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Analyzing powers for ^{2}H(d,p)^{3}H at incident energies of 30, 50, 70, and 90 keV

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Angular distributions of vector and tensor analyzing powers, iT_{11}, T_{20}, T_{21}, and T_{22}, are measured in the reaction ^{2}H(d,p)^{3}H at laboratory energies of 30, 50, 70, and 90 keV. A smooth energy dependence is observed in all tensor analyzing powers, whereas the vector analyzing powers show almost no energy dependence. The results are fitted with Legendre polynomials.

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The reactions ^{2}H(d,n)^{3}He and ^{2}H(d,p)^{3}H at very low energies are interesting for the nuclear physics of few-nucleon systems. The anisotropy of the unpolarized cross sections [1] and nonzero vector analyzing power [2–4] indicate the contributions of the entrance P and D waves are important even at deuteron bombarding energies below 100 keV. These reactions are also of interest for fusion energy applications, especially for the proposal of a "neutron-lean" ^{2}H-^{3}He fusion reactor with polarized deuterons [5]. Theoretical approaches to this problem gave conflicting evidence [6]. Spin-dependent observables, such as analyzing powers, are important for understanding of these fusion reactions. However, to our knowledge no systematic measurements of the analyzing powers for these reactions have been published except two papers [2,6] and a few reports [3,4,7]. Measurement of analyzing powers at very low energies is difficult. The main difficulties are low count rates due to rapidly decreasing cross sections as a function of energy and knowledge of the degree of polarization of the incident beam, especially its vector polarization, since no deuteron vector polarization analyzer exists at low energies. The present experiments have been made in order to see the energy dependence of analyzing powers with a high degree of accuracy. We report here measurements of all four analyzing powers, iT_{11}, T_{20}, T_{21}, and T_{22}, in the reaction ^{2}H(d,p)^{3}H induced by polarized deuterons at laboratory energies of 30, 50, 70, and 90 keV.

Experiments were performed with a polarized deuteron beam from a Lamb-shift polarized ion source at the University of Tsukuba (UTTAC) [8]. The present experiments have two characteristics that allow accurate measurements. First, the polarized ion source at UTTAC utilizes a spin filter for nuclear polarization, so we measured the beam polarization by a quench-ratio method [9] without using any nuclear reactions. We have tested the accuracy of this method with nuclear reactions and estimate it to be correct within 2% at UTTAC. Second, the emitted protons are detected simultaneously by 17 detectors placed around a scattering chamber at every 20° from +160° to −160°, so the relative values of the analyzing power have a good accuracy. The relative uncertainties of the analyzing powers are typically less than ±0.02 and the normalization uncertainty is estimated to be less than ±4%. The present data improve the accuracy substantially over previous experiments [2–4,6,7].

Measurements were made on the polarized-beam injection line by setting a small scattering chamber just after a quadrupole magnet followed by a Wien filter. This chamber is 220 mm in diameter and 90 mm in depth. Its side wall has 33 slender shaped holes, each 12 mm wide and 26 mm high from +160° to −160° in every 10° steps and covered with a 40-μm-thick Mylar foil. A liquid nitrogen trap is mounted on the top of the scattering chamber to keep a good vacuum inside the chamber (better than 1×10^{-6} Torr), which is important to avoid depolarization of the incident deuterons, especially at low energies. The incident beam was defined by double slits of 2 and 3 mm in diameter separated by 140 mm. The beam intensity was around 50 nA on target and the degree of polarization was typically 85% of the theoretical maximum. The targets were prepared by vacuum evaporation of deuterated parapolyphenyl [$(C_6D_4)_n$] either onto carbon foils with thickness of 20 $\mu g/cm^2$ or onto 5-μm-thick Al foils. When we used targets with carbon foils, we put 5-μm-thick Al foil just behind the target to stop the incident beam. Then we could measure 0° scattering. The deuteron thicknesses were measured from elastic scattering of protons at 12 MeV, which yielded between 0.7 and 1.2 $\mu g/cm^2$. The energy loss of the incident beam was estimated to be less than 10 keV.

We used proportional gas counters as proton detectors, which were arranged at 20° steps outside the scattering chamber from +160° to −160° and were in the ambient atmosphere. To reduce the background counts, we connected two counters in series and require coincidences between them. The forward counter was used for ΔE and the backward one served as a position counter. Each counter solid angle was 23 msr, which corresponded to an angular acceptance of the detector of $\Delta\theta = 3°$ and that in azimuthal angular acceptance of $\Delta\phi = 6.7°$. Each position counter was connected with a resistance in series. We could clearly distinguish signals from each counter by applying a position detecting method with charge division. A typical position spectrum from a position sensitive detector analyzer (ORTEC 464) is shown in Fig. 1. Each peak corresponds to the signals from each counter. Counters numbered 4 and 13 were shadowed by the target frame. We put 100-μm-thick Al foils in front of these shaded detectors in order to block the emitted protons from the counters. We can estimate the background from yields of these counters, which is important especially at the lower incident energies because of the small cross sections. In the present measurement, the background-to-signal ratio was less than 1/100 at $E_d = 30$ keV.

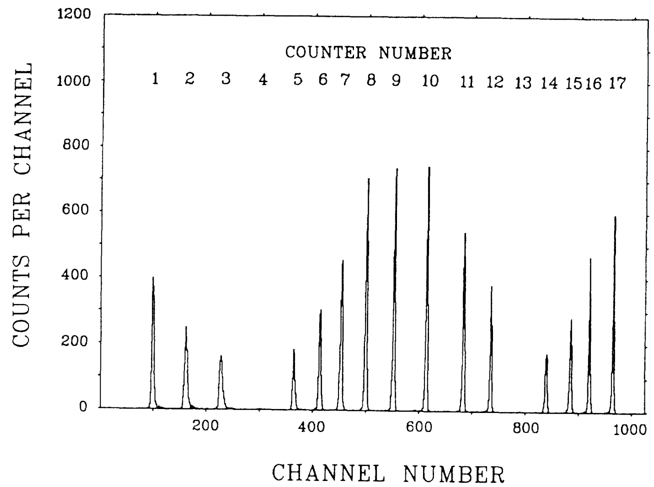

FIG. 1. Spectrum from ORTEC 464 position sensitive detector analyzer for incident deuteron beam of energy 90 keV with $m_I = 0$ magnetic substate. Each peak corresponds to the signals from each counter. The counters numbered 4 and 13 are shadowed by the target frame. The interval between channel numbers is not uniform since the series resistances are adjusted to obtain optimum pulse separation.

The vector and tensor analyzing powers, iT_{11}, T_{20}, T_{21}, and T_{22}, were obtained by measuring each cross section of the incident deuteron beams with the $m_I = +1$, $m_I = 0$, and $m_I = -1$ deuteron magnetic substates from the polarized source for the following three particular orientations of the spin-quantization axis: (1) normal to the scattering plane (Y axis) in case of the measurements of iT_{11} and A_{yy} $(= -\sqrt{3}T_{22} - T_{20}/\sqrt{2})$, (2) along the incident beam direction (Z axis) for the measurement of T_{20}, and (3) in the scattering plane at an angle of $\theta_s = 54.7°$ $(3\cos^2\theta_s - 1 = 0)$ to the Z axis for the measurements of T_{21} and T_{22}. The magnetic substate sequence of

TABLE I. Expansion coefficients of Legendre function expansion from least-squares fits to the analyzing powers for the $^2H(d,p)^3H$ reaction at $E_{lab} = 30$, 50, 70, and 90 keV. The relative errors in parentheses correspond to the last one or two digits of the value.

$A_{kq}(L)$	$E_{lab} = 30$ keV	$E_{lab} = 50$ keV	$E_{lab} = 70$ keV	$E_{lab} = 90$ keV
$A_{11}(1)$	0.1448(29)	0.1506(25)	0.1492(27)	0.1530(20)
$A_{11}(2)$	−0.0214(18)	−0.0225(16)	−0.0295(18)	−0.0305(13)
$A_{20}(0)$	−0.0596(49)	−0.0872(31)	−0.1004(26)	−0.1135(35)
$A_{20}(1)$	0.0145(78)	−0.0393(52)	−0.1013(45)	−0.1210(59)
$A_{20}(2)$	−0.6216(96)	−0.6096(66)	−0.5647(57)	−0.5768(73)
$A_{20}(3)$	0.139(11)	0.0944(78)	0.0305(66)	0.0226(89)
$A_{20}(4)$	−0.023(12)	−0.0293(83)	−0.0270(72)	−0.0446(91)
$A_{21}(1)$	−0.0079(32)	0.0279(34)	0.0475(28)	0.0700(27)
$A_{21}(2)$	0.2289(22)	0.2229(22)	0.2158(19)	0.2090(18)
$A_{21}(3)$	−0.0307(17)	−0.0237(17)	−0.0179(14)	−0.0092(14)
$A_{21}(4)$	0.0007(13)	0.0041(14)	0.0061(12)	0.0062(16)
$A_{22}(2)$	−0.1018(16)	−0.0878(17)	−0.0773(13)	−0.0696(12)
$A_{22}(3)$	0.0082(7)	0.0058(7)	0.0050(6)	0.0036(5)
$A_{22}(4)$	0.0020(5)	0.0004(4)		

the deuteron beam was changed every second.

Angular distributions of the measured analyzing powers are shown in Fig. 2. The tensor analyzing powers T_{20} near 180° were measured by using a Si solid-state annular counter. The errors indicated are statistical uncertainties only. As shown in Fig. 2, a strong difference is observed between vector and tensor analyzing powers. A smooth energy dependence is observed in all tensor analyzing powers. The vector analyzing power is mainly due to interference terms between predominantly S and P waves at low energies. Cross-section measurements show that contributions from P waves depend on energy [1]. The interesting thing is, however, that the vector analyzing powers show almost no energy dependence.

The least-squares fits were calculated according to the expansions

$$iT_{11}(\theta)=\frac{\sigma_{\rm tot}}{4\pi\sigma_0(\theta)}\sum_{L=1}^{L_{\rm max}} A_{11}(L)P_L^1(\cos\theta)$$

for the vector analyzing power, and

$$T_{2q}(\theta)=\frac{\sigma_{\rm tot}}{4\pi\sigma_0(\theta)}\sum_{L=q}^{L_{\rm max}} A_{2q}(L)P_L^q(\cos\theta)\ ,$$

for $q=0,1,2$, where θ is the center-of-mass reaction angle, and $P_L^q(\cos\theta)$ are the Legendre functions normalized according to Ref. [10]. The $\sigma_0(\theta)$ and $\sigma_{\rm tot}$ are the differential and total cross sections for an unpolarized beam, respectively. The physically meaningful number $L_{\rm max}$ of parameters $A_{kq}(L)$ was determined by calculating χ^2 as a function of $L_{\rm max}$. The value of $L_{\rm max}$ was considered to be the correct one when it satisfied the following criteria:

$$\chi^2(L_{\rm max})\approx f,\ \ \chi^2(L_{\rm max}-1)\gg f\ ,$$

$$\chi^2(L_{\rm max}+1)\approx\chi^2(L_{\rm max})\ .$$

Here f denotes the number of degrees of freedom, i.e.,

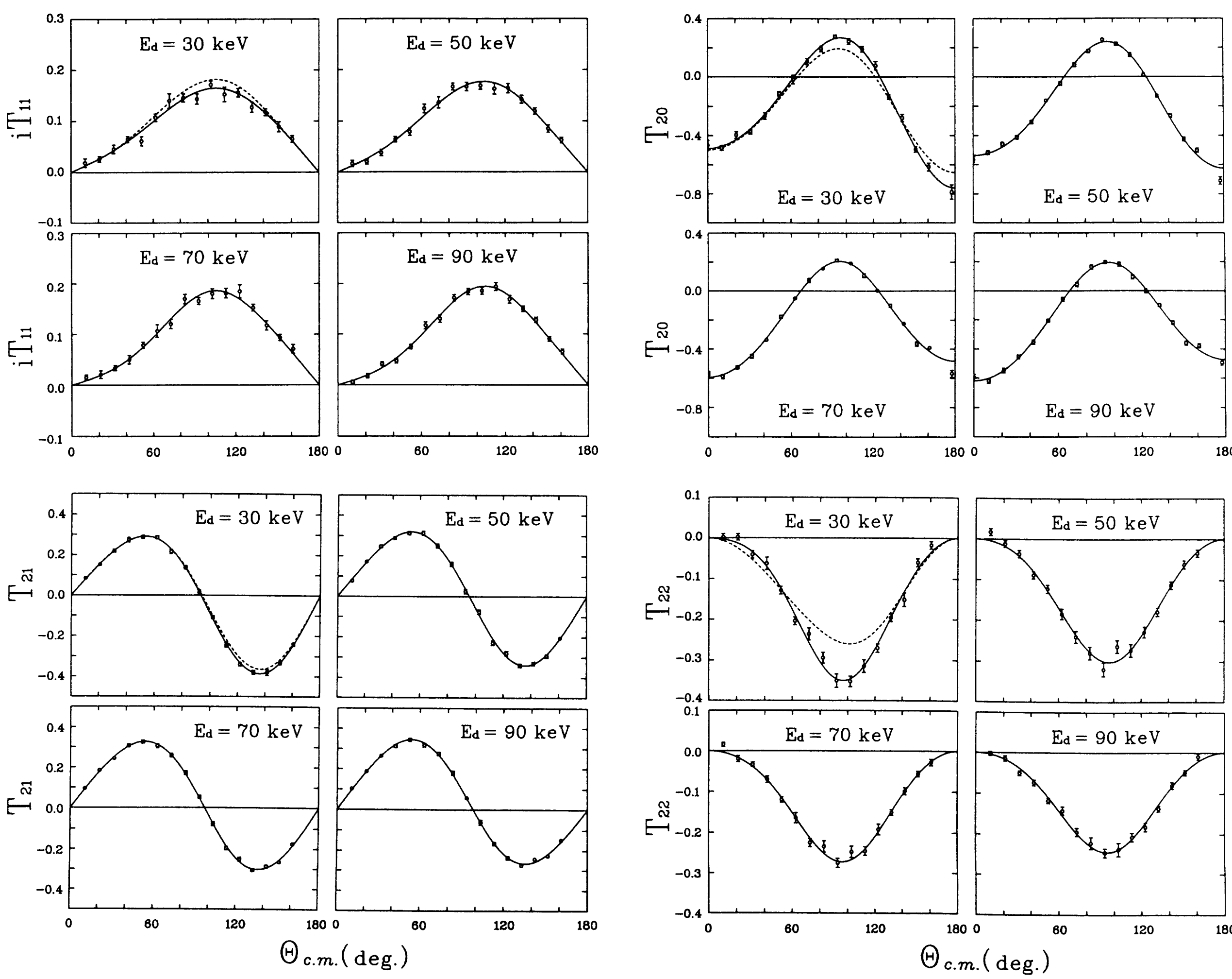

FIG. 2. Angular distributions of analyzing powers for ^{2}H$(d,p)^3$H reaction at 30, 50, 70, and 90 keV. The errors indicated are statistical uncertainties only. The solid curves are Legendre function fits. The dotted curves at 30 keV are the results of the same analysis in Refs. [3,6] .

the difference between the number of data points that have been fitted and the number of parameters used to fit. The values for $\sigma_0(\theta)$ were taken from Ref. [1]. The results of fitting are shown in Fig. 2 as solid curves. The dashed curves at 30 keV are results of the Legendre fits in Refs. [3,6] at 28 keV. As shown in Fig. 2, the present tensor analyzing power T_{21} agrees quite well with that of Ref. [6] but the vector analyzing power differs about 10% in magnitude. Distinct differences are observed in T_{20} and T_{22}, especially around 90° where there are about 25% differences in absolute magnitudes. We confirmed the consistency of the absolute values of T_{22} from two independent measurements that we made. One, as described above, is obtained from measurements of T_{22} together with T_{21} and the other is obtained from measurements of $A_{yy}(=-\sqrt{3}T_{22}-T_{20}/\sqrt{2})$, and T_{20}. The numerical values of the fit parameters are given in Table I.

The present analyzing power data show that the reaction ^{2}H$(d,p)^3$H is an effective deuteron polarization analyzer at very low energies. The reaction ^{3}H$(d,n)^4$He is a well known reaction to calibrate the tensor polarization of the deuteron beam at energies up to about 100 keV. However, at this energy only incoming S waves contribute to the reaction, so its vector analyzing power is essentially zero. The reaction ^{2}H$(d,p)^3$H is effective for vector-polarized beams as well as for tensor-polarized beams, and also we can prepare deuteron targets more easily than tritium targets.

In summary, we measured all four analyzing powers for ^{2}H$(d,p)^3$H reaction at 30, 50, 70, and 90 keV by making use of an efficient detection system and a Lamb-shift polarized ion source with spin filter from which are obtained accurate beam polarizations. These analyzing-power data should give valuable information on the analysis of the ^{2}H$(d,p)^3$H reaction at very low energies. When combined with ^{2}H$(d,n)^3$He data, which we are currently measuring, they should substantially answer the question of whether neutron-lean fusion reactions could, in principle, be designed by using polarized beams of deuterons.

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