TABLE I. Resonant cross sections and partial widths.

	Elastic	Inelastic	Mass 20	23	24	26	27
σ_R	∘∘∘	2	19	12	22	20	9
Γ_c/Γ	0.22	0.02	0.18	0.11	0.20	0.19	0.08

Finally, we emphasize that our result for the 14.7-MeV resonance is by no means a guarantee that background absorption is small for above-the-barrier heavy-ion resonances in general. As we pointed out earlier, a substantial decrease in the large $l=9$ absorption given by the optical model requires a compensating *increase* in absorption for higher l values, as otherwise the overall absorption becomes much weaker than the data will allow. Therefore, the evidence favors l-selective transparency. Chan *et al.*[8] have suggested parity-dependent absorption as a possible explanation of the oscillations in the ^{16}O + ^{12}C fusion cross section. This will be tested very effectively by experiments of the type described here.

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Determination of the Electric Quadrupole Moment of ^{7}Li by Coulomb Scattering of an Aligned ^{7}Li Ions

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The electric quadrupole moment of ^{7}Li was determined by Coulomb scattering of aligned ^{7}Li ions to be $Q = (-34 \pm 6)\ e \cdot \mathrm{mb}$. This compares favorably with the value $Q = (-41 \pm 6)\ e \cdot \mathrm{mb}$ determined by atomic-beam spectroscopy.

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The first suggestion to determine the electric quadrupole moment of a strongly deformed nucleus by nuclear physics methods was to look for deviations from the Rutherford cross section.[1] However, for unpolarized projectiles or targets the deviation from pure Rutherford scattering is due to only a second-order term in the quadrupole moment[2] and is therefore very small. For this reason experiments with unpolarized beams and targets have failed to yield reliable results for the charge quadrupole moment. The development of highly polarized heavy-ion beams for ^{6}Li, ^{7}Li (Ref. 3) and more recently for ^{23}Na (Ref. 4) enables the determination of the quadrupole moments of these nuclei by Coulomb scattering of second-rank polarized (aligned) beams. In contrast to an experiment with unpolarized beams, the observables, (the tensor analyzing powers[5]) are now first-order effects in the quadrupole moment.[2] Since only relative measurements are required to determine analyzing powers, the measurement of a quadrupole moment by this method is possible in a high-precision experiment.

It is certainly worthwhile to determine the quadrupole moment of ^{7}Li by this method. The present knowledge of the quadrupole moment of ^{7}Li stems from atomic and molecular (LiH, LiF) beam spectroscopy.[6] The contribution of the electric quadrupole interaction to the hyperfine splitting of atomic lithium is only 1×10^{-5}. The smallness of this contribution is ultimately responsible for the accuracy of 15% to which the quadrupole moment of ^{7}Li ($Q = -41 \pm 6\ e\cdot$mb) could be determined by atomic beam spectroscopy.[7] The error quoted is purely experimental and does not include any error from the calculation of the electric field gradient in a Li atom. In the present experiment the gradient of the field, the Coulomb field, is known exactly. The results of this experiment can therefore be used as a check of calculations of field gradients in atoms and molecules.

The cross section for Coulomb scattering of beams with arbitrary tensor polarization has been calculated[2] using the formalism of Coulomb excitation.[8] For a ^{7}Li beam (charge $3e$, spin $\frac{3}{2}$) aligned along the beam direction (z axis) the cross section is given by[9]

$$\sigma_{\rm al}(\theta) = \sigma_{\rm R}(\theta)[1 + (Q/9a^2)\tilde{f}_{20}(\theta)t_{20}], \tag{1}$$

where t_{20} denotes the alignment (tensor polarization)[5] of the beam and a, as usual, half the distance of closest approach. The cross section for an unpolarized beam is given by the Rutherford cross section $\sigma_{\rm R}$. The tensor analyzing power $T_{20}{}^{\rm C}$ for pure Coulomb scattering of aligned spectroscopic quadrupole moments

$$T_{20}{}^{\rm C}(\theta) = Q\tilde{f}_{20}(\theta)/9a^2 \tag{2}$$

is linearly dependent on the spectroscopic quadrupole moment Q. The energy dependence of $T_{20}{}^{\rm C}$ is exclusively determined by $a(E)$ and the angular dependence by the universal function[2]

$$\tilde{f}_{20} = \eta f_{20}(\eta, \theta)$$

which can be calculated from Coulomb integrals.[8] η denotes the Sommerfeld parameter. For $\eta > 5$ a condition which is fulfilled for the present perimental situation, f_{20} is to a very good approximation proportional to $1/\eta$.[2] In this case $\tilde{f}_{20}$ is a function of the scattering angle only.

In order to determine the spectroscopic quadrupole moment Q as accurately as possible the tensor analyzing power $T_{20}{}^{\rm C}$ should be as large as possible. Therefore the energy E has to be as high as possible [Eq. (2)], but with the requirement of pure Coulomb and negligible nuclear interaction. Further conditions regarding the energy dependence of the transmission through an ENTandem and problems with monitoring the ^{7}Li alignment at low energies[10] led to the selection of the ^{7}Li-^{58}Ni and ^{7}Li-^{208}Pb scattering at $E_{\rm Li} = 10$ and 22 MeV, respectively. Figure 1 displays, for the two selected systems, the angular distributions to be expected for $T_{20}{}^{\rm C}$ calculated with a value of the spectroscopic quadrupole moment as obtained from atomic spectroscopy.[7] The analyzing powers reach values around 0.01. The deviation from Rutherford scattering ($t_{20}T_{20}{}^{\rm C}$) to be determined is further diminished to a few permill because the alignment t_{20} of the accelerated ^{7}Li beam was between 0.3 and 0.4.

Besides the contribution due to the deformation of the ground state of the projectile there are other contributions to the analyzing power of the elastic scattering due to the real and virtual excitation of the projectile. The most important one is the inelastic scattering to the first excited state of ^{7}Li at 0.48 MeV ($J^\pi = \frac{1}{2}^-$). Although this contritubion should be treated within a coupled channel formalism it will be discussed within the semiclassical approximation[8] which turns out to be precise enough for the experimental accuracy presently achieved. With the semiclassical assumptions for the elastic and inelastic cross section

$$\sigma_{\rm el}(\theta) \approx \sigma_{\rm R}(\theta) - \sigma_{\rm in}(\theta)$$

and

$$\sigma_{\rm in} \ll \sigma_{\rm el},$$

one derives[10]

$$T_{20}{}^{\rm el} = T_{20}{}^{\rm C} - (\sigma_{\rm in}/\sigma_{\rm R})T_{20}{}^{\rm in} \tag{3}$$

for the corresponding tensor analyzing powers.

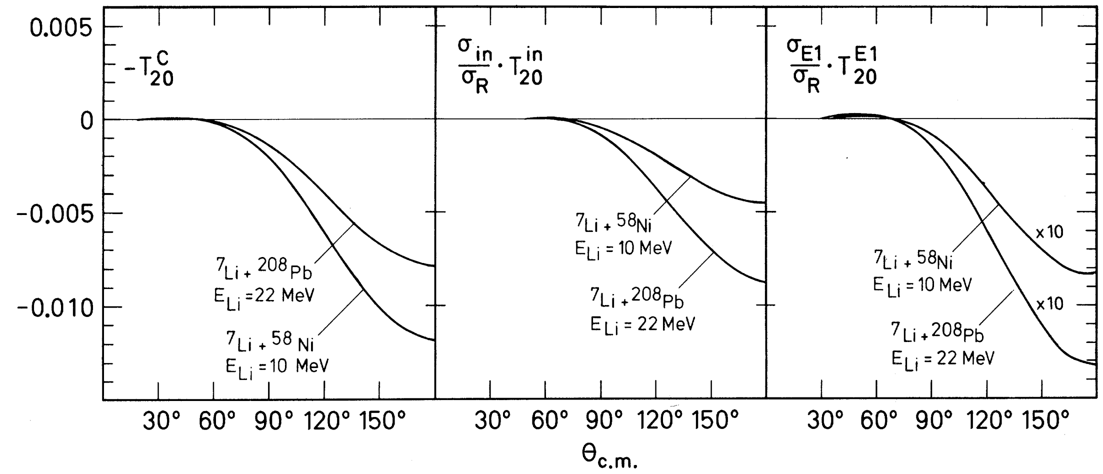

FIG. 1. Calculated angular distribution of the tensor analyzing power T_{20}^{C} for scattering of aligned ^{7}Li in a Coulomb field, of $(\sigma_{\rm in}/\sigma_{\rm R})T_{20}^{\rm in}$ for inelastic scattering and of $(\sigma_{E1}/\sigma_{\rm R})T_{20}^{E1}$ for the virtual $E1$ excitation (polarizability) of the projectile. Note that $-T_{20}^{C}$ is plotted and that the values for $(\sigma_{E1}/\sigma_{\rm R})T_{20}^{E1}$ are multiplied by a factor of 10.

Though $\sigma_{\rm in}$ is very much smaller than $\sigma_{\rm el}$ (for $\theta = 180°$ $\sigma_{\rm in}/\sigma_{\rm el} < 10^{-2}$ for both systems) the coupling to the inelastic channel can affect the rather small value of the tensor analyzing power $T_{20}^{\rm el}$ for elastic scattering if the tensor analyzing power for inelastic scattering $T_{20}^{\rm in}$ is large. $T_{20}^{\rm in}$ can be calculated semiclassically for pure Coulomb excitation,[8, 11] and indeed, it reaches considerable values for backward angles. Independent of reaction mechanism and energy, the maximum value of $T_{20}^{\rm in} = -1$ is attained for $\theta = 180°$![11] Figure 1 displays $(\sigma_{\rm in}/\sigma_{\rm R})T_{20}^{\rm in}$ for the two systems to be investigated. The inelastic cross section was calculated with a $B(E2)$ value of 8.3 $e^2 \cdot {\rm fm}^4$ and an additional correction for virtual $E1$ excitation.[12] Figure 1 shows that for both systems $(\sigma_{\rm in}/\sigma_{\rm R})T_{20}^{\rm in}$ and T_{20}^{C} are comparable. This strong influence of the inelastic channel seems to prevent any determination of the quadrupole moment of ^{7}Li without the application of complicated coupled-channel calculations and without the exact knowledge of the $B(E2)$ value. However, Eq. (3) suggests another approach which corrects exactly the contributions of the inelastic channel within the semiclassical approximation: The analyzing power of the sum of elastic and inelastic scattering is identical with the analyzing power T_{20}^{C} for Coulomb scattering of aligned quadrupole moments

$$T_{20}^{(\rm el+in)} = T_{20}^{\rm el} + (\sigma_{\rm in}/\sigma_{\rm R})T_{20}^{\rm in} = T_{20}^{C}. \tag{4}$$

The error for the spectroscopic quadrupole moment which arises from this approach can be estimated to be smaller than 1.5% for both systems.

A further contribution to be discussed is the virtual excitation of the $E1$ giant resonance. This effect can be interpreted as a contribution of the dynamic electric dipole polarization of the projectile.[8-13] The contribution of this process to Eqs. (3) and (4) can be estimated using a first-order perturbation theory[13] and assuming the polarizability tensor to be proportional to the square of the radii of the deformed ^{7}Li in the direction of the principal axis (Appendix J of Ref. 8). $(\sigma_{E1}/\sigma_{\rm R})T_{20}^{E1}$ calculated with the polarizibility α of Ref. 14 is almost an order of magnitude smaller than $(\sigma_{\rm in}/\sigma_{\rm R})T_{20}^{\rm in}$ (Fig. 1). Other possible contributions—virtual $E2$ excitation, quantum electrodynamical contributions and nuclear effects—have been considered and shown to be negligible within the presently achieved statistical accuracy for the systems and bombarding energies chosen.[10]

In order to achieve the necessary systematic and statistical accuracy for the small effect to be expected ($t_{20}T_{20} \lesssim 3\times10^{-3}$) a symmetric multicounter arrangement was used. It consisted of eleven surface barrier detectors, five on each side of the beam at backward angles and one ring counter at 180°. The target thickness (200 μg/cm^2 for ^{208}Pb, 100 μg/cm^2 for ^{58}Ni) was selected to guarantee a tolerable energy resolution ($\Delta E < 350$ keV) for backward-angle scattering. The alignment t_{20} of the beam was determined during the experiment with the ^{1}H(^{7}Li,α)α reaction which possesses at $\theta = 0°$ a maximum analyzing power[11] of $T_{20} = -1$. The systematic errors were suppressed by a routing system which allows one to reverse the sign of the alignment after a certain charge has been collected in the Faraday cup (frequency $\approx 0.5\ \mathrm{s}^{-1}$). In order to control the experiment two additional counters were installed at ± 30°. At these angles the analyzing power is very small (Fig. 1) and the measured effects provided useful information on the systematic errors. The observed effect for the monitor counters indicates that over a four-day run the systematic errors were certainly smaller than 10^{-4}.

Figure 2 displays the analyzing powers $T_{20}^{(\mathrm{el+in})}$ and T_{20}^{el} for both systems under investigation. The positive sign of the analyzing powers reflects the negative sign of the quadrupole moment of ^{7}Li. The importance of the contribution from the inelastic scattering is obvious from a comparison of the measurements. The spectroscopic quadrupole moment of ^{7}Li was extracted from $T_{20}^{(\mathrm{el+in})}$ [Eqs. (2) and (4)] by a fit to the data of the two experiments (solid lines) with Q as the only free parameter. After correcting for the effect of the virtual $E1$ excitation (17% and 7% for ^{208}Pb and ^{58}Ni, respectively) the averaged value obtained was $Q = (-34 \pm 6)e \cdot \mathrm{mb}$. Besides the statistical error, the error includes one for the determination of the beam polarization, an estimate of the error of the semiclassical approximation and an error of 50% for the correction of virtual $E1$ excitation. The observed quadrupole moment agrees quite well with the ones obtained in atomic spectroscopy.[6,7] They have been obtained using calculated electric-field gradients which seem to be reliable within the present errors.

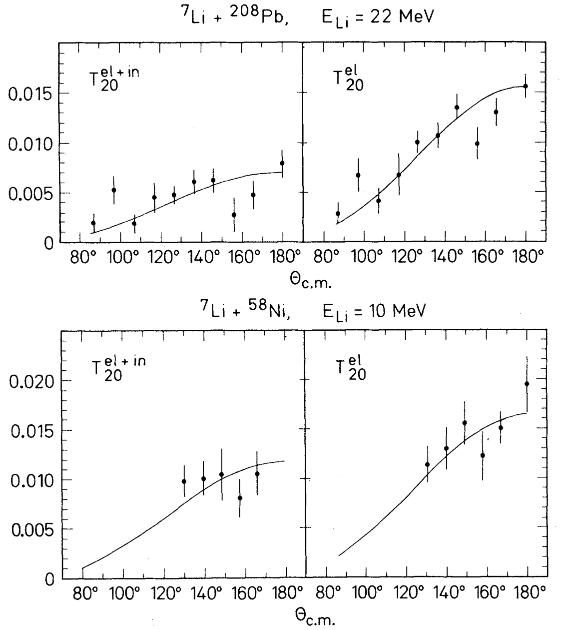

FIG. 2. Observed angular distributions of $T_{20}^{(\mathrm{el+in})}$ and of T_{20}^{el} for the interaction of ^{7}Li with ^{58}Ni and ^{208}Pb at $E_{\mathrm{Li}} = 10$ and 22 MeV, respectively. From the solid lines fitted to $T_{20}^{(\mathrm{el+in})}$ the spectroscopic quadrupole moment of ^{7}Li was determined. The solid lines for T_{20}^{el}, were calculated using these values in a semiclassical approximation.

In order to test the assumptions made, the tensor analyzing powers T_{20}^{el} have been calculated from Eq. (3) (solid lines in Fig. 2) using the quadrupole moments obtained for the individual experiments, the known $B(E2)$ value[12] and calculated analyzing powers T_{20}^{in}.[8,11] This calculation also included a correction for the virutal $E1$ excitation. The good agreement between calculation and data (Fig. 2) proves the semiclassical assumptions to be appropriate for the present state of the experiment.

The experiment described shows that the quadrupole moments of selected nuclei can be determined by Coulomb scattering of aligned nuclei with an accuracy comparable to that obtained in atomic spectroscopy. A more extensive experiment (better statistics, systematics with different targets, and bombarding energies) together with a more sophisticated analysis (coupled channels) promises considerable improvements in accuracy. At least half an order of magnitude seems to be achievable. In addition, new information can then be gained on the inelastic scattering and on the complete polarizability tensor.

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Study of Strong Spin-Isospin Mode Analog States at 4.5 MeV in ^{12}B in ^{12}C$(e,e'\pi^+)^{12}$B

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Strong spin-isospin mode, $T=1$, $T_z=1$ analog states at 4.5 MeV in ^{12}B were studied by the reaction ^{12}C$(e, e'\pi^+)^{12}$B at the electron energy $E_e=200$ MeV. The photoproduction cross sections at seven angles ranging from 30° to 150° were obtained with use of virtual-photon theory and an experimentally determined real-to-virtual photon ratio. The results are compared with theoretical calculations and also with the available data on inelastic scattering from the 19.5-MeV $T=1$, $T_z=0$ analog complex in ^{12}C.

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The photoproduction of pions near threshold and its inverse process, the radiative capture of stopped pions, preferentially excite spin-flip states in a nucleus through the dominant Kroll-Ruderman term, $\vec{\sigma}\cdot\vec{\epsilon}$ ($\vec{\sigma}$ is the nuclear spin and $\vec{\epsilon}$ is the photon polarization vector). Of special interest is the possibility of using these reactions to study the spin-flip states in the giant-resonances region—the so-called spin-isospin modes predicted by the generalized Goldhaber-Teller model.[1] In contrast to the well-known giant-resonance isospin modes[1] which have been extensively studied throughout the periodic table by photonuclear reactions and electron scattering, experimental studies of the spin-isospin modes are rather limited, most of the presently available data coming from the radiative capture of stopped pions.[2] However, this reaction has the serious limitation that the momentum transfer is restricted to a single value ($q\sim 0.6$ fm^{-1}), and therefore no information can be obtained about the multipolarities of the excited states. The inverse reaction, namely the photoproduction of charged pions, can be a more versatile tool to study the spin-flip giant resonance states since the momentum transfer can be varied to map out the form factors of the excited states.[3] The photoproduction of charged pions excites the $T=1$, $T_z=\pm 1$ spin-isospin analogs in the residual nucleus (for a $T=T_z=0$ target nucleus). The fact that the photopion reaction probes only the $T=1$ states is a unique feature which distinguishes it from other reactions such as electron scattering or pion inelastic scattering which are sensitive to both $T=0$ and $T=1$ states or their isospin-admixed states.

The purpose of this paper is to demonstrate the usefulness of photopion reactions with variable momentum transfer to obtain spectroscopic information about the spin-isospin analog states. We report here on angular distribution studies of emitted pions in the reaction ^{12}C$(e,e'\pi^+)^{12}$B* leading to the 4.5-MeV $T=1$, $T_z=1$ analog complex in ^{12}B.

Strong excitation of these states was previously observed in (π^-,γ) (Ref. 2) and $(\gamma,\pi^\pm)$ experiments at a single fixed momentum transfer.[4] The $T_z=0$ analogs which correspond to these states are located at about 19.5 MeV in ^{12}C. Inelastic electron-scattering studies[5,6] together with particle-hole shell-model form-factor calculations[7] indicate that these states are dominant-