# Surface effects in preequilibrium reactions of incident neutrons

C. Kalbach
*Physics Department, Duke University, Durham, North Carolina 27708-0305, USA*
(Received 2 October 2003; published 26 January 2004)

Recent $(n,xp)$ continuum spectra at incident energies of 28 to 63 MeV have been used to expand an earlier study at lower neutron energies of the amount of surface localization of the initital target-projectile interaction. The $(n,xp)$ data show a reduction in surface localization for heavy targets—a trend that grows with increasing bombarding energy. This target mass dependence is not evident in $(n,xn)$ reactions up to 26 MeV and should be verified with additional heavy target $(n,xp)$ data as well as $(n,xn)$ data at higher bombarding energies. It can be described and included in model calculations in terms of a difference in surface localization between initial *nn* and *np* interactions.

DOI: 10.1103/PhysRevC.69.014605 PACS number(s): 24.60.Gv, 24.10.Pa

## I. INTRODUCTION

One of the most challenging problems for preequilibrium reaction models is to account for the relative yields in the four $(N,N)$ channels (where $N$ is a nucleon) using a single, consistent set of input. An earlier paper [1] showed that in the exciton model proposed by Griffin [2] this could be accomplished if the initial target-projectile interaction for incident neutrons were assumed to occur, on average, closer to the nuclear surface than the corresponding interaction for incident protons. The parameter describing the surface peaking of the initial interaction is the average effective potential well depth in the interaction region. Unfortunately, while angle-integrated energy spectra for incident protons at energies up to 100 MeV were included in the study, incident neutron energies were largely confined to 26 MeV and below. One $(n,xp)$ reaction measured at 60 MeV suggested that the proton-neutron difference might disappear at that energy, but no conclusive trend could be observed.

Since that time, angle-integrated charged particle energy spectra at neutron energies up to 63 MeV have become available in the literature. The proton spectra have been analyzed as part of this work, while the deuteron, triton, and $\alpha$ spectra are being studied as part of an investigation of reactions with complex particles in the entrance and/or exit channel.

## II. DATA

The new data were measured at the Los Alamos Neutron Science Center (LANSCE) [3] and at Louvain-la-Neuve in Belgium [4–8]. At LANSCE, the neutron beam was a white source extending up to 50 MeV, and data are available for incident energies of 5 to 50 MeV. At Louvain-la-Neuve, there is a peak in the beam intensity at a neutron energy of 63 MeV, with a lower intensity continuum. This requires wider slices of incident energy between 28 and 63 MeV to be analyzed together using wider emission energy bins. On the other hand, the angle coverage is far more complete than at LANSCE, and the range of targets for which data have been taken and analyzed is also greater. Thus the two facilities are somewhat complementary, and the current LANSCE data on $^{28}$Si provide a check of the Louvain data.

The present work analyzes angle integrated $(n,xp)$ spectra on $^{28}$Si at $29\pm1$, $39\pm1$, and $50\pm1$ MeV from LANSCE and on targets of $^{27}$Al, $^{28}$Si, $^{59}$Co, $^{209}$Bi, and $^{238}$U at $28.5\pm1.5$, $37.5\pm1.5$, $49\pm2$, and $63\pm2$ MeV from Louvain-la-Neuve. In addition, the double differential $^{58}$Ni$(n,xp)$ data at 60 MeV [9]—previously analyzed at individual angles—were integrated over angle, and the angle integral was included in the present analysis. Since data were only measured at angles up to 77° in that experiment, the angle integration was limited to emission energies above the evaporation peak where the empirical angular distribution shape of $e^{a\cos\theta}$ [10] could be used to extrapolate to backward angles.

Two factors need to be considered with regard to these data. First, the Louvain-la-Neuve data are given in the laboratory system. Conversions from laboratory to center of mass were done for the proton, deuteron, triton, and $\alpha$ spectra from the $^{27}$Al$+n$ system at 63 MeV and the corresponding proton spectrum at 28.5 MeV. The resulting double differential cross sections were then integrated over angle. The angle-integrated spectra were plotted against the exit channel energy (i.e., the combined center-of-mass energies of the emitted particle and the recoiling nucleus) and found to agree closely with the laboratory angle integrals except at the highest emission energies. There the laboratory data extend 1 to 1.5 MeV beyond the center-of-mass data. With this level of agreement, the data from the remaining targets were left in the laboratory system and were compared with the calculated results plotted against the channel energy.

The second factor is that the incident neutrons for each spectrum are not monoenergetic but cover a range of energies that is $2-4$ MeV wide. The effect of the beam energy width was checked for the LANSCE data at $50\pm1$ MeV and at $17\pm1$ MeV, because the LANSCE results were available first. Results of calculations done at a single energy in the middle of the energy bin were compared with averages of calculations made at up to five energies across the bin. Not surprisingly, the averaged spectra are quite close to the midpoint spectrum whenever the calculated shape is fairly smooth. When sharper jumps are present, averaging is needed to smooth them out to the extent that they are smoothed in the data. Since the spectra analyzed here tend to be fairly smooth, calculations at the midpoint energy have been used. However, the 17 MeV LANSCE data on $^{28}$Si were not analyzed because the calculations show a sharp drop at the endpoint of the preequilibrium component, with the evaporation component extending to higher emission energies.

## III. METHOD

The initial target-projectile interaction involves the excitation of a target nucleon to create an excited particle-hole pair. The effects of surface localization of the interaction are seen in the emission energy spectra because the shallower potential well depth at the nuclear surface limits the amount of excitation energy that the newly formed hole degree of freedom can carry. This forces more of the available energy to be carried by the particle degrees of freedom in the resulting configuration, leading to more high-energy particle emission than in the absence of surface effects. Thus the spectral shape is harder.

The method employed in this work is the same as that used in Ref. [1]. The data analyzed are angle-integrated, inclusive energy spectra from the literature. Calculations are run for each measured spectrum using the exciton model computer code PRECO-2000 [11] with the standard global input set except that the average effective well depth in the region of the initial target-projectile interactions is varied.[1] Isospin is assumed to be conserved during the preequilibrium phase of the reaction and partially (usually about 40%) conserved at equilibrium if $E<4E_{\mathrm{sym}}$ in the composite nucleus, where $E$ is the excitation energy and $E_{\mathrm{sym}}$ is the isospin symmetry energy. Otherwise isospin is assumed to be mixed [12]. The calculated results are typically insensitive to the level of isospin conservation. Suitable values of the parameter, $V_{\mathrm{eff}}$, are then determined by comparing the shapes of the calculated spectra with experiment. The well depths are given relative to the Fermi level.

For each experimental spectrum, the range of emission energies analyzed extends from a bit above the evaporation peak to somewhat below the end point of the spectrum, where discrete states can be important and the spread in beam energy can distort the experimental results. The range of $V_{\mathrm{eff}}$ giving reasonably good agreement with experiment in overall spectral shape was tabulated, and a nominal "best" value was selected for ease in studying trends in the results. The selected $V_{\mathrm{eff}}$ ranges are somewhat subjective, so the results obtained tend to vary slightly as the process is repeated, but the overall trends remain the same.

## IV. TRENDS IN $V_{\mathrm{EFF}}$

Figure 1 shows the results on $V_{\mathrm{eff}}$ from this work and from Ref. [1]. The latter include $(n,xn)$ reactions at 14 to 26 MeV and $(n,xp)$ reactions at 14–15 MeV. The average $V_{\mathrm{eff}}$ values are displayed as a function of the fractional neu-

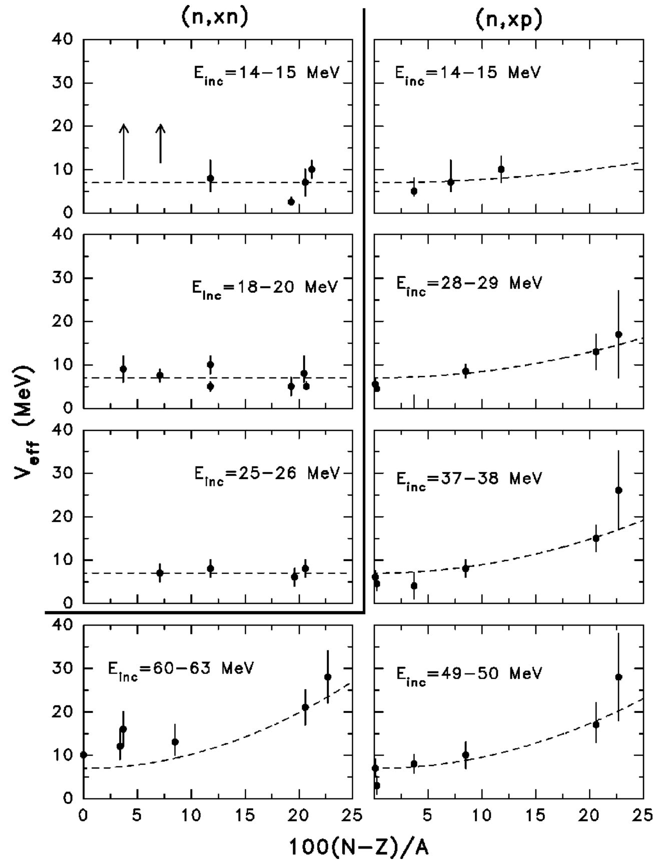


FIG. 1. Average effective well depth in the region of the first neutron-target interaction as determined from the spectral shape of inclusive neutron and proton energy spectra. The dashed curves show the adopted systematics given by Eq. (1).

tron excess of the target nucleus, though the trends look similar if the target mass number is used instead. If there were no results above 29 MeV, the hints of an increase in $V_{\mathrm{eff}}$ for $(n,xp)$ reactions on heavy targets could be ignored, and the earlier result of a constant $V_{\mathrm{eff}}=7$ MeV could be retained. But as the incident energy increases, the $(n,xp)$ reactions show a greater and greater trend for $V_{\mathrm{eff}}$ to increase for heavier targets. No such dependence is evident in the $(n,xn)$ spectra. Since the trend in the $(n,xp)$ spectra is observed in data from one laboratory and is largely dependent on only two targets, it should be regarded as tentative until it is confirmed by additional measurements. It would also be desirable to have $(n,xn)$ spectra from heavy targets at bombarding energies above 25.7 MeV where the results would be more sensitive to the lack of an $A$ dependence for $V_{\mathrm{eff}}$. However, the observed behavior is quite systematic and has been investigated further.

The situation for incident neutrons can be compared with that observed [1] for incident protons. The proton results are replotted in Fig. 2, with the inelastic and exchange channels separated and an additional point for $^{209}$Bi$(p,xn)$ added. This point was omitted in the earlier analysis because the data were only measured in the forward hemisphere. However, in the region of the spectrum where the analyses are made, the angle coverage is adequate to allow accurate angle integra-

[1] There were also some changes representing progress in the work on the complex particle channels. These occur mainly in the calculation of the direct nucleon transfer reactions and have negligible effect on the nucleon spectra.

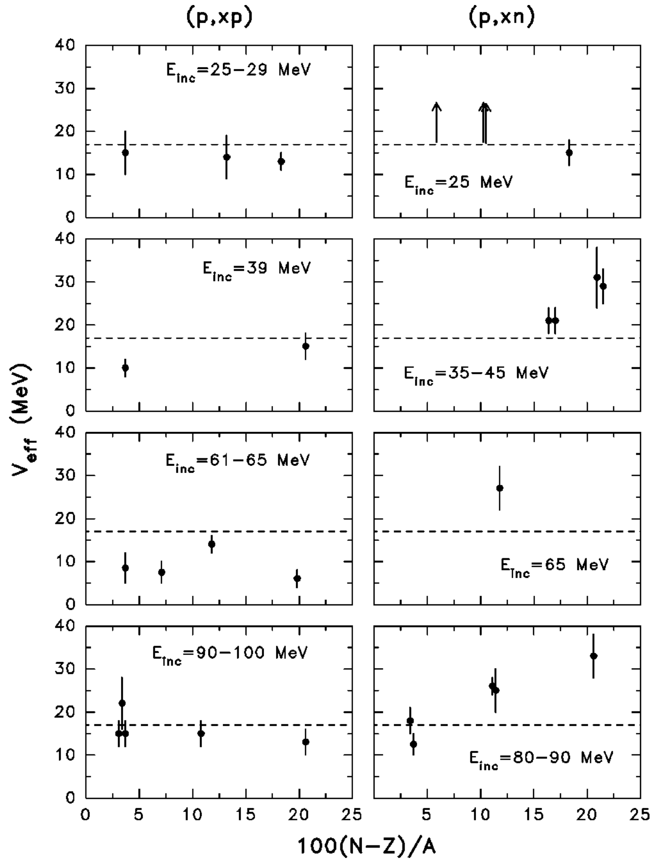


FIG. 2. Average effective well depth in the region of the first proton-target interaction as determined from the spectral shape of inclusive neutron and proton energy spectra. These results are taken from Ref. [1] with the point for $^{209}$Bi$(p,xn)$ at 90 MeV added.

tion using the systematics employed for the 60 MeV $^{58}$Ni$(n,xp)$ data. The work of Ref. [1] noted a tendency for the $(p,xp)$ spectra to yield smaller $V_{\mathrm{eff}}$ values than the $(p,xn)$ spectra, particularly for energies of 35 to 65 MeV (see Table II of Ref. [1]), but since a single value of $V_{\mathrm{eff}}$ was often adequate to explain both reaction channels, the average value of $V_{\mathrm{eff}}=17$ MeV was adopted. The trend for $(p,xn)$ to yield higher $V_{\mathrm{eff}}$ values becomes more pronounced at 90 MeV when the $^{209}$Bi point is added. As with $(n,xn)$, the $(p,xp)$ inelastic scattering spectra show fairly constant $V_{\mathrm{eff}}$ values for all targets. For $(p,xn)$ reactions, there is no clear systematic trend with target mass, though, again, the new point suggests an enhanced possibility of an increase in $V_{\mathrm{eff}}$ with $A$ such as was observed for incident neutrons. Thus, in light of the new results for incident neutrons, this question of a difference between the inelastic and exchange channels for incident protons should be reexamined with additional data.

Focussing just on the incident neutron data, the $V_{\mathrm{eff}}$ values for the $(n,xp)$ spectra can be parametrized using either a linear or a quadratic dependence on either $A$ or $(N-Z)/A$. If the observed behavior is to be linked to a physical basis (and this is just conjecture now), one possible explanation would be in terms of the neutron excess producing a neutron rich region at the nuclear surface. Thus an incident neutron would need to penetrate more deeply into the nucleus in order to excite a proton than it would to excite a neutron. The larger the neutron excess, the bigger the effect and the larger the $V_{\mathrm{eff}}$ values for $(n,xp)$ reactions. Therefore a parametrization in terms of $(N-Z)/A$ has been tentatively adopted. In addition, the value of $V_{\mathrm{eff}}$ for $N=Z$ nuclei has been fixed at the constant 7 MeV value obtained for $(n,xn)$ reactions. With these constraints, a quadratic dependence yields a better fit than a linear one.

The increase of $V_{\mathrm{eff}}$ values for heavy targets with incident energy also needs to be included. Thus the $V_{\mathrm{eff}}$ values for the $^{209}$Bi target at 27.5, 38.5, 49, and 63 MeV were plotted versus the incident laboratory energy and were found to lie nicely on a straight line passing through $V_{\mathrm{eff}}=7$ MeV at zero energy. This straight line dependence has been adopted, though a more gradual and asymptotic approach to the $V_{\mathrm{eff}}=V_0$ physical limit (where $V_0$ is the central well depth) might be desirable. In the current scheme, that limit would only be reached for the heaviest targets at an incident energy of around 115 MeV, well above the energy range considered here.

The resulting, tentatively adopted $V_{\mathrm{eff}}$ values are

$$V_{\mathrm{eff,nn}} = 7\ \ \mathrm{MeV}, \tag{1a}$$

$$V_{\mathrm{eff,np}} = \min\left(7\ \ \mathrm{MeV} + 5.2\ \ E_{\mathrm{inc}}\left[\frac{N-Z}{A}\right]^2, V_0\right). \tag{1b}$$

These results are shown as the dashed curves in Fig. 1. As in Ref. [1], the central well depth of $V_0=38$ MeV continues to be used for finite well depth corrections later in the reaction.

## V. IMPLICATIONS

Again, the mathematical form of Eq. (1) is only a matter of convenience for now. The observed but unsystematic asymmetry between the $V_{\mathrm{eff}}$ values from $(p,xp)$ and $(p,xn)$ reactions—with the $(p,xn)$ values being larger—would argue against an explanation based on a neutron rich surface region for heavy nuclei and more in favor of a difference between the inelastic and knockout processes in nucleon induced reactions. This would imply that, at least in heavier targets, the initial interactions leading to reemission of the projectile occur, on average, closer to the nuclear surface than those leading to emission of the struck particle.

If the asymmetry in $V_{\mathrm{eff}}$ for proton induced reactions is confirmed, an additional possible explanation is that the model used to describe collective excitations (from both discrete and giant resonance states) in the inelastic channels is inadequate. The collective states considered are low-lying $2+$, $3-$, and, in some cases, $4+$ states, plus the giant quadrupole resonance, and the low-energy and high-energy octupole giant resonances. If the model—an adaptation of the simple model of Kalka *et al.* [13]—were not yielding enough collective cross section at high emission energies, the exciton model would have to compensate by using a shallower potential well depth for the first interaction. Possible inadequacies in the collective model calculations were considered, but seem unlikely to explain the apparent asymmetry in $V_{\mathrm{eff}}$ between the inelastic and exchange channels. First, the model was found [1] to reproduce the target mass dependence quite well for $(n,xn)$ spectra at 14 and 18 MeV. While the incident energy dependence of the model could still be wrong, it would have to be more seriously wrong for heavy targets than light ones (at least for incident neutrons). In addition, it would have to be wrong in just such a way as to cancel out the effects of any increases in $V_{\mathrm{eff}}$ seen in the exchange channel, in order to yield the observed constant $V_{\mathrm{eff}}$ values in the inelastic channels.

Clearly more work is needed to understand the trends in $V_{\mathrm{eff}}$.

## VI. IMPLEMENTATIONS

The apparent difference between the $V_{\mathrm{eff}}$ values for $(n,xn)$ and $(n,xp)$ reactions suggests that the exciton model calculations should be changed so that different values are used for initial *nn* and *np* interactions. A similar difference between the *pn* and *pp* interactions for incident protons has not been introduced but might be needed when the systematics there become clearer.

The code PRECO was thus reprogrammed to use the $V_{\mathrm{eff}}$ values given in Eqs. (1a) and (1b) for the *nn* and *np* initial interactions, respectively, as well as for the particle emission immediately following them. This has several effects. The main one is the desired effect of softening the proton preequilibrium energy spectrum relative to the neutron spectrum in neutron induced reactions on heavy targets. The other two effects, however, have the potential to alter the neutron spectra sufficiently to reduce agreement with experiment and thus need to be investigated.

First, the relative intensities for preequilibrium proton and neutron emission are modified for heavier targets. This occurs because the relative rates for creating proton and neutron particle-hole pairs in the first projectile-target interaction are altered. The deeper well depth for the *np* interaction results in a smaller finite well depth correction to the density of states accessible in the pair creation interaction, and thus to a higher pair creation rate. This favors excitation of a proton particle-hole pair relative to the case where the same effective well depth is used for both proton and neutron excitation, resulting in more proton emission and less neutron emission. Thus there is the potential to disturb the previous agreement between calculation and experiment on the relative yields in the inelastic and exchange channels.

A second potentially detrimental effect, is a softening of the spectral shape for preequilibrium neutron emission. This is because neutron emission occurs from the $(p_\pi, h_\pi, p_\nu, h_\nu) = (1,1,1,0)$ states formed by proton pair excitation as well as from the $(0,0,2,1)$ states formed by neutron pair excitation. Here $p_\pi$, $h_\pi$, $p_\nu$, and $h_\nu$ are the numbers of proton particle, proton hole, neutron particle, and neutron hole degrees of freedom in the configuration. One mitigating factor is that more of the neutron emission occurs following neutron pair excitation than proton pair excitation, simply because there are two neutron particles available for emission compared to only one. This is enhanced because the smaller $V_{\mathrm{eff}}$ for neutron pair excitation also leads to slightly higher emission rates from the $(0,0,2,1)$ configurations.

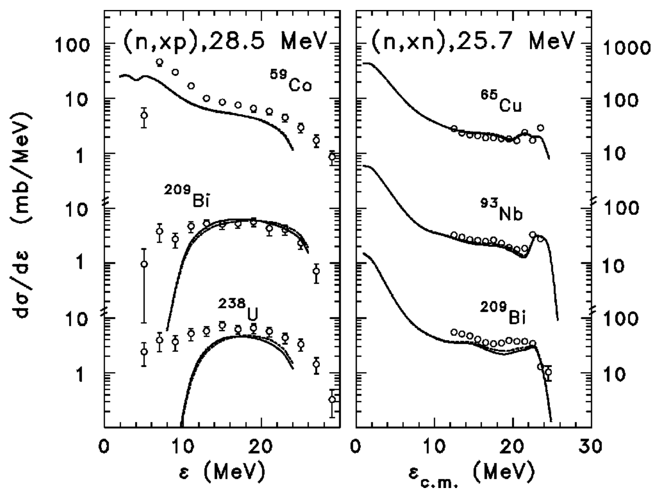


FIG. 3. Comparison between calculation and experiment for reactions at 25 to 29 MeV. The points show the 28.5 MeV $(n,xp)$ data from Refs. [6–8] and the 25.7 MeV $(n,xn)$ data from Ref. [14]. The dashed curves give the calculated spectra using $V_{\mathrm{eff}} = 7$ MeV for the initial proton and neutron pair excitations, while the solid curves give the spectra calculated using the values in Eq. (1). The $(n,xp)$ data are given in the laboratory system, while the corresponding calculations are plotted vs exit channel energy.

As will be discussed in Sec. VII, these effects are seen in the neutron spectra but do not significantly reduce the level of agreement between calculation and experiment. However, they point out the need for additional $(n,xn)$ data at higher incident energies, especially on heavy, neutron rich targets, to see if the differences observed between $(n,xn)$ and $(n,xp)$ spectra persist. *If* they do, and *if* this difference is due to a neutron rich region at the nuclear surface of neutron rich nuclei so that the *nn* and *np* initial interactions occur, on average, at different well depths, then there would be an additional effect that would tend to compensate for both of these problems. The initial interactions occur over a range of distances from the center of the nucleus, and the $V_{\mathrm{eff}}$ values represent an average over this range. When the range encompasses a neutron rich surface region, protons will mainly be present in the inner parts of this range where $V_{\mathrm{eff}}$ is larger, while the neutrons will be present throughout the range. Thus interactions in the outer part of the range will produce an enhancement of neutron excitation over proton excitation compared to what is normally calculated. Given current uncertainties, the inclusion of such an enhancement in the calculations has not been attempted.

## VII. COMPARISONS WITH EXPERIMENT

Calculations were run with the revised version of PRECO for all of the neutron induced reactions studied here and in Ref. [1], and the results were compared with the measured spectra.

Some sample neutron and proton spectra for neutron induced reactions on medium to heavy targets are shown in Fig. 3. These are for incident neutron energies of 25 to 28 MeV, where the measured $(n,xn)$ spectra would be most

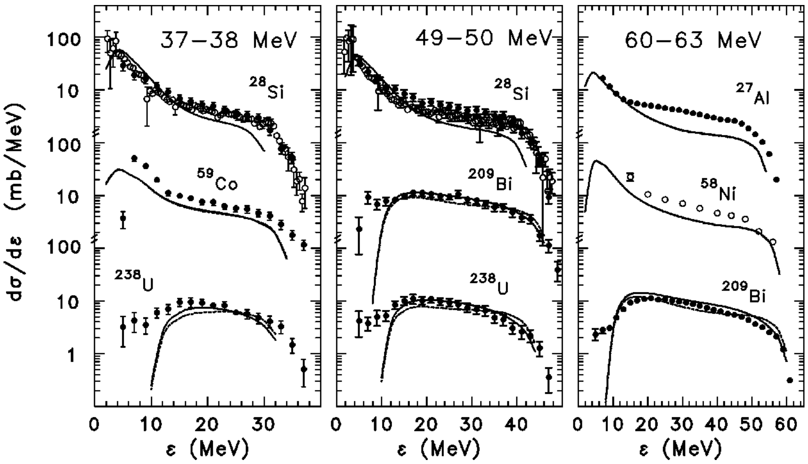


FIG. 4. Comparison between calculation and experiment for $(n,xp)$ reactions at higher incident energies. The solid points show the data from Louvain-la-Neuve [4–8] at $37.5\pm1.5$, $49\pm2$, and $62.7\pm2$ MeV given in the laboratory system. The open points show the LANSCE data [3] for $^{28}$Si at $38\pm1$ and $50\pm1$ MeV and the U.C. Davis spectrum for $^{60}$Ni [9] at 60 MeV, both plotted vs exit channel energy. The solid and dashed curves have the same significance as in Fig. 3. and are also plotted vs channel energy. For $^{28}$Si, the incident energy used in the calculations is matched to the LANSCE data which have the smaller spread in incident energy.

sensitive to possible problems from using different $V_{\mathrm{eff}}$ values for the initial *nn* and *np* interactions, and where $(n,xp)$ spectra are also available. As expected, there is a slight worsening of the tendency for the calculations to underpredict the $(n,xn)$ data [14] for heavy targets, but the level of change is not significant. Further, the current results fall between the old results (the dashed curves) and the results of using Eq. (1b) for both proton and neutron pair excitation. The changes are small because the presence of collective state and giant resonance excitation somewhat reduces the sensitivity of the calculated neutron spectra to the exciton model component and because the changes in $V_{\mathrm{eff,np}}$ are still relatively small at incident energies up to 26 MeV. Changes in the $(n,xp)$ spectra are also small but are in the direction of improving agreement with the data in spectral shape. The disagreement in intensity with the measured $^{238}$U$(n,xp)$ spectrum at 28.5 MeV disappears at the higher energies considered here, as shown in Fig. 4.

Examples of $(n,xp)$ spectra at higher energies are given in Fig. 4. For targets up through mass 60 at all incident energies, the calculated results are nearly unchanged by the new systematics in $V_{\mathrm{eff}}$ compared with using $V_{\mathrm{eff}}=7$ MeV for all initial interactions. For Bi and U the improvements in spectral shape are more noticeable and increase with increasing bombarding energy. Thus, overall, the agreement between calculation and experiment has been improved.

## VIII. SUMMARY AND CONCLUSIONS

Earlier exciton model calculations encountered difficulties in reproducing the relative intensities in the four $(N,xN)$ reaction channels using a consistent set of model input. The work of Ref. [1] showed that different amounts of surface localization of the initial target-projectile interaction for proton and neutron projectiles can explain and remove the problem at incident energies up to around 26 MeV. The data were well described by $V_{\mathrm{eff,p}}=17$ MeV for incident protons at energies up to 100 MeV and $V_{\mathrm{eff,n}}=7$ MeV for incident neutrons at energies up to 26 MeV. The present work has analyzed new $(n,xp)$ data at energies up to 63 MeV and appears to show a difference in the average effective well depth for the first interaction in an $(n,p)$ reaction compared to an $(n,n')$ reaction.

The difference seems to be a function of the incident energy and of the neutron excess of the target, as described in Eq. (1). The difference in $V_{\mathrm{eff}}$ is programmed into the exciton model code PRECO-2000, assuming that the $(n,p)$ value applies for the initial excitation of a proton particle-hole pair in the target while the $(n,n')$ value is used for the excitation of a neutron particle-hole pair. This results in a slight increase in the proton emission intensity and a corresponding decrease in the neutron emission intensity from the initial composite nucleus states for heavy targets. The changes do not, however, disturb the good overall agreement between calculation and experiment. If, however, the incident energy in Eq. (1b) were replaced by an average value of around $E_{\mathrm{inc}}=40$ MeV, then the decrease in the $(n,n')$ intensity at 14 to 25 MeV for heavy targets would more likely be a problem. The desired improvement in the spectral shape for $(n,xp)$ reactions on heavy targets is, of course, seen. Thus while the fits with $V_{\mathrm{eff,nn}}=V_{\mathrm{eff,np}}=7$ MeV are adequate for some applications, the current systematics yield improved agreement for heavy targets, especially at higher energies, and perhaps point to some interesting physical insights.

The current results should be regarded as tentative. They depend on new $(n,xp)$ data measured at a single laboratory and are particularly dependent on two heavy targets. It will be important to see if the trends are reproduced by other measurements. In addition, $(n,xn)$ measurements at higher energies are needed for a broad range of target masses to see whether the difference in $V_{\mathrm{eff}}$ between the two nucleon channels persists, and, if it does, whether the relative yields in the inelastic and exchange channels are still correctly reproduced. Finally, additional data for incident protons need to be analyzed to see if a more systematic target mass dependence can be discerned. If it can and if it indicates a clear asymmetry between the inelastic and exchange channels such as that implied here for incident neutrons, then the explanation of the current observations would most likely be in terms of a difference between scattering and knockout processes rather than the neutron excess for heavy targets.

## ACKNOWLEDGEMENTS

This work was performed at the Triangle Universities Nuclear Laboratory under U. S. Department of Energy Grant

No. DE-FG02-97ER41033. Special thanks go to Arjan Koning and his collaborators for providing tables of the Louvain results, sometimes before they were formally published, and to Robert Haight for providing the LANSCE results in tabular form. The author is also grateful to Arjan Koning for his helpful comments on an earlier draft of this paper.

[1] C. Kalbach, Phys. Rev. C **62**, 044608 (2000).
[2] J. J. Griffin, Phys. Rev. Lett. **17**, 478 (1966).
[3] F. B. Bateman, R. C. Haight, M. B. Chadwick, S. M. Sterbenz, S. M. Grimes, and H. Vonach, Phys. Rev. C **60**, 064609 (1999), and data tables supplied by the authors.
[4] S. Benck, I. Slypen, J. P. Meulders, and V. Corcalciuc, At. Data Nucl. Data Tables **78**, 161 (2001), and data tables supplied by the authors.
[5] S. Benck, I. Slypen, J. P. Meulders, and V. Corcalciuc, Nucl. Sci. Eng. **141**, 1 (2002), and data tables supplied by the authors.
[6] N. Nica, S. Benck, E. Raeymackers, I. Slypen, J. P. Meulders, and V. Corcalciuc, J. Phys. G **28**, 2623 (2002), and data tables supplied by the authors.
[7] E. Raeymackers, S. Benck, N. Nica, I. Slypen, J. P. Meulders, V. Corcalciuc, and A. J. Koning, Nucl. Phys. **A726**, 175 (2003), and data tables supplied by the authors.
[8] E. Raeymackers, S. Benck, I. Slypen, J. P. Meulders, N. Nica, V. Corcalciuc, and A. J. Koning, Phys. Rev. C **68**, 024604 (2003), and data tables supplied by the authors.
[9] C. M. Castaneda, J. L. Ullmann, F. P. Brady, J. L. Romero, N. S. P. King, and M. Blann, Phys. Rev. C **28**, 1493 (1983), and data tables supplied by the authors.
[10] C. Kalbach, Phys. Rev. C **37**, 2350 (1988).
[11] Constance Kalbach Walker, Triangle Universities Nuclear Laboratory report, 2001 (unpublished), available from the code distribution center at the National Nuclear Data Center (Brookhaven National Laboratory) and through the Radiation Safety Information Computing Center (Oak Ridge National Laboratory).
[12] C. Kalbach (unpublished).
[13] H. Kalka, M. Torjman, and D. Seeliger, Phys. Rev. C **40**, 1619 (1989).
[14] A. Marcinkowski, R. W. Finlay, G. Randers-Pehrson, C. E. Brient, and J. E. O'Donnell, Nucl. Phys. **A402**, 220 (1983); A. Marcinkowski, R. W. Finlay, G. Randers-Pehrson, C. E. Brient, R. Karup, S. Mellema, A. Meigooni, and R. Tailor, Nucl. Sci. Eng. **83**, 13 (1983).