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Preequilibrium model analysis of (p,n) reactions on nuclei in the Cr-Ni region

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The energy spectra of neutrons emitted from 25 MeV (p,n) reactions on nuclei in the Cr-Ni region have been analyzed in terms of the preequilibrium exciton model introducing effective Q values, the pairing correlation, and the modified uniform spacing model in which the uniform spacing model is modified so as to have a wide spacing at the magic number. The calculated energy spectra using the above model are in fairly good agreement with the observed spectra with pronounced structures.

I. INTRODUCTION

In general, more accurate experimental data are available for the reaction induced by charged particles than those for neutron induced reactions because of better counting statistics for reactions related to the charged particles. Since available data for the (n,p) reaction are poor, owing to the weak neutron-beam intensity, detailed features of the (n,p) reaction such as the shell effect and the odd-even effect on target nuclei are not well known for the preequilibrium proton emission.

The neutron energy spectra from the (p,n) reaction on ^{90,91,92,94}Zr, ^{92,94,95,96,97,98,100}Mo, and ^{110}Pd with 25 MeV protons and ^{90,91,92,94}Zr with 18 MeV protons were analyzed[1] in terms of the preequilibrium exciton model introducing effective Q values, the pairing correlation, and the modified uniform spacing model in which the uniform spacing model is modified so as to have a wide spacing at the magic number. For all these targets, the calculated spectra using the above model for 25 MeV protons show good agreement with the experimental ones,[2,3] not only on the absolute cross sections in the neutron energy region of 12–18 MeV, but also on the observed spectra with pronounced structures in the neutron energy region higher than 18 MeV.

In the present analysis, a similar method is applied to the analysis of the 25 MeV (p,n) reactions[3] on nuclei in the Cr-Ni region and the availability of this method is examined again.

For nuclei in the Cr-Ni region, both the neutron and proton shells are near the magic number 28. Therefore, the modified uniform spacing model should be used for both the neutron and proton shells.

II. THEORETICAL CONSIDERATION

In the present work, the energy spectra from the (p,n) reaction on nuclei in the Cr-Ni region are analyzed in terms of the preequilibrium exciton model introducing effective Q values, the pairing correlation, and modified uniform spacing model.

The effective Q value, effective proton binding energy, and the pairing correlation used in the present analysis were as follows:

In our previous work[1] we introduced the effective Q value, the effective proton binding energy, and the effective neutron, binding energy. These energies were fitted independently, but these should fulfill certain relations.

On the other hand, Kalbach[4] has recently given the separation energy S_b obtained from the liquid drop model with the pairing and shell terms neglected. Using the mass formula of Myers and Swiatecki[5] for spherical nuclei, the separation energy for a nucleus C into a particle b and a nucleus B is given by

$$S_b = 15.68(A_C - A_B) - 28.07\left[\frac{(N_C - Z_C)^2}{A_C} - \frac{(N_B - Z_B)^2}{A_B}\right] - 18.56(A_C^{2/3} - A_B^{2/3}) + 33.22\left[\frac{(N_C - Z_C)^2}{A_C^{4/3}} - \frac{(N_B - Z_B)^2}{A_B^{4/3}}\right]$$
$$-0.717\left[\frac{Z_C^2}{A_C^{1/3}} - \frac{Z_B^2}{A_B^{1/3}}\right] + 1.211\left[\frac{Z_C^2}{A_C} - \frac{Z_B^2}{A_B}\right] - I_b \,. \qquad (1)$$

Here the subscripts C and B refer to the corresponding nuclei, the quantities N, Z, and A are the neutron, proton, and mass numbers of the nuclei, and I_b is the energy required to break the emitted particle up into its constituent nucleons.

This S_b corresponds just to the effective proton or neutron binding energy given previously by us. The difference between S_b values for proton and neutron corresponds to the effective Q value for the (p,n) reaction. Thus we can make the consistent set for the various effective Q values, the effective proton neutron, and α-particle binding energies. The differences between the old[1] and new effective (p,n) Q values are smaller than 0.2 MeV for nuclei of the mass number larger than 80. However, the differences are rather large for nuclei of the mass number smaller than 80. The reason is ascribed to that when the old effective Q values were derived, the data in the region of the mass number smaller than 40 were not used in the least-squares fitting of slope b in Eq. (3) in Ref. 1, in spite of the steep increase of slope b with decreasing mass number in this region. [See Fig. 5(b) in Ref. 6]. In the present analysis, we used the effective Q values and effective proton binding energies calculated from Eq. (1).

As shown in Fig. 1, the modified uniform spacing model, in which the uniform spacing model is modified so as to have a wide spacing at the magic shell, was used for both the neutron and proton shells.

III. ANALYSIS AND DISCUSSION

The procedure of the present analysis is the same as that in the earlier work.[1]

In the present analysis we used the computer code PREANG (Ref. 7) which calculates emission spectra and angular distribution of particles emitted in the preequilibrium nuclear reaction. The calculations were carried out with the use of the test option to simulate the closed-form preequilibrium model[7] by setting the transition rates $\lambda_{n\to n-2}=0$ and $\lambda_{n\to n}=0$, where n was limited to $\bar{n}=\sqrt{2gE}$. The reaction cross sections for protons were calculated from the optical model with the parameters obtained by Mani *et al.*,[8] while those for neutrons were taken from the diagrams presented by Lindner[9] using the nonlocal optical potential by Perey and Back.

FIG. 1. Modified uniform spacing model.

Since the neutron emission from $n=3$ states is dominant at the neutron energy region of interest, more realistic state densities based on the modified uniform spacing model were used in order to describe only the density of $(1p)(1n)^{-1}$ states of the residual nucleus after $n=3$ emission as a first approximation, where n is the exciton number. For the other state densities, Williams's formula,[10] derived from the uniform spacing model, was employed. The uniform spacing shown in Fig. 1 was deduced from the level density $g_N=A/(13\times2)$. The energy gap at the magic number N or $Z=28$ shown in Fig. 1 was chosen to be $9.0/g_N-0.8$ MeV, which was nearly equal to the energy gap between $f_{7/2}$ and $p_{3/2}$ states. The pairing energies were chosen so as to obtain the overall good agreement with the peak energies in the experimental energy spectra. The pairing energies of $\Delta_n=\Delta_p=1.0$ MeV and $\Delta_n=\Delta_p=0.8$ MeV were used for ^{56}Fe and ^{58}Fe, and others, respectively. The value of $\Delta_n=\Delta_p=0.8$ MeV or 1.0 MeV seems to be rather small compared with values[11] used usually.

We have adopted the smoothing method with a 1.0 MeV width for comparison between calculated and experimental results. This choice of the width was made rather arbitrarily so as to give the similar peak width to the experimental peak width near the ground states of the residual nuclei, although the width should actually increase with increasing excitation energy because of the fragmentation[12] of the deep hole states.

The calculated neutron energy spectra were shown by the solid curves in Fig. 2. The experimental angle-integrated energy spectra[2,3] are shown by the histograms in Fig. 2. It is seen from these figures that the shapes of the calculated spectra show fairly good agreement with the experimental ones except for some target nuclei in which the calculated peak positions shift slightly from the experimental ones. The calculated energy spectra show some underestimation at the lower neutron energy region, because the spectra do not include the contribution of the compound process.

The square value of the empirical effective matrix element is expressed[13] by the relation $|M|^2=KA^{-3}E^{-1}$, where A is the mass number and E is the excitation energy of the composite nucleus. In Fig. 2, the K value for all the target nuclei analyzed here was chosen to be 400 MeV (Ref. 3) so as to obtain the overall good agreement with the absolute differential cross sections of the experimental energy spectra.

To check for systematic trends in the empirical values of M^2, Kalbach-Cine[13] assumed a dependence of the form $M^2=KE^xA^y$, where K is a constant. The values of x and y extracted from the analysis of the experimental data are given by

$$x=-1.0^{-0.8}_{+0.4},\quad y=-3.2^{-0.2}_{+0.4}\,.$$

From these results, she estimated that $x=-1$ and $y=-3$. Therefore, the K value may not be a constant because of the large errors of x and y. Therefore, we examined the target mass number dependence of the K values. The K value for each target nucleus including Zr-Mo isotopes, ^{159}Tb (Refs. 2 and 3) and Pb (Ref. 14) isotopes was adjusted so as to obtain the overall good agreement with the absolute cross sections of the experimental energy spectra. The K values are plotted in Fig. 3 as a function of the mass number. It was found from Fig. 3 that the K values are nearly constant for the 25 MeV (p,n) reaction over the wide mass number region.

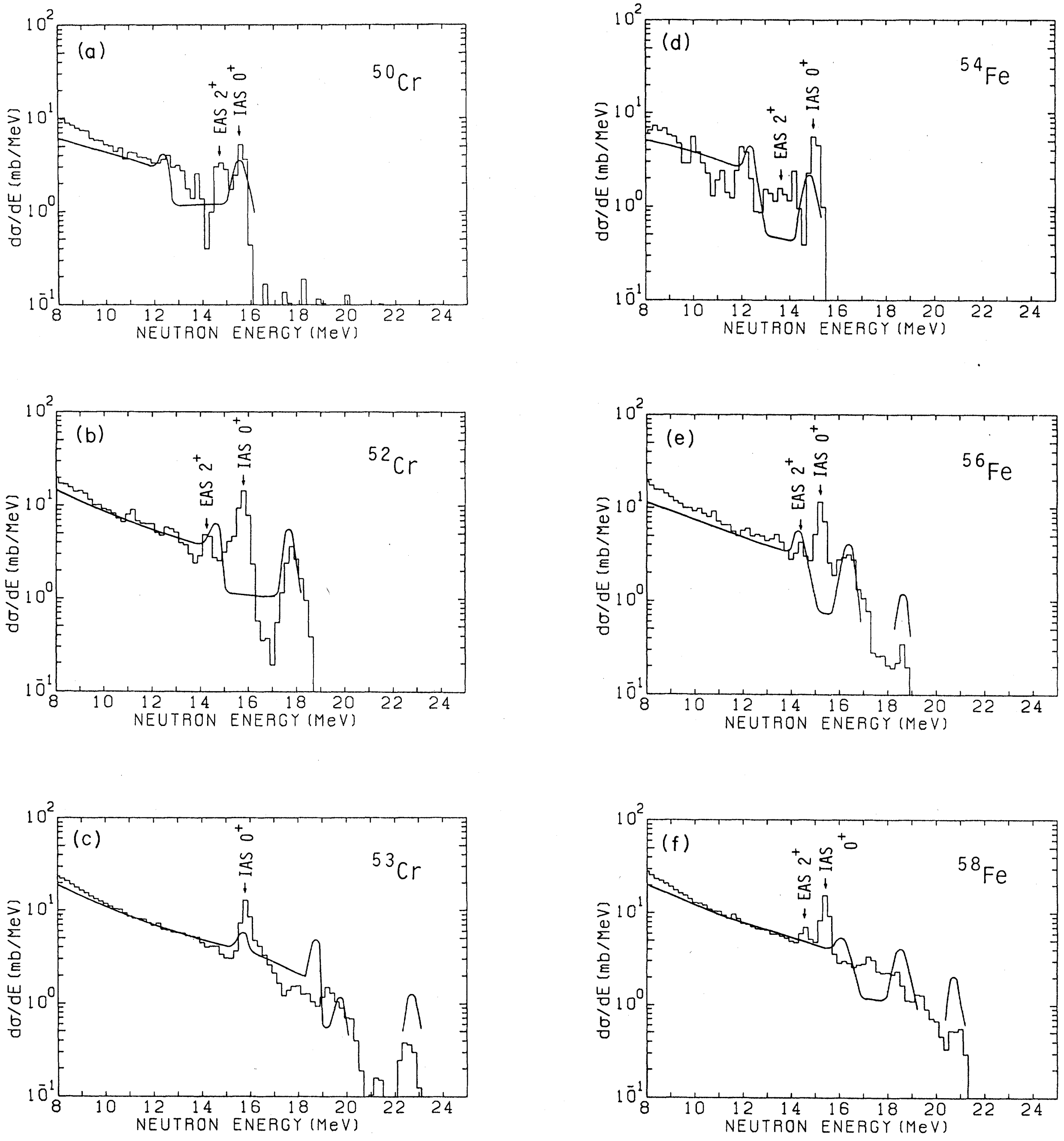

FIG. 2. Calculated and experimental angle-integrated energy spectra of neutrons for the 25 MeV (p,n) reaction. The histograms show the experimental energy spectra. The solid curves are the calculated preequilibrium energy spectra using the modified uniform spacing model, effective Q values, and the pairing correlation.

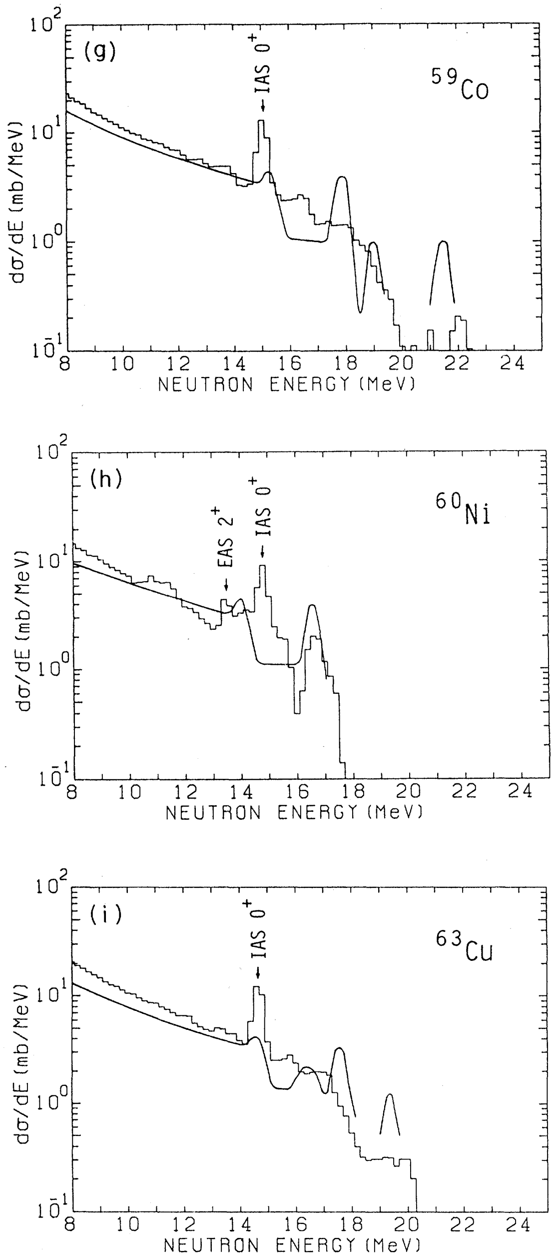

FIG. 2. (*Continued*).

IV. CONCLUSIONS

The 25 MeV (p,n) spectra in the Cr-Ni region were analyzed with the previously proposed exciton model using the effective Q values and the realistic 1p-1h state density based on the modified uniform spacing model in which the uniform spacing model was modified so as to have a wide spacing at the magic number and the pairing correlation was taken into account. The calculated spectra for the reaction on isotopes in the Cr-Ni region with 25 MeV protons show good agreement with the experimental ones not only on the absolute cross sections in the neutron en-

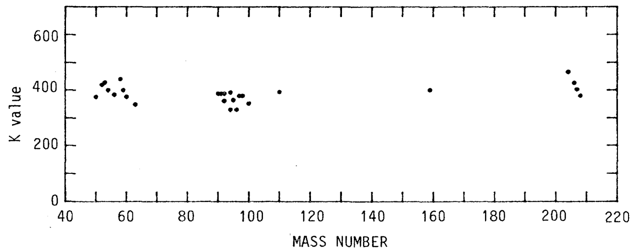

FIG. 3. K values for the 25 MeV (p,n) reaction as a function of mass number.

ergy region of 10–14 MeV, but also on the observed spectra with pronounced structures in the energy region higher than 14 MeV. This model would be applicable to the analysis of 14 MeV (n,p) reaction which is the inverse reaction of the (p,n) reaction.

It was found that the K values defined by $|M|^2=KA^{-3}E^{-1}$ are nearly constant for the 25 MeV (p,n) reaction over the wide mass number region if we use the effective Q values.

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