Electromagnetic Excitation of Aligned ^{7}Li Nuclei

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Electric ground-state properties of ^{7}Li have been measured in a consistent way by observation of the Coulomb interaction of aligned ^{7}Li ions with heavy target nuclei. Besides the quadrupole moment ($Q_s = 3.70 \pm 0.08\ e \cdot \mathrm{fm}^2$) and the $B(E2, \frac{3}{2}^- \rightarrow \frac{1}{2}^-)$ value ($8.3 \pm 0.5\ e^2 \cdot \mathrm{fm}^4$), the tensor moments of the nuclear polarizability τ_{12} and τ_{11} were determined ($\tau_{12} = \tau_{11} = 0.23 \pm 0.06\ \mathrm{fm}^3$). Present theoretical investigations on the structure of ^{7}Li reveal difficulties in providing a unified description of all four properties.

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Up to now the experimental knowledge of the quadrupole (Q) moments of light nuclei, including the Li isotopes, has not been as precise as one would desire from the viewpoint of nuclear physics, atomic and molecular physics, and solid-state physics. For the latter the Q moments of the Li isotopes are used as probes to determine reliable electric field gradients in the bulk[1] and recently on the surface[2] of various materials. The theoretical understanding of simple molecules like LiH suffers from a lack of independent knowledge of the precise value of the Q moments of the Li isotopes. For the LiH molecule a recently improved Hartree-Fock calculation for the electric field gradient at the Li nucleus[3] implies that the more than ten year old, accepted Hartree-Fock calculation[4] suffers from severe basis-truncation errors and thus yields the wrong value. That would not be notable if this calculation had not been in the past to claim one of the most exact values for Q moments in data tables.[5] Up until recently, the only way to determine the ground-state Q moments of Li isotopes was to rely on such calculations. Moreover, until now it was not realized by nuclear physicists that the determination of nuclear Q moments of light nuclei is not an independent problem, but is closely related to the determination of other electromagnetic ground-state properties, such as $B(E2)$ values, polarizabilities, etc. It is fortunate that the ^{7}Li nucleus, which is not only complex enough to provide a decent test case, but also simple enough to be handled both theoretically and experimentally (limited number of low-lying excited states), is also of general nuclear physics interest.[6,7] Moreover, the precise extrapolation to very low energies of the radiative capture cross section for the reactions $^3\mathrm{H}(\alpha, \gamma)^7\mathrm{Li}$ and $^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$, which are currently of great astrophysical interest because of their importance in the solar neutrino problem, relies on a precise knowledge of the $A = 7$ properties for energies approaching zero (ground-state properties).[8]

Experimentally, there exists up to now no consistently measured and highly accurate set of ground-state properties of ^{7}Li. Data obtained so far mainly stem from hyperfine-spectroscopy experiments[4,9] and Coulomb-excitation studies[10–12]; the latter, however, are often difficult to interpret. In particular, as now realized also for other light nuclei, the large effects of the nuclear polarizability including its tensor moments have been the origin of considerable ambiguities in the interpretation of Coulomb-excitation data of light ions.[11–14] Consequently, only a determination of all relevant parameters from *one single* data set can provide a precise knowledge of the electromagnetic properties of ^{7}Li, data which are of interest for a great many fields.

The present experiment is based on the measurement of angular distributions of tensor analyzing powers T_{20} for sub-Coulomb interaction of aligned ^{7}Li with heavy nuclei.[15] The determination of $T_{20} = (\sigma_{\mathrm{al}}/\sigma - 1)/t_{20}$ requires only the observation of the ratio of the differential cross sections for unpolarized and aligned ^{7}Li beams, σ and σ_{al}, respectively (t_{20} is the alignment of the beam). This is one of the keys to achieving the high accuracy of the experimental data.

As indicated in Fig. 1, several contributions, originating from electric-dipole and -quadrupole coupling from the ground state to other configurations of ^{7}Li, contribute to T_{20}. The tensor analyzing power for elastic scattering T_{20}^{el} is mainly determined by two terms: the reorientation coupling in the ground state, which is in first order proportional to Q_s, and the quadrupole transition to the first excited state, which strength is given by the $B(E2)$ value. The features of this coupling become transparent by consideration of the observable $T_{20}^{\mathrm{el+in}}$ (sum of elastic and inelastic

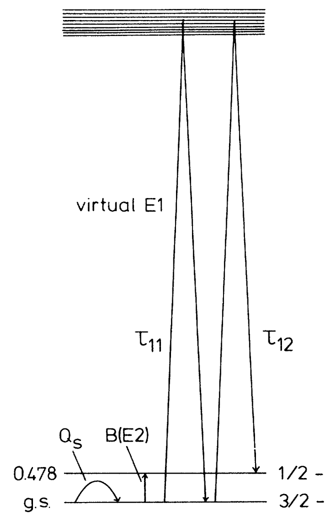

FIG. 1. Symbolic representation of the dominant processes in sub-Coulomb scattering of aligned ^{7}Li ions. Each graph corresponds to a matrix element and the associated interaction. For reasons of transparency, higher-order contributions have not been considered in the figure.

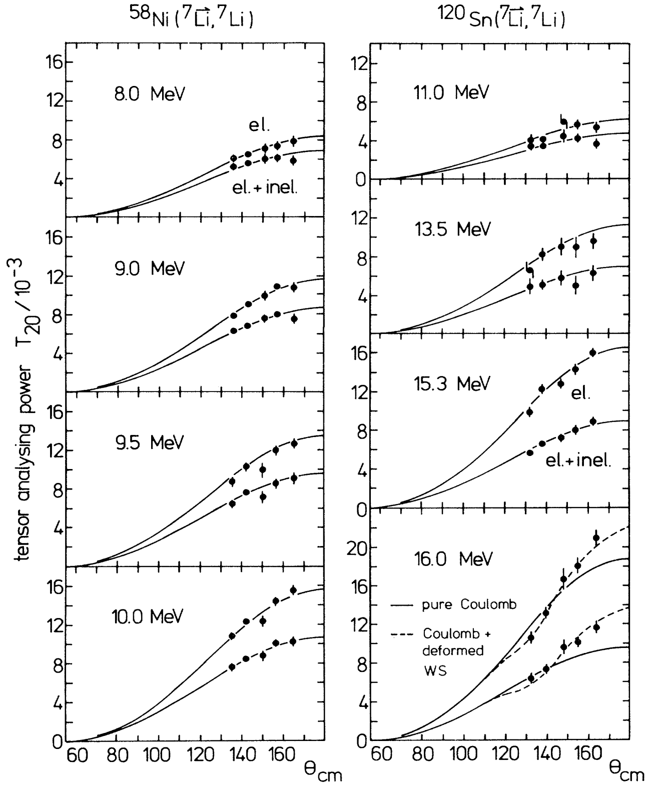

FIG. 2. Analyzing powers T_{20}^{el} and $T_{20}^{\mathrm{el+in}}$ for the scattering of ^{7}Li on ^{58}Ni and ^{120}Sn at different bombarding energies. The solid lines represent quantum-mechanical coupled-channels calculations using the parameter set of Table I (first row) for all data. The 16-MeV data demonstrate the onset of Coulomb-nuclear interference. The dashed lines have been computed with use of the parameters of Table I but including a real deformed Woods-Saxon interaction (Ref. 18).

scattering), which is essentially determined by the reorientation matrix element,[15] whereas the difference $T_{20}^{\mathrm{el}} - T_{20}^{\mathrm{el+in}}$ is dominated by the $B(E2)$ value. The electric polarizability, which may be connected to virtual dipole transitions (Fig. 1), is known to influence strongly the Coulomb-excitation processes in light nuclei. Within the limits of an adiabatic approximation,[16] it can be described by an effective polarization potential:

$$V_{\mathrm{pol}} = -\tfrac{1}{2}Z^2e^2\alpha/r^4 - (9\pi/5)^{1/2}(Z^2e^2/r^4)\tau_{if}Y_{20}(\hat{\mathbf{s}}\cdot\hat{\mathbf{r}}),$$

where Ze denotes the charge of the collision partner and α is the polarizability of the ^{7}Li nucleus. The associated analyzing powers are affected significantly only by the tensor part of V_{pol}.[17]

The contributions of the reorientation, quadrupole, and dipole excitation terms to the tensor analyzing power depend in a characteristic way on the bombarding energy and on the charge number of the target: Light targets favor the determination of Q_s, whereas the coupling to excited states is of increasing importance for heavier targets. These dependences allow separation of the individual contributions in a series of systematic measurements.

In order to make feasible such an extensive investigation of the small analyzing powers with sufficient accuracy, much care was taken to optimize the experimental arrangement. Its most important part is an ionization chamber[18] with a large solid angle (1.8 sr) and rotational symmetry with respect to the beam axis, which allowed detection of backscattered Li ions with an average counting rate of about 10 kHz. The rotational symmetry is well suited to the symmetry properties of T_{20} and eliminates to first order effects from odd-rank components of the beam polarization and from instabilities of the beam. Instrumental asymmetries are detected by four monitor counters at 20° and 30°. In all cases they were found to be smaller than the statistical errors. The polarization t_{20} of the beam was monitored continuously at the position of the target by observing the deexcitation γ rays from the $\frac{1}{2}^-$ state in coincidence with backscattered Li ions. The analyzing power for this process can be calculated accurately, thus allowing the absolute determination of the beam polarization with an error of less than 1%. Finally, we want to stress that the experimental procedure is reduced to a relative measurement between two polarization states of the beam. Therefore, errors originating from the absolute calibration of cross sections or excitation probabilities do not enter the results.

The data from the scattering of ^{7}Li on ^{58}Ni and ^{120}Sn at different energies and scattering angles are displayed in Fig. 2. The analysis was performed in terms of a quantum-mechanical coupled-channel theory by use of the program ECIS79.[19] With this code running on a fast computer (Cray-1), it was possible to calculate the small analyzing powers with sufficient accuracy and to extract all four parameters Q_s, $B(E2)$, τ_{11}, and τ_{12} within a χ^2 minimization procedure. The final results are listed in Table I.

All data are described consistently with one single parameter set (solid lines in Fig. 2). No significant dependence of the parameters on angle, energy, or target is observed, provided that the bombarding energy does not exceed a critical value, i.e., the assumption of pure Coulomb interaction is valid. Measurements at higher energies allowed determination of this critical threshold in our experiment—10.3 and 15.4 MeV for the target nuclei ^{58}Ni and ^{120}Sn, respectively. As an example, the scattering on ^{120}Sn at 16 MeV is shown in Fig. 2, where the onset of Coulomb-nuclear interference becomes visible.

The total errors quoted in Table I were obtained from the error matrix of the fitting procedure, including systematic sources which originate from the evaluation of the spectra and from the determination of angles, energies, and the beam polarization. Furthermore, also considered are uncertainties of the analysis due to numerics, and the neglect of additional nuclear states in target and projectile, and of other sub-Coulomb contributions such as $M1$ interference, vacuum polarization, atomic screening, and relativistic effects.[22] However, compared to the statistical errors, all of these processes have small effect on the analyzing powers.

Our result for Q_s is in excellent agreement with the value $Q_s = -3.66 \pm 0.03$ $e\cdot\mathrm{fm}^2$ deduced by Green from molecular spectroscopy data on ^{7}LiH.[4] Very recent studies[3] on the electric field gradient in ^{7}LiH claim that the earlier Hartree-Fock calculations of Green contain substantial basis-set truncation errors, and favor a significantly larger quadrupole moment of -4.06 $e\cdot\mathrm{fm}^2$. Earlier measurements (Egelhof *et al.*,[15] -3.4 ± 0.6 $e\cdot\mathrm{fm}^2$, and Orth, Ackerman, and Otten,[9] -4.1 ± 0.6 $e\cdot\mathrm{fm}^2$) are not accurate enough for a clear-cut decision!

Data from other experiments, yielding results on more than one quantity at the same time, are listed together with theoretical predictions in Table I. The values obtained by Häusser *et al.*[11] agree favorably with the present ones, whereas those of Bamberger *et al.*[12] and Vermeer *et al.*[10] seem to disagree. However, this inconsistency turns out to be artificial only, if considered in connection with the strong correlation between $B(E2)$ and the tensor moment τ_{12} of the polarizability. The important role of the polarizability is most easily seen by setting τ_{11} and τ_{12} in the present analysis to equal zero. A corresponding fit then results in $Q_s = -3.90$ $e\cdot\mathrm{fm}^2$ and $B(E2) = 6.92$ $e^2\cdot\mathrm{fm}^4$!

Theoretically, several recent cluster and shell-model calculations reproduce the measured value of Q_s quite well (Table I and Kanada, Liu, and Tang,[23] -3.70 $e\cdot\mathrm{fm}^2$). At the same time, however, such calculations tend to underestimate the actual $B(E2)$ value (Table I and Walliser *et al.*,[24] 7.55 $e^2\cdot\mathrm{fm}^4$). It is a pity that most of the theoretical studies do not try to give a unified description of the ground-state properties of ^{7}Li as a whole. Kajino, Matsuse, and Arima[7] recently presented an investigation within this spirit (but without a discussion of the polarizability). They found

TABLE I. Results of the present experiment and selected previous ones in comparison with theoretical predictions (last three rows).

	Q_s ($e\cdot\mathrm{fm}^2$)	$B(E2)$ ($e^2\cdot\mathrm{fm}^4$)	τ_{12} (fm^3)	τ_{11} (fm^3)
Present experiment	-3.70 ± 0.08	8.3 ± 0.5	0.23 ± 0.06	0.23 ± 0.06
Bamberger *et al.* (Ref. 12)	-1.0 ± 2.0	7.4 ± 0.1	0.1^a	· · ·
Häusser *et al.* (Ref. 11)	-3.66^b	8.3 ± 0.6	0.21 ± 0.03	· · ·
Vermeer *et al.* (Ref. 10)	-4.0 ± 1.1	7.42 ± 0.14	0.15 ± 0.01	· · ·
Bouten and Bouten (Ref. 20)	-3.62	6.26	· · ·	· · ·
Kajino *et al.*[c] (Ref. 7)	-3.50	6.61	· · ·	· · ·
Mertelmeier and Hofmann (Ref. 21)	-3.71	6.80	· · ·	· · ·

[a]Theoretical estimate (Ref. 13).
[b]Assumed value.
[c]With modified-Hasegawa-Nagata effective interaction (Ref. 7).

for various effective nucleon-nucleon potentials entering their calculations roughly a linear relation between Q_s and $B(E2)$. The results of the present experiment are slightly beyond the range of this relation.

The influence of the polarizability of ^{7}Li has been found experimentally to be surprisingly large. Models which attribute it to a virtual excitation of the giant dipole resonance fail by at least half an order of magnitude.[25] It may be concluded that the main contribution to the polarizability is not connected with the giant dipole resonance. Because of the very low-lying α-t threshold of ^{7}Li, virtual breakup into the α-t continuum, as proposed first by Smilansky, Povh, and Traxel,[13] seems more likely to be a proper explanation. Further model calculations are highly desirable to clarify this point.

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$$\tau_{12}=\left(\frac{20}{81\pi^3}\right)^{1/2}\frac{\hbar c}{r_0^2}\frac{Ak_0}{Ze}\langle I_1||M(E2)||I_2\rangle k,$$

where $r_0=1.2$ fm and $k_0=3.5\mu_B$/MeV.

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