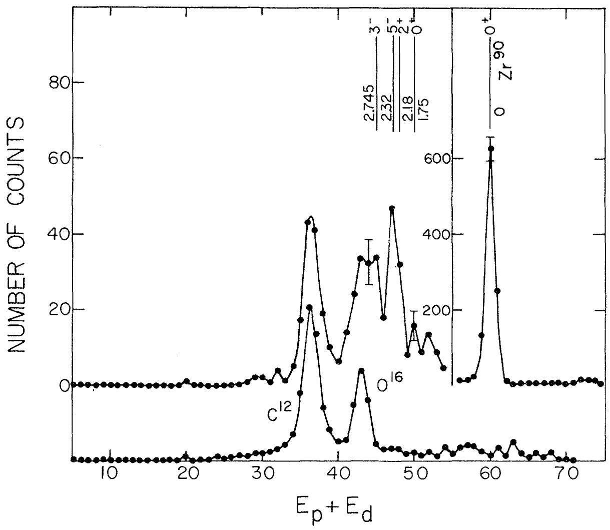

FIG. 3. Population of states of the final (and target) nucleus. The upper curve is for the Zr^{90} target, and the lower curve is for Mylar.

reaction thus appears to be useful for the investigation of proton-unstable regions in light nuclei as well as in medium-A nuclei.

*This work was supported by the U. S. Office of Naval Research under Contract No. 00014-67-A-0305-0005.

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USE OF POLARIZED DEUTERONS TO DETERMINE THE TOTAL ANGULAR MOMENTUM TRANSFER IN STRIPPING REACTIONS*

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For more than a decade the deuteron stripping reaction has played an important role in nuclear spectroscopy. From the shape of the differential cross section of the outgoing nucleon at forward angles, it is possible to determine the orbital angular momentum l of the captured nucleon.[1] However, since the captured nucleon has spin, the total angular momentum transfer, j, is not uniquely determined, i.e., $j = l \pm \frac{1}{2}$. If j as well as l could be determined, the spin of the residual nucleus would be determined in those cases where one is dealing with spin-zero target nuclei.

Our method to determine the spin of the residual nucleus is by measurements of the directional correlation of the reaction products in $(n, \gamma\gamma)$ reactions with thermal neutrons or in $(d, p\gamma)$ reactions. Such measurements are usually difficult.[2] Recently, a method to determine j from stripping reactions has been proposed by Lee and Schiffer et al.,[3,4] who observed that for a given l, the shape of the angular distributions in (d,p) reactions shows a systematic dependence on j. However, even the best analyses of stripping reactions have not been successful in reproducing the observed dependences.[4] In addition, since the effects usually appear in regions away from the stripping peak, they may be obscured by compound-nucleus processes.

Measurements of the polarization of the outgoing nucleon in stripping reactions have been suggested as another possible method.[5] Because of experimental difficulties, only a few measurements have been made[6] and thus any comparison with theory becomes difficult and any formulation of empirical rules questionable.[7] Instead of studying the outgoing nucleon polarization,[8] one may investigate the effects on the stripping cross section when polarized deuterons are used to initiate the reaction.[9,10] As the beam intensity from polarized-ion sources improves, this type of experiment becomes much more attractive than a polarization measurement.

We have measured the vector analyzing power, $P_d(\theta)$, for a number of (d,p) reactions for which j and l had been determined previously.[11]

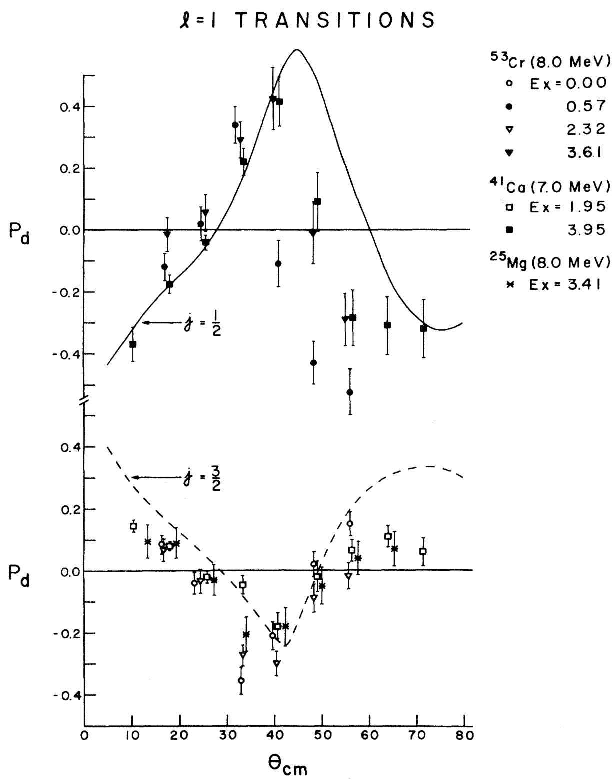

FIG. 1. The vector analyzing power $P_d(\theta)$ for seven (d,p) reactions with $l=1$. Final nucleus, incident deuteron energy, and excitation energy of the residual nucleus are indicated in the key. The solid (open) symbols are for $j=\frac{1}{2}$ $(\frac{3}{2})$ transitions. The solid (dashed) curve is a distorted-wave Born-approximation calculation of $P_d(\theta)$ for the $j=\frac{1}{2}$, 3.95-MeV $(j=\frac{3}{2}$, 1.95-MeV) state in ^{41}Ca for an incident deuteron energy of 7.0 MeV.

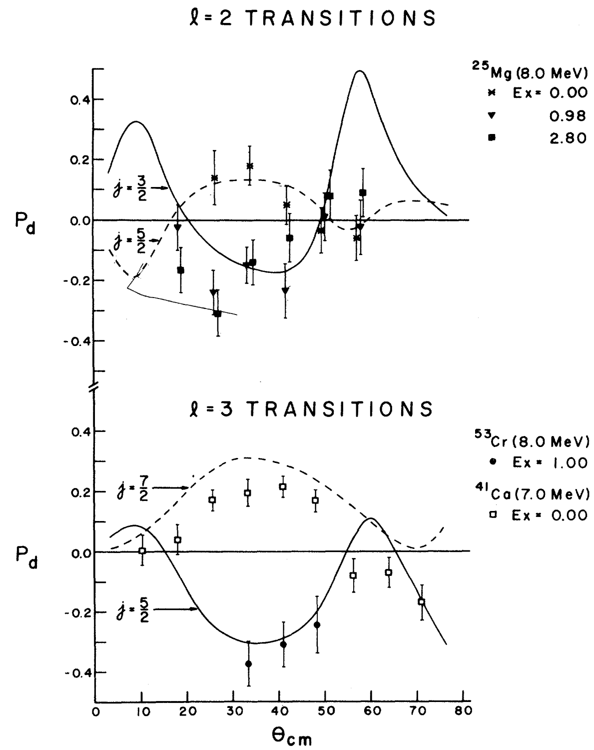

FIG. 2. The vector analyzing power $P_d(\theta)$ for three (d,p) reactions with $l=2$ and two with $l=3$. Final nucleus, incident deuteron energy, and excitation energy of the residual nucleus are indicated in the keys. The solid (open) symbols are for $j=l-\frac{1}{2}$ $(l+\frac{1}{2})$ transitions. The solid curve for the $l=2$ transition is a distorted-wave Born-approximation calculation of $P_d(\theta)$ for the $j=\frac{3}{2}$, 1.28-MeV state in ^{29}Si for an incident deuteron energy of 10.0 MeV. The dashed curve assumes that $j=\frac{5}{2}$. The solid (dashed) curve for the $l=3$ transitions is the calculation of $P_d(\theta)$ for $j=\frac{5}{2}$, 0.39-MeV $(j=\frac{7}{2}$, 0.0-MeV) state in ^{59}Ni (^{41}Ca) for an incident deuteron energy of 10.0 (7.0) MeV.

The vector analyzing power is identical to the vector polarization of deuterons in the inverse reaction initiated with unpolarized protons.[12] For the inverse reaction the vector polarization of the deuterons is simply the expectation value of the spin in the direction normal to the scattering plane and is positive when parallel to $\vec{k}_p \times \vec{k}_d$, where $\vec{k}_p$ and $\vec{k}_d$ are the propagation vectors of the protons and deuterons, respectively. The experiment was carried out with the proton detector at a reaction angle θ and the polarization axis of the deuteron beam perpendicular to the reaction plane. Measurements were made with a spin-up deuteron beam (polarization axis parallel to $\vec{k}_d \times \vec{k}_p$) and with a spin-down beam. The spin-up and spin-down intensity ratio is related to the vector polarization p of the incident beam and to $P_d(\theta)$ by the equation[13]

$$\frac{I_{\text{up}}}{I_{\text{down}}}=\frac{1+\frac{3}{2}pP_d(\theta)+c}{1-\frac{3}{2}pP_d(\theta)+c}. \tag{1}$$

The polarization p of the beam is known from other experiments.[14] The quantity c is a sum of products of tensor polarization parameters of the incoming beam and tensor analyzing powers of the reaction. The sign and magnitude of c do not change when vector polarization is reversed. The tensor polarization of the beam is small enough that c can be neglected.[15]

The vector analyzing power for seven $l=1$ transitions is shown in Fig. 1. The results demonstrate a pronounced difference between $P_d(\theta)$ for $j=\frac{1}{2}$ and $j=\frac{3}{2}$ reactions. Near the stripping peak, which is located at approximately 20°, the slopes of $P_d(\theta)$ for the two values are of opposite sign. The reaction $^{52}\mathrm{Cr}(d,p)^{53}\mathrm{Cr}$ to the 3.61-MeV state in $^{53}\mathrm{Cr}$ had been tentatively identified as a $j=\frac{3}{2}$ reaction by thermal neutron capture γ-ray directional correlations[16] and also by γ-ray–particle coincidence techniques[17] for the reaction $^{52}\mathrm{Cr}(d,p\gamma)^{53}\mathrm{Cr}$. The measurement of $P_d(\theta)$ for this transition strongly suggests that $j=\frac{1}{2}$, and it is placed for comparison with those for two known $j=\frac{1}{2}$ reactions.[18] Figure 2 shows $P_d(\theta)$ for three $l=2$ transitions and two $l=3$ transitions. Here the difference between the two different j values is not as striking but still clearly visible. Near the stripping peaks, which occur at approximately 30° for the $l=2$ transitions and at approximately 40° for the $l=3$ transitions, the sign of P_d is different for different j. The indicated errors are statistical standard deviations combined with uncertainties in the beam polarization and background subtraction, as well as an uncertainty of 3.5% resulting from neglecting c in Eq. (1).

The use of polarized beams as a possible spectroscopic tool clearly is enhanced if the observed dependences can be understood theoretically. From distorted-wave Born-approximation calculations with vector spin-orbit coupling,[19] it is found that at forward angles $P_d(\theta)$ for a particular l and j is rather insensitive to variations in the amount of spin-orbit coupling in the deuteron channel[20] and is a slowly varying function of the excitation energy of the residual nucleus, the target nucleus mass, and the incident deuteron energy. However, the calculated $P_d(\theta)$ depends strongly on the assumed value of j. The curves shown in Figs. 1 and 2 are predictions[21] of $P_d(\theta)$ for representative transitions.

We would like to thank Dr. G. R. Satchler for making the results of the calculations available to us. We thank Dr. J. P. Schiffer for the chromium target and Dr. P. Schwandt for many helpful discussions.

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*Work supported in part by the U. S. Atomic Energy Commission.

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[5]H. C. Newns, Proc. Phys. Soc. (London) A66, 477 (1953). For references see L. J. B. Goldfarb, in International Symposium on Polarization Phenomena of Nucleons. 2nd, Karlsruhe, 1965. Proceedings, edited by P. Huber et al. (Birkhauser Verlag, Stuttgart, Germany, 1966), p. 203.

[6]Most of the measurements have been made for very light target nuclei. Compound-nucleus effects may significantly influence the polarization of the outgoing nucleon even in the stripping peak.

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[8]One may also measure the asymmetries for (p,d) reactions induced by polarized protons. The polarization analyzing power for a (p,d) reaction is identical to the proton polarization in the inverse reaction. See, for example, N. S. Chant, P. S. Fisher, and D. K. Scott, Nucl. Phys. A99, 668 (1967).

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[12]See, for example, G. R. Satchler, Nucl. Phys. 8, 65 (1958).

[13]The equations given by A. Trier and W. Haeberli [Phys. Rev. Letters 18, 915 (1967)] also apply to the present case. See also Ref. 10.

[14]P. Extermann, Nucl. Phys. A95, 615 (1967).

[15]If the tensor analyzing powers of the reaction are 0.1 in magnitude, $|c| \leq 0.035$. Correspondingly, the change in $P_d(\theta)$ is 3.5% of its value.

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[19]G. R. Satchler (private communication).

[20]At backward angles and for very light nuclei, $P_d(\theta)$ depends significantly on the amount of spin-orbit coupling in the deuteron channel.

[21]The calculated $P_d(\theta)$ curves for the reaction $^{40}\mathrm{Ca}(d,p)^{41}\mathrm{Ca}$ are from an extensive analysis that had been made for that reaction. [L. L. Lee, Jr., J. P. Schiffer, B. Zeidman, G. R. Satchler, R. M. Drisko, and R. H. Bassel, Phys. Rev. 136, B971 (1964).] The deuteron

potential used is the average of the fits to the elastic data at 11.0 and 12.0 MeV. The deuteron spin-orbit coupling was neglected. The neutron potential included a spin-orbit coupling. A Gaussian finite-range function was used. Further parameters are given in the above reference. The nickel and silicon calculations are similar to those for calcium. For nickel a Perey deuteron potential, type B [C. M. Perey and F. G. Perey, Phys. Rev. 132, 755 (1963), and a Perey proton potential [F. G. Perey, Phys. Rev. 131, 745 (1963)] were used. For silicon a deuteron potential which gives an average fit to the elastic data in the energy range 8-12 MeV (real part of central potential is 120 MeV) and a Perey proton potential were used.

ELECTRICITY, GRAVITY, AND COSMOLOGY

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(Received 5 September 1967)

Thirty years ago, Dirac[1] expressed the opinion that very large dimensionless universal constants, such as the ratio of electrostatic and gravitational forces between two protons $e^2/\gamma m_p^2 = 1.24\times 10^{36}$, cannot possibly be pure mathematical numbers which will be derived sometime by somebody from some as yet nonexisting theory. He suggested that such very large pure numbers which sometimes occur in science must rather be considered as variable parameters characterizing the present state of the universe. Dirac noticed that the above-given large number, representing the ratio of electrostatic and gravitational forces, is very close to another large pure number which expresses the present age of the universe in terms of the elementary units of time, often called les tempons by French physicists. The tempon is defined as the duration which is necessary for light to cover a distance equal to the "classical" radius of an electron. Thus, one tempon (τ) is equal to $(e^2/mc^2)(1/c) \cong 10^{-23}$ sec. Assuming that the present age of the universe is about 10 eons (one eon is 10^9 y) or 3×10^{17} sec, we find that it is about 3×10^{37} tempons old. This number is fairly close (within a factor of $2\pi^2$) to the previously mentioned large ratio. Thus Dirac proposed to consider γ not as a constant at all but as a variable decreasing in inverse proportion to the age of the universe.

Ten years later, Teller published a short article[2] in which he argued that the decrease of γ with time would contradict the existing paleontological evidence. On the basis of the thermonuclear theory of the sun's energy production, he proved that, if γ decreases in inverse proportion to the age t of the universe, the luminosity of the sun must have been decreasing as t^7 and should have been considerably higher in the past geological eras. Also, if γ used to be larger, the diameter of the earth's orbit must have been smaller in the past, as can easily be proved on the basis of the law of the conservation of angular momentum. Combining these two factors, and taking for the age of the universe the value of about 2 eons (accepted by astronomers at that time), Teller showed that during the Cambrian era (some 500 million years ago) the surface of the earth must have been at the temperature up to and above 100°C and the oceans would have been boiling, making life uncomfortable for trilobites. In the pre-Cambrian era there would have been no oceans at all and all water would have existed only as superheated vapor in the atmosphere.

Since Teller's original article was published, the astronomically estimated age of the universe has been brought up to about 10 eons (9.25 eons to be exact),[3] so that the time period separating us from the Cambrian era became a smaller fraction of the total age of the universe. Correspondingly, the "age of boiling oceans" moved back in time, making the Cambrian and pre-Cambrain eras safe for marine life. On the other hand, still more recently, paleontologists have found the remainder of bacteria and algae in the deposits the age of which is estimated to be 3.1 eons by radioactivity-dating method.[4] And, even though Teller's argument makes life safe for the inhabitants of the Cambrian ocean, it certainly threatens the life of organisms living a few eons ago.

Also, a new approach has been developed to check the possibility of the brighter sun without any reference to the life on the surface of the earth. Pochoda and Schwarzschild[5] have