Analyzing Powers of Continuum Spectra of Reactions ^{28}Si, ^{58}Ni, ^{209}Bi $(p_{\text{pol}}, p'X)$ and (p_{pol}, dX) at 65 MeV

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Analyzing powers of the continuum energy spectra from the reactions ^{28}Si, ^{58}Ni, ^{209}Bi$(p_{\text{pol}}, p'X)$ and (p_{pol}, dX) at 65 MeV have been measured. The analyzing powers of the continuum spectra were found to be small at forward angles and to be very large and positive at backward angles. These features indicate the importance of the spin-dependent interaction in the understanding of the continuum spectra.

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Nuclear reactions such as $(p,p'X)$ and (p,dX) induced by protons of 50–100 MeV are interesting for the study of the preequilibrium process, because the velocity of the incident protons at these energies is close to that of the Fermi motion of the nucleons in the target nucleus. A typical spectrum of light particles from these reactions shows different reaction mechanisms. There is in the low-energy end a prominent peak due to the evaporation of protons; and at the upper end the typical direct-reaction contribution leading to distinct final states in the residual nuclei. The wide and flat continuum region, seen in between, can be attributed to the preequilibrium process. The cross section for these continuum spectra is characterized by a strong forward peaking, whereas the compound contribution is symmetric about 90°.

Many different approaches[1-6] have been developed to interpret such continuum spectra. None of these models includes spin-dependent interactions. However, experiments with polarized protons could provide more insight into the reaction mechanism of the preequilibrium process. Large polarization effects can be expected if the particles are emitted through a direct process. An example of this is the reaction leading to discrete levels in the low-excitation-energy region. On the other hand, the analyzing power A_y is expected to be small if the particles are emitted through an indirect process. An extreme example is the evaporation (compound) process where zero A_y is expected since the particles are emitted after many collisions and have lost their intial polarization. Thus it is very interesting to measure the A_y of the continuum spectra in between.

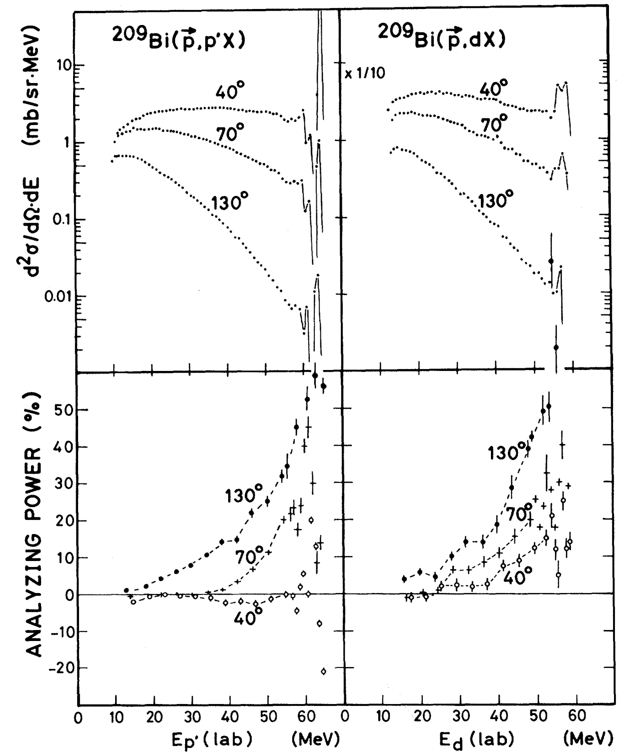

FIG. 1. Continuum energy spectra from the $(p_{\text{pol}}, p'X)$ and (p_{pol}, dX) reactions for 65-MeV polarized protons on ^{209}Bi at 40°, 70°, and 130° (upper) and extracted analyzing powers (lower).

In the intermediate energy region (polarized proton beams of 300–800 MeV) the A_y of the continuum spectra have been measured and applied to distinguish between different reaction models.[7–11]

In this Letter we report experimental results of the analyzing power A_y of the continuum spectra of the reactions ^{28}Si, ^{58}Ni, ^{209}Bi($p_{\text{pol}}, p'X$) and (p_{pol}, dX) at 65 MeV. Similar experiments[12] have been recently reported; however, their measurements were limited in a particular angular range or in a certain range of the excitation energy. Continuum spectra were measured at laboratory angles from 20° to 150°. The polarized protons from the atomic-beam-type polarized-ion source were accelerated by the azimuthally varying field cyclotron at the Research Center for Nuclear Physics, Osaka University. Typical beam current was 50 nA on target with a polarization of 68%. The beam polarization was reversed every 300 msec and its polarization was monitored continuously with a ^{12}C polarimeter.[13] The emitted protons and deuterons were detected by a pair of counter telescopes positioned at symmetric angles to the beam. Each counter telescope consisted of a Si detector of 400-μm thickness and a high-purity Ge detector of 15-mm thickness. Protons and deuterons were identified by the ΔE and E signals. The ^{28}Si, ^{58}Ni, and ^{209}Bi targets were self-supporting metallic foils with thicknesses ranging from 2 to 44 mg/cm^2. The analyzing power A_y of the continuum spectra was determined as $PA_y = (\alpha - 1)/(\alpha + 1)$, where P is the beam polarization and α is given by

$$\alpha = \left(\frac{L\uparrow/R\uparrow}{L\downarrow/R\downarrow}\right)^{1/2},$$

where L and R are the summed counts of an appropriate energy bin in the left and right counters and the arrow indicates the spin direction of the incident beam. The effect of target thickness on A_y was examined by comparing the A_y of a thin target with that of a thick one and it was found to be negligible in the present experiment. The background produced by edge scattering from the detector slits was estimated from the p-p scattering data.[14] Since the ratio of an elastic peak

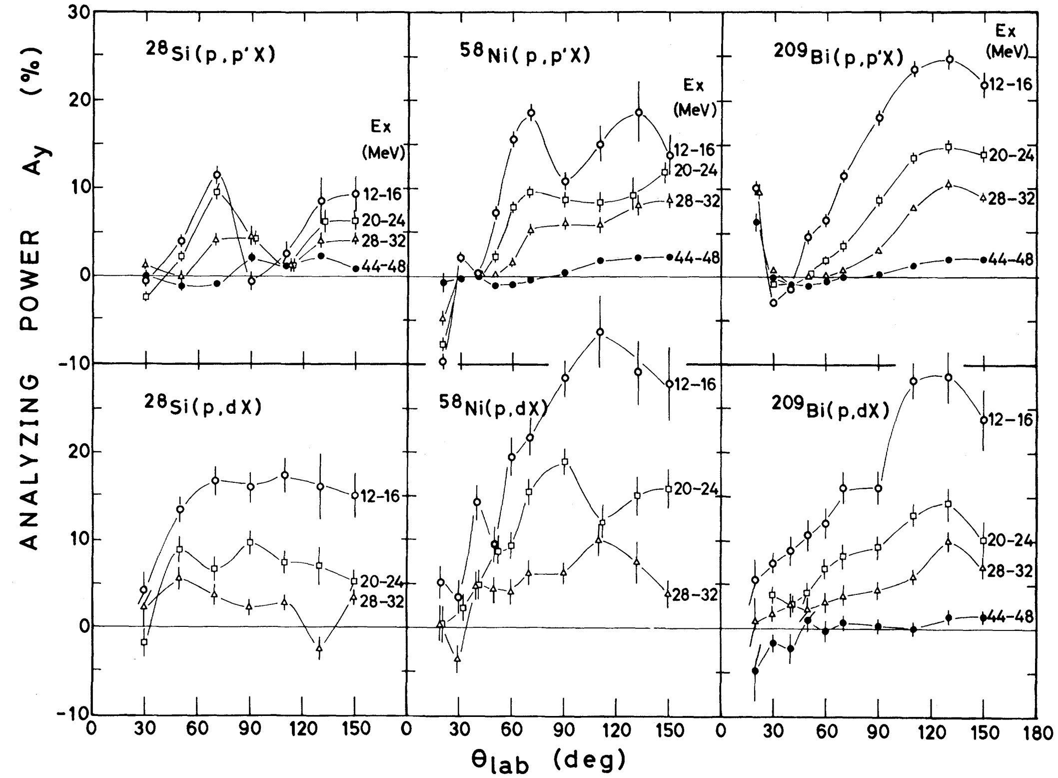

FIG. 2. Angular distributions of A_y from reactions ^{28}Si, ^{58}Ni, ^{209}Bi (p_{pol}, $p'X$) and (p_{pol}, dX). A_y values were obtained by averaging over 4-MeV energy bins as indicated in the figure. Solid lines are drawn to guide the eye. The errors indicated are statistical.

to slit-scattered background was 10^3-10^4 at forward angles, we expect no significant contribution from the slit-edge scattering to the observed A_y values. Other systematic errors considered are in all cases smaller than the statistical error.

Figure 1 shows plots of the differential cross sections $d^2\sigma/d\Omega\,dE$ and A_y for the reactions ^{209}Bi($p_{\mathrm{pol}}, p'X$) and ^{209}Bi(p_{pol}, dX) at laboratory angles of 40°, 70°, and 130°. Prominent features of the present results are the following: (1) At the excitation energies above 10 MeV ($E_{p'} < 55$ MeV and $E_d < 50$ MeV) A_y is nonzero and varies smoothly and slowly with excitation energy. In the region of the excitation energy below 10 MeV A_y oscillates due to the contribution from the strong discrete levels. (2) A_y is small at 40° where the preequilibrium process is important and it is unexpectedly large at 130° where the shape of the continuum spectrum resembles that of a conventional evaporation spectrum. (3) A_y becomes smaller as the energy of the proton or deuteron becomes lower and at the evaporation region A_y approaches zero.

The angular distributions of A_y of the continuum spectra of the reactions ^{28}Si, ^{58}Ni, ^{209}Bi($p_{\mathrm{pol}}, p'X$) and (p_{pol}, dX) are plotted at the excitation energies of 14, 22, 30, and 46 MeV in Fig. 2. There is a trend that A_y increases at backward angles. If the protons emitted in the forward angles are produced through a preequilibrium process in which spin-dependent interactions play no significant role, A_y should show a common pattern for all the target nuclei. However at 20° the A_y of the reaction ^{58}Ni($p, p'X$) is negative and the A_y of the reaction ^{209}Bi($p, p'X$) is positive. This result may indicate that spin-dependent interactions as well as the nuclear structure effects have to be taken into account in the understanding of the continuum energy spectra obtained from the ($p, p'X$) reaction.

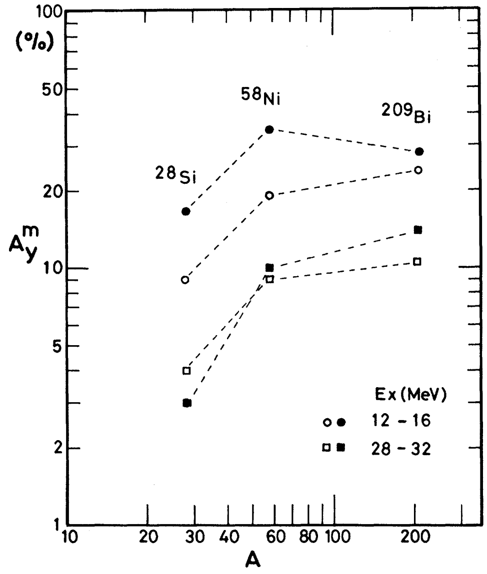

FIG. 3. Maximum value A_y^m of the backward analyzing power ($\theta_L \geq 110°$) as a function of the target mass number A at $E_x = 14$ and 30 MeV. Open and closed symbols are for ($p_{\mathrm{pol}}, p'X$) and (p_{pol}, dX) reactions, respectively.

Target mass dependence of A_y for typical excitation energies are displayed in Fig. 3 where the maximum value A_y^m of A_y at backward angles ($\theta_L \geq 110°$) is plotted against target mass number A. The A_y^m for the ^{58}Ni and ^{209}Bi targets show almost the same values but the A_y^m for ^{28}Si is appreciably smaller. However we could not conclude whether the small A_y^m value in ^{28}Si arises from the mass dependence or nuclear-structure effects in ^{28}Si.

We have also measured the A_y of the α particles from the reaction ^{209}Bi($p_{\mathrm{pol}}, \alpha X$). At backward angles the A_y are positive and larger than those of ($p_{\mathrm{pol}}, p'X$) and (p_{pol}, dX) reactions as was shown in Fig. 4. Note that for the ($p_{\mathrm{pol}}, \alpha X$) reaction the exit α channel has no spin-dependent interaction. In other words these large A_y values are mainly due to the entrance-channel effect.

The most striking feature is seen in the backward data. The slope of the continuum spectrum at 150° resembles that of an evaporation spectrum. Therefore one usually assumes that the

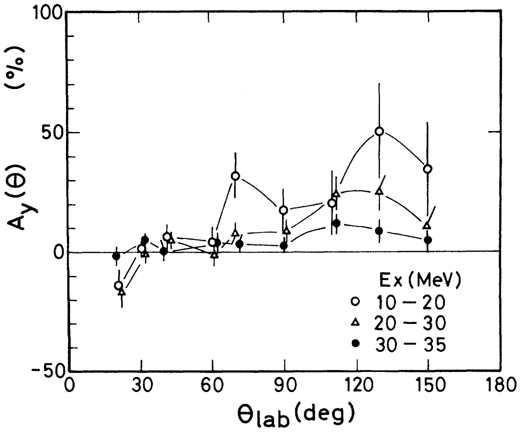

FIG. 4. Angular distribution of A_y from ^{209}Bi (p_{pol}, αX) reaction. Values were obtained by averaging over 10-MeV energy bins as indicated in the figure. Solid lines are drawn to guide the eye. The errors quoted are statistical.

backward-angle spectrum could provide a reasonable estimate for the evaporation yield. However, large analyzing-power values in the high-energy region may suggest that the direct-reaction process is very important and constitutes a large fraction of the continuum spectrum even at backward angle.

From the theoretical point of view, the preequilibrium process for nucleon emission is the simplest and the most fundamental. However, the processes for complex-particle emission are not as clear. Our data show that the gross shapes of the A_y for the (p, dX) reaction are similar to those of the $(p, p'X)$ reaction for all target nuclei even though the A_y of the $(p, p'X)$ reaction shows more structure than that of the (p, dX) reaction (see Fig. 2). This result might add new information to clarify the nuclear-reaction mechanism of complex-particle emission.

The present features of A_y for the continuum spectra suggest the importance of inclusion of the spin-dependent interaction in preequilibrium reaction models. Therefore it is interesting to apply a more sophisticated method such as a multistep direction-reaction theory developed recently by Tamura *et al.*,[15] where continuum energy spectra of (p, p') and (p, α) reactions were reproduced successfully.

Finally it should be remarked that the measurement of the analyzing power of the continuum spectra adds a new element to the study of the preequilibrium process and may lead to obtaining deeper insight into the reaction mechanism.

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