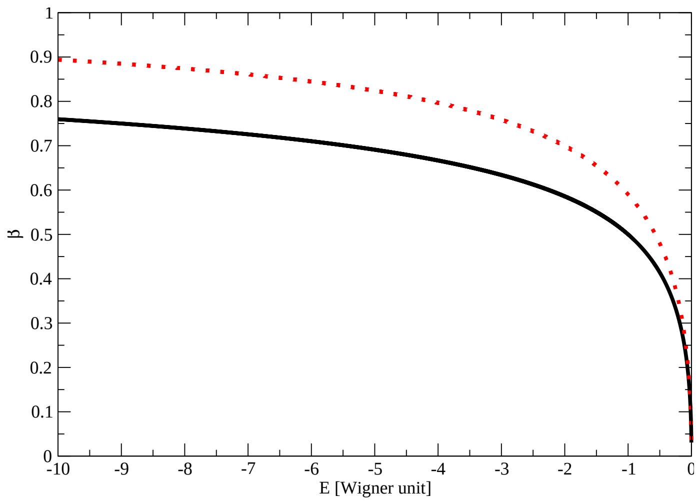

Fig. 2 – Width renormalization factor for 1s-wave without (solid line) and with background/Buttle correction (dotted line) according to R-matrix.

This fact seems to be connected to the important contribution of the background R-matrix in the region of the lowest energy internal state [18] (the contribution at the energy of the lowest internal state of all the higher energy internal states). This contribution changes mainly the energy behaviour of the renormalization factor for the reduced width, Fig.2.

We consider the splitting of the configuration space in three regions:

- $r \leq a_a \simeq 0.2 fm$. The interaction in this region is responsible for the annihilation, *i.e.* transition in a variety of mesonic channels.
- $a_a \leq r \leq a \sim$ few fm. The interaction in this region couples only the baryon-antibaryon channels.
- $r \geq a$, the asymptotic region where only a Coulomb interaction may be present.

In the second region the interaction can be taken as one boson exchange potential, OBEP, and it can be related to the one boson exchange potential for baryon-baryon systems. If the SU(3) symmetry would be exact for baryons as well as for mesons, then the OBEP will be SU(3) invariant. But this symmetry is broken at least via the physical masses of the baryons. However, we suggest that the Hamiltonian in this region is approximately SU(3) invariant. In the third region the interaction is diagonal in physical channels, but the different baryon masses, see Fig.1, break the SU(3) symmetry. Therefore, the symmetry-conserving and the symmetry-breaking part of the Hamiltonian are spatially separated. This approach is similar in spirit to the Robson's R-matrix treatment for the isobaric analogue resonances in nuclear physics [55].

The most general SU(3) invariant potential between a baryon octet and an antibaryon octet may involve products of SU(3) tensor operators acting on baryons and antibaryons, respectively, coupled to SU(3) scalars. If this potential is given by meson exchange, which in the quark model can be members of singlet or octet, the potential should be given only in terms of octet operators. Starting with the octet tensor operator formed by the generators of the su(3) Lie algebra, T_8, we can form two octet operators: $F_8 = [T_8 \cdot T_8]_{8_S} \sim T_8$ and $D_8 = [T_8 \cdot T_8]_{8_A}$ (this is due to the fact that for su(3) Lie algebra the octet representation appears twice in the tensor product of two octet representations). Therefore, the most general potential for baryon-antibaryon interaction can be written, apart from an SU(3) scalar as a sum of terms $[F_8^b \cdot F_8^a]_1$, $[F_8^b \cdot D_8^a]_1$, $[D_8^b \cdot F_8^a]_1$, $[D_8^b \cdot D_8^a]_1$. These terms are similar to the SU(2) isospin invariant Lane potential in nuclear physics $\vec{t_1} \cdot \vec{t_2}$.

We can always eliminate the mesonic annihilation channels and the R-matrix will be a reduced one involving complex internal eigenstate energy and complex reduced widths. We expect that the properties of the internal R-matrix states remain governed mainly by the dynamics in the intermediate region: internal eigenstates belong to the irreducible representations appearing in the tensor product of two octet SU(3) representations (one singlet, two octet, two decouplet and one 27-plet) and their reduced width in different channels are related to SU(3) Clebsh-Gordan coefficients. In our case only Clebsh-Gordan coefficients of the form $< D; Y = 0, I, I_3 = 0 | Y^b, I^b, I_3^b; Y^a, I^a, I_3^a >$ appear, where D denotes the irreducible representation appearing in the tensor product of the two octet representations.

8. THRESHOLD BEHAVIOUR IN $p\bar{p}$ ELASTIC SCATTERING AND $(p\bar{p} \rightarrow \Lambda\bar{\Lambda})$ REACTION

The experimental data [48] on strangeness production channel ($\bar{p}p \rightarrow \bar{\Lambda}\Lambda$), Fig.4, and elastic backward cross section ($\bar{p}p \rightarrow \bar{p}p$), Fig.3, present nonmonotonic behaviour which might be related to resonances due to quasi-nuclear states or to the presence of thresholds for new baryon-antibaryon channels.

The incoming $\bar{p}p$ channel may have isospin 0 or 1. The $\bar{\Lambda}\Lambda$ channel has isospin 0. One can expect a threshold effect at the opening of the $\bar{\Lambda}\Lambda$ channel in the elastic cross section. It should manifest either as a dip or as distorted resonant-like

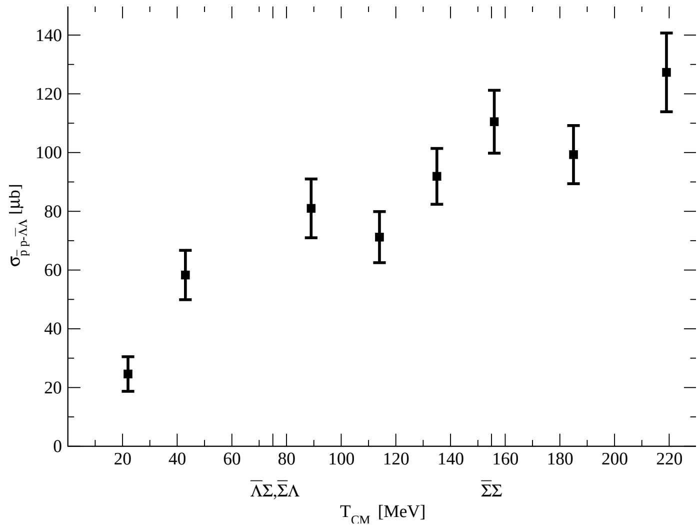

Fig. 3 – Cross section for the reaction $\bar{p}p \to \bar{\Lambda}\Lambda$ [48].

forms, depending on background phase-shift. The same is true for the opening of the $\bar{\Lambda}\Sigma$ channel (isospin 1) or $\bar{\Sigma}\Sigma$ channel (isospin 0,1 or 2). We have to note that the $\bar{\Sigma}\Sigma$ channel presents attractive Coulomb interaction. A "'threshold continuity theorem"' for energy averaged collision matrix element of competing open channel should take place at $\bar{\Xi}\Xi$ threshold.The total energy-averaged cross-section of competing open channel is continuous across $\bar{\Xi}\Xi$ threshold channel while elastic channel

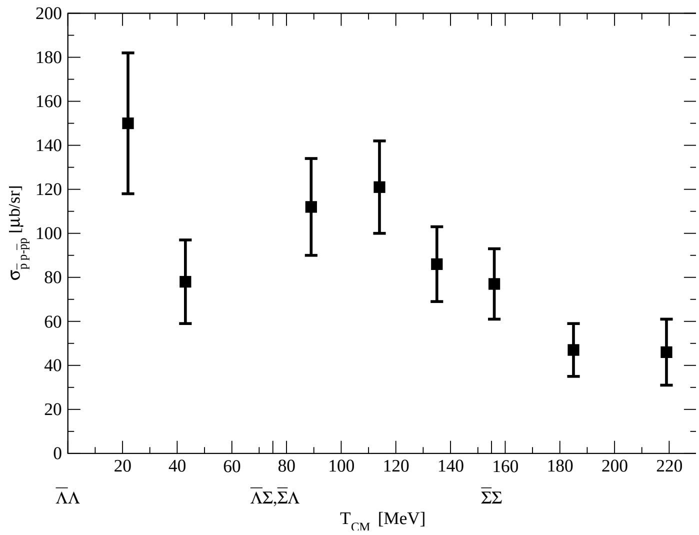

Fig. 4 – Differential antiproton-proton backward elastic cross section [48].

cross-section should be subject to an abrupt decrease above threshold. (see [45] for electron scattering at Rydberg threshold).

In the hyperon production reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ one can expect threshold effect at the opening of the $\bar{\Sigma}\Sigma$ channel, but not at the opening of the $\bar{\Lambda}\Sigma$ channel.

⋆⋆⋆

The study of baryon-antibaryon interaction at relatively low energy continues to be an actual experimental topic. Using antiprotons created by the CERN proton synchrotron, the Low Energy Antiproton Ring (LEAR) facility allowed (1982-1996) to obtain high quality experimental data on $\bar{p}p$ elastic scattering and annihilation at low energy [46] and on strange baryon production reaction, $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, at low energy of $\bar{\Lambda}\Lambda$ in the center of mass frame [47].

Hadron physics studies using antiprotons will be possible from 2018 at $\bar{\mathrm{P}}$ANDA experiment (Antiproton Annihilation in Darmstadt), one of the four scientific pillars of FAIR (Facility for Antiproton and Ion Research) in Darmstadt [49].

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