# Elastic and Quasielastic Scattering of 110-MeV Polarized $^{23}$Na from $^{90}$Zr

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Angular distributions of the analyzing powers ${}^{T}T_{k0}$ ($k=1,2,3$), $T_{20}$, and $T_{21}$ for elastic and quasielastic scattering of 110-MeV polarized $^{23}$Na from $^{90}$Zr and the cross section for quasielastic scattering have been measured. Vanishing odd-rank tensor analyzing powers and the validity of the shape-effect relations indicate the importance of the projectile deformation for the interaction potential. The data are well explained by coupled-channel calculations using realistic double-folding potentials and taking into account projectile deformation and excitation.

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Since the early days of heavy-ion research[1] many investigations, mainly theoretical ones, were performed dealing with the influence of deformation and alignment of colliding nuclei on the interaction potential.[2] Reasons for this interest had various origins, ranging from the possibility to lower the Coulomb barrier in the earlier papers[1] to the highly speculative predictions of a potential pocket in the interaction barrier of very heavy deformed nuclei in the very recent ones.[3] Since experimentally mainly intrinsically deformed spin-zero nuclei were used (e.g., Ref. 4) the observed effects manifested themselves in quantities which are an average over all possible nuclear alignment axes. There are only a few exceptions: light-ion interaction with an aligned Ho target[5] and a series of experiments with aligned $^{7}$Li beams.[6-8] Even though these experiments exhibited unambiguously the influence of nuclear deformation, notwithstanding their importance, either for Ho the limitation in the experiment itself or the special properties of the loosely bound nucleus $^{7}$Li limited partly their conclusiveness. But the availability of polarized beams of the well deformed nucleus $^{23}$Na at the MP tandem accelerator of the Max-Planck-Institut für Kernphysik in Heidelberg[9] permits now the study of the deformation dependence of heavy-ion interactions in much more detail.

At present, heavy-ion interactions at energies above the Coulomb barrier are well described by a combination of semimicroscopical and phenomenological approaches. The real interaction is generated almost parameter free by folding the densities of the interacting nuclei with a "universal" effective nucleon-nucleon force, commonly chosen as the M3Y force.[10] The radial dependence of the imaginary potential is chosen phenomenologically identical to the one found for the real interaction, but its strength has to be determined by a fit to the data. Dealing now with aligned deformed ions their deformation has to be treated explicitly[11] and generates a tensor potential ($T_R$ type[12]). Moreover, deformed nuclei have low-lying collective levels for which coupling cannot be subsummed in an effective potential, but has to be treated also explicitly. It is the main purpose of this Letter to find out whether under such circumstances the interaction of polarized deformed heavy ions with a spherical target can be treated by the above sketched combination of semimicroscopical and phenomenological approach and if so, what new ingredients are essential. We will approach the answer in two steps: First, we will discuss global features of the polarization data to learn about the gross properties of the interaction; afterwards, we will briefly discuss the analysis of the data using a double-folding potential.

The polarized $^{23}$Na beam was produced by the atomic-beam source for polarized heavy ions installed at the Heidelberg MP Tandem accelerator.[9] The polarization is produced by optical pumping. When leaving the source the $^{23}$Na$^{-}$ ions are almost all in one single $m$ substate of the nuclear spin. To avoid systematic errors, data were taken by switching rapidly between the $m$ substates with a high-frequency transition. The beam currents at the target were up to 30-nA $^{23}$Na$^{9+}$. The polarization of the beam was determined by nuclear reactions for which the analyzing powers can be calculated, either Coulomb excitation of the polarized projectiles or the $^{1}$H($^{23}$Na,$\alpha$)$^{20}$Ne(g.s.) reaction at 0°.[13] For the detection of the scattered Na ions six silicon detectors with an angle separation of 5° were used on either side of the beam. The size of the apertures in front of the counters were chosen such that the kinematical energy shift was smaller than the energy resolution of the counters. The overall energy resolution using a 100-$\mu$g/cm$^{2}$ $^{90}$Zr target was of the order of 400 keV FWHM, which is not sufficient to separate events from elastic scattering and from the excitation to the first excited state of the projectile $^{23}$Na at $E_x=0.44$ MeV. Therefore, a complete data set for quasielastic scattering (sum of elastic and inelastic) is presented. However, from an energy spectrum with an unresolved quasielastic line it is still possible to extract analyzing powers for the elastic channel: Since analyzing powers are *ratios* of cross sections only the high-energy part of the line was used which was not "contaminated" by inelastic events.

It is now advisable not to use cross sections for the individual $m$ substates themselves, but rather to combine them to analyzing powers of various tensor ranks $k$.[14,15] (Transformed to the Madison convention ${}^T T_{10} = \sqrt{2} i T_{11}$, and in Cartesian coordinates for spin-$\frac{3}{2}$ particles ${}^T T_{20} = A_{yy}$.) For an operative and partly pictorial definition of the second-rank tensor analyzing powers, see Fig. 1 in Ref. 6. Figure 1 displays angular distributions of the first-, second-, and third-rank tensor analyzing powers for elastic and quasielastic scattering. For the latter also an angular distribution of $d\sigma/d\sigma_R$ could be determined. Analyzing powers $T_{kq}$ are those defined according to the Madison convention[15] ($z$ axis along beam axis), whereas the ${}^T T_{k0}$ refer to a transversal coordinate system with the $z$ axis normal to the scattering plane.[6,15] Both first- and second-rank tensor analyzing power data form complete sets, whereas out of the three independent components of the third-rank tensor analyzing powers only one was determined experimentally.

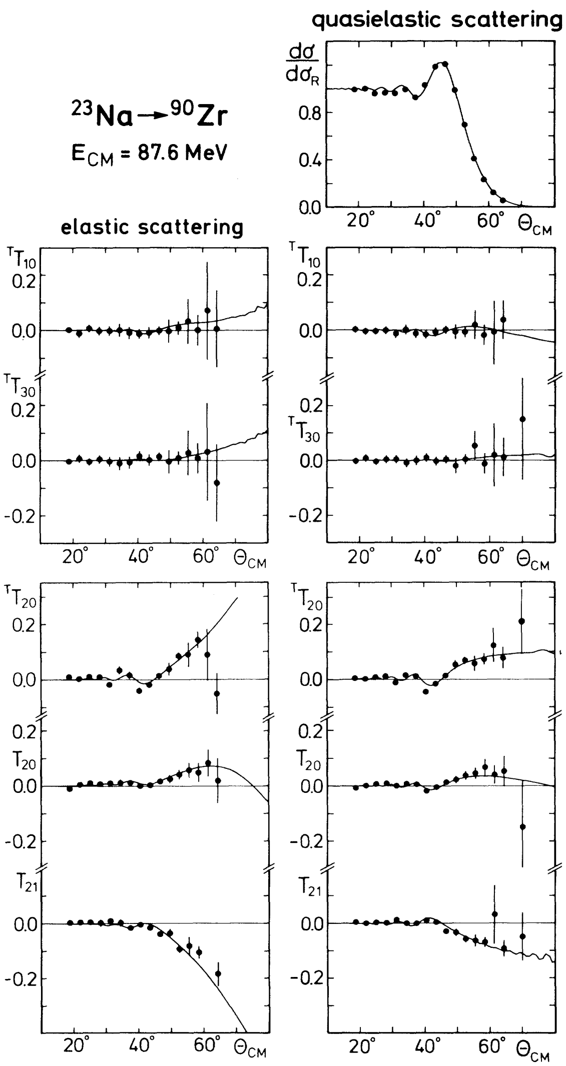


FIG. 1. Angular distributions of $d\sigma/d\sigma_R$, ${}^T T_{k0}$ ($k=1,2,3$), $T_{20}$, and $T_{21}$ for quasielastic scattering (sum of elastic and inelastic scattering to the first excited state of the projectile) and elastic scattering for the interaction of 110-MeV polarized ${}^{23}Na$ with ${}^{90}Zr$. $d\sigma/d\sigma_R$ could not be determined for elastic scattering. The solid lines are coupled-channel calculations with a double-folding optical potential as input.

The odd-rank tensor analyzing powers which reflect mainly the action of static and/or dynamic spin-orbit forces are found consistent with zero. In contrast the second-rank tensor analyzing powers reach quite substantial values. Both features point to a tensor interaction as the main one besides the central interaction. If it stems from the projectile deformation ($T_R$ type), geometrical relations between the second-rank tensor analyzing powers, the so-called "shape-effect relations," can be derived;[6,16] these read

$$T_{2q}(\theta) = -\left(\frac{16\pi}{5}\right)^{1/2} Y_{2q}\left(\frac{\pi-\theta}{2}, 0\right) {}^T T_{20}(\theta), \quad q=0,1,2. \tag{1}$$

To test them, the data for ${}^T T_{20}(\theta)$ were connected by dashed lines in Fig. 2. The solid lines in the plots of $T_{20}(\theta)$ and $T_{21}(\theta)$ are calculated "inserting" into Eq. (1) the "dashed line" for ${}^T T_{20}$ which describes the data

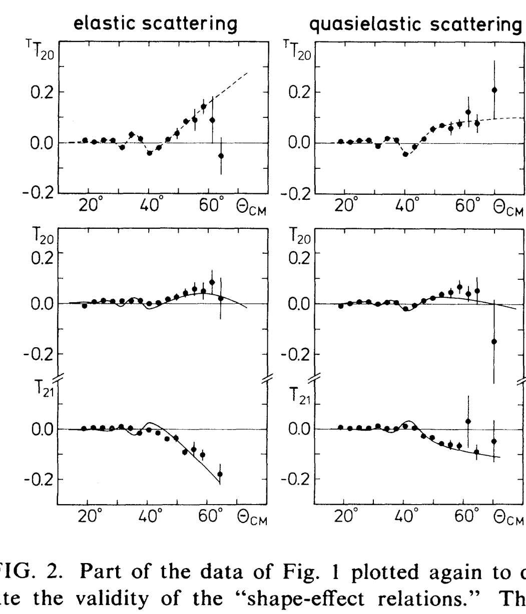


FIG. 2. Part of the data of Fig. 1 plotted again to demonstrate the validity of the "shape-effect relations." The solid lines are calculated by means of Eq. (1) from the dashed line drawn through the ${}^T T_{20}$ data points.

almost perfectly. Altogether it becomes quite evident that the ($T_R$) tensor potential generated by the quite large quadrupole moment of $^{23}$Na and, as will be seen below, to a less extent the $E2$ coupling between ground and excited states of the aligned $^{23}$Na projectile are the essential additional pieces to understand such polarization data as well for elastic as for quasielastic scattering. Similar results were found recently for the $^{23}$Na+$^{208}$Pb interaction at 170 MeV.[17]

The data were now analyzed quantum mechanically using the coupled-channel code ECIS[18] and a double-folding potential with free strength parameters. The derivation of the potential followed closely the procedure developed previously for the analyses of data obtained with polarized $^7$Li.[8,11] The starting point is an *Ansatz* for the real nucleus-nucleus potential

$$V(r,\hat{\mathbf{r}}\cdot\hat{\mathbf{P}})=\int\int\rho_P(r_P,\hat{\mathbf{r}}_P\cdot\hat{\mathbf{P}})\rho_T(r_T)v(|\mathbf{r}+\mathbf{r}_P-\mathbf{r}_T|)d\mathbf{r}_P d\mathbf{r}_T\,. \tag{2}$$

The effective M3Y nucleon-nucleon force[10] is denoted by $v$ and the densities of projectile ($^{23}$Na) and target ($^{90}$Zr) by $\rho_p$ and $\rho_T$, respectively. The vector $\mathbf{r}$ connects the centers of projectile and target (Fig. 3). $\hat{\mathbf{P}}$ is a unit vector along the symmetry axis of the $^{23}$Na nucleus chosen in Fig. 3 perpendicular to the scattering plane, an alignment necessary for the determination of the analyzing power $^TT_{20}$. The density of the projectile is split into a monopole and a quadrupole part according to

$$\rho_P(r_P,\hat{\mathbf{r}}_P\cdot\hat{\mathbf{P}})=\rho_0(r_P)+Q^M\rho_2(r_P)Y_{20}(\hat{\mathbf{r}}_P\cdot\hat{\mathbf{P}})\,. \tag{3}$$

$Q^M$ is the spectroscopic-mass quadrupole moment of $^{23}$Na which was related to the spectroscopic charge quadrupole moment $Q^C=10.06\ e\cdot\mathrm{fm}^2$ by[19]

$$Q^M=(A/Ze)Q^C\,. \tag{4}$$

In the actual calculations Eq. (2) was rewritten in terms of the Fourier transform of the mass distributions and of the M3Y force. This is advantageous since electron-scattering data can be used directly for the experimentally determined charge distributions ($^{23}$Na, Ref. 20; $^{90}$Zr, Ref. 21). In order to take into account excited states of the projectile (complex) transition potentials are needed. Analogous to the collective rotational model they were chosen to have the same radial form as the second-rank tensor potential but with a strength scaled to the experimentally determined transition probabilities of the considered states.

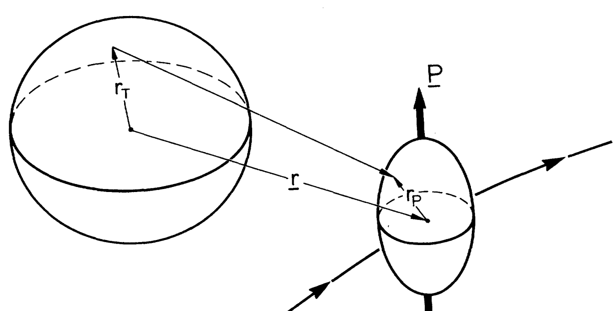


FIG. 3. Coordinates used in the *Ansatz* for the double-folding potential. The unit vector $\hat{\mathbf{P}}$ points along the symmetry axis of the $^{23}$Na projectile. It is chosen in this example perpendicular to the scattering plane, a configuration necessary for the determination of the analyzing power $^TT_{20}$.

The double-folding potential does not predict *a priori* the imaginary part of the optical potential. In order to minimize the number of free parameters the absolute strength parameter $N$ of the M3Y force was chosen complex assuming identical radial form factors for the real and imaginary parts of the optical potential.

As it stands now the double-folding potential has no explicit spin-orbit potential. A double-folding spin-orbit potential would be very weak because of the paired nucleon spins in both projectile and target. Therefore it was omitted. However, neglecting it does not necessarily mean that odd-rank tensor analyzing powers vanish. As it was explained in previous papers coupling to excited states of the polarized projectile is able to generate odd-rank tensor analyzing powers as well.[8,22]

The coupled-channel calculations took into account coupling to the first- and second-excited state of $^{23}$Na including reorientation terms of these levels as well. Coupling to excited states in $^{90}$Zr was found to be negligible. The only free parameter to be fitted was the strength $N$ of the M3Y force. The solid lines in Fig. 1 display the outcome of the fit resulting in

$$N=1.105+0.521i\,.$$

It is remarkable that this result agrees quite well with those derived from the interaction of unpolarized nuclei. The real part of $N$ is found close to 1, a value to be used if the real part is calculated parameter free. The imaginary part of $N$ is found close to the values obtained in analyses of interacting unpolarized nuclei, but only if the data are treated by a coupled-channel method taking into account the most important channels. Neglect of coupling to these channels results in quite a visible increase of $\chi^2$ per data point. For the elastic scattering the coupled-channel calculations displayed in Fig. 1 lead to $\chi^2=0.99$ whereas it increases to $\chi^2=1.65$ if only reorientation in the ground state is taken into account.

We can summarize by saying that the data are well described by the semimicroscopic procedure used so far mainly for interacting unpolarized nuclei. Within the effective nucleon-nucleon force there is no need for a spin-orbit interaction. The only sizable polarization effect stems to a large extent from the spectroscopic deformation and excitation of the projectile which has to be included in the calculations in order to reproduce the substantial second-rank tensor analyzing powers.

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