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THE FESHBACH-KERMAN-KOONIN THEORY: PROBLEMS AND PROSPECTS[1]

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The present status of FKK calculations is reviewed, with particular attention to outstanding problems. In recent years the theory has been improved in several respects, in particular by including transitions from the P to the Q chain, distinguishing between proton and neutron interactions, isolating the multistep direct (MSD) component by the subtraction method, and including multiple emission and alpha-particle emission. It is now possible to separate the continuum cross-sections for neutron and proton inelastic scattering into their MSD, multistep compound (MSC) and compound nucleus (CN) components. The peaks at high emission energies due to the excitation of low-lying resolved collective states are easily identified, and it is now known that there are appreciable collective contributions to the continuum. Outstanding problems concern the variation of the effective nucleon-nucleon strength V_0 with energy, from nucleus to nucleus and for different reactions.

1. Introduction

During the last decade there have been many studies of pre-equilibrium reactions, and some degree of understanding has been attained (Gadioli and Hodgson, [1]). It is established that these reactions take place, and several theories have been developed that allow their cross-sections to be calculated with some degree of confidence. Nevertheless many problems still remain, and these form the subject of the present meeting.

Among the quantum-mechanical theories of pre-equilibrium reactions, that due to Feshbach, Kerman and Koonin [2] (FKK) has been formulated in detail (Bonetti *et al* [3, 4]) and applied extensively to analyse experimental data. There still remains, however, some disagreement concerning the fundamental justification of this theory. The original formalism was expressed in terms of non-DWBA matrix elements, whereas the first successful calculations of Bonetti *et al* [5] used normal DWBA matrix elements. Subsequently Feshbach realised that in the original paper the statistical averaging had not been correctly carried out, and that when this is done the non-DWBA matrix elements are converted into DWBA matrix elements, thus justifying the calculations of

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Bonetti *et al.* Feshbach's arguments have however not been universally accepted, and until a consensus is achieved the problem must remain open.

Although it can now be said that the theory is well-established, there is still much to be done. In particular, it can be subjected to more critical tests and applied to a wider range of reactions. One question is particularly important: it is sometimes rather easy, by adjusting parameters, to fit a particular set of experimental data, but does this imply that we have achieved a better physical understanding of the reaction? How can we distinguish between curve-fitting and physics? This is a critical question at the present stage of our understanding.

The first criterion is a precise fit to the experimental data. What is meant by a precise fit depends on the circumstances; for example we require higher precision for elastic scattering than for reactions. Some of the problems associated with experimental data are discussed in Section 2. If we do not fit the data it can mean several things: (a) The data may be wrong. We have to be very confident of our theory to believe this, and any doubts must be resolved by a re-examination of the data or by a re-measurement, (b) The theory may break down. This could be a radical breakdown that cannot be corrected or it could be that some effect has been neglected that can be added to the theory. Examples of this are the inclusion of P to Q chain transitions and collective contributions to the continuum. These and other recent developments of the FKK theory are described in Section 3. The significance of a precise fit to the data is greater if the data are themselves precise, particularly if there is some structure that is reproduced by the theory.

The second requirement for a physically meaningful theory is that a wide range of data is fitted with a consistent set of parameters. It is often rather easy to fit a single set of data by varying the parameters of the theory, but this may have little physical significance. It is highly desirable to reduce the number of parameters by fixing them by other studies, and also by fitting in a consistent way the cross-sections of many different reactions. This is discussed in more detail in Section 4.

2. Experimental data

There are many problems connected with the selection of experimental data to test nuclear reaction theories. Initially, when the overall validity of the theory is being studied, it is usually quite easy to find suitable data already published. Later on, when the theory has been shown to be generally successful, much more accurate data are required for detailed studies. This is the stage reached in analyses using the FKK theory.

Detailed studies often require data of a special type; for example if we want to see if the theory can account for both (n,n') and (p,p') cross-sections with a consistent set of parameters, we need data for both reactions at the same energies for the same nuclei. Such data are not available, so analyses can only be made by using data at nearby energies, correcting for the difference. It would be preferable to have data at the same energy, and this requires a specific measurement to be made.

Higher accuracy is often of critical importance for the identification of particular physical processes. Thus the first analysis of collective contributions to the continuum region in (n,n') reactions [6] used early data and there was rather little evidence for structure in the continuum. The data of Takahashi *et al* [7] has a higher energy resolution and shows marked structure that is well reproduced by the calculations, providing strong evidence for the physical reality of the calculations.

Finally, the data must be correct. Theoreticians often underestimate the difficulty of obtaining accurate and reliable data. There are many things that can go wrong and many checks and corrections to be made. Sometimes data show very surprising features that are contrary to accepted theories. This may be due to a new effect but in such cases it is important to examine the experimental results very carefully, particularly if the experimentalists themselves did not draw attention to the potential importance of the result.

3. Development of the FKK theory

The Feshbach-Kerman-Koonin theory distinguishes between two reaction chains, the multistep direct and the multistep compound. In multistep direct reactions (MSD) at least one particle, usually the projectile, remains in the continuum, whereas in the multistep compound reactions (MSC) all nucleons remain bound. These are called the P and Q chains respectively.

The FKK formalism was first used by Avaldi *et al* [8] and by Bonetti *et al* [5] to calculate the MSD cross-sections of several (p,n) reactions from 25 to 45 MeV. Subsequently the formalism was extended to include the analysing powers (Bonetti *et al* [9]) and used to analyse experimental data for ^{58}Ni (p,p') at 65 MeV.

At lower energies it is necessary to include the contribution of the MSC process, and this was done by Bonetti *et al* [8, 9, 10]. These early analyses showed that an incoherent superposition of the MSD and MSC cross-sections is able to give a good overall account of the cross sections of pre-equilibrium reactions from 10 to 50 MeV with consistent values of the parameters (Bonetti and Colombo, [11]).

In the following years many analyses were made of MSC reactions (Herman *et al* [12]; Field *et al* [13]; Chadwick *et al* [14, 15]; Koumdjieva and Hodgson [16]; Olaniyi *et al* [17] and Demetriou *et al* [18]) and MSD reactions (Holler *et al* [19]; Mordhorst *et al* [20]; Trabandt *et al* [21, 22]; Marcinkowski *et al* [23]; Scobel *et al* [24], Cowley *et al* [25], Richter *et al* [26, 27]) and these established the validity of the FKK theory over a wide range of energies and target nuclei.

With increasing precision of the analysis it has become clear that the FKK theory must be modified and developed in several ways. These include the incorporation of transitions from the P to the Q chain after the initial interaction, more accurate ways of separating the contributing reaction mechanisms, the inclusion of collective excitations in the continuum region and the emission of alpha-particles. These developments will now be summarised.

In the original FKK formalism the P and Q chains remain distinct after the initial interaction, but many subsequent analyses showed that this gives MSC cross-sections that are too large to fit the experimental data. This is the result of allowing all the compound nucleus cross-section to pass through the 2p1h state, and may be avoided by allowing transitions from the P to the Q chain to take place after the initial interaction

(Chadwick, [28]; Marcinkowski *et al* [29, 30]; Chadwick and Young, [31]; Marcinkowski and Kielan [32], Lenske *et al* [33]). This has been done in two ways, firstly as a single transition and secondly by summing the transitions at each stage. Chadwick and Young [31] evaluated the fraction R of the incident flux that goes immediately to the Q chain as the ratio ρ_1^B/ρ_1 of the bound to the total phase space of 1p-1h excitations. The fraction going to the P chain is then $(1-R)$. Not all this flux, however, is emitted by the MSD process, but only a fraction $(1-R')$ of the incident flux. The remaining flux $(R'-R)$ must be added to the Q-chain and is the additional P to Q transition.

A gradual absorption model, considering the P to Q transitions at each stage of the P-chain, has been formulated by Marcinkowski *et al* [29, 30]. The MSD flux is $(1-R')$ as before, but now the remaining flux is divided using the same phase space factor so that $R'\rho_1^B/\rho_1$ goes to the Q chain and $R'(1-\rho_1^B/\rho_1)$ to the P chain. This latter flux all goes eventually to the Q-chain, an amount $R'(1-\rho_1^B/\rho_1)\rho_2^B/\rho_2$ at the second stage and so on. Summing all these gives a total flux $R'(1-\rho_1^B/\rho_1)$ to the Q-chain after the first stage.

As shown in Fig. 1 the inclusion of P to Q transitions substantially reduces the MSC cross-section and improves the fit to the ^{93}Nb(n,n') cross-section. A similar comparison for the corresponding ^{93}Nb(n,p) reaction shows a somewhat improved fit and again a lowered MSC cross-section; in this case it is the angular distribution for outgoing energies around 12 MeV that show more clearly the dominance of the MSD reaction in this energy region. A similar result was obtained by Lenske *et al* [33]. It is notable that there are substantial differences both in shape and magnitude between the MSC cross-sections given by the two models. Since the gradual absorption model is more general, and is easy to calculate, it is preferred over the simpler model.

A more detailed formalism for P to Q chain transitions that uses the FKK transition matrix instead of a phase space factor has been developed by Arbanas *et al* [34]. By removing an approximation made by FKK, they express the MSC cross-section as a sum of four terms taking into account the possible P to Q transitions. Calculations were made with both normal and non-normal matrix elements, and the results compared with the angle-integrated cross-section of the ^{93}Nb (n,n') reaction at 14 MeV. This comparison shows that a better fit is obtained with the non-normal DWBA matrix elements and this was also found for the ^{107}Ag(n,n') reaction at 14 MeV by Chadwick *et al* [35] contrary to the work of Kumabe *et al* [36]. However some calculations of the ^{90}Zr(p,n) reaction at 80 MeV by the same authors showed a large calculated excess cross-section for emission energies below 40 MeV, indicating that multistep reactions are greatly over-estimated. Until the reason for this is established and corrected, calculations with normal DWBA matrix elements are preferred.

Most of the early analyses were designed to test either the MSC or the MSD formalism, and so the data were chosen so that either one or the other process dominates. Thus MSC analyses were made of the energy spectra in the backward direction from reactions at low energies, and MSD analyses were made of double differential cross-sections at high energies. In most cases, however, both processes contribute and in addition there are contributions from compound nucleus emission and collective excitations. The earlier analyses used the optical model transmission coefficients to calculate the MSC cross-section and chose a value of the effective nucleon-nucleon interaction strength V_0 to fit the MSD cross-section. The collective excitations are assumed to be responsible only for the resolved peaks at the higher outgoing energies, and the compound nucleus cross-sections are calculated from statistical theory.

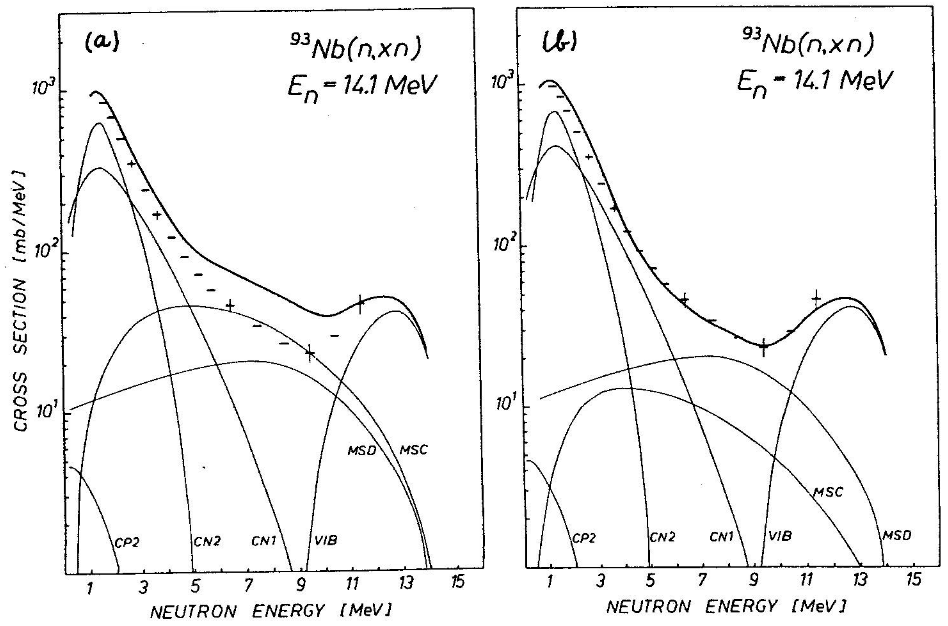

Fig. 1. Multistep calculations of the ^{93}Nb (n,n') cross-section at 14.1 MeV (a) without and (b) including P to Q chain transitions using the gradual absorption model. The inclusion of these transitions enhances the MSD cross-section and greatly reduces the MSC cross-section (Marcinkowski and Kielan, [32]).

It is however desirable to develop more precise methods of separating these contributions. Thus Chadwick and Young [31] evaluated the MSC and MSD cross-sections and adjusted their normalisations to optimise the fit in the intermediate energy region. Demetriou *et al* [18] removed the compound nucleus and MSC contributions, which are symmetric about 90° in the CM system, by subtracting double differential cross-sections for pairs of complementary angles, thus leaving only the MSD and the collective cross-sections. Assuming that the collective contributions are confined to the peaks at higher emission energies, the remaining cross-section is MSD only, and may be compared with similarly-subtracted FKK calculations. This has been done for the

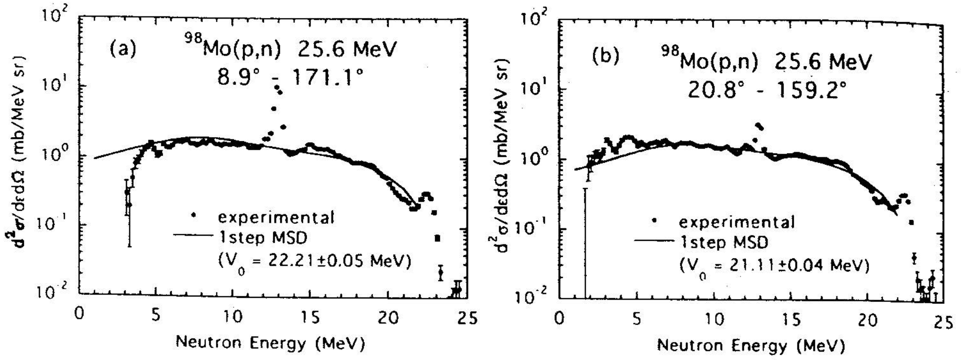

Fig. 2. Subtracted double differential cross-sections for the ^{98}Mo (p,n) reaction at 25.6 MeV for two pairs of complementary angles compared with similarly-subtracted FKK MSD calculations. The curves are normalised to the data and the values of the effective interaction V_0 are given for each angle pair; these are in satisfactory agreement with each other (Watanabe *et al* [37]).

^{93}Nb (n,n') reaction at 14 MeV. The fit is good except in the region of the collective peaks, and the values of the effective nucleon-nucleon interaction strength V_0 obtained by normalising to the data are consistent for each angle pair. A more severe test of the subtraction method is provided by the (p,n) reaction which does not have appreciable collective contributions. This is shown by the analysis of the ^{98}Mo (p,n) reaction at 25.6 MeV in Fig. 2. The subtraction method is sensitive to the accuracy of the fit to the angular distributions, and also assumes that there are no collective excitations in the continuum region. Providing the MSC cross-section is isotropic, the method of Chadwick and Young is identical to the subtraction method over the same energy region, and gives a result integrated over all angles.

The possibility of such collective excitations has been studied by Marcinkowski *et al* [38, 39]. The cross-sections of (p,n) reactions on several nuclei from 9 to 27 MeV were analysed by the FKK theory. Since collective contributions to this reaction are small, this establishes the value of V_0. Using the same parameters, the corresponding (n,n') cross-sections were calculated, and there was a shortfall compared with the data, indicating the presence of collective contributions to the continuum. This was confirmed by calculating the collective contributions using the experimental values of the energies and strengths of the low-lying collective states, and including the contributions of the giant multipole resonance, if any, using the energy-weighted sum rule. The results of this calculation, when added to the other contributions, are in good accord with the data (Marcinkowski *et al* [38]). In this way a consistent analysis of (p,n) and (n,n')

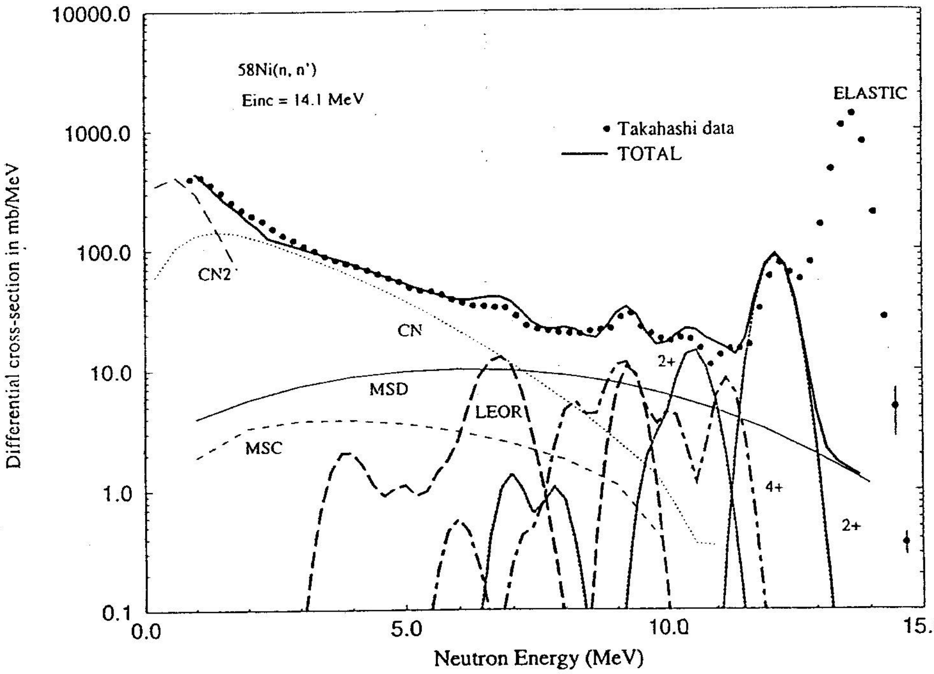

Fig. 3. The angle-integrated energy spectrum of neutrons inelastically scattered by ^{58}Ni at 14.1 MeV (Takahashi *et al* [7]) compared with MSC, MSD and collective cross-sections (Demetriou *et al* [39]).

reactions can be made that includes all the contributing processes. Further studies of the contributions of collective excitations (Demetriou *et al* [39]) showed that they are able to account for the resonance structure of the (n,n') energy spectra (see Fig. 3). This structure was also reproduced by Lenske *et al* [33], using a microscopic model.

The FKK theory has recently been extended to include alpha-particle emission by Olaniyi *et al* [40], using the knock-out model. It is assumed that the incident proton collides with a pre-formed alpha-particle in the target nucleus and knocks it out, the proton being captured into an orbit in the residual nucleus. The transition matrix is expressed in terms of the wavefunctions of the initial and final states and the proton-alpha particle effective interaction, and is multiplied by the probability of finding the alpha-particle in the target nucleus. Double differential cross-sections for the (p,α) reaction at 30 and 44.3 MeV on several nuclei were analysed using the subtraction method. Some results are shown in Fig. 4. The angle-integrated cross-sections show a strong peak at lower energies attributable to compound nucleus emission, and this was

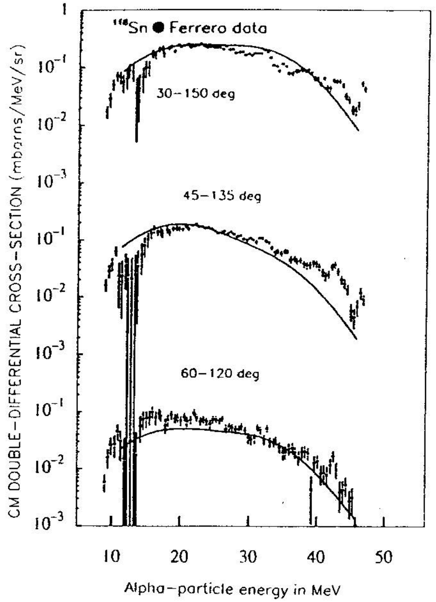

Fig. 4. Subtracted double-differential cross sections for the (p,α) reactions at 30 MeV for ^{118}Sn compared with similarly subtracted zero-range MSD FKK calculations using the alpha-particle knock-out model (Olaniyi *et al* [40]).

evaluated using the Hauser-Feshbach theory. The total cross-section is well described by the sum of compound nucleus and MSD processes. At these energies, the contribution of two-step processes is quite small, but at higher energies the two and three-step process become increasingly important, especially at the lower outgoing energies. Further analyses have been made of the ^{59}Co(p,α) reaction at 120 MeV, including these higher-order processes. To do this, the computer program was modified to include the $(p,p')(p',\alpha)$ and $(p,n)(n,\alpha)$ two-step processes and the four $(p,N)(N,N')(N',\alpha)$ three-step processes. All these processes contribute incoherently and, as they each include just one nucleon-alpha interaction and one alpha-particle pre-formation factor, they are all multiplied by the same normalisation factor. The calculations fit the data quite well, except for the backward angles at low ejectile energies, due to the omission of higher order processes. The $(p,p')(p',\alpha)$ and $(p,n)(n,\alpha)$ two step processes dominate at the higher ejectile energies and have similar angular distributions, and the three-step processes become more important as the ejectile energy decreases. As expected, the angular distributions become less forward-peaked as the number of steps increases.

4. The parameters of the FKK theory

It is an important condition for the physical validity of a theory that the parameters are not arbitrarily adjustable, but can be obtained from other studies. Most if not all of the parameters of the FKK theory can be fixed in this way, but there remains some flexibility that requires further study. The parameters of the FKK theory are the optical potentials, the level density parameters and those of the effective nucleon-nucleon interaction, and these will now be discussed.

The optical potentials that describe the distortion of the incoming and outgoing waves may be obtained from analyses of the appropriate elastic scattering data, or from a well-established global set. This is a well-established procedure in most reaction analyses but suffers from the serious defect that the matrix elements that determine the elastic scattering may not determine to the same degree the reactions. It is thus possible, and is indeed found (Watanabe *et al* [37]) that different optical potentials that fit the elastic scattering give markedly different reaction cross-sections. There is no easy way to overcome this difficulty, and so when different analyses are being compared it is essential to use the same optical potentials in each of them.

There is a similar sensitivity to the level density parameters. There are several compilations in general use, and they give somewhat different results. In order to make a meaningful comparison of values of the strength V_0 of the effective nucleon-nucleon interaction from different reactions it is therefore necessary to use the same optical model potentials and level density formulae throughout.

The remaining parameter is the strength V_0 of the effective nucleon-nucleon interaction, usually taken to have the Yukawa form with range 1fm. The cross-sections are insensitive to the value chosen for the range, providing the value of V_0 is re-adjusted. Since the value of V_0 determines the overall normalisation of the cross-section, it is usual to treat it as an adjustable parameter and to determine its value by the best fit criterion. The values obtained in different analyses can then be compared with each other, and with theoretical calculations.

Several analyses of (n,n') reactions (Field *et al* [13]; Olaniyi *et al* [17]) showed that the cross-sections for several target nuclei can be fitted by essentially the same value of V_0, although subsequent analyses using a wider range of nuclei gave some evidence of dependence of V_0 on the target nucleus.

Analyses of nucleon reactions over a range of energies gave values of V_0 that varied with energy in the same way as the real part of the nucleon optical potential, as is indeed expected from the simple folding model. The absolute value of V_0 is also given by the folding model, and agrees well with the empirical values of V_0, as shown in Fig. 5.

This work shows that the parameters of the FKK theory are all obtainable from other work, so that it now becomes possible to study in more detail the accuracy of the calculations made with these parameters. It is first of all essential to include the collective excitations to the continuum for inelastic scattering, as described in Section 3. If this is not done, the cross-section will be included in the MSD component, giving substantially greater values of V_0, as was indeed found by Watanabe *et al* [37] and Demetriou *et al* [18]. Inclusion of the collective contribution also allows an analysis of (n,n') and (p,n) cross-sections to be made with a consistent parameter set (Marcinkowski *et al* [38],

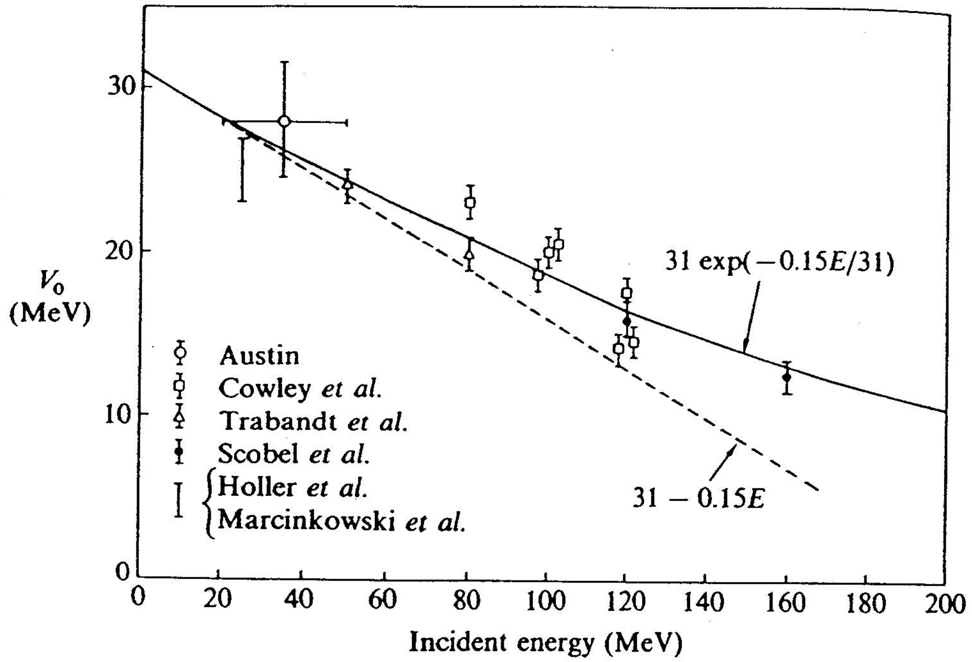

Fig. 5. The effective nucleon-nucleon interaction strength V_0 as a function of incident nucleon energy with a Yukawa form factor of range 1 fm. The full curve shows the energy dependence of the nucleon optical potential normalised to the value at low energies obtained from the real part of the nucleon optical potential using the folding model. The points are obtained from Austin [42], Cowley *et al* [25], Trabandt *et al* [21, 22], Scobel *et al* [24], Holler *et al* [19] and Marcinkowski *et al* [30].

Demetriou *et al* [39]). The same parameter set failed, however, to fit the corresponding (p,p') cross-sections. The reason for this is still being studied, but it is possible that the effective interaction strength depends on the reaction, and that the folding model is insufficiently accurate to give a precise value of V_0. Further progress towards a consistent account of all reactions may well depend on the development of more sophisticated interactions, and this is being studied by Lindsay [41].

To sum up the present situation for the values of V_0 for nucleon reactions, the energy variation seems to be quite well understood, some reactions can be analysed with a consistent set of parameters, but others may require a different value.

A similar analysis has been made for the values of W_0 extracted from analyses of (p,α) reactions (Demetriou and Hodgson, [43]). The energy variation follows that of the real part of the alpha-particle optical potential. The absolute value, however, depends on the alpha-particle preformation factor, which is not yet known and depends on the structure of the individual nucleus.

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