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Analysis of compound nucleus contributions from (α, p) reactions in Ni and Sn regions*

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Compound nucleus contributions to (α, p) reactions on nuclei in the Ni and Sn regions are obtained and compared with Hauser-Feshbach calculations. The noncompound nucleus contributions are found to change mainly the spectral magnitude of the cross section without substantially affecting the spectral shape. Both Gilbert-Cameron and back-shifted parameters deduced from level counting data give cross sections in reasonable agreement with experiment.

[NUCLEAR REACTIONS Fe, Ni, Zn, Cd, Sn (α,p), $E=15$, 18 MeV. Measured compound nucleus contributions.]

I. INTRODUCTION

In recent years, statistical theory has been used to explain nuclear reactions induced by 10–25 MeV nucleons and α particles.[1,2] Experimental cross sections have been compared with the predictions of Hauser-Feshbach calculations which include complete treatments of angular momentum and isospin.[3] The measured cross sections usually were contaminated by noncompound nucleus (NCN) contributions and, at best, only very crude corrections for this were applied. The purpose of this paper is to obtain unambiguous compound nucleus (CN) cross sections by an experimental method which has been developed and applied to (p,p'), (p,α), and (α,α') reactions.[4] The method utilizes the fact that the Q-value dependence in statistical theory greatly enhances neutron emissions compared with charged particle emissions for reactions with heavy isotopes. These CN cross sections are then compared with statistical theory (Hauser-Feshbach calculation). Since the level density is an important input to these calculations, both Gilbert-Cameron[5] and back-shifted[6] level density parameters are used.

II. EXPERIMENTAL

(α,p) reactions on nuclei in Ni region (Fe, Ni, Zn) and Sn region (Cd, Sn) were investigated. Both 15 and 18 MeV incident α particles were used for nuclei in the Ni region and only 18 MeV α particles were used in the Sn region. Protons were observed with a detector telescope with a 50 μm ΔE detector and a 2000 μm E detector. Particle identification was done by gating the $E+\Delta E$ pulses with $E\times\Delta E$ pulses. All targets were of thicknesses between 1 to 2 mg/cm^2. Two detection angles, 75° and 135°, were used. Angular distributions are also obtained for the Zn isotopes. Figure 1 shows the typical raw data. Spectra from different runs usually agreed to 15%.

III. ANALYSIS

The method for separating NCN and CN contributions used here has been discussed in Ref. 4. NCN contributions usually have a slow variation for neighboring nuclei, but that is not the case for the CN contribution which is highly Q value sensitive. For the heavy isotopes, neutron CN decay has a much higher probability than charged particle emission because the latter is suppressed by the Coulomb barrier. Therefore, in heavy isotopes, CN proton emission is negligible and all the protons observed come from NCN processes. When one moves towards lighter isotopes, the Q values for (α, n) reactions become more negative, and consequently, the CN neutron emissions are suppressed to the point that CN proton emissions become appreciable. This variation in cross sections among isotopes is shown in Fig. 1 which shows proton spectra from different Sn isotopes. One can see that for heavy isotopes, the spectra virtually coincide, since they consist practically all of NCN processes

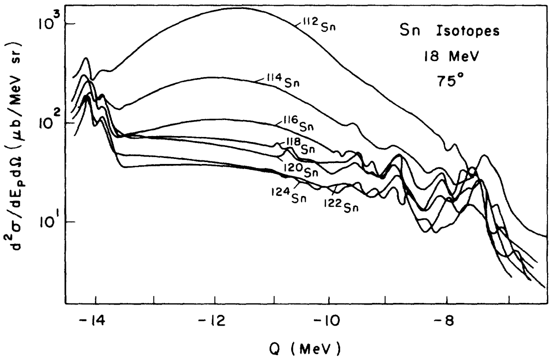

FIG. 1. Raw spectra of Sn (α, p) reactions.

which do not change appreciably among isotopes. The higher proton cross sections in the lighter isotopes are due to CN emissions. In these isotopes, neutron emissions are suppressed and proton emissions are enhanced. The method we used is to identify NCN contributions as the spectrum of the heaviest isotope, i.e., ^{124}Sn for Sn isotopes and ^{116}Cd for Cd isotopes, which can be eliminated from the spectra of the lighter isotopes by subtraction.

For nuclei in the Ni region, ^{70}Zn is a heavy enough nucleus in the sense that the total proton spectrum is practically all NCN (~95%). Figure 2 shows the total proton spectra of ^{68}Zn and ^{70}Zn for different angles. The ^{68}Zn spectra are 40% or less higher than the ^{70}Zn spectra. This means ^{68}Zn may have CN contributions of up to 40% which conforms with the predictions of the Hauser-Feshbach theory. This is also true for ^{64}Ni. Since our ^{70}Zn target is not isotopically pure and ^{70}Zn spectra have to be obtained by subtracting off contributions from other isotopes, the ^{68}Zn and ^{64}Ni spectra were used as the NCN spectra, respectively, for Zn isotopes and (Ni, Fe) isotopes with a minor correction for CN contributions.

The average of the CN contributions from the 75° and 135° data are then compared with the predictions of the angle-integrated Hauser-Feshbach calculation. Isotropy is assumed in making the comparison. A discussion of the calculation will be given in the following paragraphs.

In (α, p) reactions, since α particles have isospin equal to zero and $T_>$ states in the CN are not excited, the only isospin consideration necessary is the neutron decays to $T_>$ levels. Usually, the $T_>$ level density is assumed to be the same as that of the $(N+1, Z-1)$ nuclei with the excitation energy corrected for the Coulomb energy shift U_C.[7] The displacement in energy effectively decreases the $T_>$ level density compared with the $T_<$ level density by a factor of $\exp[-(aU_C)^{1/2}]$ where a is the level density parameter. Since U_C is $\gtrsim 8$ MeV for the nuclei considered, the $T_<$ states have much higher level densities and present a much larger phase space for neutron decays. Though neutron decays to $T_>$ levels are usually negligible ($\lesssim 1\%$), they are included in all calculations.

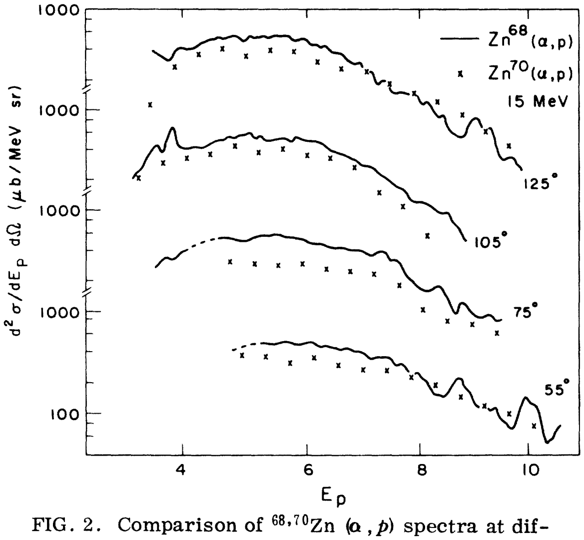

FIG. 2. Comparison of ^{68,70}Zn (α, p) spectra at different detection angles.

The magnitudes of the calculated proton spectra are highly dependent on the optical parameters used. Just by using two different sets of proton optical parameters proposed, respectively, by Perey[8] and Becchetti,[9] the difference in spectral magnitudes is ~10% without changing the spectral shapes. Since we use optical parameters both for the incoming and outgoing channels, the errors can easily be larger. Also, in the calculation, we should use only the CN parts of the transmission coefficients and inverse cross sections. We correct for this by taking the cross section for CN formation to be 80% of the total reaction cross section. Due to these considerations, a 20% error

TABLE I. Compilations of level density parameters from the Gilbert-Cameron and the Dilg group's (back shifted) schemes. Δ's have units of MeV and a's and T's have units of MeV^{-1}.

Target nucleus	Residual nucleus		Gilbert-Cameron	Back shifted
^{54}Fe	^{57}Co	Δ	1.27	0.05
		a	6.04	7.24
		T	1.26	
^{56}Fe	^{59}Co	Δ	1.29	0.11
		a	7.02	7.49
		T	1.13	
^{58}Ni	^{61}Cu	Δ	1.29	0.14
		a	6.71	7.75
		T	1.16	
^{60}Ni	^{63}Cu	Δ	1.41	0.30
		a	7.75	8.00
		T	1.05	
^{62}Ni	^{65}Cu	Δ	1.50	0.43
		a	8.70	8.26
		T	0.97	
^{64}Zn	^{67}Ga	Δ	1.50	0.46
		a	9.44	8.51
		T	0.91	
^{66}Zn	^{69}Ga	Δ	1.50	0.49
		a	10.10	8.76
		T	0.87	

TABLE II. Compilation of level density parameters from the Gilbert and Cameron scheme. The Δ's have units of MeV and the *a*'s and *T*'s have units of MeV^{-1}.

Target nucleus	Residual nucleus		Gilbert-Cameron
^{106}Cd	^{109}In	Δ	1.24
		a	15.04
		T	0.63
^{110}Cd	^{113}In	Δ	1.14
		a	16.87
		T	0.59
^{112}Sn	^{115}Sb	Δ	1.14
		a	16.84
		T	0.58
^{114}Sn	^{117}Sb	Δ	1.32
		a	16.10
		T	0.57
^{116}Sn	^{119}Sb	Δ	1.15
		a	14.84
		T	0.56

in spectral magnitude is possible. On the other hand, the shapes of the spectra are not as sensitive to different sets of optical parameters because they depend only on the relative energy dependence of the optical model calculations. In this work, the α particle optical model parameters used are from McFadden and Satchler,[10] the proton parameters are from Perey,[8] and the neutron parameters are from Becchetti.[9]

The level density is another input to the calculations. The magnitudes of proton cross sections are determined by level densities used in all exit channels and the shape of the proton spectrum is only dependent on the level density of the residual nucleus of the proton channel. Two level density schemes are used separately for calculations, i.e., the Gilbert-Cameron[5] (GC) and back-shifted[6] (BS) schemes. The GC scheme uses a combination of constant temperature dependence and Fermi gas dependence, while the BS scheme uses only a Fermi gas dependence. Except for the parameter used in the proton channel, the correctness of the parameters is difficult to judge. The GC and BS parameters used for proton channels are listed in Tables I and II. They come from Refs. 5 and 6 and are derived from data by counting levels.

IV. RESULTS AND DISCUSSION

(Fe,Ni,Zn) region

Since the NCN contributions in this mass region, i.e., ^{64}Ni and ^{68}Zn spectra, have similar spectral shapes in log scale as the spectra of the lighter

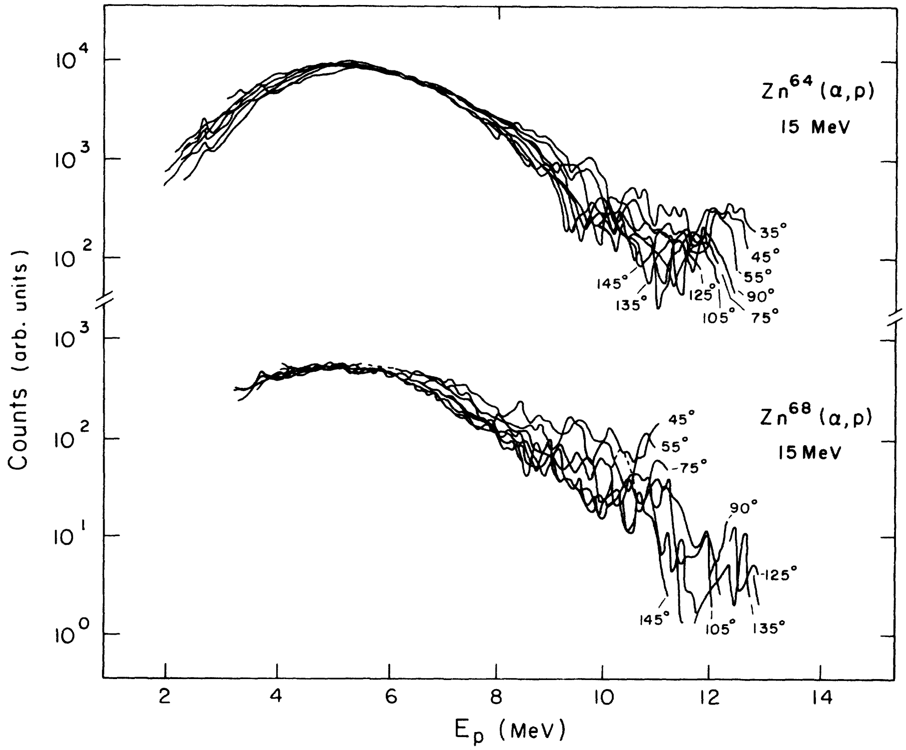

FIG. 3. Angular distributions of observed protons from ^{64,68}Zn (α, *p*) reactions with 15 MeV α particle energy.

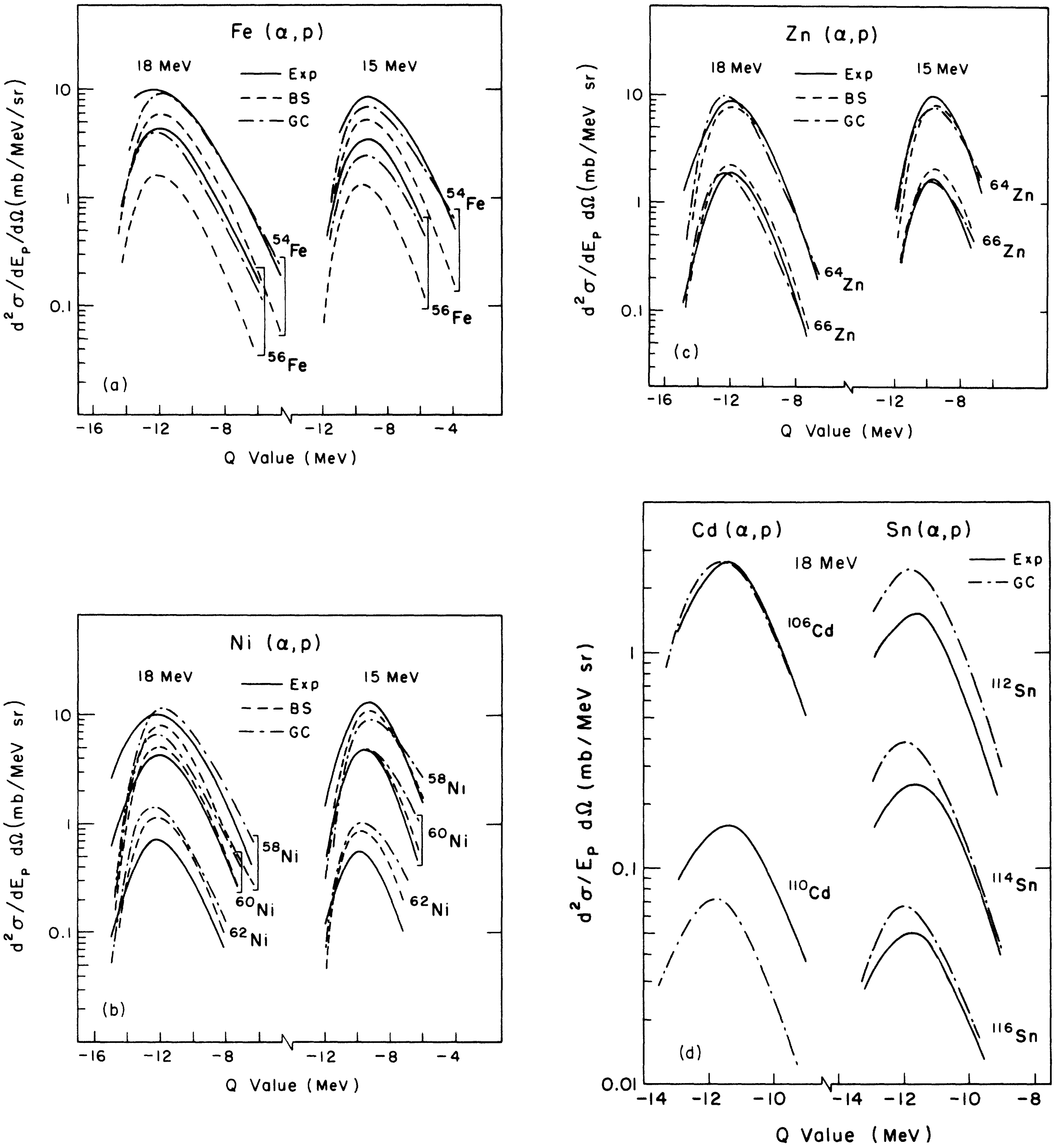

FIG. 4. CN proton spectra from (α, p) reactions compared with calculations using Hauser-Feshbach theory.

isotopes (see Fig. 3), the subtraction of NCN contributions only changes the magnitudes of the cross sections, e.g., 3% for ^{60}Ni and 30% for ^{62}Ni, without changing the spectral shapes. Figure 4 shows experimental spectra after the NCN contributions have been subtracted, along with the predicted spectra using BS and GC level density parameters. The BS parameters are generated from Ref. 6 by Dilg's group. In general, both BS and GC parameters can produce spectra in reasonable agreement with the experiment. All the spectral magnitudes agree better than a factor of 2 except for the BS parameters for Fe. And BS parameters in most cases give a better agreement in spectral shape. The parameters are listed in Tables I and II.

It is interesting to note in Fig. 3 that the angular distributions of protons from ^{64}Zn and ^{68}Zn are both isotropic to approximately the same degree despite the fact that ^{64}Zn is practically all CN and ^{68}Zn is more than 60% NCN. This indicates that isotropy is not a sufficient indication for total CN contributions.

(Cd,Sn) region

In the lighter isotopes in this mass region, the NCN contributions again mainly change the magnitudes of the cross sections, e.g., 3% for ^{112}Sn and 30% for ^{116}Sn, and only change the spectral shapes slightly. The CN contributions are shown in Fig. 4 together with the results of Hauser-Feshbach calculations using GC parameters. Reasonable agreement is found. No BS parameter calculations are used because they are not complete in this region. The parameters used are listed in Tables I and II.

V. CONCLUSION

CN contributions are separated using an experimental method and compared with calculations using different level density schemes. For most nuclei, the spectral magnitudes are predicted correctly to better than a factor of 2 with GC and BS level density parameters, which instead of derived from data of charged particle spectra, are determined from data of counting levels. The NCN contributions are found to modify the spectral magnitudes of the differential cross sections without significantly changing the shapes of the spectra.

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