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A ΔE-E System to Study Heavy Ion Reactions*

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A ΔE-E particle identifier, using a proportional counter as ΔE detector, has been constructed in order to identify reaction productsof heavy ion reactions. In this work, the performance of this instrument is presented in studying transfer and fusion reactions.

Construiu-se um identificador de partículas E–ΔE, que utiliza um contador proporcional como detector ΔE, com o objetivo de se identificar produtos de reações que envolvem íons pesados. Neste trabalho, apresenta-se o desempenho desse instrumento no estudo de reações de transferência e fusão nuclear.

1. INTRODUCTION

The study of most heavy ion reactions usually involves the identification of the outgoing particles in the various open exit channels (e.g.: elastic scattering, transfer reactions, evaporation residues following complete fusion etc.) . In order to study these reactions, a ΔE-E system for particle identification has been constructed with a proportional counter'as the ΔE detector and a silicon surface barrier diode as the B detector. The particle identification is achieved from the analysis of a bi-parametric spectrum constructed from the ΔE and E puises which,

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after being processed by conventional electronics, are stored on magnetic tape by the IBM/360-44 computer in a ΔE vs E array.

2a. DESCRIPTION OF THE PARTICLE IDENTIFIER

The scheme of the proportional counter telescope is shown in Fig.1. The ΔE counter is a single wire proportional counter of 69 mm effective length, with a diameter of 21.5 mm. A 20 μm gold plated tungsten wire is surrounded by guard-rings in order to restrict the charge collection to regions of homogeneous field. A silicon detector located inside the proportional counter measures the remaining energy (E) of the particle, after is passes through the gas. The proportional counter is operated with P-10 (90% Ar + 10% CH_4)* . A cartesian manostat maintains a continuous gas flow through the proportional counter and the pressure is kept constant within ±0.2 torr or 0.2%, whichever is greater. The entrance window consists of either a 240 μg/cm^2 thick MAKROFOL** or a 30 μg/cm^2 to 150 μg/cm^2 thick home-made WNS foil.[1]

The proportional counter telescope can be easily mounted inside the 1 meter diameter scattering chamber located on the 30° line, experimental area B, of the Pelletron Accelerator Laboratory[2].

2b. THE BI-PARAMETRIC SPECTRUM

In order to construct a bi-parametric spectrum from the simultaneous measurements of the two parameters E and ΔE, the raw data are stored event by event in an on-line DDP-516 computer, using an interface developed at this laboratory[3]. The data are then transferred automatically to the disk of the IBM/360-44 computer and finally, in an off-line

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* Purchased from Manostat Corporation, 20 North-Moore Street, New York B, New York.

** This material is produced by Bayer, Rua Domingos Jorge, 1000, Santo Amaro, São Paulo SP.

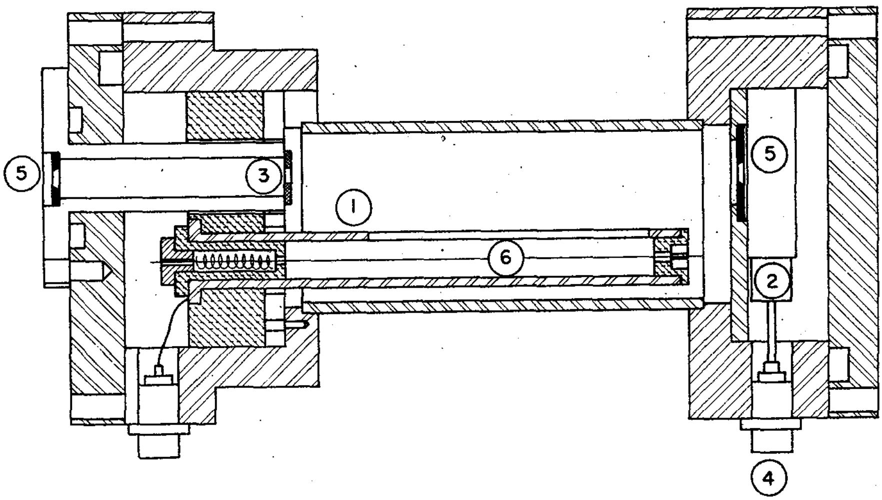

Fig.1 - Vertical cross-section view of the proportional counter: 1. guard-rings; 2. solid state detector; 3. entrance window; 4. microdot connectors; 5. slits; 6. wire.

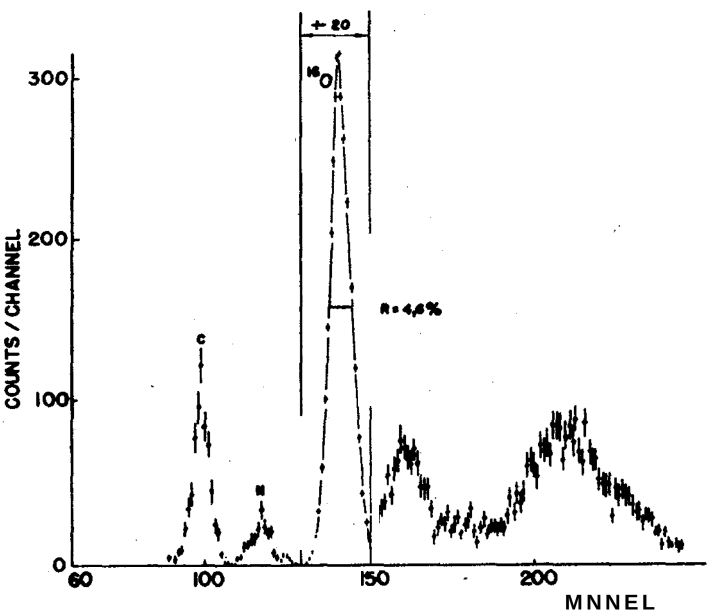

Fig.2 - Spectrum of the ΔE pulses in coincidence with E pulses, obtained from the reaction $^{27}Al + {}^{16}O$.

process, the bi-parametric spectrum is constructed, stored on magnetic tape, and printed.

A set of computer codes was written for analyzing the bi-parametric spectrum. With these codes, it is possible to select interesting regionsof the spectrum, and project them onto either or both the parameters axes.

3. RESULTS

With the aim of studying the characteristics of the proportional counter telescope, a 150 μg/cm^2 ^{27}Al target was bombarded with 30 MeV ^{16}O ions. The reaction products were detected at $\theta_{LAB} = 45^o$. A spectrum of the ΔE pulses in coincidence with the E pulses is shown in Fig.2. The resolution obtained for elastically scattered ^{16}O is 4.6%.

A bi-parametric spectrum of the reaction products from the same reaction, for an incident energy of 38 MeV, is shown in Fig.3. Elemental separation is clearly demonstrated in this ΔE vs E array. A selected region of the Z = 7 locus and its projection onto the E axis is shown in Fig.4. This projection shows two groups which, by kinematic considerations, correspond to ^{15}N leaving the residual nucleus ^{28}Si in either the ground state or the first excited state. This is a typical example of a direct transfer reaction and, in this case, one proton is transferred from ^{16}O to ^{27}Al.

In order to test the proportional counter telescope for fusion reactions, a 10 μg/cm^2 natural carbon target was bombarded by 34.3 MeV ^{16}O ions. Figure 5 shows a bi-parametric spectrum where the reaction products were detected at $\theta_{LAB} = 6^o$. The curves of energy loss drawn in that figure were calculated from tables by Northcliffe and Shilling[4]. The reaction products having Z $\geq$ 10 were interpreted as evaporation residues following complete fusion. Finally, we show the angular distributions for the evaporation residues in Fig.6. The curves drawn in that figure are only a guide for the eye. Our results are in good agreement with those reported by Sperr *et al.*[5]

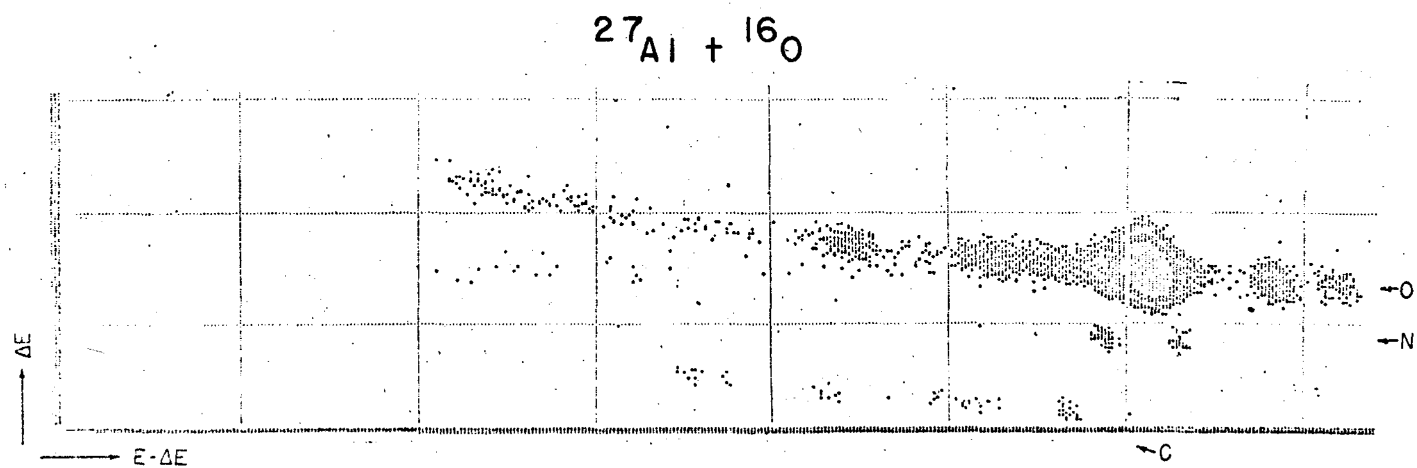

Fig.3 - Bi-parametric spectrum for the reaction products produced by 38 MeV ^{16}O ions bombarding a ^{27}Al target.

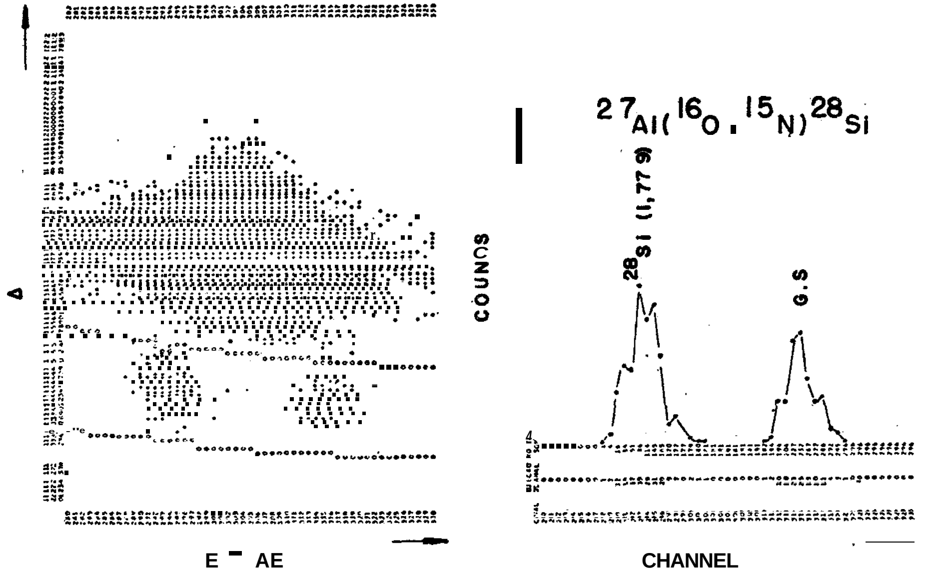

Fig.4 - A selected region of the Z = 7 charge locus and its projection onto the E axis.

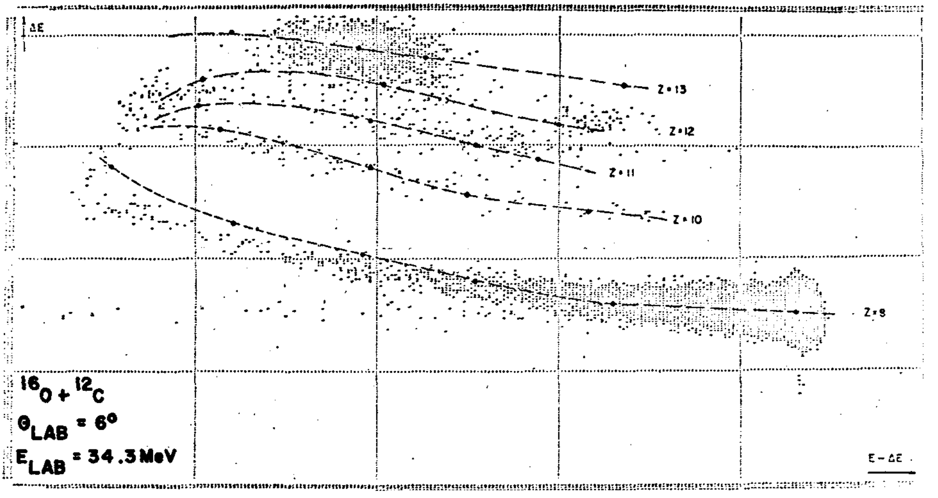

Fig.5 - A bi-parametric spectrum for the reaction products from the reaction $^{12}C+^{16}O$.

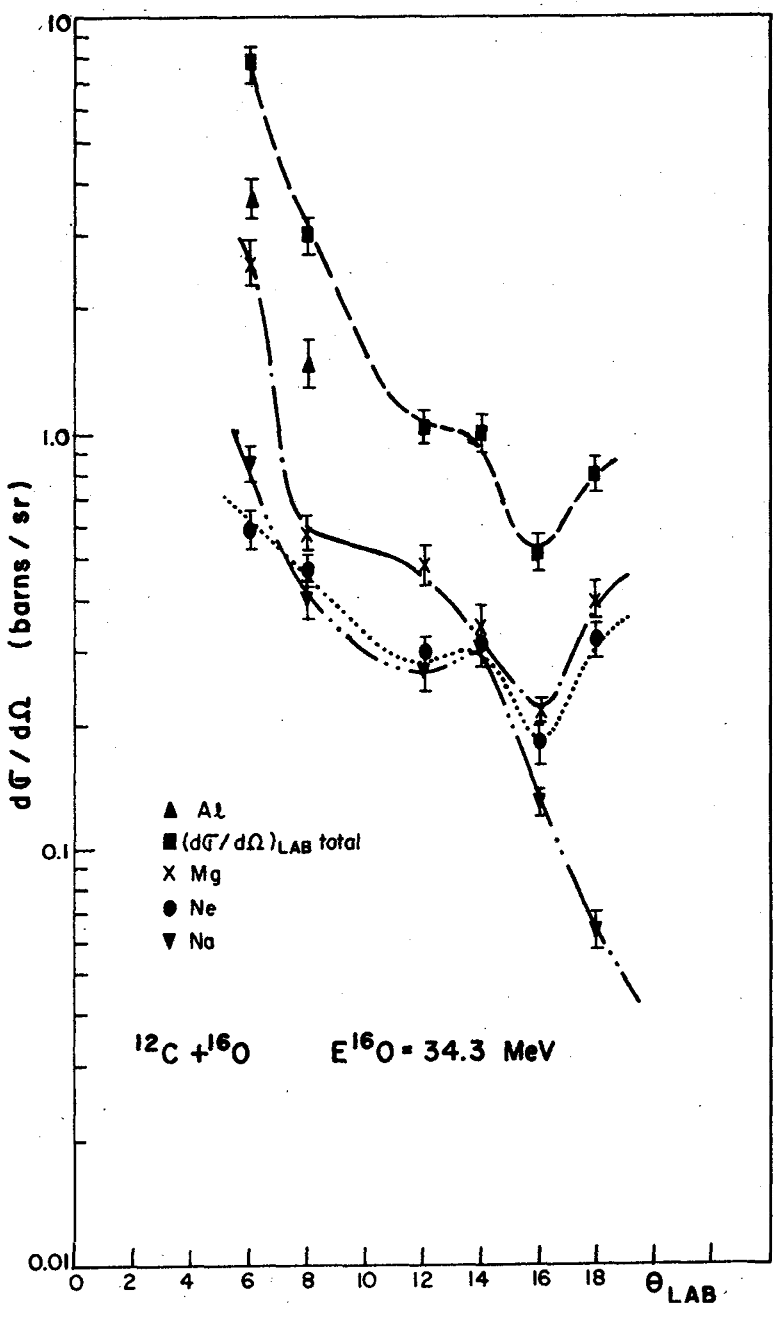

Fig.6 - Angular distributions for the evaporation residues following complete fusion for the reaction $^{12}C + ^{16}O$.

4. CONCLUSION

We have used the proportional counter telescope mainly to study fusion reactions, direct transfer reactions, and deep inelastic collisions between the so-called "light" heavy ions. Our system has shown good performance in identifying products of heavy ion reactions.

The proportional counter has the following advantages: i) the energy loss in the detector can be smaller than that of the thinnest ΔE silicon detector. For example, a gas pressure near 10 torr is equivalent to a silicon detector about 1 μm thick; ii) they are not damaged by heavy ions; iii) they are of easy construction; iv) the cost is low. These aspects make our ΔE-E partícle identifier an important tool in the study of heavy ion reactions.

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On the Behaviour of a Potential Resonance Near the Top of a Broad Barrier

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The behaviour of the resonances of a one-dirnensional square well with a squarre barrier is investigated as a function of the width of the barrier. A non-monotonic dependence of resonance energy and width on the width of the barrier is found. Implications of these results for the interpretation of resonances near deuteron thresholds in nuclear reactions are discussed.

Investiga-se o comportamento das ressonâncias em um poço quadrado unidimensional, de barreira quadrada, em função da largura da barreira. Encontra-se uma dependência não monotônica da energia de ressonância, e da correspondente largura, em função da largura da barreira. Discutem-se as consequências desses resultados na interpretação das ressonâncias, próximas aos limiares do deuteron, em reações nucleares.

Recently, a number of resonances in reactions involving few nucleons were interpreted as potential resonances in a specific channel[1,2]. Shape and width of the barrier are of great importance to understand the behaviour of such resonances. In Ref.1, a number of resonances near thresholds were analysed. Mainly deuteron thresholds were considered but ^6Li, for example,

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may also be of interest. It is notable that these fragments have large root mean square radii and by consequence give rise to a wide, flat, Coulomb barrier.

The purpose of the present paper is to show that such a property of the barrier is significant. Indeed, we shall see that we can considerably reinforce the arguments given in Ref.1 by discussing a simple model for such a situation.

We choose a square well with a square barrier and analyse the behaviour of the poles of the scattering matrix as a function of the width of the barrier. In this way, we will be able to discuss the behaviour of energy and width of resonances as well as that of the energy of bound states. The parameters V_0 V_1 of the potential (Fig.1) are chosen in such a way that we may study simultaneously the behaviour of bound states, resonances lying deep inside the barrier near threshold, others lying near the top of the barrier and others far above. The dimensions are chosen such that $m = 1/2$ and $\hbar = 1$. The behaviour of the poles of the S-matrix, in the complex k–plane, as a function of the barrier width b, ranging from 0 to 1.5, is shown in Fig. 2.

The behaviour of those poles, corresponding to energies near the top of the barrier, below or above, is notable as it implies a non monotonic behaviour of energy and width as a function of the barrier width, b. In order to display the properties of the poles more clearly, we show in Fig.3, the energies of the first bound states and resonances, as well as thewidth of the resonances as a function of b. We notice the following features:

a) The energy of the lowest bound state is little influenced by the barrier but increases monotonically;
b) The energy of the second bound state increases mnotonically up to the threshold; the following decrease in energy corresponds to a virtual state as may readily be seen from the position of the corresponding pole on the negative imaginary k-axis. For even wider barriers, the pole migrates to complex k values and a mnotonous increase of the energy as a function of the barrier width is recovered. The irregularity of the behaviour here is due to the threshold exclusively. This is confirmed by the fact that an

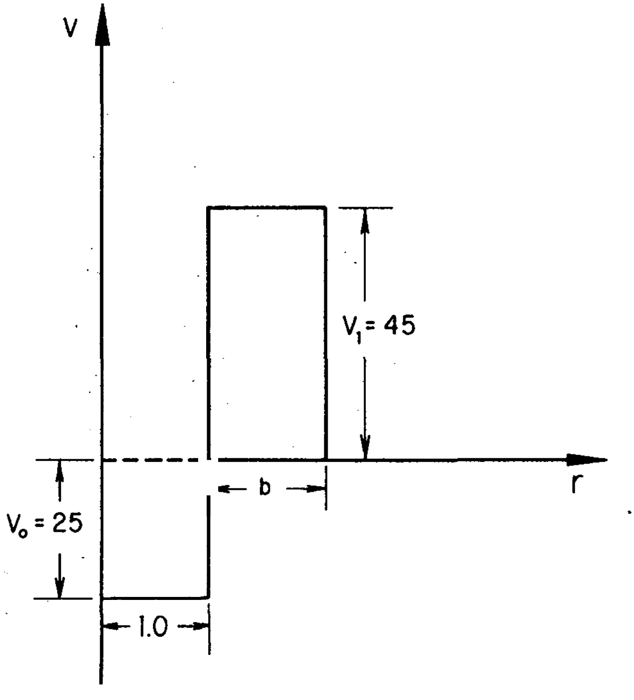

Fig.1 - The potential used for the computation.

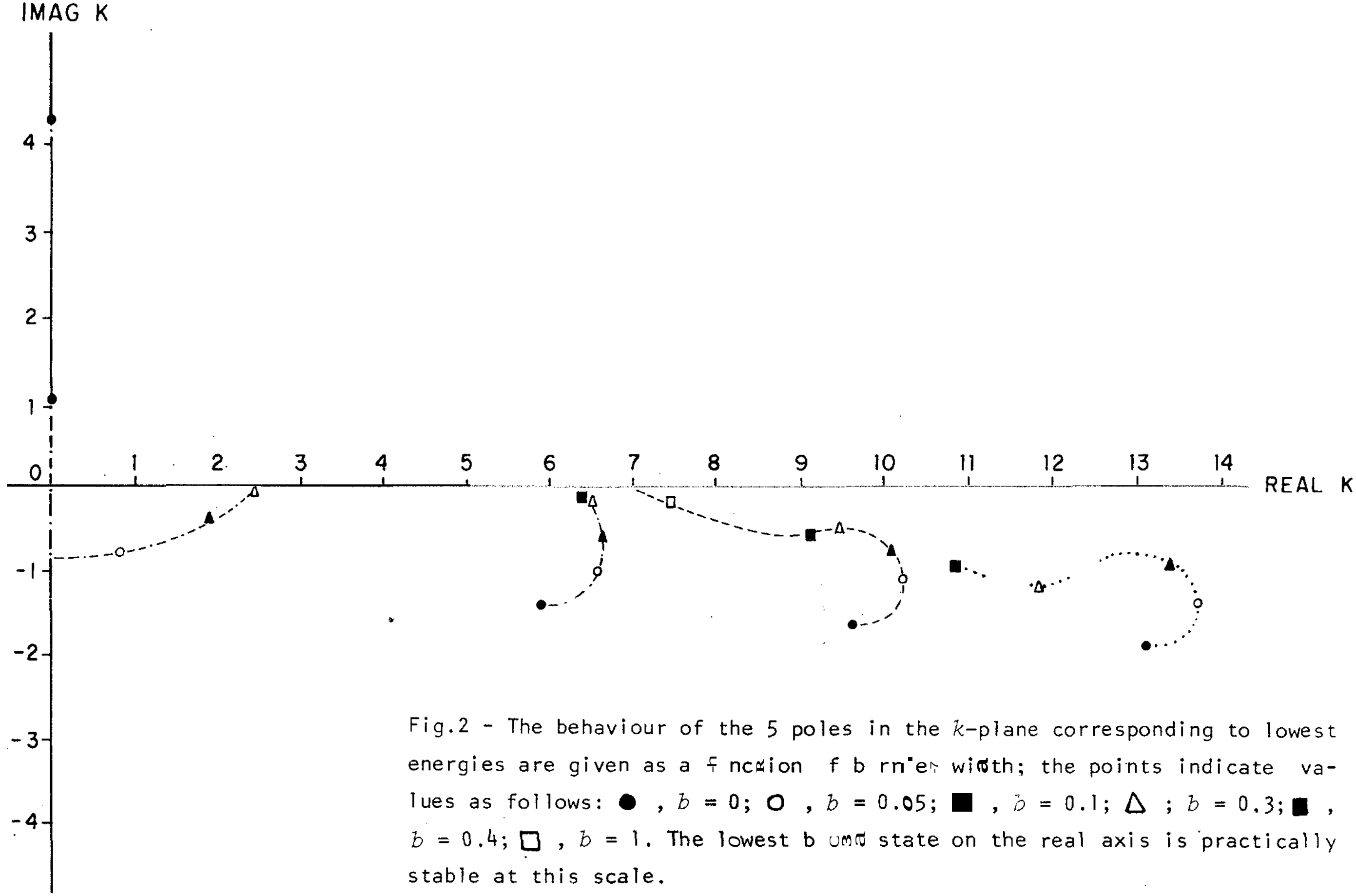

Fig.2 - The behaviour of the 5 poles in the k-plane corresponding to lowest energies are given as a function of barrier width; the points indicate values as follows: ● , $b = 0$; ○ , $b = 0.05$; ■ , $b = 0.1$; △ ; $b = 0.3$; ■ , $b = 0.4$; □ , $b = 1$. The lowest bound state on the real axis is practically stable at this scale.

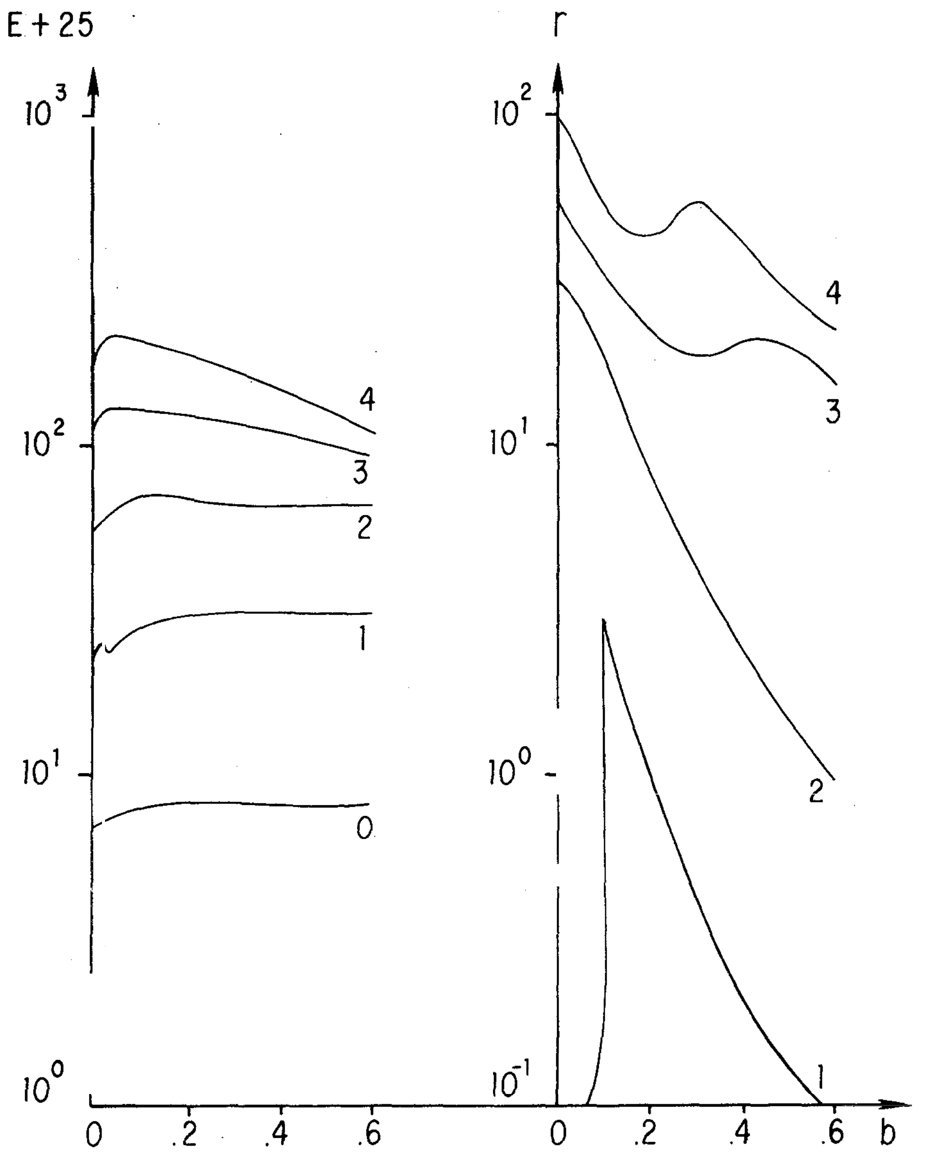

Fig.3 - The energy E + 25 for the lowest bound state and resonances, as well as the width Γ of the latter, are displayed on logarithmic scale as a function of the barrier width *b*.

analogous behaviour occurs for the expulsion of a bound state into the continuum for a well only as a function of the well depth[3].

c) The third pole near but below the top of the barrier displays a notable behaviour as a function of energy, that may be of importance in relation to nuclear reactions. While first, as expected, we find an increase in energy, as the barrier grows broad the energy decreases again. The width of the resonance decreases monotonically as a function of the width b of the barrier;

d) The fourth and fifth states display similar features: the resonance energy increases for small barrier width in order to decrease as the barrier becomes wider. In the region where the energy behaviour becomes monotonically decreasing, we find a local minimum fo the resonance width. These and all higher poles (not displayed) approach the top of the barrier in the limit of large b.

We may add that other sets of parameters V_0, V, were analysed and the results substantiate the above remarks.

If we argue in terms of resonances in a well and penetration factors, these results are rather puzzling; if, on the other hand, we consider the convergence of the poles towards the top of the barrier, we get a hint as to the understanding. Indeed, Nussenzveig[3] has shown (if we take into account that he plots the poles in a kb rather than a k-plane) that for a purely repulsive square potential all poles are drawn towards the top of the barrier. If the width of a barrier becomes large we expect a similar behaviour.

Discussing, e.g. the third pole, we may then argue as follows: while the barrier is narrow, no poles are near and the increase of potential energy with increasing barrier width will push the energy up in a similar way as it happens for low lying states. As the barrier gets broad, many poles converge towards the top of the barrier, and we may invoke level repulsion to explain the consequent decrease in energy of the resonance corresponding to the third pole. Using the language of perturbation theory, the increase in energy is a first order effect while the decrease is a higher order one.

Having thus gained a qualitative understanding of this behaviour, we proceed to discuss some possible implications for nuclear reactions. As mentioned earlier, this study was originated by the investigation of certain reactions in few nucleon systems that seemed to display "threshold states", that were potential resonances just above certain deuteron, triton or ^{3}He thresholds. While this interpretation[1] seemed quite successful in some cases and proved to have predictive power, it fails to explain why these resonances consistently occur above the threshold whereas an occurrence below would seem equally likely; similarly, they could occur further above and be too wide to observe. The present results indicate that these resonances are rather associated with the broad top of the Coulomb barrier, that is present in all cases discussed in Ref.1, than with the threshold. This would immediately take care of the above mentioned fact as the non monotonic behaviour of a resonance in this region as a function of energy makes it very stable against changes that may occur from one system to the next. Should the well be actually deep enough to bind a given state, another one should migrate down towards the top of the barrier; note that in these reactions the barriers are not as high as in the model, thus eliminating the possibility of resonances deep inside the barrier.

On the other hand, if the well is not deep enough, the effectmaydisappear because, although a purely repulsive potential attracts poles, their width--to-energy spacing relation is such that isolated resonances do not occur. Thus, this argument cannot refute the objections raised in Ref.2 against the occurrence of such states in deuteron-deuteron and similar channels.

This also sheds some light on some recent proposals in heavy ion reactions, where resonances on top of the barrier were supposed to explain certain features[4]. While a more detailed discussion, including complex potentials is necessary, we can surmise that the local minimum of the width (d) may well be responsible in reducing the number of contributing poles, and thus conclude that the attractive part of the potential is also of importance.

Finally, we wish to note that the effects discussed above are essentially a feature of the scattering process and we cannot expect to find the mentioned effect by a quasibound calculation. This is readily understood because, in a quasibound calculation, we have to truncate our function arbitrarily inside the barrier in order to avoid approxirnating a threshold rather than a resonance.

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