8 September 1967, Volume 157, Number 3793 SCIENCE

Polarized Protons as Nuclear Probes

Spin-dependence of nuclear reactions offers new approach to study of nuclei and nucleon-nucleus processes.

Louis Rosen

Some of the most intriguing questions in basic physics have to do with the atomic nucleus—its structure, its properties, and the forces which bind its constituents.

Although nuclear forces are very strong—about 10^{40} times as strong as gravitational forces—and although, like gravitational forces, they are not shielded by any means at present known to us, they are nonetheless well concealed and inaccessible to study by any of the classical probes which have been available to us. They are inaccessible because they have an extremely short range ($\sim 10^{-13}$ centimeter) and therefore are almost completely contained within the nucleus. The nucleus, on the other hand, is difficult to dismantle in an orderly fashion, because it is tightly bound and very small—more than 10,000 times smaller than the atom in which it resides.

In order to study the nucleus, and the forces which govern its properties and structure, one must rely in good part on probes which interact strongly with nuclei, whose de Broglie wavelength is comparable to the size of the nucleus, and whose energy, if the probe carries a charge, is sufficient to overcome the Coulomb barrier of the nucleus. This barrier is somewhat less than 10 million electron volts (Mev) for medium-weight nuclei and singly charged incident particles.

One of the most useful sources of information about nuclei has been experiments in which one bombards a target of the nucleus under investigation with monoenergetic nucleons and measures the energy and angular distribution of the reaction products. Until relatively recently, almost all nucleon beams used in such experiments were unpolarized—that is, they contained a random distribution of spin states. This often limits the amount of information derivable from a given experiment, since, as we now know, nuclear reactions are spin-dependent.

In this article I describe one of the programs at Los Alamos, in which I participated over a period of 10 years. It was based on the use of polarized beams of protons to probe the atomic nucleus, in a search for a better understanding of its properties and its interactions with nucleons. Initially the objective was merely to determine whether the spin-orbit interaction postulated by the shell model would manifest itself in the scattering of medium-energy protons by complex nuclei. Later the objective shifted to the use of polarized beams for studying the nucleon-nucleus scattering process. It was postulated that polarized beams would impose additional constraints on the scattering process and thereby help to elucidate some of its features. An equivalent viewpoint is the belief that, since polarization is, by its nature, an interference phenomenon, it ought to be very sensitive to at least some aspects of the nucleon-nucleus interaction process, and this in fact turned out to be the case.

The experiments discussed here were performed with polarized protons of 10- and 14-Mev energy. This seemed an appropriate energy range since it exceeds the Coulomb barrier for many nuclei and yet is not much larger than the binding energy of nucleons in nuclei. The experiments described constituted the first systematic investigation of the scattering of medium-energy polarized protons by complex nuclei (1, 2).

Experiments with Polarized Protons

This discussion is confined to the scattering of nucleons and therefore to particles of spin ½. When I speak of polarization I mean the spin expectation value for a beam of particles; this is defined as follows. An unpolarized beam is assumed to comprise an equal mixture of two completely, but oppositely, polarized beams. A partially polarized beam can be described as being composed of a mixture containing a fraction $|P|$ of a completely polarized beam and a fraction $1 - |P|$ of an unpolarized beam. It follows that the degree of polarization is uniquely defined by the quotient of the difference and sum of the number of particles with spins directed up and down; that is,

$$P = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}.$$

If polarization arises in the scattering of a nucleon by a nucleus, it does so because protons of upward (or downward) spin are preferentially scattered to the right (or left), and vice versa. If, in a beam of nucleons, those of a given spin orientation are preferentially scattered to the right (or left), it then follows that one can, at least in principle, measure the polarizing power of the scatterer by permitting the beam to undergo two co-planar scatterings at identical energies and scattering angles. For infinitely thin targets composed of infinitely massive nuclei, both scatterings can occur at the same energy and

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angle, and the final asymmetry (A) in the intensity, following the second scattering, is given by

$$A = \frac{I_R - I_L}{I_R + I_L} = |P|^2 ,$$

where I_R and I_L represent the scattering intensities to the right and left, respectively. The polarizing power or analyzing power of each target is represented by P.

Figure 1 is a diagram of an idealized co-planar double-scattering experiment in which each scatterer has a polarizing (or analyzing) power of ⅓—that is, the probability of scattering downward-spinning particles to the right is twice that of scattering upward-spinning particles to the right, and vice versa for scattering to the left (*3*).

When the experiments under discussion were initiated, the only feasible way to prepare a polarized proton beam was to scatter an unpolarized beam from a suitable target (*4*). The first problem, therefore, had to do with the choice of target. It had been suggested by Schwinger (*5*) that low-energy nucleons scattered by He^4 might be polarized because Li^5 (and He^5) was believed to have a low-lying state which would be split by coupling of the nucleon spin to its orbital angular momentum. Following detailed calculations by Critchfield and Dodder (*6*) of the phase shifts which describe polarization by He^4 scattering, Heusinkveld and Freier (*7*) showed experimentally that low-energy protons are indeed polarized when scattered by He^4. It was subsequently predicted by Gammel and Thaler, on the basis of phase-shift analyses, that 10-Mev protons elastically scattered through large angles by He^4 nuclei would be very strongly polarized. In 1957 we set about the task of preparing a high-intensity, highly polarized beam of protons by scattering from He^4 nuclei. The problem appeared formidable because, when protons are scattered through a large angle by He^4, a good part of the initial kinetic energy is lost to the He^4 recoil, making it difficult to use the scattered protons in a second scattering process. Secondly, how is one to know the degree of polarization imparted to the proton beam? Figure 1 shows how the absolute polarization can be determined in a double-scattering experiment provided both scatterings occur at the same energy and angle. This can hardly be accomplished in the usual way because (i) the He^4 mass is not infinite as compared to the proton mass and (ii) use of an infinitely thin target would lead to zero counting rates. The problem was circumvented by the following device. Instead of bombarding He^4 with protons, we bombarded a hydrogen target with α-particles. Because an α-particle energy E_α, when hydrogen is bombarded with α-particles, is equivalent in the center-of-mass system to a proton energy of ¼ E_α when He^4 is bombarded with protons, it is possible to use rather energetic α-particles and still achieve an interaction at low center-of-mass energy. Furthermore, the forward-directed protons correspond to large-angle scattering in the center-of-mass system, where the polarization effects had been calculated to be large. Now, by interposing an absorber between first and second scatterings, it is possible to match precisely the condition of scattering for the two interactions and thus achieve an absolute measurement of the polarization in one double-scattering experiment (*8*). The very first such experiment (*9*) yielded the gratifying result that, at a scattering angle of 130 degrees in the center-of-mass system, a beam of completely polarized 10-Mev protons could be produced by α-particle scattering from hydrogen. Eventually we achieved by this means an intensity of 10^7 protons/$cm^2 \cdot sec$, which is rather respectable even by today's polarized-ion-source standards.

Having achieved a high-intensity, highly polarized beam of protons and a means of determining the polarization, we set about scattering it from a large number of nuclides. The experimental data consisted of simple measurements of the right-left asymmetry as a function of angle. With knowledge of the degree of polarization of the beam, one could determine, for each target nucleus, the angular dependence of the polarization which would have resulted from the scattering of an unpolarized beam. In fact, for an initial polarization of 100 percent, the observed asymmetry is precisely equal to the polarizing power of the target, if one assumes time-reversal invariance.

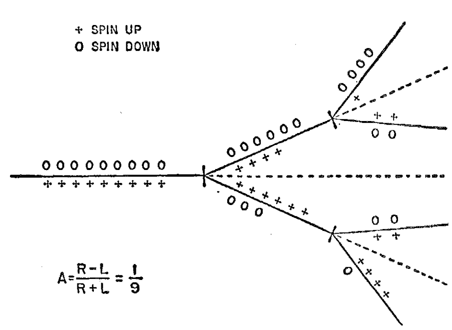

Fig. 1. Distribution of spin states in an idealized double-scattering experiment in which each target has a polarizing power of ⅓.

Figure 2 shows typical results for 14.5-Mev protons and a number of nuclei. The ordinate gives the polarization and the abscissa gives the scattering angle.

Qualitative Observations

One of the objectives of our earliest experiments was to determine whether there is a strong spin-orbit interaction at energies in the vicinity of the energy at which nucleons are bound to nuclei. Such an interaction is postulated by the shell model (*10*). According to this model, the nucleons in a nucleus move almost independently of one another in a central force field generated by all the nucleons. However, in addition to this central force field, the shell model invokes a strong spin-orbit force which accounts for the ordering of levels: nucleons whose spin and orbital angular momentum are in the same direction are more strongly bound than nucleons whose spins have direction opposite to that of their angular momentum. Such an interaction between spin and orbital momentum would manifest itself, for the scattering of free nucleons, by spin polarization of the scattered beam. From Fig. 2 it may be seen that this is precisely what happens for all complex nuclei, so long as the incident energy is well above the Coulomb barrier.

It may also be seen that the polarization patterns are quite uniform, the polarization varying smoothly with scattering angle and nuclear size. This indicates that a diffraction mechanism is operative.

As mentioned above, the asymmetry-polarization equality in a double-scattering experiment is based on the assumption of time-reversal invariance. For targets of zero spin, parity conservation alone assures the asymmetry-polarization equality. Since very large polarizations were achieved from many nuclei, we set out to test the validity of assumptions of time-reversal invariance and parity conservation in strong interactions. It had already been established that parity conservation breaks down in weak interactions. With He^4 as an analyzer, polarizations were measured for elastic scattering of protons by a number of nuclei of high spin. We then prepared a polarized beam as described above and measured asymmetries at identical energies and angles. We were able to show that, to rather high precision (~1 percent), there was no breakdown of time-reversal invariance.

Conservation of parity requires that the polarization produced by elastic scattering occur perpendicular to the plane of scattering and not in the plane of scattering. The requirement prompted an experiment, suggested by Lee and Yang (*11*), to test the assumption of parity conservation in strong interactions by searching for polarization in the plane of scattering. Again the results were negative.

Still another question which presented itself had to do with the strength of spin-spin interactions. This problem was attacked from two directions. In one experiment we scattered completely polarized protons from neighboring nuclei whose spins differed by $3/2\ \hbar$ and $5/2\ \hbar$. No significant difference was observed in the polarization patterns, and from this it was concluded that the spin-spin interaction was not strong as compared to the spin-orbit interaction. In a second investigation we performed a triple-scattering experiment. The first scattering produced a polarized beam. This beam was then doubly scattered from Be^9. The third scattering determined the change in polarization resulting from the second scattering. Any change in polarization must be due to spin-flip, which, in turn, could only be due (if parity is conserved) to spin-spin interactions. This experiment showed that for 14-Mev protons scattered from Be^9, spin-flip interactions represent less than 8 percent of the total.

Notwithstanding the large efforts which have been made during the past 30 years to understand the atomic nucleus, we are still very far from a satisfactory solution to the overall problem. Ideally one hopes for an understanding of nuclear phenomena in terms of field theories in which meson fields replace the internucleonic forces. Although we now have identified an abundance of mesons of varying masses, charges, and coupling constants, it has not been possible to formulate a theory, in terms of these parameters, which is applicable to real nuclei.

A less ambitious approach is to describe nuclei and nuclear reactions in terms of forces among nucleons and perhaps in terms of such fundamental quantities as the nucleon's mass, charge, and magnetic moment. Here too, the mathematical difficulties thus far have been insurmountable, even with the assumptions that only two-body forces are involved and that we know how to describe them.

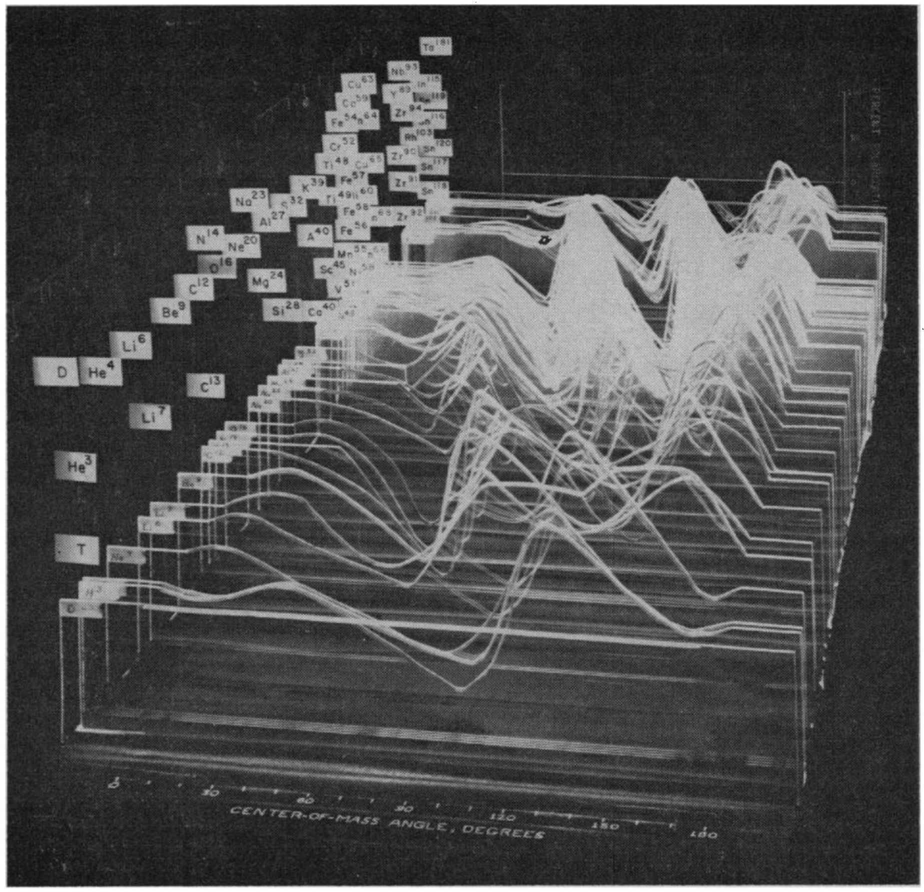

Fig. 2. Three-dimensional representation of the systematics in the angular dependence of the polarization produced by elastic scattering of 14.5-Mev unpolarized protons from various nuclei.

In view of our lack of success in attempts to describe nuclear phenomena on the basis of first principles, it is not unreasonable to explore the possibilities of achieving a phenomenological description, and a number of useful models have been developed. For example, the shell model describes the structure of the nucleus on the basis of the assumption that, inside a nucleus, each nucleon moves in an average field of force generated by all the other nucleons and that each nucleon interacts hardly at all with other individual nucleons. At the opposite extreme is the compound nucleus model, based on the assumptions that (i) in the interaction of a nucleon with a nucleus all the nucleons are strongly involved, (ii) energy is shared in a statistical fashion, and (iii) the decay of the compound nucleus is analogous to an evaporation process and hence quite independent of its mode of formation. A model which represents an attempt to reconcile the strong- and weak-interaction models is the so-called optical model, in which the nucleus is replaced by a complex potential which permits reactions to proceed in a variety of ways. It is this model that I use here to show that it is possible to correlate many nuclear properties and to describe a great many nuclear data with a simple model having a small number of parameters which are mainly invariant with respect to nuclear species and energy of interaction.

From the polarization data on approximately 50 nuclides at energies of 14.5 Mev and 30 nuclides at energies of 10.5 Mev, it was obvious that very large polarization is a general characteristic of the scattering of medium-energy protons by all nuclides for which the Coulomb barrier is less than the incident proton energy (*12*).

It was also observed that the angular dependence of the polarization varies smoothly with nuclear size. In particular, there is a simple dependence of polarization on momentum transfer; that is, for a given maximum or minimum of the polarization, the product of momentum transfer and nuclear radius is approximately constant for all nuclei studied. This brings to mind the intensity distribution predicted by the simple theory of the diffraction of a plane wave by a completely absorbing sphere. If R is the radius of the sphere and θ is the scattering angle, the differential elastic-scattering cross section is proportional to

$$\left[\frac{J_1(2k_1R \sin[\theta/2])}{2k_1R \sin(\theta/2)}\right],$$

where J_1 is a first-order Bessel function and k_1 is the momentum transferred to the target nucleus. We see that, for a maximum or minimum in the diffraction pattern, the argument of J_1 must be constant. In view of the regularities in the polarization and the constancy of $k_1 R \sin(\theta/2)$ versus A for corresponding maxima and minima, we were encouraged to pursue an analysis of the polarization data, in terms of a diffraction model, which must rely on the relative importance of the cooperative behavior of the entire nucleus as opposed to effects of detailed structure.

We decided to attempt a description of the polarization data in terms of the so-called optical model of Feschbach, Porter, and Weisskopf (*13*). In this model the many-body problem of the interaction of a nucleon with all the nucleons in a nucleus is reduced to a two-body problem by invoking a potential between the incoming nucleon and the target nucleus. According to the optical, or "cloudy crystal ball," model, the interaction of a nucleon with a complex nucleus is analogous to the interaction of light with a semitransparent optical medium. Just as in the latter case one represents the effect of all the electrons by a complex index of refraction, so, in the case of a nucleus, one represents the average effect of all the nucleons by a complex potential. Even the earliest form of this potential, in which both the real and imaginary parts were taken as square wells and from which spin-orbit interactions were omitted, was highly successful in describing the dependence on energy and nuclear size of total neutron cross-section data obtained by Barschall's group at the University of Wisconsin (*3*). Refinements in the optical model, whereby the potential wells are given rounded corners and sloping sides and a spin-orbit term is added, made it possible to describe elastic-scattering data as well as total cross sections. The main difficulties with the model have been (and to some extent these difficulties persist) that the parameters seemed not to be unique, and that a different set was usually required to fit different kinds of data and sometimes to fit different energies as well. It was this deficiency that we hoped to overcome by better defining the model parameters through polarization experiments.

The method used to fit the polarization data was utilization of an automatic search routine to discover the parameters which best describe the data. The calculations involve the numerical integration of the Schrödinger equation for each partial wave in order to construct the scattering amplitude. This can be written as

$$f(\theta) = C(\theta) + D(\theta)\,\bar{\sigma} \cdot \bar{\ell},$$

where $f(\theta)$ is the total scattering amplitude for scattering through angle θ, $\bar{\sigma}(2\bar{s}/\hbar)$ is the Pauli matrix for the nucleon, $\bar{\ell}$ is the orbital angular momentum in units of $\hbar$, and $A(\theta)$ and $B(\theta)$ take account of the Coulomb term and the complex phase shift. The calculations involve sums over Legendre polynomials from $\ell = 0$ to $\ell = \infty$ for $A(\theta)$ and from $\ell = 1$ to $\ell = \infty$ for $B(\theta)$. It should be recognized that the differential cross sections are given by $\sigma(\theta) = |A|^2 + |B|^2$, while the right-left asymmetry for a double-scattering process, in which P_1 and P_2 represent the polarizing power of the two scatterers, is proportional to

$$\frac{\mathrm{Re}\, A\, B^*}{|A|^2 + |B|^2},$$

where Re AB^* represents the real part of the complex term AB^*. Since $|B|^2$ is usually $<< |A|^2$, cross-section data determine $|A|^2$ very well but $|B|^2$ hardly at all. On the other hand, polarization depends linearly on A and B and should determine them with comparable precision.

The specific form of the potential invoked to describe nuclear data is still a matter of faith and tradition, moderated by educated guesses. However, the success of the general optical-model potential is undisputed. The form of the potential which the polarization data led us to is as follows:

$$V(r) = -Vf(r) - iUg(r) - V_s h(r)\bar{\sigma} \cdot \bar{\ell} + V_c(r),$$

where $V(r)$ is the radial dependence of the complete potential seen by the incoming particle; V is the depth of the real part of the central potential; U is the depth of the imaginary part of the central potential; $f(r)$ is the radial dependence of the real part of the central potential; $g(r)$ is the radial dependence of the imaginary part of the central potential; V_s is the strength of the spin-orbit potential; $h(r)$ is the radial dependence of the spin-orbit potential; and V_c is the Coulomb particle. The real central potential is assumed to have a radial dependence of the type proposed by Woods and Saxon (*14*):

$$f(r) = [1 + \exp\left(\frac{r-R}{a}\right)]^{-1}.$$

It is characterized by a radius $R = R_o M^{1/3}$, where M is the mass number, and a diffuseness a. It is this potential which corresponds to the shell-model potential and which accounts for diffraction scattering. The imaginary potential accounts for nonelastic processes and encompasses compound-nucleus formation.

Because at low energies the exclusion principle will suppress interaction of the incoming nucleon with nucleons inside the nucleus, we use for $g(r)$ a term proportional to the derivative of $f(r)$ but with a different diffuseness, which is usually designated b. The derivative term concentrates absorption on the nuclear surface.

For the radial dependence of the spin-orbit potential, $h(r)$, we assume a Thomas term, as in atomic physics. This means that the polarization depends on the gradient of the central potential and therefore should be rather sensitive to the details of the nuclear surface. This, too, is borne out by experiment. The Coulomb term, V_c, is calculated on the basis of an assumed uniformly charged sphere of radius R.

It proved possible, with only six parameters (V, U, V_s, r_o, a, and b) to describe all the polarization data at energies of 10.5 and 14.5 Mev. Furthermore, the parameters do not vary with nuclear species; only one of them, $V(r)$, varies with energy, and even this variation is quite mild (0.33 Mev/1 Mev). Figure 3 shows how well the potential with average parameters describes polarization data for energy of 14.5 Mev. The main difference between our parameters and the best parameters previously determined on the basis of elastic-scattering data (*15*) is that the depth of our spin-orbit potential and the depth of the imaginary potential are much smaller, whereas the imaginary diffuseness is considerably larger.

The model being used must, by its very nature, predict a smooth variation with energy and nuclear mass of observables. It must therefore average over energy and over the details of nuclear structure. The latter will manifest themselves as fluctuations of the polarization from the average, and they appear in a rather dramatic way. We had access to about 20 separated isotopes in one region of the periodic table, from Ti^{48} to Zn^{68}, in sufficient quantities to serve as targets (*16*).

When we made detailed studies on these isotopes and extended our measurements to large scattering angles, we discovered that at large angles the measured polarizations fluctuated strongly for neighboring isobars, isotopes, and isotones. Furthermore, the addition of a proton produced an effect on the polarization pattern opposite to that produced by the addition of a neutron. This behavior may be seen in Fig. 4. The solid lines are drawn to aid the eye. The predictions of our model follow the trends, on the average, as may be seen from Fig. 3, but not the detailed fluctuations. Data of the kind displayed in Fig. 4 may provide a means for studying the detailed structure of the nuclear surface as it is altered by the addition of a single nucleon. One needs to compare the experimental data with the predictions of the optical model and then correlate the deviations with physical aspects of the nucleus.

Comparison of the data with predictions of the model revealed still another fascinating phenomenon. At five mass regions in the periodic-table interval from lithium to tin, large anomalies occur in the angular dependence of the polarization at large scattering angles. A simple calculation shows that these anomalies occur for nuclei whose circumference is just of a size to accommodate an integral number of wavelengths of the incoming proton. So here we have an effect which appears to be associated with a standing wave on the nuclear surface. Furthermore, the region of nuclear size over which this effect sets in and then disappears may be related to the diffuseness of the nuclear surface. If it is, the data would indicate that the nuclear density falls off to a small fraction of its maximum value over a distance of about 10^{-13} centimeter, in qualitative agreement with the value of the parameter a in our potential.

As mentioned above, we have assumed that the spin-orbit potential is proportional to the gradient of the central potential. If this be so, it is not surprising that polarization measure-

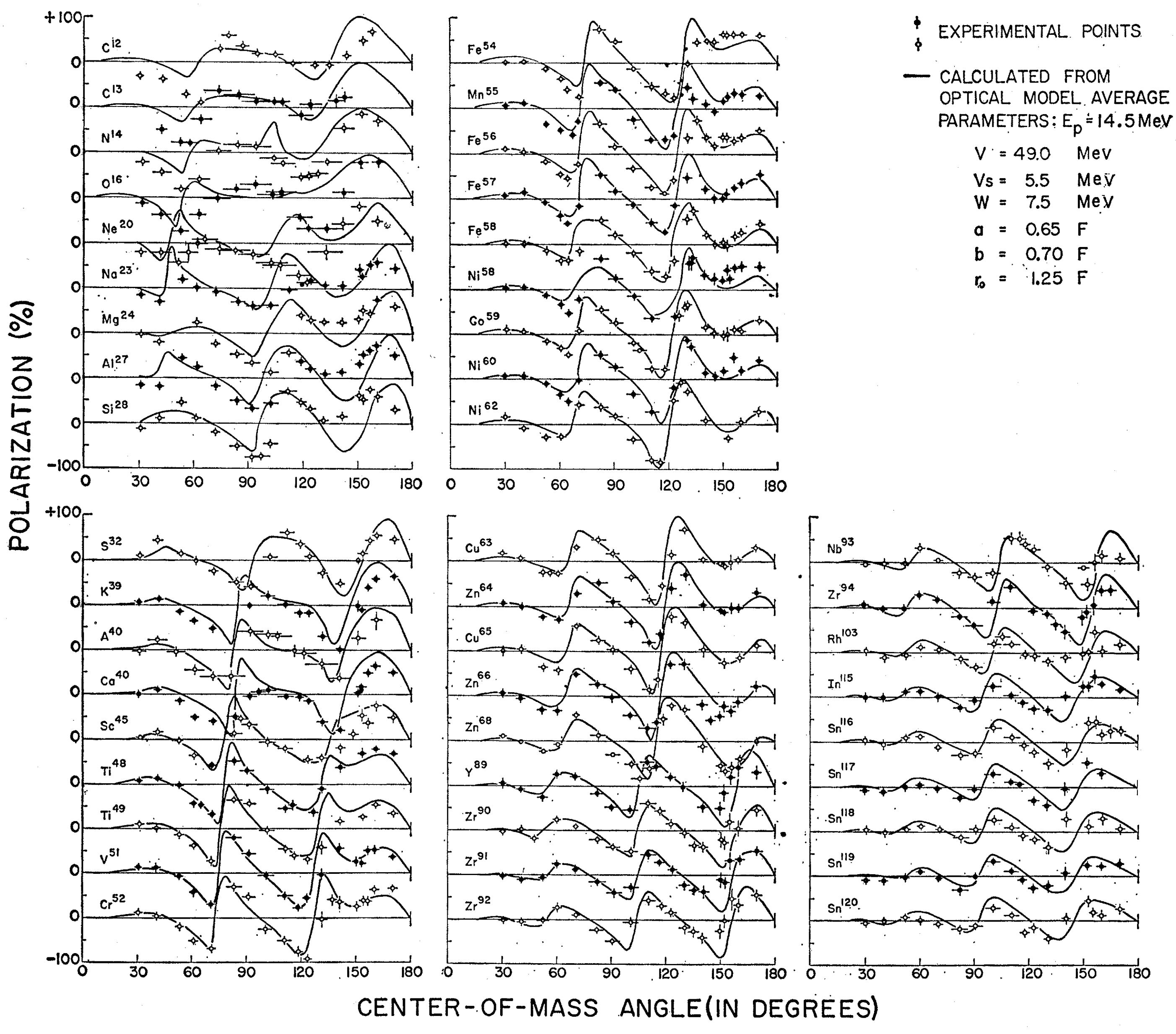

Fig. 3. Comparison of angular dependence of the polarization produced by elastic scattering with optical-model predictions.

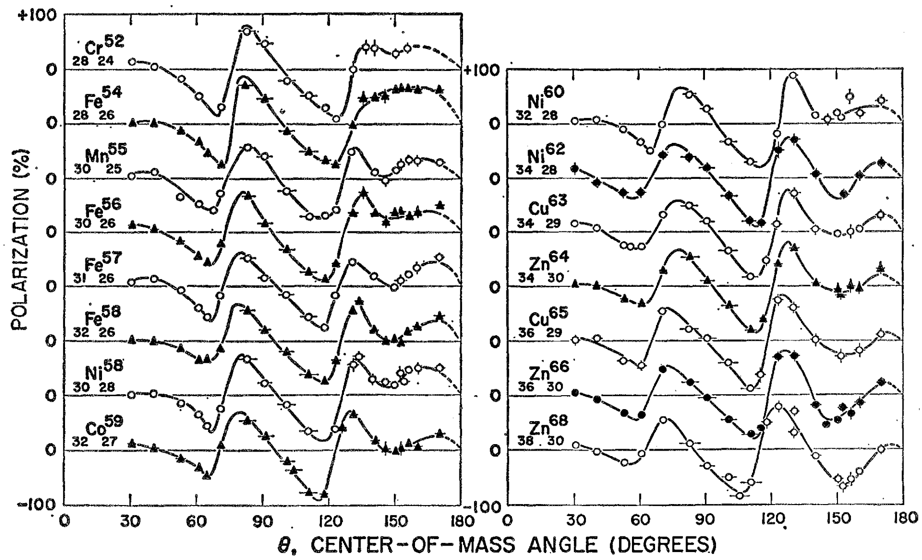

Fig. 4. Fluctuations in the angular dependence of the polarization at large scattering angles for neighboring nuclei.

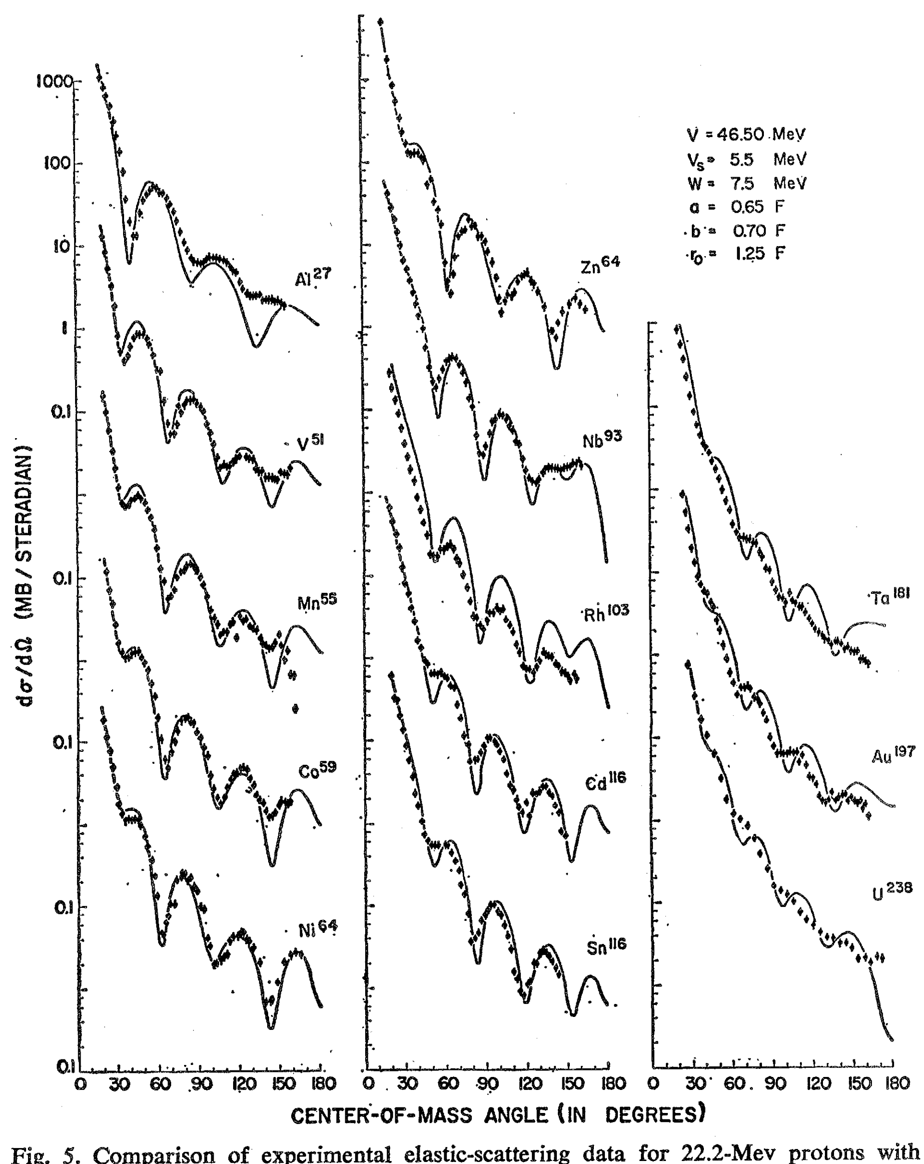

Fig. 5. Comparison of experimental elastic-scattering data for 22.2-Mev protons with optical-model predictions. Data points, from C. B. Fulmer, *Phys. Rev.* **125**, 631 (1962); solid curves, values calculated from optical-model parameters.

ments should constitute a sensitive means for probing the nuclear surface.

Returning now to the deduced potential, we must ask whether that potential is capable of reproducing other data at other energies. Figure 5 shows a comparison of the prediction for this potential with the results of a series of experiments on elastic-scattering angular distributions at energy of 22 Mev. The agreement is quite impressive. In fact, we have found that the potential deduced as described reproduces with acceptable fidelity elastic scattering, polarization, and total cross-section data for protons of energy up to ~ 40 Mev, where the constraints on the deduced potential which are provided by the exclusion principle start to break down.

In view of the success in the case of protons, it was natural to ask whether an analogous potential could be developed for neutrons. This would be important practically, as well as satisfying intellectually. We first assumed that all of the geometrical parameters determined for protons would hold for neutrons and that the spin-orbit term would likewise be the same. We knew, from very basic arguments, that V and W must differ for neutrons and protons. We proceeded to determine V and W for neutrons by requiring that our potential reproduce a large amount of 14-Mev neutron scattering data. Having established V and W, we sought to determine the range in energy and nuclear mass for which the neutron potential would correctly predict elastic and reaction and total cross sections without altering any parameters except the real central potential, which we assumed varied with energy, as in the case of protons. To summarize our results, I can say that it is indeed possible to predict with confidence neutron cross sections for "average" nuclei over the entire periodic table and for energies ranging from a few hundred kilovolts to at least 20 Mev (*17*). Figure 6 gives a typical comparison of measured and predicted differential elastic-scattering cross sections. Within recent months we have used the above potential to calculate all the differential elastic-scattering cross sections at energies above 200 kev (*18*) which are listed by the AEC Nuclear Cross Section Advisory Group as a requirement for AEC-sponsored developments in nuclear energy.

I have indicated a few of the ways in which polarized protons have been used to explore nuclear reactions and nuclear structure. There are others (*1*).

In pickup reactions such as (*p*,*d*), (*p*,*t*), (*p*,He^3), or (*p*,α), measurements of the right-left asymmetry provide information on the total angular momentum transferred. Such data also elucidate the role of the spin-orbit force in pickup reactions, and this must be known for a distorted-wave Born approximation analysis; otherwise one cannot describe the distorted waves.

Again, if one uses polarized nucleons with polarized targets, one can directly study spin-spin interactions. For this, targets of high polarization are required, and a few are already available.

Inelastic scattering of polarized nucleons also provides data on reaction mechanisms. For example, measurements of angular correlation between the γ-rays and scattered nucleons reveal whether or not a spin-flip has occurred and which magnetic substates in the target nucleus have been populated. Simple measurements of angular distribution from inelastic scattering indicate whether or not a true compound nucleus was involved in the reaction.

Finally, I merely point out that experiments involving elastic and inelastic scattering of polarized nucleons can be used to identify parameters of levels in the compound nuclei; charge-exchange reactions can yield similar information.

In conclusion, it is worth noting that the experiments described provide still another example of a basic research project, started for the sole purpose of learning a little more about the laws of nature, which has led to an improved description of processes which have the most direct kind of practical application.

Summary

Experiments based on the use of polarized protons led to (i) delineation of the spin-orbit part of the optical-model potential and (ii) an improved unified description of the nucleon-nucleus interaction within the framework of the optical model. Data obtained by means of a six-parameter potential are correlated for essentially all complex nuclei and over an energy region ranging from several hundred

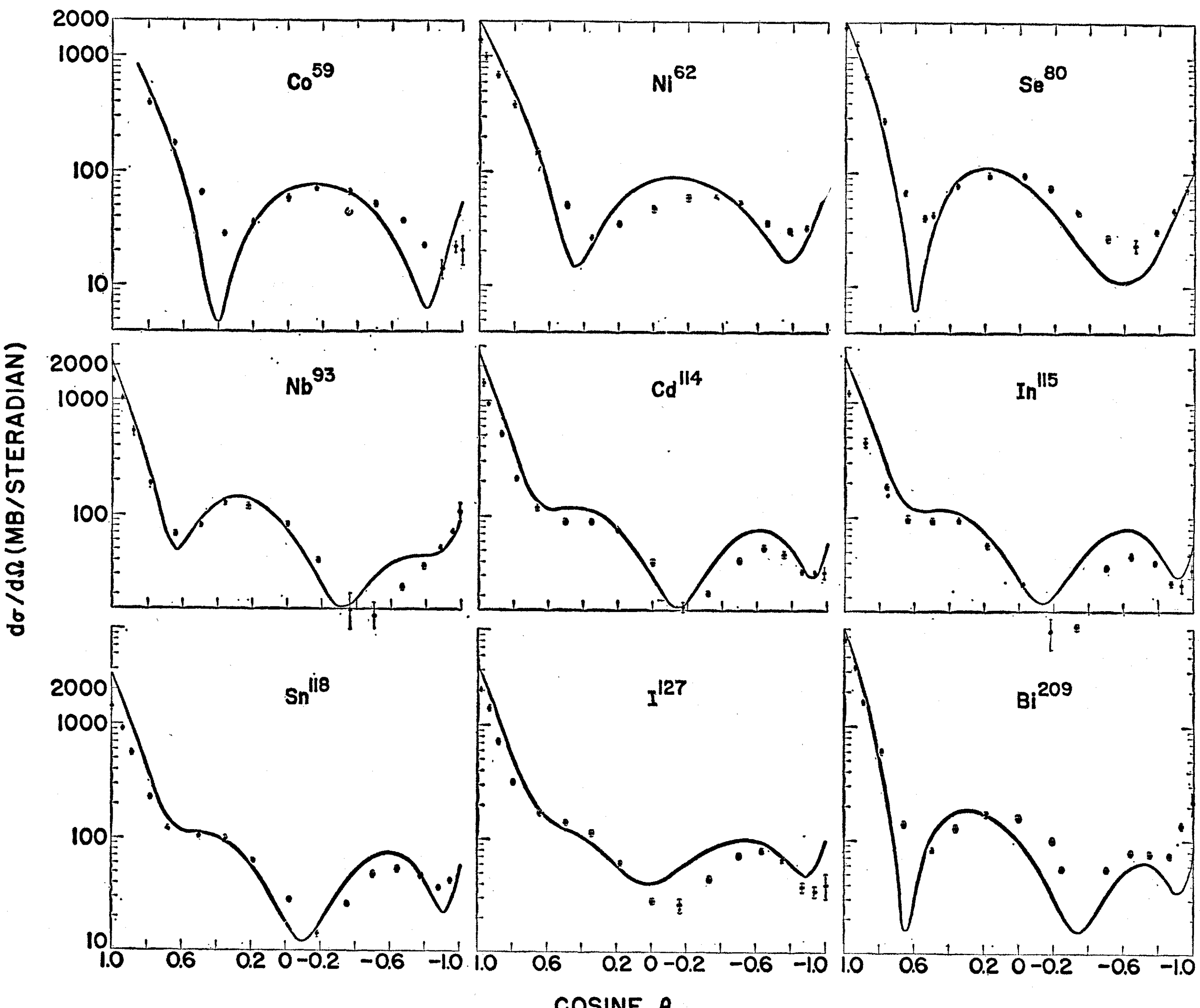

Fig. 6. Comparison of experimental elastic-scattering data for 4.0-Mev neutrons with optical-model predictions. Data points, from Gorlov *et al.*, *Soviet Phys. "Doklady" (English Transl.)* **9**, 806 (1965); solid curves, values calculated from optical-model parameters, including compound elastic scattering.

thousand to several tens of millions of electron volts for the following observables: polarization produced by elastic scattering, differential cross sections for elastic scattering, and reaction and total cross sections. None of the parameters varies with nuclear species, and only one varies with energy.

Polarized protons were used to test the assumptions that reactions involving strong nuclear forces are invariant under parity and time-reversal operations. These experiments bear not only on fundamental symmetries but also on nuclear structure, because they involve the basic interactions.

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16. My associates and I are indebted to Dr. George Rogosa at the AEC, who made available to us a large fraction of the stockpile of these isotopes.
17. At energies below ~5 Mev one must supplement the calculation of potential scattering with one which takes account of compound elastic scattering—formation of a compound nucleus which decays through the entrance channel. However, this can be done rigorously on the basis of a theory of Hauser and Feschbach, and without the addition of free parameters.
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19. The work described here was performed under the auspices of the U.S. Atomic Energy Commission. I acknowledge with appreciation the assistance of Mrs. Kay Harper in the preparation and editing of the manuscript.

Sickle-Cell Trait in Human Biological and Cultural Evolution

Development of agriculture causing increased malaria is bound to gene-pool changes causing malaria reduction.

Stephen L. Wiesenfeld

Medical anthropology has been moving increasingly into central areas of anthropological theory. Alland (*1*) has demonstrated some of the ways in which medical anthropology may serve "as a major link between physical and cultural anthropology, particularly in the areas of biological and cultural evolution." The purpose of this article is to examine the relationship between the sickle-cell trait, malaria, and agriculture in east and west Africa so as to derive hypotheses regarding concomitant human biological and cultural evolution.

Malarial infection, both natural and experimental, and mortality from such infection are consistently lower in individuals having the sickle-cell trait (*2*, *3*). The normal population has reduced fertility rates as compared to the "sickler" population in endemic areas (*4*). Also, the distribution of the sickle-cell trait in tropical Africa parallels that of subtertian malaria (*3*, *5*), so it is reasonable to believe that malaria is the selective agent producing high frequencies of the sickle-cell trait in the area of sub-Saharan Africa stretching from the east coast to Gambia on the west coast. Livingstone (*5*) proposed that malaria in west Africa became hyperendemic when large tracts of tropical rain forest were reclaimed for agriculture, by multiplying the number of breeding places for the *Anopheles gambiae* species complex, which contains major vectors of hyperendemic malaria (*6*).

Two important areas in the interaction of the sickle-cell trait, malaria, and agriculture have not been examined previously. First, not all agricultural systems have the same effect on the development of malaria and of high frequencies of the sickle-cell trait. The data presented here show that agricultural systems do differ in this respect, with one, the Malaysian agricultural system (*7*, *8*), having a greater effect than any other. Second, the effects of changes in the frequency of an adaptive gene on the incidence of the disease selecting for it have not been fully examined. Computer models were developed to determine the nature of the interaction of the sickle-cell trait and malaria, and it was found that increasing frequencies of the sickle-cell trait cause reductions in malaria parasitism by reducing the number of people capable of being infected in a population. Both of these arguments are critical to the hypothesis that the development and differentiation of the Malaysian agricultural system is intimately bound to changes in the gene pools of populations using this agricultural system. The action of high frequencies of the sickle-cell trait is to reduce the environmental limitation of malarial parasitism on these populations, thus allowing more human energy to flow into the development and maintenance of the Malaysian agricultural system. A number of lines of evidence are presented here to support the hypothesis.

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