PHYSICAL REVIEW C VOLUME 14, NUMBER 2 AUGUST 1976

Pre-equilibrium model evaluation of neutron spectra from proton-induced reactions

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(Received 22 March 1976)

Calculations of energy spectra of neutrons emitted from (p, n) reactions were performed on the basis of the pre-equilibrium exciton model. The results were compared with several experiments, covering the range from $A = 27$ to $A = 208$ of target masses, and from 17.6 to 63.8 MeV of incident proton energy. Within the limits of accuracy of both calculations and experimental data, the theoretical previsions were found adequate, and provided reasonable evaluations of the yields of pre-equilibrium neutron emissions.

[NUCLEAR REACTIONS (p,n) for $18 < E_p < 64$ MeV. Calculated neutron energy spectra with pre-equilibrium statistical model.]

I. INTRODUCTION

Very recently Blann *et al.* have reported[1] the results of some measurements, by a time of flight technique, of the energy spectra of neutrons emitted in reactions induced by 25-, 35-, and 45-MeV protons in ^{48}Ca, ^{90}Zr, ^{120}Sn, and ^{208}Pb. By analyzing their results both with the "hybrid model" and with the "geometry dependent hybrid model", the authors reach the conclusion that only a theory taking into account a strong contribution to the observed phenomena from surface interactions can reproduce the data; while a disregard of geometry effects in the interaction process would yield calculated cross sections at variance with the experiments. The disagreement would be especially important for high energy spectral regions, where the anticipated values would be lower than those observed by as much as an order of magnitude.

Now, the calculations presented by Blann *et al.* appear to assume a distinction between surface and volume interactions based mainly on the hypothesis that in a surface process practically no hole states should be excited. The implication for the pre-equilibrium model would therefore be that at incident proton energies of a few tens of MeV the emission of high energy neutrons takes place from 2p-0h rather than from 2p-1h states. This contradicts, however, the evidence brought out by our group in studies of (p,xn) excitation functions.[2-5] In fact, it was found in those studies that the neutron yields could be interpreted quite satisfactorily with the exciton model assuming an initial 2p-1h configuration. Furthermore, just in the particular case of (p,n) reactions, the reasonably wide range of available experimental data made it possible to test the above assumption for incident energies from 10 to 80 MeV and for target nuclei of mass number from 50 to 170. Given the adequate results obtained in explaining the main characteristics of the (p,n) process (which, it may be recalled, provides the yield of neutrons emitted with the maximum permissible energy), it was resolved to make use of the experimental data concerning this process to determine the absolute value of the decay rates for exciton-exciton interactions. The decay rates actually determined were those applicable to the transition from a 2p-1h to a 3p-2h configuration; the dependence of the rates on energy and exciton number was estimated on the basis of the Fermi gas model.[2,4] It was encouraging that the rates thus obtained proved appropriate also for neutron induced reactions[6,7,21] and again later on for processes initiated by α particles and π^- mesons.[8,9]

The conclusions of Blann *et al.* would appear to throw doubt upon the validity of our previous results. Therefore, we decided to reanalyze in the framework of the exciton model the new data presented by Blann *et al.* To make the analysis more comprehensive, we extended our study to all the data, as far as known to us, on neutron spectra from proton induced reactions measured by other authors[10-13] at different incidence energies and for other targets. Many of these results have already been examined[11,12] and found fairly well reproducible assuming a 2p-1h initial configuration; it seemed, however, worthwhile to subject all the available data to the same type of analysis, using only one set of values of the decay rates for exciton-exciton interaction.

II. ANALYSIS

A. Basic expressions

The exciton model has been discussed in some detail in previous articles,[8,14,15] so that presently it should suffice to rewrite only a few specific formulas.

The neutron spectrum of interest here is assumed to be given by the incoherent sum of contributions from pre-equilibrium emission and compound nucleus evaporation. The latter contribution results in a component strongly peaked around a kinetic energy of the emitted neutrons of the order of

$$2T \approx 2(E^n_{max}/a)^{1/2},$$

where T is the "nuclear temperature" of the residual nucleus (after emission of one nucleon) at the maximum permissible excitation energy, and a the level density parameter. The calculation of the evaporative component is a well-known problem that can be solved taking into account the possible sequential emission of neutrons, within a fair degree of approximation by means of a formula due to Le Couteur and Lang.[16] Here, however, in the interest of higher accuracy this component was evaluated with a Monte Carlo procedure.

The pre-equilibrium component is introduced to explain the high energy "tail" of the spectrum, and can be obtained from the expression[8]

$$\sigma(\epsilon_\nu)d\epsilon_\nu = \sigma^a(E_p)\left\{\frac{W_c^{n_0}(U,\epsilon_\nu)d\epsilon_\nu}{W_c^{n_0}(U)+W_{eq}^{n_0}(U)} + \sum_{\substack{n=n_0+2\\ \Delta n=+2}}^{\bar{n}}\left[\prod_{\substack{j=n_0\\ \Delta j=+2}}^{n-2}\frac{W_{eq}^j(U)}{W_c^j(U)+W_{eq}^j(U)}\right]\frac{W_c^n(U,\epsilon_\nu)d\epsilon_\nu}{W_c^n(U)+W_{eq}^n(U)}\right\}, \qquad (1)$$

where n_0 is the exciton number of the initial configuration, $\bar{n}=(2gU)^{1/2}$ (with g density of single nucleon states and U effective excitation energy of the composite system), and $\sigma^a(E_p)$ is the cross section for composite nucleus formation. $W_c^n(U,\epsilon_\nu)$ is the decay rate for emission from an n-exciton (p particles, h holes) state of a neutron with energy ϵ_ν (channel energy):

$$W_c^n(U,\epsilon_\nu)d\epsilon_\nu = \frac{1}{\pi^2\hbar^3}\frac{A}{A+m_\nu}\frac{1}{\omega_{p,h}(U)}(2S_\nu+1) \times m_\nu\sigma_{\mathrm{inv},\nu}(\epsilon_\nu)\epsilon_\nu\omega^{(\nu)}_{p-1,h}(U_R), \qquad (2)$$

denoting with $\omega_{p,h}(U)$ and $\omega^{(\nu)}_{p-1,h}(U_R)$ the densities of states of the composite and residual nucleus, respectively, and with $\sigma_{\mathrm{inv},\nu}(\epsilon_\nu)$ the inverse neutron cross section. $W_c^n(U)$ is the total decay rate for emission of one particle, under the simplifying assumption that it can be only a neutron or a proton,

$$W_c^n(U) = \int_0^{E_\nu^{max}} W_c^n(U,\epsilon_\nu)d\epsilon_\nu + \int_0^{E_\pi^{max}} W_c^n(U,\epsilon_\pi)d\epsilon_\pi, \qquad (3)$$

where the meaning of unidentified symbols is obvious. Finally, $W_{eq}^n(U)$ is the decay rate for exciton-exciton interaction.

B. Calculation parameters

To carry out the calculations, several quantities appearing in the above formulas must be evaluated. In this subsection we give an account of our selection. The inverse cross sections were obtained within the framework of the exciton model itself by means of the expressions reported elsewhere[17] by Gadioli *et al.*

The state densities were calculated with two different procedures, depending on whether we were dealing with low incident energies ($E_p \leq 26$ MeV) and nuclei far from shell closures or the other way round. In the first case, Ericson's[18] formulas were used, or rather their modified form allowing separate accounting of protons, neutrons, proton holes, and neutron holes (cf., e.g., Ref. 6); the single nucleon state density was assumed equal to $(A/13.3)$ MeV^{-1}, corresponding to "a" parameter values given by the rule $a \approx (A/8)$ MeV^{-1}. In the second case a direct combinatory calculation of state densities was carried out which took into account the Pauli principle, the finite depth of the potential well, and the gap in the single particle state sequence occurring on completion of a magic shell; the state density was assumed to vary according to the law $\frac{3}{2}(A/\epsilon_F^{3/2})\epsilon^{1/2}$ for energies lower than the Fermi energy ϵ_F, and to remain constant (with an equidistant state spacing value equal to that obtaining at the Fermi energy) for higher energies. The Fermi energy was taken equal to 20 MeV, the value deduced, in a square well approximation, from the spacing of slow neutron resonances. This choice of ϵ_F does not affect appreciably the numerical results since, while it is true that a more realistic well should be deeper, the single nucleon states with energy lower than Fermi's would have broader spacings than for a square well. These effects compensate each other to a large extent when calculating the state densities, as shown by Gadioli, Gadioli Erba, and Sona[4] by comparing the results for a square well with $\epsilon_F = 20$ MeV and for an "harmonic oscillator" well with $\epsilon_F = 40$ MeV. The gap hypothesis, that is an approximate representation[19] of the well-known discontinuities due to shell effects, was used here with the following values of the gap width D: for $N=126$,

TABLE I. Decay rates $W_{eq}^{p,h}(U)$ for exciton-exciton interactions utilized in present work (the unit of the decay rates is 10^{22} sec^{-1}).

U (MeV)	$W_{eq}^{2,1}$	$W_{eq}^{3,2}$	$W_{eq}^{4,3}$	$W_{eq}^{5,4}$	$W_{eq}^{6,5}$	$W_{eq}^{7,6}$
0	0	0	0	0	0	0
5	0.053	0.04	0.035	0.03	0.025	0.02
10	0.17	0.13	0.11	0.092	0.08	0.072
15	0.33	0.26	0.22	0.18	0.16	0.15
20	0.53	0.42	0.35	0.30	0.27	0.24
25	0.72	0.61	0.51	0.44	0.39	0.35
30	0.89	0.81	0.69	0.60	0.53	0.48
35	1.01	0.99	0.88	0.78	0.69	0.62
40	1.14	1.18	1.08	0.97	0.86	0.78
45	1.23	1.33	1.27	1.15	1.04	0.95
50	1.33	1.50	1.46	1.35	1.24	1.13
55	1.39	1.61	1.62	1.53	1.42	1.31
60	1.46	1.75	1.80	1.73	1.62	1.51

$Z=82$, $D\approx 1.4$ MeV; for N or $Z\approx 50$, $D\approx 3$ MeV; for N or $Z\approx 20, 28$, $D\approx 1.8$ MeV. The first two values were derived by an analysis of experimental data[19] and by combinatory calculations based on a set of single nucleon states obtained from Nilsson's model[20]; the third value was suggested by the pattern of single nucleon states in spherical nuclei given by the same model. It should be remarked, however, that the dependence of the final results on the D value is quite weak, as will be discussed in Sec. II C.

The decay rates for exciton-exciton interactions are the same as those used in previous works by our group[4,5,14,15]; their numerical values are given in Table I. It may be recalled that these quantities were obtained semiphenomenologically, according to the procedure already mentioned in the introduction.

C. Results

Data from several experiments were analyzed, namely, those reported by Verbinski and Burrus[12] for spectra produced by protons of $E_p \approx 18$ MeV on ^{115}In, ^{181}Ta, and ^{208}Pb; by Kalbach *et al.*[11] at $E_p \approx 18$ MeV on ^{103}Rh, ^{105}Pd, ^{159}Tb, and ^{169}Tm; by Grimes *et al.*[10] at $E_p \approx 24$ and 26 MeV on ^{51}V; by Blann *et al.*[1] (for the reactions quoted in the introduction), and by Watcher at $E_p \approx 64$ MeV on ^{27}Al. Some other existing data at low energies have not been considered. In fact, the contributions to the spectra of pre-equilibrium and evaporation neutrons overlap differently, depending on the excitation energy of the composite nuclear system and on the mass of the target nucleus. Since the relative importance of the pre-equilibrium contribution decreases by lowering the energy and the target mass, making the detection of nonevaporative effects increasingly uncertain, it was felt not rewarding to consider experiments at $E_p < 18$ MeV, or, even at 18 MeV, on targets with $A < 100$. The reliability in separating pre-equilibrium from evaporation effects, however, improves quite rapidly with energy, so that all data at higher energies become usable even for comparatively light targets.

1. Data of Verbinski and Burrus

As a preliminary remark, it can be observed that the measured neutron yields appear quite high. The authors report, in Table I of their work,[12] the experimental cross sections for neutron production. From these, by evaluating theoretically the probabilities for emission from the excited composite nuclei of x neutrons and y protons, one can infer the absorption cross sections $\sigma^a(E_p)$ for the incident protons. Now, an underestimate of the $\sigma^a(E_p)$ would be obtained, e.g., if pre-equilibrium emission were assumed to be absent, and the average number $\bar{n}_\nu$ of neutrons evaporated from the compound nucleus were computed. We found that $\bar{n}_\nu$ would amount to 1.99 for In, 2.51 for Ta, and 2 for Pb, giving underestimated absorption cross sections of 3613, 1366, and 1685 mb, respectively. Still, such cross sections are definitely higher than those deduced either with the optical model or with the exciton model (in the last case, by means of the formulas of Ref. 17), both of which appear in reasonable accord with the reaction cross sections measured

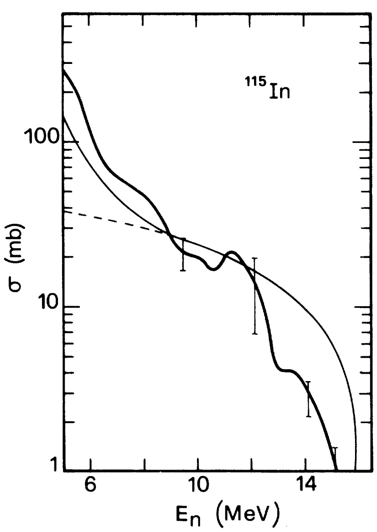

FIG. 1. Calculated (smooth line) and measured (heavy line with error bars) energy spectra of neutrons emitted by ^{115}In bombarded with 18.3 MeV protons. The contribution of pre-equilibrium emissions is indicated by the dashed line. The experimental results are from the work of Verbinski and Burrus (Ref. 12).

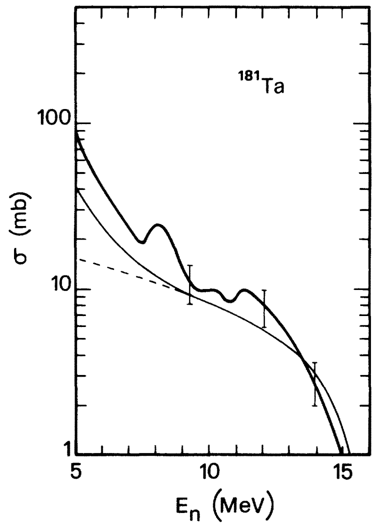

FIG. 2. The same as Fig. 1, for ^{181}Ta bombarded with 18 MeV protons.

by beam attenuation techniques.

In this situation, it did not seem significant to try to compute absolute cross sections to be compared with the experimental results of Verbinski and Burrus. We restricted ourselves to calculate with the exciton model the probability of preequilibrium emission from the excited composite nucleus of neutrons with energy ϵ_ν, and then multiplied by these probabilities the absorption cross sections deduced from the data reported by the authors. Obviously, the implicit assumption in this procedure is that, whatever the reason for the greater than expected cross sections, it does not cause peculiar distortions in the energy distributions of the emitted neutrons. It is seen in Figs. 1–3 that the trends of the high energy portions of the neutron spectra of Verbinski and Burrus can be reasonably reproduced.

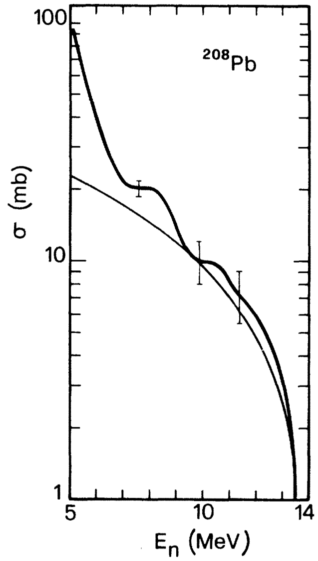

FIG. 3. The same as Fig. 1, for ^{208}Pb bombarded with 17.6 MeV protons. In this case, only the calculated preequilibrium contribution is shown.

2. *Data of Kalbach et al. and of Grimes et al.*

The calculations for the nuclei studied by these authors were performed with all the required parameters chosen *a priori*, as specified in Sec. II B. The resultant fits are shown in Figs. 4 and 5; considering that they were obtained without any adjustment, the agreement with the experiments appears on the whole satisfactory. Only for the high energy part of the ^{103}Rh spectrum is there some discrepancy, both in absolute values and in shape, between calculations and data. We are unable to offer an argument to explain this discrepancy, and we merely point out that the problem concerns only one nucleus out of several. On the other hand, the provisions of the exciton model

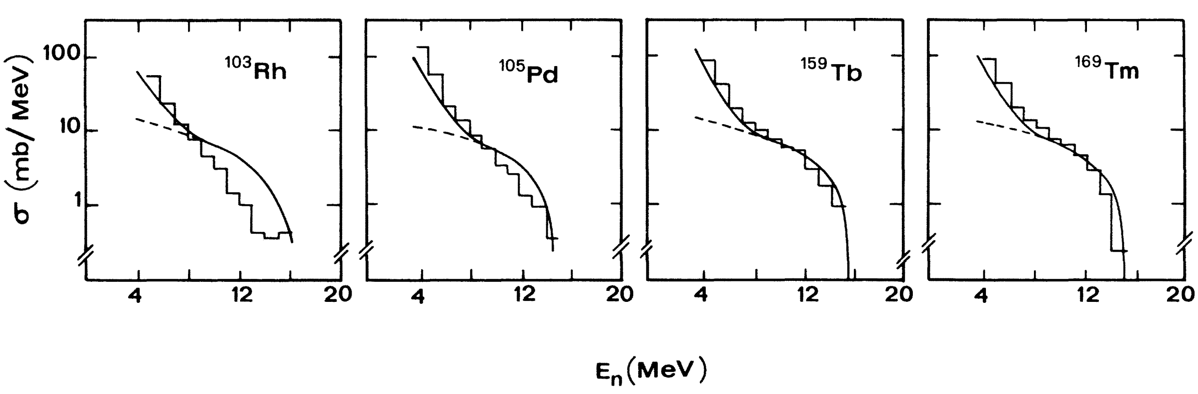

FIG. 4. Calculated (smooth lines) and measured (histograms) neutron spectra from ^{103}Rh, ^{105}Pd, ^{159}Tb, and ^{169}Tm bombarded with 18 MeV protons. The experimental results are from the work of Kalbach *et al.* (Ref. 11).

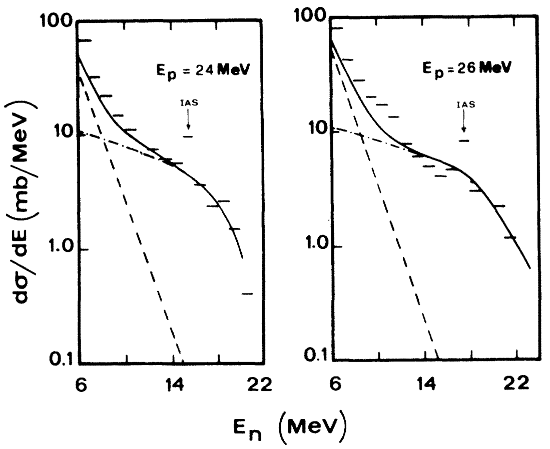

FIG. 5. Calculated (full lines) and measured (dashes) neutron spectra from the $^{51}V(p,n)$ reaction at $E_p = 24$ and 26 MeV. Pre-equilibrium and evaporative contributions are shown by broken lines (point-dashed and dashed, respectively). The experimental results are from the work of Grimes *et al.* (Ref. 10).

depend rather weakly on specific properties of the particular nuclei, so that it is difficult to see how the model could be made to account for an apparently singular behavior of the ^{103}Rh nucleus.

In the experimental spectra of ^{51}V there is clear evidence for the isobaric analog state excited in ^{51}Cr. This state is selectively populated in a process that a statistically founded model could not be expected to foresee.

3. Data of Blann et al.

Also for the nuclei studied by these authors, the exciton model calculations were carried out barring *ad hoc* adjustments of parameters. The comparison of the computed results with the experimental data is displayed in Figs. 6–9. From inspection of these figures, the following conclusions can be drawn. At $E_p = 25$ MeV, the average behavior of the experimental spectra is satisfactorily reproduced, both in shape and absolute values. At $E_p = 35$ MeV, essentially the same conclusion applies; it may be noticed, however, that for ^{48}Ca the calculated absolute values are lower by an average 30% than the measured ones. At $E_p = 45$ MeV, fairly good agreement is reached again for the shapes in all cases, and for the values in ^{208}Pb; but in ^{48}Ca, ^{90}Zr, and ^{120}Sn the calculations give estimates low on the mean by some 50%.

Considering the theoretical approximations, one might be satisfied to conclude that discrepancies of the order of 50%, and present only in some cases, are well within the uncertainties of the numerical evaluations, and that on the whole the exciton model can reproduce these experimental data with reasonable accuracy. Although this is in fact our opinion, we feel somewhat disturbed by the suspicion of a trend suggesting an impairment of the model adequacy when the incident energies are raised beyond 35 MeV. No hint of such a trend was detected in the study of excitation functions of (p,n) reactions,[2,4,5] so that it may be worthwhile to compare the cross sections considered earlier with the data analyzed here, and to discuss their consistency.

The measurements of the excitation functions were carried out by means of the activation method, while those of the neutron spectra employed

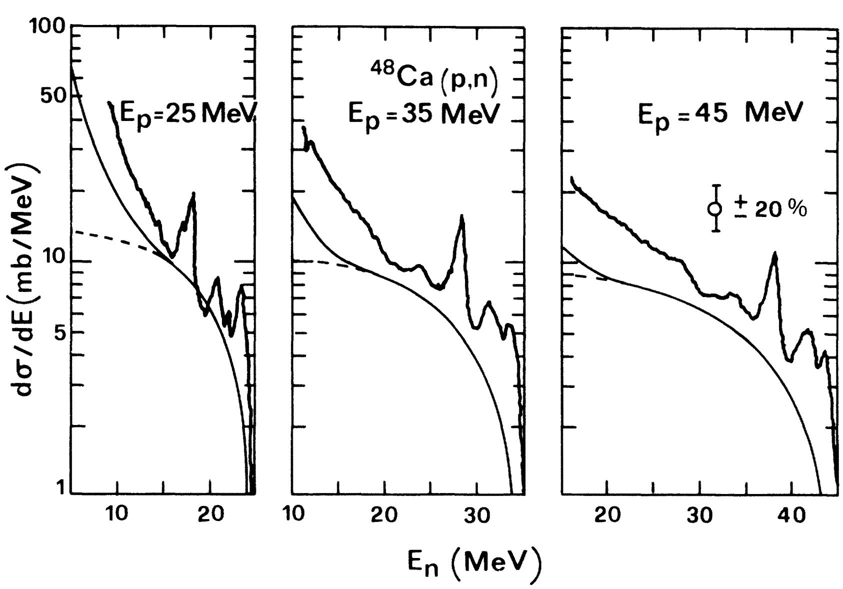

FIG. 6. Calculated (smooth lines) and measured (heavy lines) neutron spectra from the $^{48}Ca(p,n)$ reaction at $E_p = 25$, 35, and 45 MeV. The pre-equilibrium contribution is indicated by the dashed curves. The experimental results are from the work of Blann *et al.* (Ref. 1).

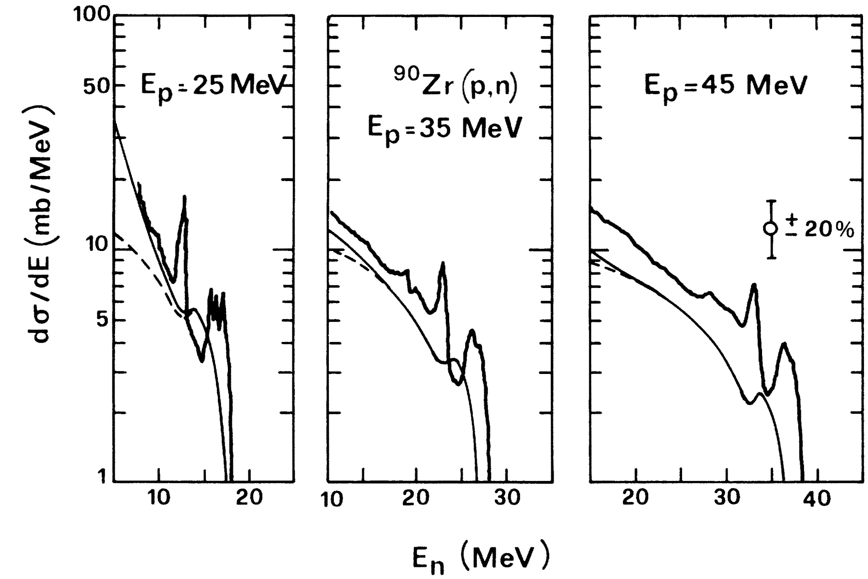

FIG. 7. The same as Fig. 6 for the $^{90}Zr(p,n)$ reaction.

the time of flight technique. We have compared the (p,n) reaction cross sections derived in the two cases for incident energies of 35 and 45 MeV. In order to do this, we evaluated the integrals of the high energy portions of the neutron spectra. Although the evaluation of these integrals cannot be very precise, we think that the approximation attainable is sufficient to make the desired comparison significant.

Two integrals were computed from each spectrum by choosing different intervals of integration, namely between E^n_{max} and $E^n_{max} - B_{2n}$, and between E^n_{max} and $E^n_{max} - (B_{2n} + \Delta_{2n} - \Delta_{1n})$, where B_{2n} denotes the binding energy of the second neutron in the emission sequence, and Δ_{1n} or Δ_{2n} the pairing energies of the residual nuclei after the emission of one or two neutrons, respectively. In any case it was assumed that when energetically possible the emission of a second neutron from the residual nucleus actually takes place. The γ decay competing with the emission of the second neutron was neglected, so that the (p,n) cross sections de-

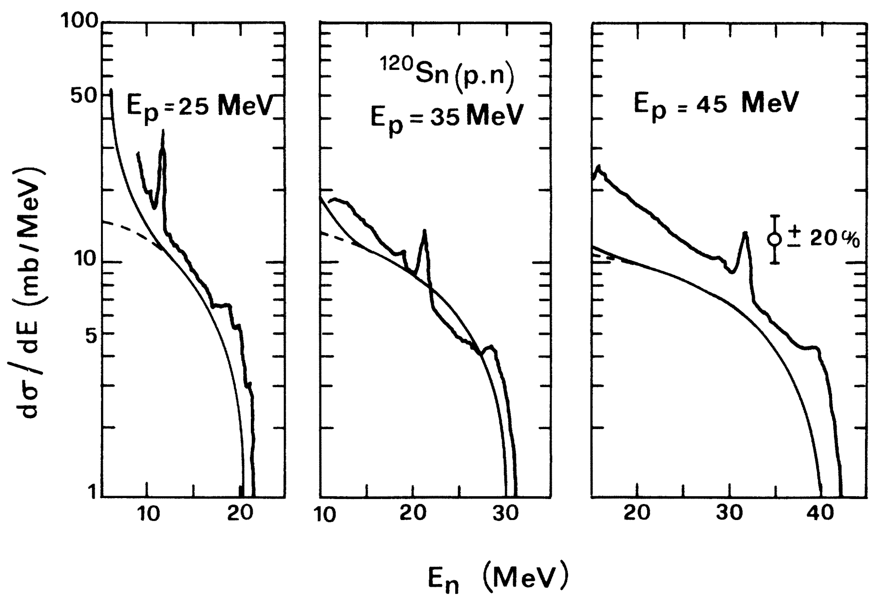

FIG. 8. The same as Fig. 6 for the $^{120}Sn(p,n)$ reaction.

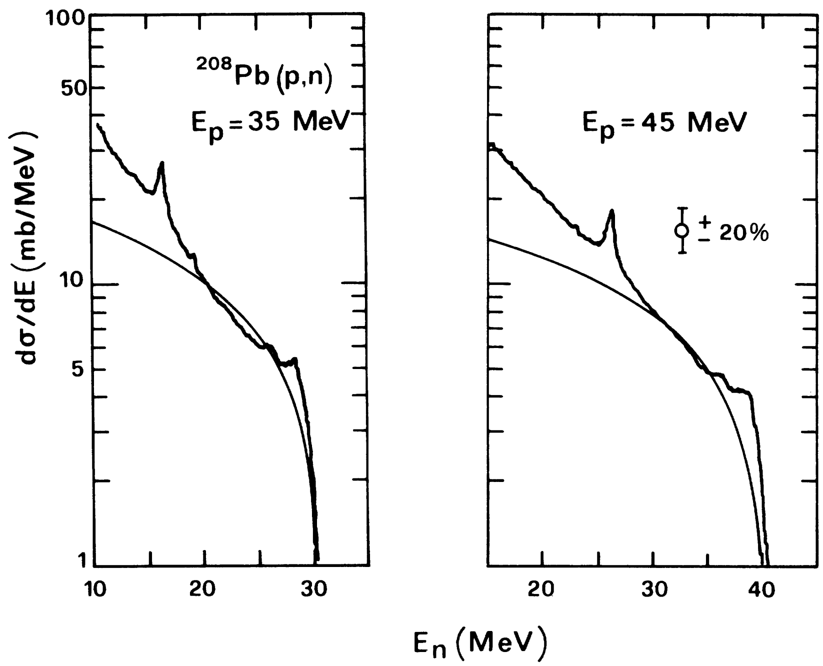

FIG. 9. Calculated (smooth lines) and measured (heavy lines) neutron spectra from the ^{208}Pb(p,n) reaction at E_p = 35 and 45 MeV. The experimental results are from the work of Blann *et al.* (Ref. 1). In this figure only the pre-equilibrium contributions to the calculated spectra are shown.

duced by integrating the neutron spectra are expected to be underestimated. This expectation, however, does not apply to the ^{90}Zr case, since after emission of one neutron the binding energy of the last proton in the residual nucleus is so low as to make its emission competitive with that of a second neutron; by disregarding, as we did, the possibility of this occurrence, the ^{90}Zr cross section may turn out to be a little overestimated.

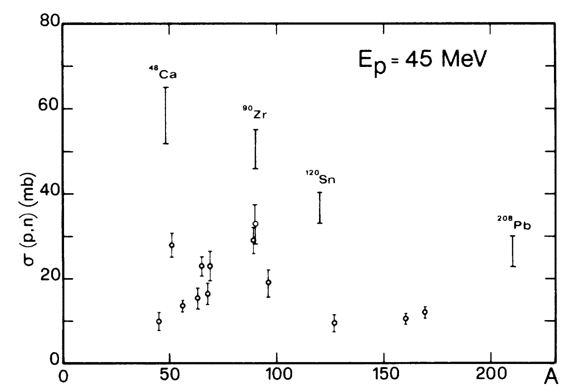

FIG. 10. Comparison of the high energy neutron yields from the results of Blann *et al.* (Ref. 1) (vertical bars) with those obtained by activation techniques (circles), for (p,n) reactions at E_p = 45 MeV. The activation measurements are for ^{45}Sc, ^{68}Zn (Ref. 22); ^{51}V, ^{56}Fe, ^{65}Cu (Ref. 5); ^{63}Cu (Ref. 23); ^{69}Ga (Ref. 24); ^{90}Zr (Ref. 27), ^{89}Y, ^{160}Gd, ^{169}Tm (Ref. 2); ^{96}Mo (Ref. 25); ^{127}I (Ref. 26).

The outcome of the comparison is as follows. At E_p = 35 MeV, the cross sections deduced from the neutron spectra are reasonably consistent with the indications of activation measurements, except that for ^{48}Ca the former cross sections appears too high by a factor of about 2. At E_p = 45 MeV, the situation is best illustrated with reference to Fig. 10. There the cross sections deduced from the neutron spectra are denoted by vertical bars whose lower and upper ends indicate the values calculated by excluding and including, respectively, the pairing energies in the determination of the lower limits of integration of the spectra; the pairing energies were taken from the work of Nemirovski and Adamchuck.[28] On the same figure the cross sections measured by the activation method are given with open circles. It is seen that the cross sections derived from the data of Blann *et al.* for ^{48}Ca, ^{90}Zr, and ^{120}Sn have greater values than those that would fit in the pattern displayed by the results of the activation measurements. It can also be mentioned that the ^{120}Sn cross section is greater at 45 MeV than at 35 MeV, in contrast with the general trend of the cross sections given by the activation method. Now, the above cases of cross sections differing from the expectations of the activation measurements actually correspond to the instances where the reproduction of the absolute values of the spectral distributions was found less satisfactory.

The results for ^{208}Pb deserve a more specific discussion. There are no measurements by the activation method beyond $A \approx 170$. The cross section deduced from the spectra would seem to be higher than those extrapolated by the results of the activation measurements, but it can be argued that such extrapolation would be wrong. In fact, just on the basis of the exciton model it is expected that there should be a rise in the cross sections of Pb in comparison with the values prevailing for nuclei of mass number around 170. This is so because for Pb (i) the binding energy of the incident proton is low, so that the excitation energy of the composite nucleus is some 10% less than for lower mass nuclei: this has the effect of decreasing the density of states of the composite nucleus, thereby increasing the decay rate for particle emission; (ii) the binding energy of the next-to-last neutron is about the same as for nuclei with $A \approx 170$, and therefore the (p,n) pre-equilibrium cross section has a tendency to rise as $A^{1/3}$ (cf. Ref. 2): the opposite tendency is shown instead by nuclei with A from ≈ 100 to ≈ 170 because in this mass region this binding energy decreases from $\approx 8-9$ MeV to ≈ 6.5 MeV; (iii) shell effects are present which decrease the density of states of the composite nucleus, while the low energy state densities of the residual nuclei are not, in first approximation, affected. On account of these reasons, we think that the Pb cross sections obtained by integrating the spectra can be understood, and accordingly are prepared to find that the neutron spectrum can be fairly well reproduced also at $E_p = 45$ MeV.

Like Pb, the three other target nuclei ^{48}Ca, ^{90}Zr, and ^{120}Sn are also magic, so that it is natural to ask whether their cross sections might have been raised above those of neighboring nuclei by shell effects alone. This seems, however, unlikely. Shell effects should have a rather moderate influence in the high energy spectral region, where the contribution of emissions from states in the initial configuration is preponderant. Then the residual nucleus states ought to be (1 proton, 1 neutron hole) states, whose density would scarcely be affected by the presence of the "gap" occurring on completion of a magic shell. The reduction in state densities is therefore confined to the composite nucleus, so that the increase of the pre-equilibrium cross section can only be modest. This reasoning is supported by the fact that the shapes of the high energy parts of the spectra are fairly well reproduced by our calculations, whereas if the state densities of the residual nuclei were appreciably changed by shell effects the measured spectra should have a steeper slope. In connection with the accounting of shell effects on state densities, we would like to remark that the assumption sometimes adopted of introducing "effective" single nucleon state densities smaller than those given in Sec. II B, and nearly equal for both composite and residual nuclei, appears awkward. Actually the importance of shell effects diminishes strongly as the excitation energy increases so that, given the sizeable differences in energy between the composite and the residual nucleus when high energy neutrons are emitted, the corresponding "effective" single nucleon state densities should not be comparable.

To conclude this discussion, we express the opinion that there is no evidence that exciton model calculations should become less reliable for incident particle energies beyond some 35 MeV, and/or for magic nuclei. Rather, it would be futile to strive to reproduce accurately, with the same set of calculation parameters, experimental data that do not appear reconcilable between themselves within the experimental uncertainties quoted by the different authors. We chose to trust the decay rates derived from the experiments performed by the activation method, because the results available from this kind of experiments furnish a reasonably copious and consistent collection of nuclear data.

4. The data of Watcher et al.

Results of measurements by Watcher *et al.*[13] on the ^{27}Al(p,n) reaction, at $E_p = 63.8$ MeV, have been

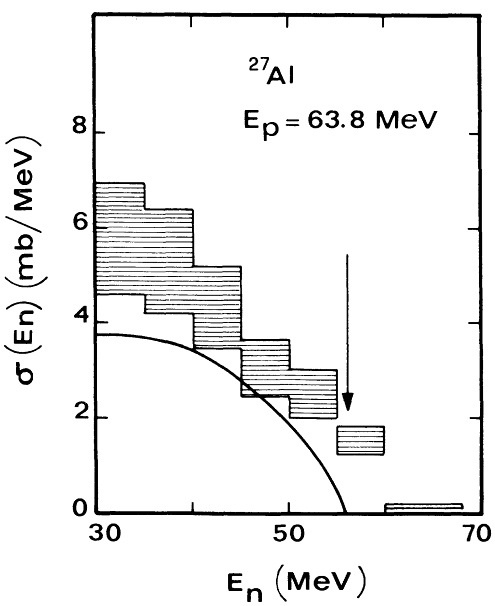

FIG. 11. Calculated (smooth curve) and measured (histogram) neutron spectra from the ^{27}Al(p,n) reaction at $E_p = 63.8$ MeV. The experimental results are from the work of Watcher *et al.* (Ref. 13).

recently made available to us through the courtesy of Bertrand of Oak Ridge National Laboratory. The data consist of the neutron differential energy spectra, taken at laboratory angles $\theta = 20°$, $45°$, $60°$, and $135°$.

The c.m. integrated spectrum, for a channel energy $E_\nu \geq 30$ MeV, is reported in Fig. 11. In this spectral region, only *first chance* pre-equilibrium neutron emissions are expected, and the predominant contribution to the spectrum is that due to emissions from states in the initial configuration. The vertical breadth of the hatched area indicates, for each integration interval, uncertainties in the cross sections of the order of 20%, which stem in part from the statistical errors given by the authors, and in part from the interpolation errors in computing the integrals.

The exciton model cross sections, shown by the smooth curve, were again obtained with *a priori* calculations. The curve runs some 30% lower than the average derived from the measured data, but this can be considered in our opinion as good an agreement as might be reasonably expected. In fact, ^{27}Al is a quite light nucleus which, on account of the energy of the incident projectile, is brought to a rather high excitation; therefore the accuracy of prevision of the state densities cannot be great. Besides, the errors of the experimental measurements cannot be just the statistical ones: additional errors, e.g., are evidenced in the backward spectra by the very presence of neutrons with energy greater than the maximum allowed (in Fig. 11, this energy is pointed out by an arrow).

III. CONCLUSION

It is found, from the study of (p,n) reactions in several nuclei from ^{27}Al to ^{208}Pb, that the pre-equilibrium components of the differential energy spectra of the emitted neutrons can be on the whole fairly well reproduced by exciton model calculations, using the same decay rates for exciton-exciton interactions as applicable to different incident particles and reactions, and without introducing any geometry dependence of the interaction process.

The few instances, at incident energies greater than 35 MeV, where the calculated cross sections differ somewhat (however, by no more than about 50%) from the measured ones, are shown to correspond to cases of disagreement between the cross sections measured by the time-of-flight technique and the values that would be needed to fit in with the results collected by the activation method.

The authors wish to acknowledge several exchanges with Professor M. Blann, and to thank him for sending the results of the work by himself and his collaborators prior to publication. Thanks are also due Dr. F. E. Bertrand for supplying the unpublished data of J. W. Watcher *et al.*

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