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Compound-Nucleus Contribution for (p, α) Reaction from Sn and Cd Isotopes

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A clean separation of compound-nucleus and direct-reaction processes in (p, α) reaction was made for 12- and 17-MeV protons bombarding on Cd and Sn isotopes. Results indicated the compound-nucleus contributions for ^{112}Sn give isotropic angular distribution for the α particles. Shapes of the energy spectra of emitted α particles were in good agreement with statistical theory calculation, but absolute cross sections were larger than predicted by a factor of 2 to 7.

I. INTRODUCTION

This is an experiment to separate compound-nucleus (CN) contributions from direct reaction (DR) contributions to (p, α) reactions on Sn and Cd even isotopes and to analyze the former. What is called DR in this paper includes all non-compound-nucleus reactions. In Fig. 1, the spectra of (p, α) reactions on different Sn even isotopes are shown. The cross section decreases very rapidly as the isotopic mass increases. The reason is that the cross sections of particle emission for CN reaction are very sensitive to Q values, and when the Q value of the (p, n) reaction on Sn isotopes changes from -7 MeV for ^{112}Sn to -1 MeV for ^{124}Sn, other types of particle emission are suppressed for heavier isotopes due to the competition with the highly probable neutron emission. Therefore, in the cases of heavier isotopes (p, α), reaction cross sections can be attributed completely to DR contributions. This fact is reflected by the resemblance of the spectra of ^{124}Sn and ^{122}Sn because DR cross sections depend only on nuclear structure and they should be approximately the same for different isotopes. Also, the similarity of DR cross sections among isotopes makes it a good approximation to use the (p, α) contribution from ^{124}Sn as the DR contribution to other Sn isotopes. This method was designed previously for (p, p') reactions and good agreement was found with statistical theory calculations.[1,2]

II. EXPERIMENT

A block diagram of the electronics used is shown in Fig. 1. Protons of 12- and 17-MeV energy were obtained from the University of Pittsburgh three-stage Van de Graaff accelerator. The beam was collimated by a circular slit (0.64 cm in diameter) 10 cm in front of the target. The targets used were self-supporting foils of Sn and Cd isotopes with thicknesses ranging from 1 to 3 mg/cm^2. Two scintillation detectors located at 25° on either side of the beam were used as monitors. Energy windows of these two detectors were centered on the peaks of elastically scattered protons. These monitors proved to be useful in cases where targets were nonuniform. The emitted α particles were detected by a telescope consisting of two surface-barrier charged-particle detectors. The ΔE front detector and E back detector were, respectively, 50 and 2000 μm thick. The emitted α

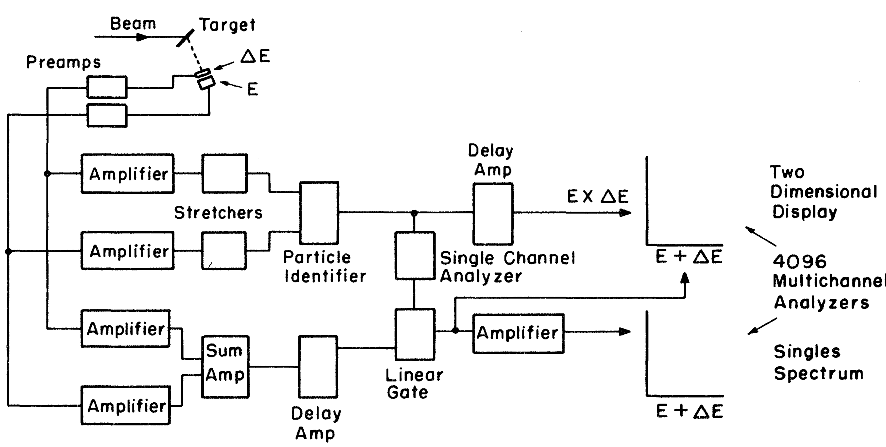

FIG. 1. Electronics used in the experiment.

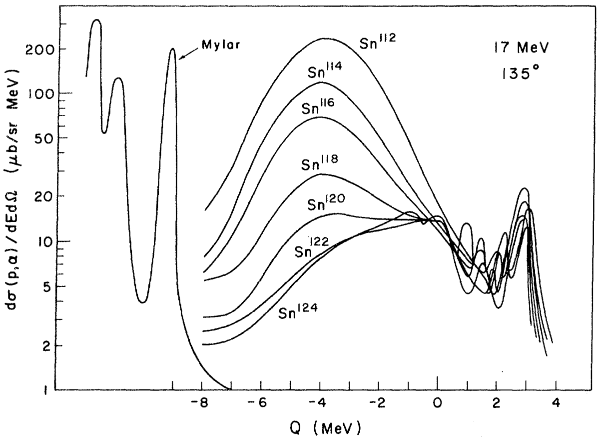

FIG. 2. The experimental (p, α) cross section of Sn isotopes at 17-MeV incident energy and observed at lab angle 135° before subtracting off the DR contributions.

particles were observed at 75 and 135° laboratory angles. The normal of the targets made angles of 45 and 135° with the direction of the beam when the detection angles were 75 and 135°, respectively. The energy loss ΔE of the α particles was approximately 0.1 MeV at an α-particle energy of 12 MeV. α-particle groups emitted from carbon and oxygen impurities were easily subtracted off by comparing with spectra from Mylar. In fact, they do not contribute to the regions of interest (Fig. 2). The beam was collected by a Faraday cup. The typical current used was about 180 nA. Independent runs were taken at different times on the same targets.

Since the cross sections of (p, α) reactions are low for heavier isotopes, i.e., ~1 mb for ^{118}Sn, the percentage error introduced by statistics amounts to 30%. This is reflected in the consistency check of results from different runs. Therefore the final values of the cross sections $\sigma_{CN}(p, \alpha)$, which were obtained by subtraction of two energy spectra, may have errors up to a factor of 2 for ^{120}Sn. This error decreases very rapidly for lower isotopic masses where the (p, α) cross section increases, i.e., 40% for ^{118}Sn and 10% for ^{112}Sn.

TABLE I. Q values in MeV.

Target	Reaction (p,n)	(p,α)
^{124}Sn	−1.40	2.24
^{122}Sn	−2.39	2.49
^{120}Sn	−3.46	2.69
^{118}Sn	−4.48	2.75
^{116}Sn	−5.28	2.68
^{114}Sn	−6.47	2.46
^{112}Sn	−7.58	2.75
^{116}Cd	−1.25	3.19
^{114}Cd	−2.21	3.04
^{112}Cd	−3.37	3.01
^{110}Cd	−4.71	2.92
^{106}Cd	−7.52	2.61

III. THEORY

We shall now briefly discuss the theoretical basis of the method used in separating CN and DR processes. When the incident protons come into interaction with the nuclei, either CN or DR processes are initiated. For CN processes, after the compound nuclei are formed, they can decay by different modes: neutron emission, proton emission, α-particle emission, etc. According to Blatt and Weisskopf,[3] for a compound-nucleus reaction $X(a, b)Y^*$, i.e., $a+X \to Y^*+b$, the cross section is proportional to F_b, given by

$$F_b(E_{by}) = \frac{2M_b}{\hbar^2}(2s_b+1)\int_0^{E_{by}} \sigma_b(\epsilon_\beta)\epsilon_\beta\,\omega(E_{by}-\epsilon_\beta)\,d\epsilon_\beta\,. \tag{1}$$

Here M_b and S_b are, respectively, the mass and

TABLE II. Calculated value for F using Eq. (1).

Incident proton energy = 17 MeV Isotope	F_n	F_p	F_α	Incident proton energy = 12 MeV Isotope	F_n	F_p	F_α
^{124}Sn	3.36×10^{10}	3.31×10^{6}	3.06×10^{5}	^{124}Sn	2.06×10^{8}	4.48×10^{3}	8.29×10^{1}
^{122}Sn	4.74×10^{10}	5.32×10^{6}	1.17×10^{6}	^{122}Sn	1.78×10^{8}	5.32×10^{3}	2.94×10^{2}
^{120}Sn	2.39×10^{10}	1.57×10^{7}	2.52×10^{6}	^{120}Sn	6.51×10^{7}	1.16×10^{4}	5.87×10^{2}
^{118}Sn	1.19×10^{10}	3.36×10^{7}	2.17×10^{6}	^{118}Sn	2.18×10^{7}	1.68×10^{4}	4.85×10^{2}
^{116}Sn	3.36×10^{9}	2.52×10^{7}	1.79×10^{6}	^{116}Sn	4.88×10^{6}	1.42×10^{4}	4.96×10^{2}
^{114}Sn	4.74×10^{8}	1.89×10^{7}	8.11×10^{5}	^{114}Sn	5.64×10^{5}	1.46×10^{4}	2.17×10^{2}
^{112}Sn	7.30×10^{7}	1.00×10^{7}	5.96×10^{5}	^{112}Sn	6.32×10^{4}	9.19×10^{3}	2.73×10^{2}
^{116}Cd	2.87×10^{4}	4.11×10^{7}	5.34×10^{6}	^{116}Cd	1.26×10^{9}	2.38×10^{4}	1.46×10^{3}
^{114}Cd	8.27×10^{10}	3.26×10^{7}	4.12×10^{6}	^{114}Cd	2.83×10^{8}	1.84×10^{4}	1.27×10^{3}
^{112}Cd	1.47×10^{10}	2.75×10^{7}	2.25×10^{6}	^{112}Cd	4.31×10^{7}	1.89×10^{4}	1.32×10^{2}
^{110}Cd	1.78×10^{9}	1.59×10^{7}	1.13×10^{6}	^{110}Cd	4.31×10^{6}	1.13×10^{4}	4.62×10^{2}
^{106}Cd	8.93×10^{6}	4.23×10^{6}	1.38×10^{5}	^{106}Cd	1.85×10^{4}	6.70×10^{3}	9.76×10^{1}

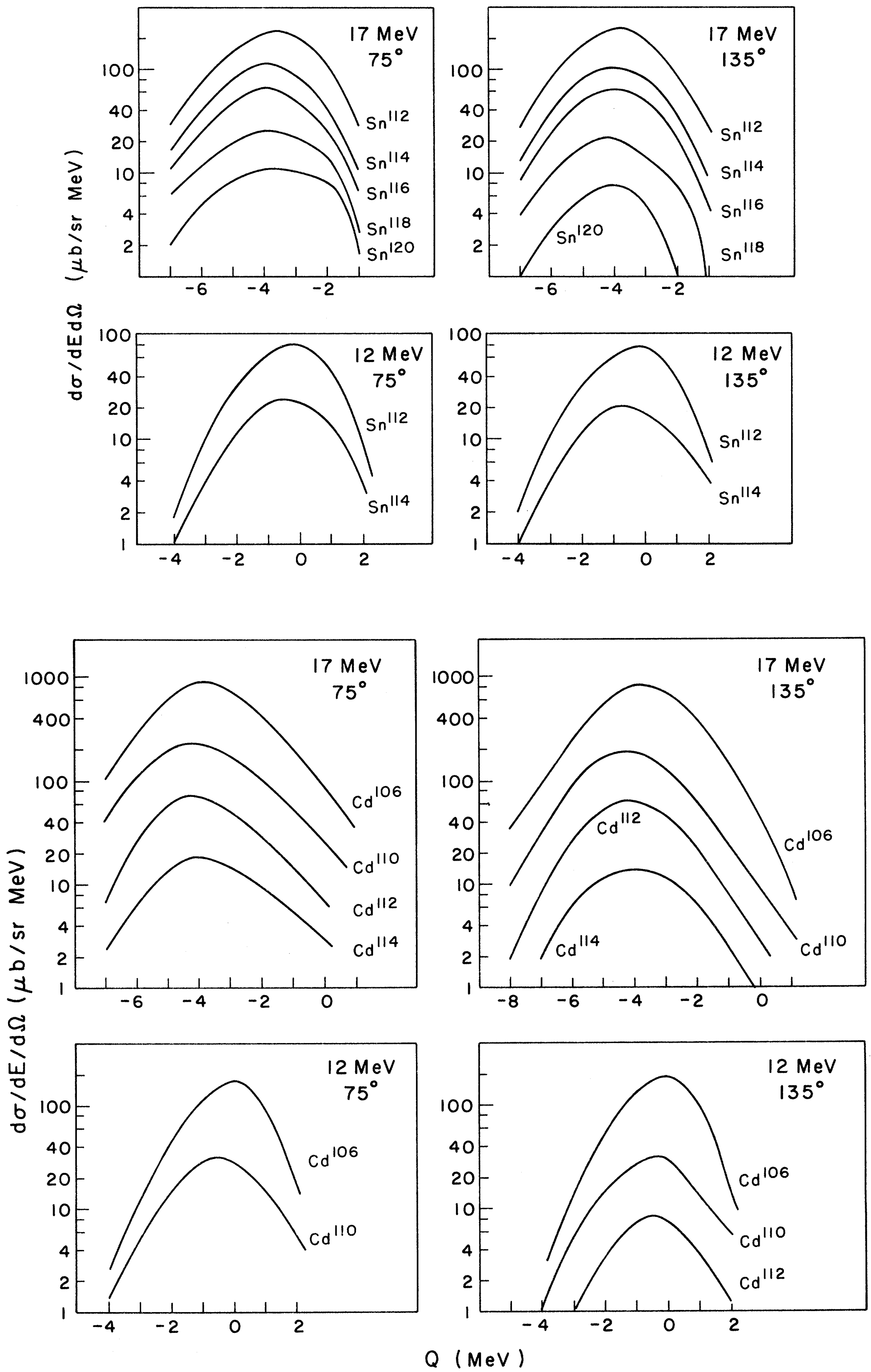

FIG. 3. $\sigma_{CN}(p, \alpha)$ observed experimentally.

TABLE III. Summary of experimental values of $\sigma_{CN}(p,\alpha)$ (see discussion of accuracy, Sec. II).

Incident proton energy (MeV)	Target	Experiment 75° $\sigma_{CN}(p,\alpha)$ (mb)	75° $F_\alpha/\sum F$	135° $\sigma_{CN}(p,\alpha)$ (mb)	135° $F_\alpha/\sum F$	Theory $F_\alpha/\sum F$
17	^{112}Sn	9.9	1.2×10^{-2}	10.4	1.18×10^{-2}	7.14×10^{-3}
	^{114}Sn	4.7	5.4×10^{-3}	4.4	5.0×10^{-3}	1.70×10^{-3}
	^{116}Sn	2.8	3.1×10^{-3}	2.7	3.0×10^{-3}	5.28×10^{-4}
	^{118}Sn	1.2	1.4×10^{-3}	0.9	$1.\times10^{-3}$	1.81×10^{-4}
	^{120}Sn	0.5	$6.\times10^{-4}$	0.2	$3.\times10^{-4}$	1.06×10^{-4}
	^{106}Cd	39.8	4.53×10^{-2}	36.7	4.18×10^{-2}	1.04×10^{-2}
	^{110}Cd	11.1	1.26×10^{-2}	8.7	9.9×10^{-3}	6.25×10^{-4}
	^{112}Cd	3.1	3.5×10^{-3}	2.8	3.2×10^{-3}	1.53×10^{-4}
	^{114}Cd	0.8	$9.\times10^{-4}$	0.6	$7.\times10^{-4}$	4.96×10^{-5}
12	^{112}Sn	2.9	4.6×10^{-3}	2.8	4.4×10^{-3}	3.75×10^{-3}
	^{114}Sn	0.9	$1.\times10^{-3}$	0.8	$1.\times10^{-3}$	3.74×10^{-4}
	^{106}Cd	5.8	9.0×10^{-3}	6.0	9.4×10^{-3}	3.72×10^{-3}
	^{110}Cd	1.2	1.4×10^{-3}	1.1	1.8×10^{-3}	1.07×10^{-4}
	^{112}Cd	···	···	0.2	$4.\times10^{-4}$	1.7×10^{-5}

spin of the emitted particle. $\sigma_b(\epsilon_\beta)$ is the inverse cross section, a collision with the energy ϵ_β between b and the excited nucleus Y^*, the latter having the excitation energy $E_{by}-\epsilon_\beta$. The level densities ω were calculated by the Gilbert-Cameron composite level density.[4] E_{by}, the maximum available energy, is the sum of the incident-proton energy and the Q value with the correction necessary for using Gilbert-Cameron level density. For neutrons, we use $\sigma_n(E)=\pi(R+\lambda\!\!\!^-)^2$. Here R is the radius of the nucleus ($=1.5\,A_{fm}{}^{1/3}$) and $\lambda\!\!\!^-$ is the de Broglie wavelength of the incident particle. For protons and α particles, the inverse cross sections were calculated using the optical model.[5] The optical-model parameters for protons were taken from Ref. 6. Since the optical-model parameters for α particles with incident energy less than 24 MeV are not available, those at 24.7 MeV were used with a linear extrapolation of the imaginary potential (W).[7] The absolute cross sections by CN processes for the (p,α) reactions, $\sigma_{CN}(p,\alpha)$, can be written as

$$\sigma_{CN}(p,\alpha)=\sigma_{CN}(p)\frac{F_\alpha}{F_n+F_p+F_\alpha+\cdots}\ . \qquad (2)$$

Here $\sigma_{CN}(p)$ is the CN formation cross section for the incident proton and was taken as 80% of the total reaction cross section[8] (640 and 880 mb at 12 and 17 MeV, respectively).

Table I gives the Q values; Table II shows that F_n is much larger than F_p and F_α, which means the compound nucleus usually decays by neutron emission. Also, F increases when the Q value increases. At 17 MeV for ^{124}Sn, F_p/F_n and F_α/F_n are of the order 10^{-4}. In other words, neutron emission is so probable for CN processes that α particles observed in the experiment should be attributed completely to DR processes (see more detailed discussion in Refs. 1 and 2). On the other hand, DR contributions depend on the structures of the target nuclei. Since the nuclear structures of all even-A isotopes are similar, the DR contributions from them will be nearly the same. Therefore, the energy spectra of ^{124}Sn can be taken as the DR contributions for all even-A Sn isotopes, and the CN contributions for the lighter isotopes can be obtained simply by subtracting off the α-particle spectrum of ^{124}Sn from the α-particle energy spectra of these isotopes. The total cross sections for the CN contributions, $\sigma_{CN}(p,\alpha)$, will be equal to the total areas under the energy spectra after subtraction, multiplied by 4π, which uses the approximate isotropy

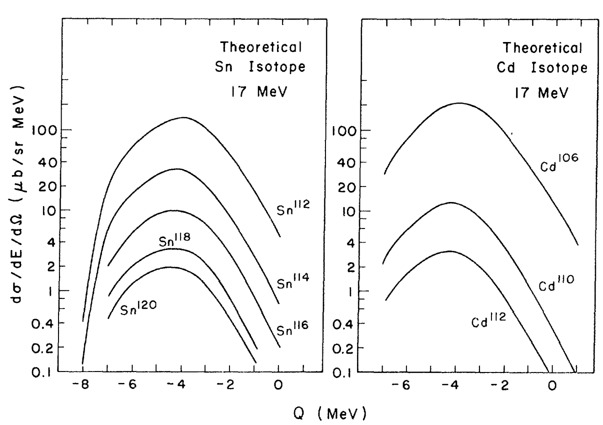

FIG. 4. $\sigma_{CN}(p,\alpha)$ calculated using statistical theory.

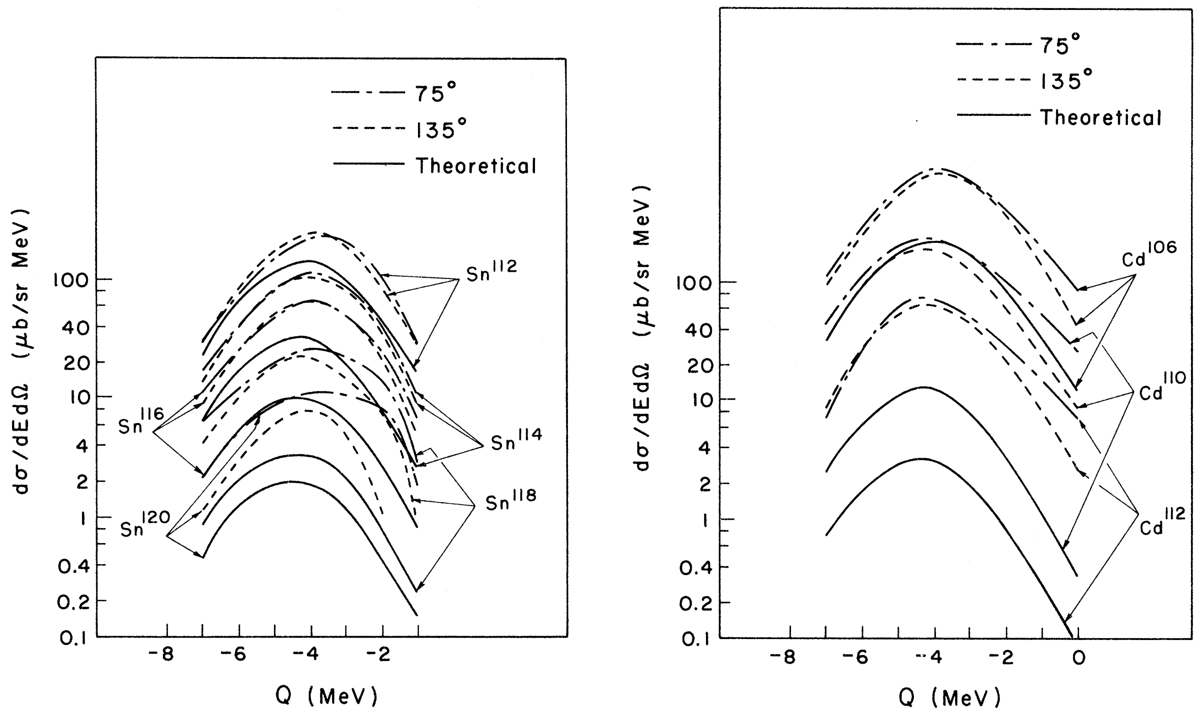

FIG. 5. Comparison of $\sigma_{CN}(p, \alpha)$ obtained by theoretical calculation and experiment.

of angular distribution of the CN process. The same procedure can be followed for the even-A Cd isotopes and ^{116}Cd (Fig.3). The fact that the (p, α) reaction for ^{124}Sn and ^{116}Cd is completely DR is also demonstrated by the close resemblance of the ^{122}Sn and ^{124}Sn (p, α) energy spectra (Fig. 2).

IV. RESULTS

Experimental values of $\sigma_{CN}(p, \alpha)$ are summarized in Table III. Theoretical predictions and experimental results can be compared in two ways. From (2), we have

$$\frac{\sigma_{CN}(p, \alpha)}{\sigma_{CN}(p)} = \frac{F_\alpha}{F_n + F_p + F_\alpha} . \tag{2'}$$

The right side of (2′) can be calculated using Eq.

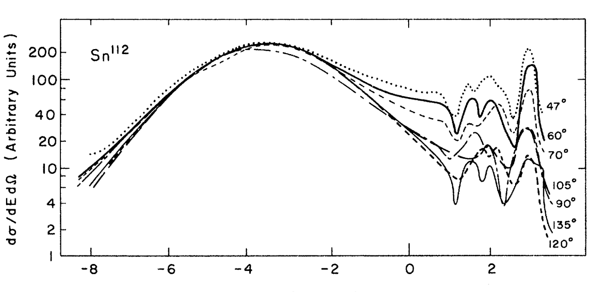

FIG. 6. Angular distribution of ^{112}Sn(p, α) reaction cross section.

(1). The left side of (2′) is obtained experimentally as described in the last section. Also, the energy spectra of Fig. 3 can be constructed theoretically by calculating the integrand of (1) and applying appropriate normalization (Fig. 4), i.e.,

$$\frac{d\sigma_{CN}(p, \alpha)}{dE d\Omega} = \sigma_{CN}(p) \frac{2M_\alpha}{\hbar^2} (2s_\alpha + 1) \frac{\sigma_\alpha(E) E \omega(E_{by} - E)}{F_n + F_p + F_\alpha} .$$

Both of these comparisons show that the shapes of

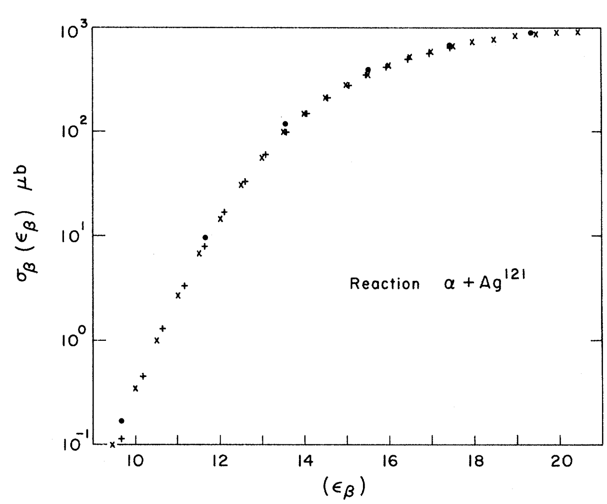

FIG. 7. The inverse cross section $\sigma_\alpha(\epsilon_\beta)$ calculated using the optical model with a different optical-model parameter from Ref. 7.

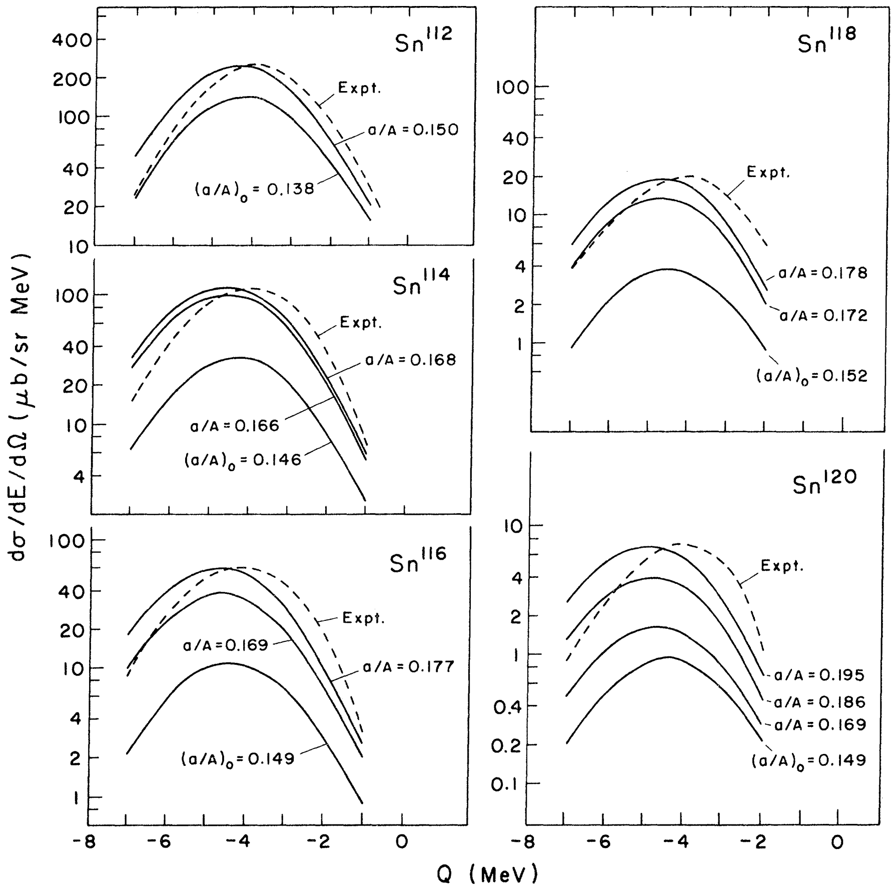

FIG. 8. Theoretical calculation of $\sigma_{CN}(p,\alpha)$ using different level density parameters, a/A, and compared to experimentally observed data.

the spectra are in reasonable agreement considering the uncertainty in the experimental energy scale and the $\sigma_{CN}(p, \alpha)$'s observed were larger than theoretical predictions (Table I, Fig. 5). The CN contributions are found to be isotropic for ^{112}Sn (Fig. 6). This is as expected from statistical theory.

Since the $\sigma_{CN}(p, \alpha)$ spectrum has the largest contribution from the region where $\sigma_\alpha(\epsilon_\beta)$ is rapidly rising (Fig. 7), $\epsilon_\beta \approx 12$ MeV, F_α is extremely sensitive to variations in $\sigma_\alpha(\epsilon_\beta)$. $\sigma_\gamma(\epsilon_\beta)$ was calculated using different sets of optical-model parameters from Ref. 7 and the extrapolation procedure described corresponding to variations in r_0 between 1.56 and 1.39 fm, but no appreciable differences were found, as can be seen from Fig. 7. For the lighter isotopes, we see from Fig. 8 that the calculated magnitudes of the $\sigma_{CN}(p, \alpha)$ spectra can be brought into agreement with those obtained experimentally by changing the level density parameter a/A, e.g., from 0.138 to 0.150 for ^{112}Sn, without seriously affecting the agreement in the shape of the spectra. For heavier isotopes, one cannot get agreement in the magnitude of $\sigma_{CN}(p, \alpha)$ without de-

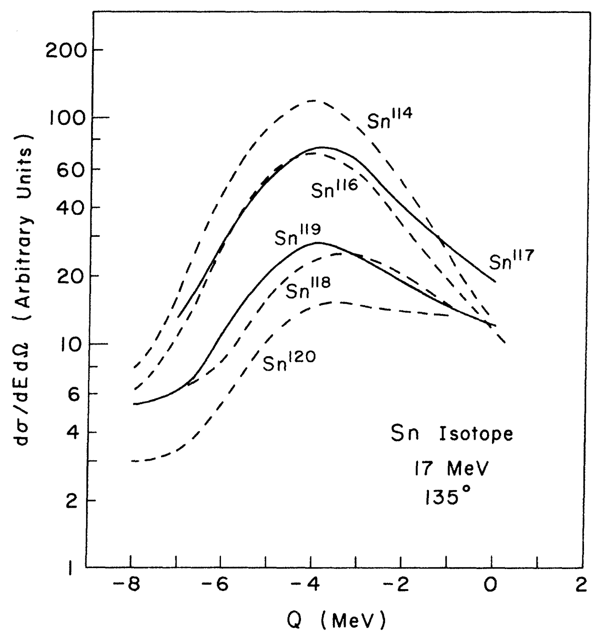

FIG. 9. Total (p, α) cross section observed for Sn odd isotopes.

stroying the agreement in shapes.

Data have been taken using targets of ^{117}Sn and ^{119}Sn. Figure 9 shows that the α-particle spectra observed fall reasonably well among the spectra observed for even-A isotopes.

V. SUMMARY AND DISCUSSION

The CN contributions to (p, α) reactions were cleanly separated from the DR contributions and the former were found to have isotropic angular distributions for ^{112}Sn. The shapes of the CN energy spectra were found to be in reasonably good agreement with predictions from statistical theory for nuclear reactions based on the Gilbert-Cameron level-density parameters, but the measured absolute $\sigma_{CN}(p, \alpha)$'s were found to be too large. In the light isotopes where the $\sigma_{CN}(p, \alpha)$'s are large and accurately determined, this discrepancy is only about a factor of 2, and it can be removed by changing the level-density parameters by a not unreasonable amount (about 15%). However, in the heavy isotopes, the discrepancy between the measured and calculated $\sigma_{CN}(p, \alpha)$'s ranges up to a factor of 10, and it can only be removed by changing the level-density parameters by an unreasonably large amount and thereby destroying the agreement between experiment and theory on the shapes of the spectra.

Several possible sources of the discrepancy were investigated. Firstly, we may restore the agreement in shapes of spectra after changing a/A by also changing the inverse reaction cross section of the α particle, $\sigma_\alpha(\epsilon_\beta)$. However, we have already shown in Fig. 7 that $\sigma_\alpha(\epsilon_\beta)$ is very insensitive to differences in various sets of optical-model parameters. Secondly, the contamination from CN processes to (p, α) energy spectra of ^{124}Sn and ^{116}Cd might be important, but these effects are negligible according to statistical reaction theory $[\sigma_{CN}(p, \alpha)/\sigma_{DR}(p, \alpha) < 1\%$ for ^{124}Sn$]$, and this fact is verified by the considerable difference in spectral shape between these and the lighter isotopes in Fig. 2. Lastly, the discrepancy may be introduced by a reaction mechanism other than CN and DR processes which becomes important for heavy isotopes. According to what we observed, this reaction mechanism exhibits the following characteristics:

1. Competition with neutron emission must be important in determining the (p, α) cross section, since there is no other reasonable explanation for the rapid decrease in $\sigma(p, \alpha)$ with increasing isotope mass.
2. The energy spectra are peaked at about the same energy as spectra emitted from compound-nucleus reactions. Evidence for this is seen in the similarities among spectra from all isotopes in Fig. 4 after the direct-reaction contributions have been subtracted off, although there does seem to be an additional bump at higher energy in spectra from the heavier isotopes.

Suppose that the DR contributions change by 20% from ^{124}Sn to ^{112}Sn; this, when coupled with the error introduced by statistics, may be able to explain a difference up to a factor of 2 for heavier isotopes.

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