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EMPIRICAL EVIDENCE FOR RELATION BETWEEN THRESHOLD EFFECTS AND NEUTRON STRENGTH FUNCTION

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In the present letter one proves, by analyzing experimental data, that the mass-dependent magnitude of threshold effects observed in deuteron stripping reactions on $A \approx 90$ mass target nuclei is proportional to the $3p$-wave neutron strength function.

В данной работе на основе анализа экспериментальных данных приводится доказательство того, что зависимая от массы величина пороговых эффектов, наблюдаемых в реакциях дейтронного стриппинга на ядрах с массой $A \approx 90$, пропорциональна $3p$-волновой нейтронной силовой функции.

INTRODUCTION

The problems of threshold effects in nuclear reactions [1] and of the neutron strength function [2] were formulated in early days of low-energy nuclear physics; nevertheless they both are still topical basic subjects of research in contemporary nuclear physics (see, for example, [3, 4]). The present work does establish an empirical relation between the $3p$-wave neutron strength function and the anomal effect observed at threshold of neutron analogue channel, in deuteron stripping reactions on $A \approx 90$ mass target nuclei.

By analyzing existing experimental cross-section data on this (d, p) threshold anomaly, one proves that the magnitude of the effect is proportional to the $3p$-wave neutron strength function. According to this result, the threshold effects depend not only on penetration factors of neutron opening channel but also on spectroscopic amplitude of zero-energy neutron single particle resonance.

1. PHYSICAL ASPECTS OF THRESHOLD PHENOMENA

The threshold effects in a multichannel system originate in conservation of the flux; in a hydrodynamical picture, the opening of a new reaction channel results in a redistribution of flux in old open channels. The magnitude of a threshold effect depends, via penetrations factors, on amount of flux absorbed and re-emitted by threshold channel. If the threshold channel has no (Coulomb and centrifugal) barriers, its penetration factors depend linearly on wave number and this results in a «cusp» in open channels cross-sections [1]. Physical conditions implied by a threshold cusp are general ones; however, the experimental studies have shown that threshold effects are rather related to some restrictive conditions. An exhaustive analysis [3] of threshold effects in low-energy nuclear reactions on light nuclei has proved that these effects do occur only if a resonance is coincident with neutron threshold and if the resonance has a large reduced width (≈ Wigner unit) for decay in neutron threshold channel. A threshold resonance, overlapping neutron channel, does amplify the flux exchange of threshold channel with open ones. This type of threshold effects, observed with light nuclei, proceeds via compound nucleus reactions.

A threshold effect in direct reactions was evinced in deuteron stripping on medium-mass target nuclei [5]. The main experimental characteristics of this threshold anomaly are: 1) the anomaly does not appear for lowest neutron threshold but rather it is related to opening of $(d,\bar{n})$ neutron analogue channel; 2) it manifests itself mainly as a dip (reversed resonant peak) in excitation functions; the dip half-width is typically 0.7 MeV; 3) the magnitude of the threshold dip is dependent on mass of target nucleus. In this letter we prove that the mass dependence of threshold anomaly is related to residual nucleus in the exit neutron channel, and it follows the mass dependence of $3p$-wave neutron strength function.

The first experimental characteristic [1] was considered [5] as an experimental evidence for isospin coupling of exit proton and analogue neutron channels. The isospin coupling of analogue proton and neutron channels is basis for a Coupled Channel Born Approximation model [6]. Lane has proposed a phenomenological model [7] based on zero-energy p-wave neutron single particle resonance, specific to $A \approx 90$ mass nuclei; by isospin coupling it is reflected as a resonant structure in S-matrix element of analogue proton channel. According to this model, the magnitude of the threshold effect is dependent on isospin coupling strength of proton to neutron analogue channel. If this assumption is taken literally, the threshold anomaly strength should be nearly the same for all nuclei in $A \approx 80{-}100$ mass area. In this letter one studies the mass dependence of threshold anomaly strength, by analyzing the corresponding experimental cross-section data published in literature, for the following target nuclei: ^{80}Se [8], ^{86}Kr [9], ^{88}Sr [10], ^{90}Zr [5, 11, 12], ^{92}Zr [13], ^{92}Mo [13], ^{94}Zr [13], ^{94}Mo [13] and ^{106}Cd [11]. For this purpose, one uses two approaches: a «computational» one based on the Lane model and an «empirical» model-independent one. In the first approach the strength of the anomaly is the only free (fit) parameter of the S-matrix threshold term. In the second approach, one evaluates the relative strength of anomaly in cross-section data, as a function of mass number. From both approaches one obtains that the magnitude of the threshold effect depends on mass number similarly to the $3p$-wave neutron strength function.

2. EVALUATION OF THE STRENGTH OF (d,p) THRESHOLD ANOMALY

The phenomenological model for (d,p) threshold anomaly, proposed by Lane [7], is based on neutron resonance interplay of $3p$-wave neutron single particle resonance with threshold, for $A \approx 90$ mass nuclei. The isospin interaction couples to p wave of the analogue proton channel, resulting in a p-wave resonant term in the scattering matrix of the (d,p) reaction:

$$S_{dp} = S^0_{dp} + S^\pi_{dp} = S^0_{dp} + \sum_{j_p=1/2,3/2} \frac{\alpha_{j_p}(\hbar^2/ma^2)}{E_{j_p} - E - (S_1 + iP_1 - b)\gamma_n^2 - (i/2)\Gamma'} \qquad (1)$$

with S^0_{dp} as a (d,p) reaction DWBA background S-matrix element; E_{j_p} — energy eigenvalues corresponding to boundary condition *b* at neutron channel radius *a*; γ_n^2 is the neutron reduced width; S_1 and P_1 are p-wave $(l = 1)$ neutron shift and penetration factors; Γ' is sum of the proton decay width and of broadening width; α_{j_p} — phenomenological coupling parameters of proton and neutron analogue channels.

The peculiarity of this S-matrix element is strong energy dependence near threshold of the resonance denominator (S_1 and P_1), resulting in a change of energy scale («compression factor»).

According to the Lane model, the threshold anomaly strength is a free fit parameter. One has to remark that these parameters are subject to some physical constraints as dependence on input channel energy. A computational study of this problem does show that their mass dependence remains practically unchanged, even if they are considered energy-independent. The Lane model did reproduce morphologically the anomaly; a rather extensive experimental and computational study was presented in the work [11].

The transition amplitude describing background and anomal reactions mechanisms consists, according to the Lane formula, of a DWBA term and a threshold resonant term. These terms are constructed, respectively, in transferred angular momentum coupling scheme, and in the total angular momentum coupling scheme, and they are added up in the code DWUCK [14]. The DWBA description of the background is realized in terms of deuteron [15] and proton [16] optical global parameters and by a suitable choice of spectroscopic factors; afterwards the background parameters are kept fixed during anomaly's calculations.

The experimental and theoretical cross-sections obtained with the above method for the ^{88}Sr$(d,p)^{89}$Sr stripping reaction are displayed in Fig 1. The spectroscopic coefficient is previously determined from forward angular distribution. In fit one uses the same absolute value of α parameter for different deuteron angular momenta compatible with proton p wave. Similar analyses were done for the other anomalies listed above. The minimization procedure is based on the gradient method using the Minuit package [17].

The «empirical» strengths of anomaly and their errors obtained by a standard analysis are presented in Fig. 2, a (triangles) together with $3p$-wave neutron strength function experimental data. The recent experimental $3p$-wave neutron strength function for the investigated cases, i. e., ^{80}Se [18], ^{86}Kr [19], ^{88}Sr [20], ^{90}Zr [21], ^{92}Zr [21], ^{92}Mo [21], ^{94}Zr [22], ^{94}Mo [22] and ^{106}Cd [23] are plotted with filled circles.

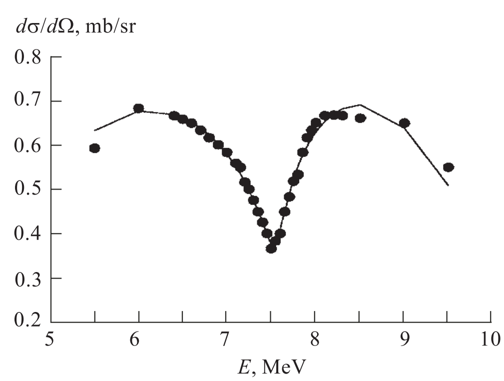

Fig. 1. Experimental (•) and computational (–) cross-section for ^{88}Sr$(d,p)^{89}$Sr deuteron stripping at $\theta = 160^\circ$ incident angle

The anomaly strength in empirical procedure is evaluated from the maximal deviations of the cross-section with respect to median values at half-widths points of the anomaly dip. The magnitude of the anomaly is normalized with respect to (d,p) background cross-section including corresponding spectroscopic factor. The median value is obtained by integrating the experimental cross-section using the trapezoidal method with an energy incremental step of about 0.1 MeV. The background cross-section is interpolated within its asymptotic values by using a one-dimensional data interpolation method with spline functions. This procedure results in a global parameter for anomaly's magnitude with no explicit reference to different deuteron channels which are contributing to the same p-wave proton channel.

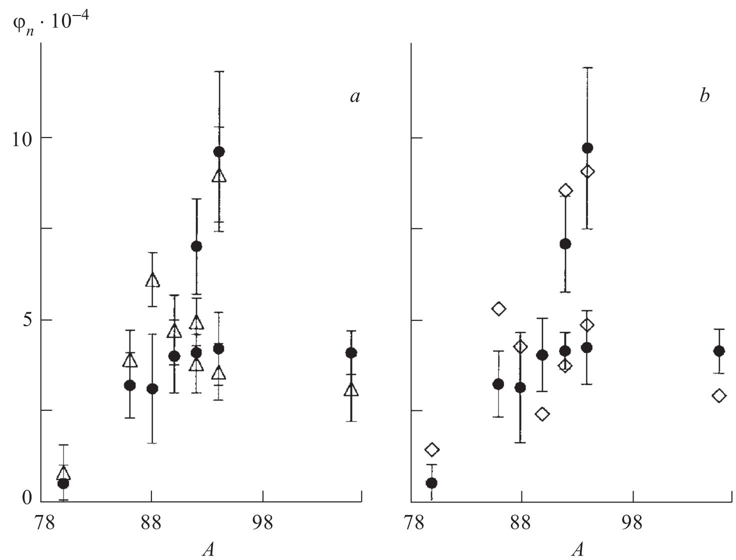

Fig. 2. The mass dependence of $3p$-wave neutron strength function (•) and of the «empirical» (△ (a)) and «computational» (◇ (b)) strengths of the anomaly

The model evaluated strengths are plotted versus mass number A in Fig. 2, b (unfilled diamonds). The errors of the numerical evaluated strengths have been extracted from the Error Matrix generated by the MINOS procedure (see Ref. [17]). The evaluated spectroscopic strengths of anomaly, considering a 90 % C. L., are in agreement with the experimental values of the neutron strength function.

CONCLUSIONS

The present letter proves, within «computational» and «empirical» frameworks, that the magnitude of deuteron stripping threshold anomaly observed with $A \approx 80-100$ mass target nuclei is proportional to the $3p$-wave neutron strength function. According to the present work, the threshold effects depend not only on penetration factors of opening channel, as in Cusp Theory, but also on the spectroscopic amplitude of neutron state in opening channel. This result is a «computational» and «empirical» demonstration corresponding to the ancestral source of anomaly which is zero-energy neutron p-wave single particle resonance.

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