Coulomb Excitation of ^{8}Li

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We have observed the excitation of the first excited state ($E_x = 0.98$ MeV, $J^\pi = 1^+$) of the radioactive, neutron-rich nucleus ^{8}Li ($J^\pi_{\text{g.s.}} = 2^+$) from its inelastic scattering on $^{\text{nat}}$Ni at $E(^8\text{Li}) \simeq 14.6$ MeV. Cross sections measured out to large $\theta_{\text{c.m.}}$ agree well with Coulomb-excitation probabilities and have been used to deduce an $E2\uparrow$ transition rate for the $2^+_{\text{g.s.}} \rightarrow 1^+$ excitation in ^{8}Li*. The latter [$B(E2\uparrow) = 55 \pm 15$ e^2fm^4] is large relative to nearby stable nuclei, but comparable to the neighboring neutron-rich nucleus ^{10}Be. The relevance of the data to predicted "neutron-halo" giant dipole resonances in unstable nuclear projectiles is considered.

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Coulomb excitation (COULEX) is a proven method[1,2] for studying electromagnetic transition strengths in nuclei. Suzuki, Ikeda, and Sato[3] have predicted the existence of new types of such transitions, i.e., those from the splitting of the $E1$ giant dipole resonance due to excess "halo" nucleons in neutron-rich or proton-rich nuclei (high T_z). The large disassociation cross sections observed for ^{11}Li may be related to such excitations.[4] Coulomb excitation of high-T_z projectiles should be a powerful method of exciting and observing these new modes of excitation since projectile COULEX is highly favored in scattering from a high-Z stable target (by a factor of $Z^2_{\text{tgt}}/Z^2_{\text{proj}}$). Also, $E\lambda$ excitations, in particular the $E1$ giant dipole resonance, are greatly enhanced and can exhibit very large cross sections and λ-dependent angular distributions.[1,2]

We have studied the scattering of a beam of the neutron-rich β-unstable nucleus ^{8}Li from $^{\text{nat}}$Ni with emphasis on observing COULEX of the ^{8}Li projectile. At $E(^8\text{Li}) \simeq 14.6$ MeV we have measured the nuclear grazing angle to be at $\theta_{\text{c.m.}} \gtrsim 90°$. Hence, the inelastic excitation data at $\theta_{\text{c.m.}} < 90°$ should be dominated by COULEX, as also verified by subsequent distorted-wave Born-approximation (DWBA) calculations.

The nucleus ^{8}Li has a ground-state (g.s.) spin $J^\pi = 2^+$, while the first excited level, which is particle stable,[5] has $J^\pi = 1^+$. Thus $M1$, $E2$, and $M3$ excitations are allowed, with $E2\uparrow$ strongly favored. In contrast, the known γ decay of ^{8}Li$^*_{0.98}$ is primarily via an $M1$ transition,[5] but with a small $B(M1\downarrow) \approx 3$ Weisskopf units (W.u.) ($\tau = 12$ fs).

The experiments were performed using an angle-resolved and energy-resolved 14.3–14.9-MeV ^{8}Li beam from the University of Michigan–University of Notre Dame radioactive-nuclear-beam (RNB) facility.[6–8] Typically the energy resolution was 400–500 keV FWHM, the beam spot diameter was about 5 mm, the angular divergence of the beam was ±4°, and its intensity was 10^5–10^7 sec^{-1}. The measurements were made using a very pure and uniform 1.1-mg/cm^2 $^{\text{nat}}$Ni target. Cross sections were normalized to ^{8}Li+Au Rutherford scattering using thin (0.5–0.9-mg/cm^2) Au targets of known thicknesses.

Although our apparatus (a superconducting solenoid) has a relatively narrow ^{8}Li energy bandpass, there is the possibility of excitation of the ^{8}Li in the primary production reaction ($^7\text{Li} + {}^9\text{Be} \rightarrow {}^8\text{Li} + {}^8\text{Be}_{\text{g.s.}}$) resulting in a satellite peak approximately 1 MeV below the main ^{8}Li beam group. This limited an earlier attempt[9] to observe ^{8}Li$^*_{0.98}$+Au COULEX cleanly. In order to limit the amount of ^{8}Li$^*_{0.98}$ in the secondary beam, we developed an adjustable z-axis block which can be situated to eliminate almost all of the ^{8}Li$^*_{0.98}$ produced at the primary target. Nonetheless, one still needs to make direct measurements of the ^{8}Li beam-energy profile, which is done using elastic scattering at $\theta_{\text{lab}} \lesssim 30°$ from high-purity Au and Ni targets. One can then adjust the movable block to insure that $\ll 1\%$ of the beam occurs 1 MeV below the beam centroid energy. For example, the forward-angle spectra from $^{\text{nat}}$Ni (Figs. 1 and 2; Table I) exhibit only a small low-energy tail ($< 0.3\%$). In contrast, ^{8}Li+Ni spectra taken at $\theta_{\text{c.m.}} \gtrsim 45°$ exhibit events at an excitation energy expected for ^{8}Li$^*_{0.98}$, and in some cases that of ^{58,60}Ni* ($E_x \simeq 1.2$–1.4 MeV). Since we are observing an excited projectile which decays in flight with a mean lifetime of 12 fs, the velocity (and therefore energy) spectrum will be Doppler broadened and shifted. However, this effect should only contribute about 80 keV to the broadening, which is much less than

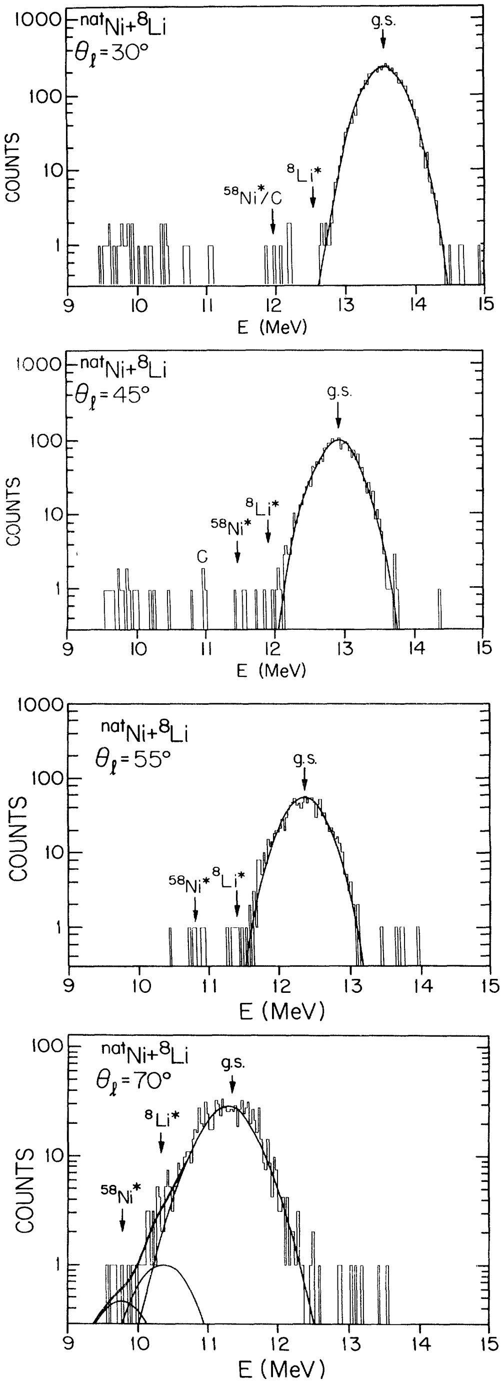

FIG. 1. ${}^8\mathrm{Li}+{}^{\mathrm{nat}}\mathrm{Ni}$ elastic- and inelastic-scattering spectra at $E({}^8\mathrm{Li}) \simeq 14.6$ MeV for the laboratory angles indicated. The curves shown are fits to the elastic and, at $\theta_{\mathrm{lab}}=70°$, the inelastic ${}^8\mathrm{Li}$ groups using the $\theta_{\mathrm{lab}}=30°$ elastic line shape (see text).

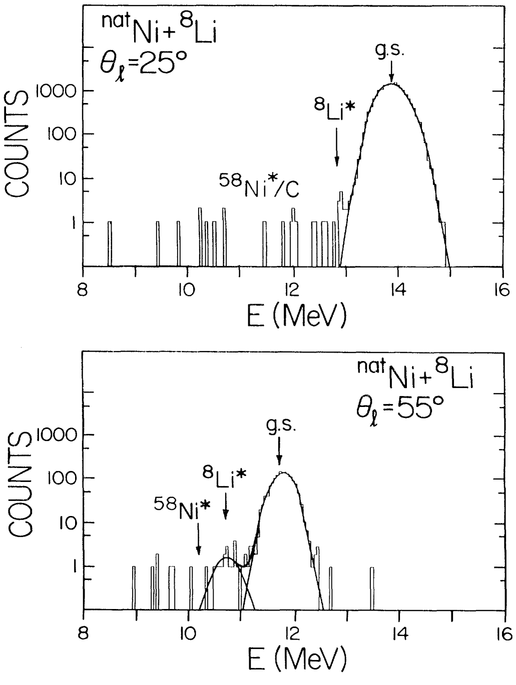

FIG. 2. Data and line-shape fits, similar to those displayed in Fig. 1, at forward and backward angles taken simultaneously using two small-aperture, good-energy-resolution Si detector telescopes.

our beam-energy resolution of 400–500 keV (FWHM).

Experiments were done during two different running periods utilizing two different detector configurations. The first set of measurements[10] (Fig. 1) used a single large-aperture, modest-energy-resolution ΔE-E-XY position-sensitive detector telescope[6–8] while the later measurements (Fig. 2) used two, small-aperture ΔE-E telescopes having better energy resolution. The latter dual-telescope configuration gave simultaneously accurate monitoring of the beam profile via forward-angle Rutherford scattering, along with measurement of large-angle COULEX (Fig. 2).

Data from the first set of measurements (Table I, detector A) were analyzed by fitting empirical or analytical (Gaussian) line shapes to the most forward-angle g.s. elastic peaks where excitation of ${}^8\mathrm{Li}^*_{0.98}$ should be negligible, i.e., at $\theta_{\mathrm{lab}} < 30°$ (Fig. 1; Table I). This line shape is determined primarily by the energy distribution of the secondary ${}^8\mathrm{Li}$ beam, with smaller contributions from the detector energy resolution and the energy spread in the target. Thus, this *same* line shape provides an excellent fit to the g.s. peak at $\theta_{\mathrm{lab}}=45°$ and 55°. It also yields good fits at $\theta_{\mathrm{lab}}=70°$ (Fig. 1), provided that the g.s. linewidth is slightly increased to account for tilting of the Ni target and hence a slightly increased ${}^8\mathrm{Li}$ energy spread. After fitting the g.s. peak, one observes a statistically significant excess of events at $E_x = 1 \pm 0.1$ MeV which increases with increasing θ_{lab} and cannot be attributed to Ni* (Fig. 1). The excitation probabilities, $P(\theta) \equiv \sigma_{\mathrm{inel}}(\theta)/\sigma_{\mathrm{el}}(\theta)$, deduced from either the excess events observed or the line-shape fits, are consistent with each other and are given in Table I along with the ap-

TABLE I. Excitation probabilities: $^8\mathrm{Li}^*_{0.98}+\mathrm{Ni}$; $E_{\mathrm{lab}}(^8\mathrm{Li})=14.6$ MeV. Energy at target center (1.1 ± 0.1 mg/cm^2 $^{\mathrm{nat}}\mathrm{Ni}$).

θ_{lab} (deg)	$\theta_{\mathrm{c.m.}}$ (deg)	σ/σ_R [a]	$P(\theta)$ [b] (%)	Detector telescope[c]
15	17	1.0 ± 0.1	<0.25	B
20	22	1.0 ± 0.1	<0.3	A
25	27	1.1 ± 0.1	<0.3	B
30	33	0.9 ± 0.1	<0.18	A
45	50	0.83 ± 0.15	0.50 ± 0.15	A
45	50	1.03 ± 0.15	<1.2	C
Ave.		0.93 ± 0.10	0.50 ± 0.15	$A+C$
55	61	0.98 ± 0.15	1.0 ± 0.3	A
55	61	1.01 ± 0.15	1.2 ± 0.3	C
Ave.		0.99 ± 0.10	1.1 ± 0.2	$A+C$
62	69	0.95 ± 0.15	d	A
70	77	0.91 ± 0.15	2.4 ± 1.2	A
90	98	0.56 ± 0.10	d	A

[a] Measured ratio to Rutherford elastic scattering, normalized to $^8\mathrm{Li}+\mathrm{Au}$ scattering and forward-angle $^8\mathrm{Li}+\mathrm{Ni}$ scattering where it is assumed $\sigma/\sigma_R=1.0$.

[b] Mean excitation probability deduced from fits to g.s. and region at $E_x\simeq0.98$ MeV.

[c] Various ΔE-E detector telescopes used in the measurements (see text).

[d] Measurement of elastic scattering only; insufficient statistics for accurate $P(\theta)$ determination.

propriate uncertainties.

Likewise, the second set of measurements (Fig. 2) were analyzed in a similar fashion and yield the results displayed in Table I (detectors B and C). These agree well with the earlier measurements (detector A), in particular at $\theta_{\mathrm{lab}}=55°$ where the group at $E_x\simeq1$ MeV is cleanly resolved (Fig. 2).

The averaged inelastic excitation probabilities deduced for the $^8\mathrm{Li}^*$ group are shown in Fig. 3. They are seen to peak, if at all, for $\theta_{\mathrm{c.m.}}>55°$, as expected for either an $M1$ or $E2$ transition,[1,2] although an $M1$ transition would have its maximum at $\theta_{\mathrm{c.m.}}<180°$. We have done both classical COULEX (Refs. 1 and 2) and DWBA COULEX calculations, the latter including a small contribution from nuclear excitation. Assuming that $M1$ excitation is small[1,2] relative to $E2$ excitation, normalization of these calculations to the measured $P(\theta)$ yields $B(E2\uparrow)=55\pm15$ $e^2\mathrm{fm}^4$. In addition, large-angle spectra taken for $^8\mathrm{Li}+\mathrm{Au}$ at $E_x\simeq1$ MeV set an upper limit for $B(E2\uparrow)$ of $^8\mathrm{Li}^*\leq120$ $e^2\mathrm{fm}^4$ which is compatible with the $^8\mathrm{Li}+\mathrm{Ni}$ results. We note that the former $B(E2\uparrow)$ implies a transition strength of about 50 W.u.

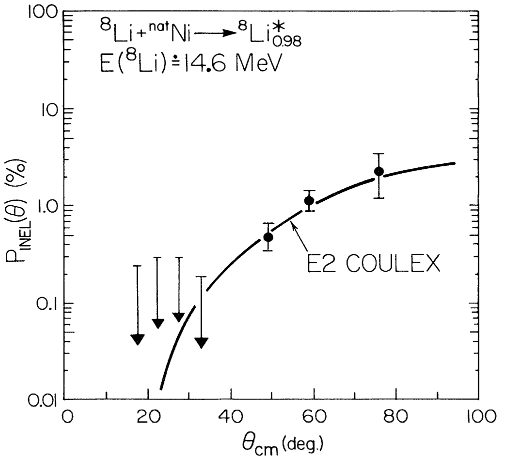

FIG. 3. Observed inelastic excitation probability (Table I) as a function of $\theta_{\mathrm{c.m.}}$ for the $^8\mathrm{Li}^*_{0.98}$ group seen in the $^8\mathrm{Li}+{}^{\mathrm{nat}}\mathrm{Ni}$ spectra. The curve is an $E2$ COULEX calculation with $B(E2\uparrow)$ adjusted to fit the data (see text).

There are also indications of COULEX of the $^{58,60,62}\mathrm{Ni}$ $J^\pi=2^+$ levels in the $^8\mathrm{Li}+{}^{\mathrm{nat}}\mathrm{Ni}$ spectra (Figs. 1 and 2). The statistics of these measurements (due to the $Z^2_{\mathrm{proj}}/Z^2_{\mathrm{tgt}}$ suppression of target excitation), and background of 0.2%–0.5% in this excitation region, only allow one to confirm that the $B(E2\uparrow)$ values for these nuclei are in the range 500–2000 $e^2\mathrm{fm}^4$. These limits are consistent with the known values of 700–900 $e^2\mathrm{fm}^4$.

A conventional shell-model calculation[11] using effective charges and parameters appropriate for $A=4$–12 yields $B(E2\uparrow)=2.9$ $e^2\mathrm{fm}^4$. Hence, even more so than for $^7\mathrm{Li}$ [where[12] the measured $B(E2\uparrow)=8$ $e^2\mathrm{fm}^4$], $^8\mathrm{Li}$ apparently exhibits a strongly enhanced $B(E2\uparrow)$ relative to the predicted shell-model value. In this respect $^8\mathrm{Li}$ appears to be similar[5] to $^{10}\mathrm{Be}$, a nearby high-T_z nucleus, which also exhibits a strongly enhanced $B(E2\uparrow)$ ($\simeq50$ $e^2\mathrm{fm}^4$), as deduced from γ decay studies. However, a $2^+_{\mathrm{g.s.}}\rightarrow1^+$ transition ($^8\mathrm{Li}$) should be suppressed (by $\geq60\%$) relative to a $0^+_{\mathrm{g.s.}}\rightarrow2^+$ transition ($^{10}\mathrm{Be}$) due to the spin and Z_{proj} factors involved.[1,2] While one might thus expect a $^8\mathrm{Li}$ $B(E2\uparrow)$ of ≤30 $e^2\mathrm{fm}^4$, it should be noted that the nucleus ^{8}Li ($N/Z=5/3$) is more neutron rich than ^{10}Be ($N/Z=6/4$) which might enhance the transition probability. It is, in fact, the most neutron-rich projectile for which COULEX to a particle-stable level has been observed. In addition, low-lying $E1$ excitations, including those to particle-unstable levels, could affect the observed $2^+_{\text{g.s.}} \rightarrow 1^+$ rate. In most situations, this is a small but observable effect of a few percent,[11] which can become significant[12] in light nuclei such as ^{6}Li. It usually acts to reduce $B(E2\uparrow)$ but this may not necessarily be the case in high-T_z nuclei, where the giant dipole resonance (GDR) may have unusual low-lying components.[3] In contrast, the known[5] g.s. quadrupole moment of ^{8}Li implies a relatively small reorientation effect.[1,2,12]

Although ^{8}Li* is unstable to neutron emission for excitation energies above 2 MeV, the region $E_x=1.5$–2.0 MeV (Figs. 1 and 2) could conceivably contain low-lying fragments of the predicted GDR $E1$ excitations.[3] We can set a limit of $B(E1\uparrow) \leq 0.2\ e^2\text{fm}^2/\text{MeV}$ for this region of excitation from classical or DWBA COULEX calculations.[1,2] These limits can be compared with calculations[13] for low-lying $E1$ excitations in ^{11}Li which predict $B(E1\uparrow) \sim 0.1\ e^2\text{fm}^2/\text{MeV}$.

In addition to the COULEX measurements reported here, we have also observed ^{8}Li inelastic scattering in $^8\text{Li}+{}^{12}\text{C}$ at $E=14$ MeV. These results, which confirm those presented here, will be reported elsewhere.[14]

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