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Lifetimes, Energies, and Branching Ratios of ^{28}Si Excited States

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The γ decay of ^{28}Si energy levels excited in the ^{27}Al$(p,\gamma)^{28}$Si reaction has been investigated with a 20-cm^3 Ge(Li) detector. Energies of levels below 7 MeV have been measured to an accuracy of <1 keV by comparison with the ^{56}Co spectrum. The 6878-keV 3^- and 6889-keV 4^+ doublet is found to be split by 10.9 ± 0.5 keV; decay of the 6878-keV state to the 4617-keV level has been definitely established. Several branching ratios have been measured for the first time, or with improved accuracy. Mean lifetimes of excited states have been derived from observed γ-ray Doppler shifts, with the following results: 4617 keV (0.061 ± 0.004 psec), 7380 keV (0.013 ± 0.003 psec), 7416 keV (0.040 ± 0.003 psec), 8260 keV (0.014 ± 0.006 psec), 8588 keV (0.025 ± 0.005 psec), 9163 keV (0.039 ± 0.005 psec), 9316 keV (<0.01 psec), and 10 213 keV (0.015 ± 0.007 psec); previously published lifetimes have been confirmed for levels at 1779, 6276, 6878, 7798, and 8413 keV. A probable spin-parity assignment of 2^+ is made for the 9163-keV state. The small $E2$ transition strengths from the level at 7416 keV to the ground and first excited states are consistent with Hartree-Fock predictions that this is the 2^+ member of a rotational band whose ground state is the 6.68 (0^+) level.

I. INTRODUCTION

RECENT theoretical work on the ^{28}Si level scheme has included particle-hole calculations,[1] an approach based on the SU_3 classification scheme,[2] and Hartree-Fock calculations.[3,4] Results do not agree well with existing experimental information. The need for additional, accurate measurements is apparent, so that future refined calculations can be tested. The experimental situation up to 1967 is summarized by Endt and Van der Leun.[5]

The present work was undertaken to establish ^{28}Si level energies with improved accuracy, to determine branching ratios and decay modes, and, in particular, to investigate electromagnetic decay rates of states up to ~ 10 MeV. Large-volume Ge(Li) detectors now make possible the study of γ-ray spectra from (p,γ) resonances at high resolution. The accuracy of energy measurements often makes it possible to establish decay schemes from singles spectra, relying on energy sums rather than coincidence measurements. We have measured γ-ray spectra for six strongly excited resonances from 1262 to 2319 keV in the ^{27}Al$(p,\gamma)^{28}$Si reaction, all of which populate a large number of ^{28}Si levels.

The lifetimes of excited states were determined using the Doppler-shift attenuation method (DSAM).[6,7] The relatively small nuclear recoil velocity in this reaction results in nuclear scattering having a greater effect on the γ-ray Doppler shift than atomic scattering. Energy loss and mean multiple scattering angle due to nuclear collisions were calculated on the basis of the work of Lindhard *et al.*[8] and Blaugrund.[9] The resonances at $Ep=1451$ and 1589 keV were chosen for the Doppler-shift measurements in order to strongly populate a large number of levels.

II. EXPERIMENTAL PROCEDURE

A. General

The proton beam from the University of Oregon 4-MeV Van de Graaff is analyzed by a homogeneous-field deflecting magnet and defined at the magnet exit by adjustable, water-cooled slits. Stability at resonance is usually better than 1 part in 2000. Quadrupole doublets are located both at the entrance to the magnet and after the exit slits to permit tight focusing of the beam onto the target. The proton beam passes through collimating apertures and an 8-in.-long liquid-nitrogen cold trap before it strikes the target. The number of protons hitting the target is measured with a beam-current integrator. The target area is shielded on the top and all sides by 16-in.-thick walls of solid concrete blocks. Furthermore, the main experimental area is separated from the accelerator and analyzing magnet by a 24-in. concrete wall.

Thin aluminum targets were prepared by evaporation onto 0.04-cm-thick gold backings. The use of high-purity gold backings instead of tantalum backings employed previously reduced the 6129.3 ± 0.4 keV ^{19}F$(p,\alpha\gamma)^{16}$O γ ray[10] to the point where it usually was not observed. Direct water cooling of the targets permitted currents of greater than 10 μA for periods of 24 h or longer without noticeable target deterioration. The liquid-nitrogen cold trap located directly in front of the target has helped considerably in reducing background due to buildup of contaminants. No

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evidence of the 2367-keV $^{12}C(p,\gamma)^{13}N$ γ ray has ever been found in our Ge(Li) spectra.

B. γ-ray Spectra

A 20-cm^3 Ge(Li) detector,[11] reverse-biased at -2450 V, was used to detect γ rays for the resonance spectra and Doppler-shift measurements. The electronics consisted of a Tennelec TC-130 FET preamplifier, TC-200 main amplifier, TC-250 postamplifier, and a Nuclear Data ND-161 4096-channel analog-to-digital converter. Data were collected with the aid of a PDP-7 computer. The resolution of the detector was 3.4 keV for the ^{60}Co γ rays and rose to about 13 keV for 10 000-keV γ rays. The peak-to-Compton ratio for the ^{60}Co γ rays is 12:1, and the double-to-single escape ratio is $(3.2\pm0.1){:}1$.

To determine γ-ray energies below 5 MeV, the spectrum from a ^{56}Co radioactive source was measured simultaneously with the resonance spectra. Most of the ^{56}Co lines are known to ±0.3 keV.[12] Including errors associated with the determination of peak centroids, over-all errors in measured line energies could therefore be kept to $<(\pm1$ keV). Whenever possible, single-escape and full-energy peaks were used along with the double-escape peaks in energy calibrations. Corrections were made for recoil effects and Doppler shifts. To determine γ-ray energies above 5 MeV, an internal calibration scheme utilizing the known Q value of the reaction was used. In the energy range from the (4497.1 ± 0.5)-keV line to the line which links the resonance state with the 1778.9-keV first excited state, the energy-versus-channel relation was approximated by a linear function with a quadratic correction. The correction was determined by comparison of cascade sums with the resonance–to–1778.9-keV transition energy.[13] An estimated over-all accuracy of better than ±4 keV was attained in this range.

The relative-efficiency curve for the 20-cm^3 Ge(Li) detector was established up to 3500 keV on the basis of the known ^{56}Co intensities.[12] At higher energies, the double-escape efficiency was determined using data from levels which are populated and decay by single transitions. The relative number of counts directly yields the relative efficiency. The efficiency curve found in this manner agrees well with that obtained by a Monte Carlo calculation for a 20-cm^3 detector.[14]

In the analysis of spectra, a peak-search routine written for the IBM 360/50 computer was employed. This program automatically locates all peaks in a spectrum, least-squares fits a Gaussian plus background to each peak, and computes centroids, peak widths, and peak areas after background subtraction.

C. Lifetime Measurements

The DSAM lifetime measurements were made with the 20-cm^3 Ge(Li) detector located at 0° and 120° relative to the incident-beam direction. A 7-keV-thick water-cooled target was used; this was more than sufficient to stop all ^{28}Si recoils. Typical measurements lasted 16–24 h at an average beam current of 10 μA. Data were recorded with the 4096-channel analyzer, at a conversion gain of 1 keV per channel. In many cases, the double-escape, single-escape, and full-energy peaks were used in determining the Doppler shifts. Lifetimes were then determined from the ratio $F(\tau)$ of observed Doppler shifts to the full shift which would be obtained for very short lifetimes or for recoil into a vacuum. Knowledge of the recoil velocity as a function of time in the slowing-down medium permits $F(\tau)$ to be calculated from the theoretical expression

$$F(\tau)=\frac{T}{\tau}\int_0^\infty\left[\exp\left(\frac{-\theta}{\tau/T}\right)\right]\left(\frac{V}{V_0}\right)\langle\cos\phi\rangle d\theta\,. \tag{1}$$

Here, θ and V are dimensionless variables corresponding to time and velocity, T is a constant for each stopping medium, and $\langle\cos\phi\rangle$ is the mean recoil multiple scattering angle. All quantities are as defined by Blaugrund.[9] In the numerical evaluation of $F(\tau)$ the energy-loss curve due to nuclear collisions as given by Lindhard *et al.* was approximated by seven straight lines.

Errors in the analysis are caused by the uncertainty in peak centroid determinations and by the uncertainty in the determination of zero and gain shifts between measurements at two different angles. The centroid error was identified with the standard deviation of the corresponding parameter in the least-squares fitting of the γ-ray peak. The zero and gain shift corrections were found from the measured apparent shifts of γ rays that are known to be unshifted in energy (such as ^{56}Co peaks), and from shifts of peaks whose lifetime is so short as to give a full Doppler shift (e.g., resonance transitions). The error was then associated with the average deviation of these points from the least-squares-fitted correction curve.

III. RESULTS

Resonance γ-ray spectra were obtained for the $^{27}Al(p,\gamma)^{28}Si$ reaction at the 1262-, 1451-, 1589-, 1978-, 2212-, and 2319-keV resonances.[15] For preliminary information about the decay scheme at each resonance, a complete spectrum up to 12 MeV was recorded. Most spectra were measured with the Ge(Li) detector at 55° to the incident beam, 1.5 in. from the target. For precise energy measurements and better branching-ratio determinations, smaller portions of the spectra were expanded and accumulated. Data obtained during the

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TABLE I. Relative intensity of γ-rays in the decay of resonant states.[a]

Transition from the resonant state to the final state (keV)	Resonant-state energy (keV) 1262	1451	1589	1978	2212	2319
1778.9	43	15	45	41	75	20
4617	6	11	22		7	10
6276	1.6	2	3.2	21	3.0	17
6878	32		6	14		
6889	1.8					
7380			7	4	1.4	27
7416	7		1.7	4	1.9	
7798		8	1.0		<0.9	2.6
7935	0.5			2	0.4	
8260			1.6			5
8413	1.8	3	2.4			
8588		12	0.8	6	5.0	3.4
9163			3.4	4	3.3	8
9316	1.3	49	0.9	<3		
9382	0.7					
9415					<2.0	3.0
9482						4.0
10 213			5	4		
10 541		<0.5				
10 914	1.4					
11 076	2.9					

[a] Estimated over-all accuracy on resonant transitions is ±15%.

Doppler-shift measurements were also utilized in the final intensity estimates. Measured decay modes and branching ratios for the six resonance levels are summarized in Table I. Yields for most resonances between 1262 and 2319 keV are summarized in Table II. Values were normalized to $(2J+1)\Gamma_p\Gamma_\gamma/\Gamma=40$ eV for the 991.82-keV resonance.[5]

A typical expanded γ-ray spectrum is shown in Fig. 1. The gain was set at ~1 keV per channel in order to take full advantage of the detector resolution and to bring out the finer details of the lower-energy γ rays. The resolution is about 8 keV at 4100 keV, as can be seen from the inset of the 5099- and 5110-keV double-escape peaks. The insets show the interesting 5100-keV doublet[16,17] and the 1658.9-keV transition between the states at 6276 and 4617 keV. The 1368-keV γ ray from the ^{27}Al$(p,\alpha\gamma)^{24}$Mg reaction confirms the well-established 3^- character of this $Ep=1262$-keV resonance level.[16,18] The decay scheme for this resonance, shown in Fig. 2, includes the γ-ray energies and excited-state branching ratios found in the present work.

TABLE II. Resonance yields measured in the ^{27}Al$(p,\gamma)^{28}$Si reaction between 1262 and 2319 keV.

Ep[a] (keV)	$(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$[b] (eV)	Ep[a] (keV)	$(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$[b] (eV)
1262.2	14	1647	1.1
1276	1.7	1669	20
1316.88	20	1680	3.0
1328.1	4.0	1726	27
1363.72	21	1746	2.5
1381.3	57	1797	9.5
1388.4	39	1917	6.6
1451	4.3	1978	11
1499	2.5	2054	33
1514	17	2161	6.2
1568	0.7	2195	3.6
1571	2.4	2212	43
1589	15	2319	15

[a] Energies listed for the first seven resonances are from the tabulation of Endt and Van der Leun (see Ref. 5); the others are from Antoufiev *et al.* (see Ref. 15).

[b] Errors associated with the resonance yields are estimated as ±30%.

The $Ep=1451$-keV resonance is interesting since it decays strongly to the lowest $T=1$ state[5] at 9316 keV. Figure 3 shows a spectrum covering the energy interval from 2500 to 8000 keV. This spectrum clearly shows the strong 3040- and 7537-keV transitions. Of special importance is the absence of a ground-state transition, which is crucial in establishing the spin of the 9316-keV state as 3^+; the 2^+ $T=1$ state then is at 9382 keV.[19] The inset illustrating the region where the double-escape peak for a 9316-keV γ ray would lie shows no evidence of a peak. We place an upper limit of 0.1% on this possible branching. The strong 3040-keV branching to the 6276-keV state has not previously been noted. The weak peak at 8762 keV in Fig. 3 was seen only at this resonance and may be due to a transition from a state at 10 541 keV to the 1779-keV level. However, this conclusion is tentative. A careful search for the corresponding 2445-keV primary γ ray was unsuccessful within statistics.

TABLE III. Energy of ^{28}Si levels.

Previous results[a] (keV)	Present work (keV)	Previous results[a] (keV)	Present work (keV)
1778.7±0.2	1778.9±0.2	8587± 8	8588±2
4614 ±6	4617.1±0.5	9167±10	9163±3
6272 ±6	6276.1±0.8	9319± 7	9316±3
6878 ±3	6878.3±1.0	9379±10	9382±4
6887 ±4	6889.2±1.0	9410±14	9415±4
7382 ±8	7380 ±2	9491±10	9482±4
7415 ±8	7416 ±2	···	10 213±4
7798 ±8	7798 ±2	···	10 541±6
7932 ±8	7935 ±3	10 909±10	10 914±3
8260 ±8	8260 ±2	11 089±10	11 076±3
8411 ±8	8413.4±1.0		

[a] Reference 5.

The existence of the level at 10 213 keV, which has not previously been reported, is confirmed by the presence of transitions into and out of it at two separate resonances.

A summary of the energy-level determinations from the present investigation is presented in Table III. The over-all agreement with previous results[5] is always within the stated errors. The error in the energy of the 8413-keV state is particularly small, because of the presence of the accurately determined 1535-keV branch-

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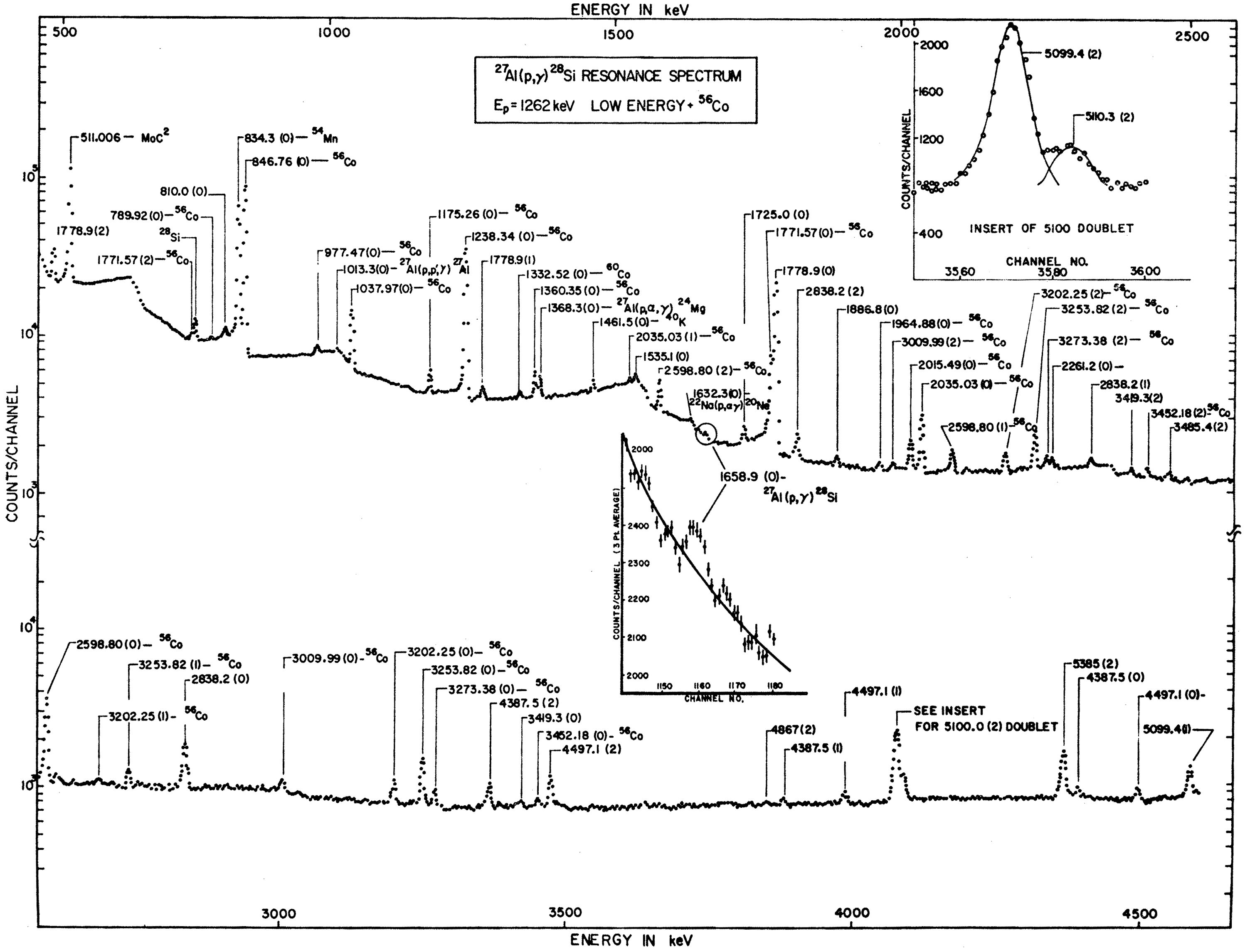

FIG. 1. Low-energy γ-ray spectrum obtained with a 20-cm³ Ge(Li) detector at the 1262-keV ^{27}Al(p,γ)^{28}Si resonance. Data were taken with a ND-4096 multichannel analyzer, with the amplifier gain set to give about 1 keV/ch. The detector was located at 55° to the incident beam, 1.5 in. from the target. Near the strong peaks, every point is plotted; elsewhere, a four-point average is used. Insets show the decay from the 6878–6889-keV doublet and the 1659-keV transition from the 6276- to the 4617-keV state. Contaminant γ rays and their origins are all labeled except for the 810-keV γ ray which may be due to neutron capture by the Ge(Li) detector.

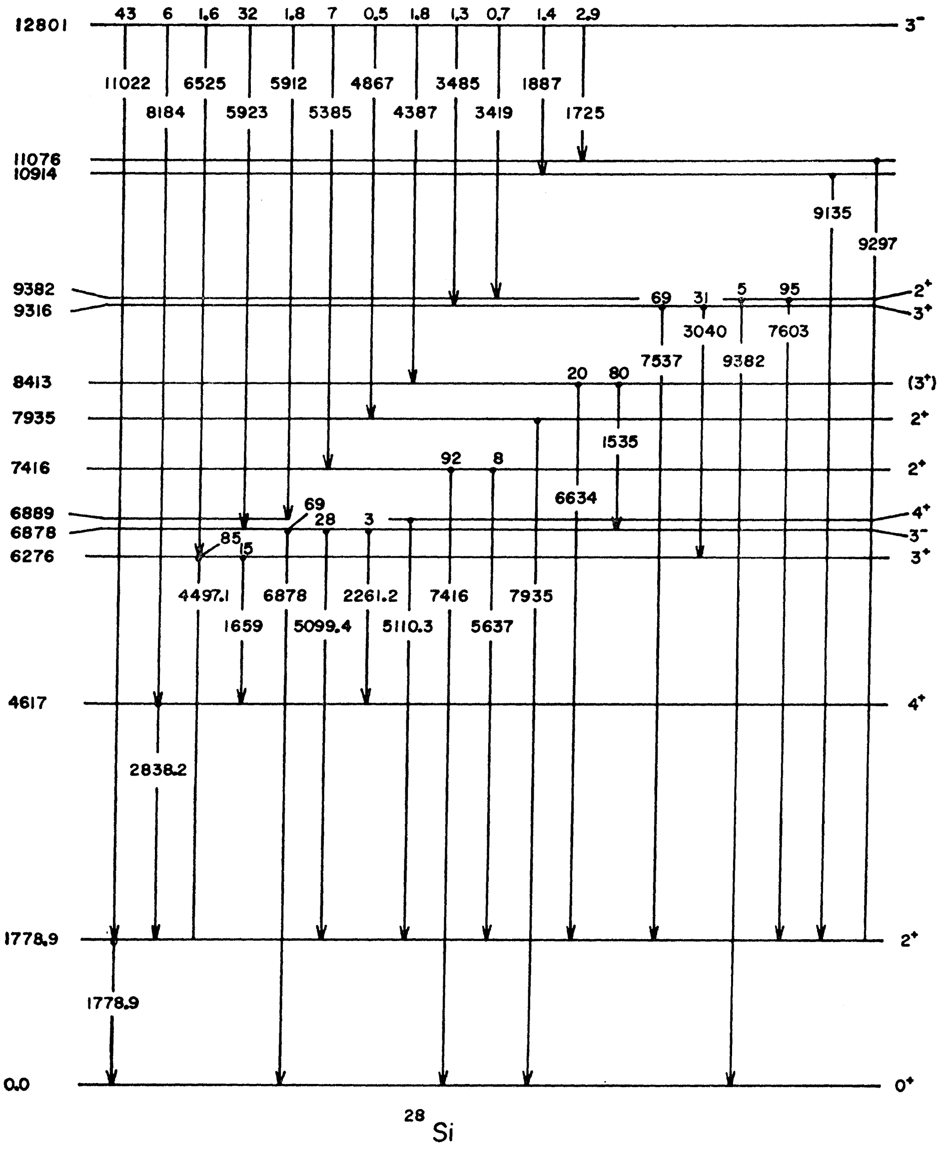

FIG. 2. γ-ray decay scheme for the levels populated in ^{28}Si at the $Ep=1262$-keV resonance in the ^{27}Al$(p,\gamma)^{28}$Si reaction. Indicated energies and branching ratios are best values obtained from studies of all resonances investigated.

ing to the 6878-keV state. The accuracy of the remaining levels above the 6878-keV state is smaller, because the calibration procedure was based on the (11 582.8±3.0)-keV Q value of the reaction.[20]

Table IV summarizes the branching ratios determined as the average of intensity results obtained from spectra taken at all six resonances plus the Doppler-shift spectra.

Lifetime measurements utilizing the DSAM were made at the $Ep=1451$- and 1589-keV resonances. The latter resonance was particularly useful, as is apparent from the decay scheme in Fig. 4. Thirteen lifetimes were measured at this resonance. Only the 6889-keV level could not be measured, because of the weakness of the 5110-keV transition. It was assumed throughout the analysis that the resonance-level lifetimes are short compared with those being measured, and the resonance transitions were used to correct for zero and gain shifts as noted in Sec. II C. In Fig. 5 typical data are shown for the Doppler shifts of the 6809-, 6843-, and 6878-keV γ rays; the relevant portion of the decay scheme is also indicated.

Lifetime results are summarized in Table V; they agree within error with earlier results tabulated by Endt and Van der Leun[5] for the levels at 1779, 6276, 6878, 7798, and 8413 keV. The present measurement of 0.061 ±0.004 psec for the 4617-keV second excited 4^+ level is in strong disagreement with the earlier value. A possible source of error in our measurement is the population of the 4617-keV state from states other than

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[20] T. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 32 (1965).

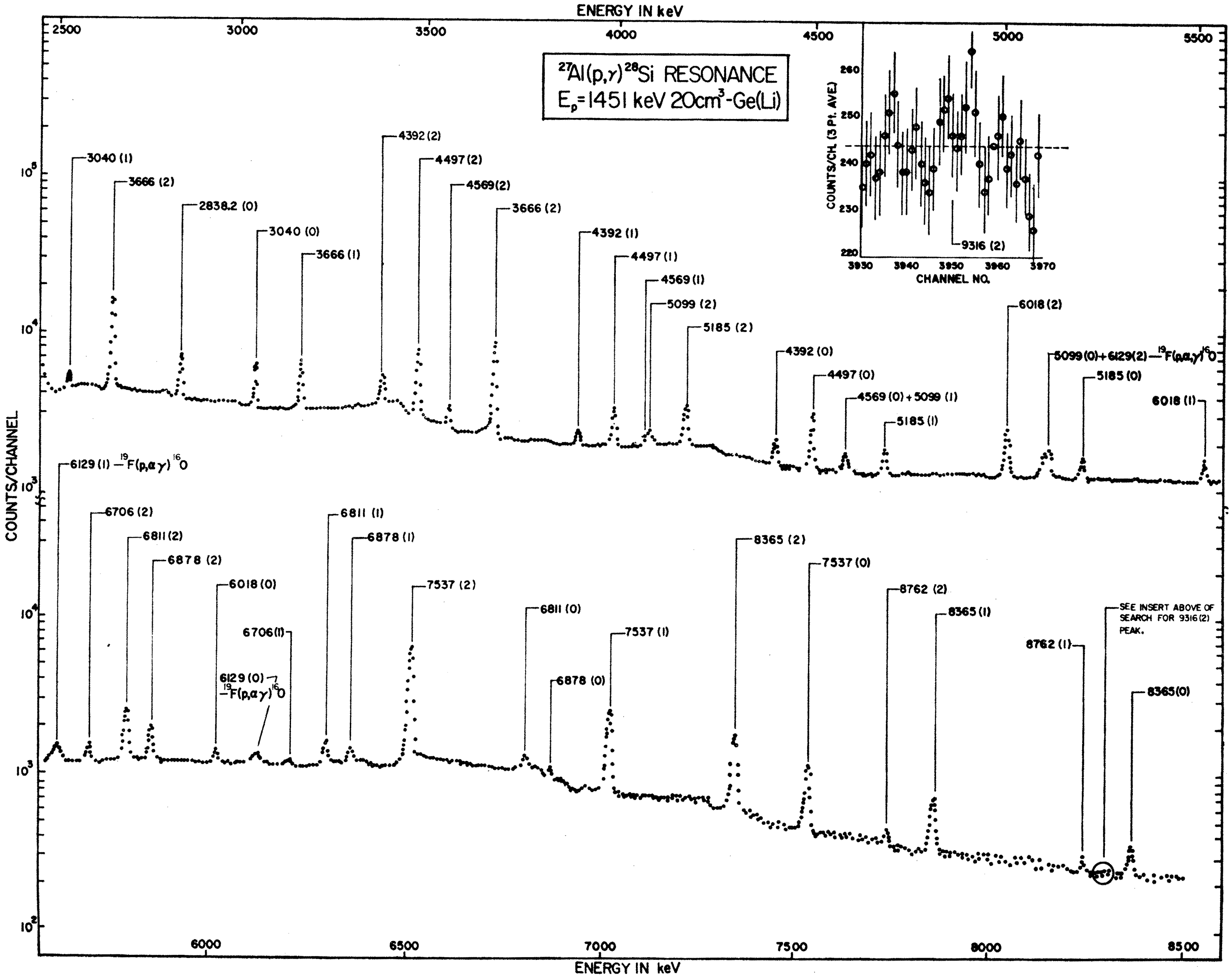

FIG. 3. γ-ray spectrum from 2500 to 8500 keV obtained at the $E_p = 1451$-keV resonance in the $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ reaction with amplifier gain set to about 1.5 keV/ch. Data were taken with a ND-4096 multichannel analyzer. The detector was located at 55° to the incident beam, 1.5 in. from the target. Near the strong peaks, every point is plotted; elsewhere, a four-point average is used. Of particular interest at this resonance is the strong population of the 9316-keV, $T=1$ state.

TABLE IV. Branching-ratio determinations for ^{28}Si levels.

Initial state (keV)	Final state (keV)	Previous results[a] (%)	Present work (%)	Initial state (keV)	Final state (keV)	Previous results[a] (%)	Present work (%)
6276	1779	90	85± 5	8588	G.S.	<5	<1
	4617	10	15± 5		1779	(80)	100
6878	G.S.	67	69± 4		4617		<5
	1779	33	28± 4		6276	(10)	<5
	4617	(2)[b]	3± 1		6878	(10)	<5
6889	1779	100	100	9163	G.S.		23±12
7380	G.S.	45	45± 4		1779		48±14
	1779	55	55± 4		4617		29±10
7416	G.S.	90	92_{-0}^{+8}	9316	G.S.	<2	<0.1
	1779	10	<8		1779	100	69± 5
7798	1779	67[c],75	79±10		4617		<1
	6276	33[c],25	21±10		6276		31± 5
7935	G.S.	80	100	9382	G.S.	5	<7
	1779	20	<25		1779	95	>93
8260	G.S.	20	<15	9415	G.S.		<10
	1779	80	100		1779		37±10
8413	G.S.	...	<4		4617	100[c]	63±10
	1779	8	20±10	9482	G.S.		100
	4617	4	<5		1779		<4
	6276	2	<5	10 213	G.S.		<15
	6878	86	80±10		1779		100

[a] Reference 5.
[b] R. Nordhagen and A. Tveter, Nucl. Phys. **63**, 529 (1965).
[c] R. E. Azuma, L. E. Carlson, A. M. Charlesworth, K. P. Lachson, N. Anyas-Weiss, and B. Lalonie, Can. J. Phys. **44**, 3075 (1966).

the resonance level, with correspondingly longer mean lives. In the case of the $Ep=1589$-keV resonance, for example, this would not have affected the present result since only about 7% of the transitions to the 4617-keV level do not originate at the resonance level. Furthermore, the effect of these other transitions is to increase the observed lifetime rather than to decrease it.

IV. DISCUSSION

The accurate energy measurements of the 5099.4- and 5110.3-keV γ rays, coupled with the known decay mode of the 6878-keV level to the ground and first excited state confirm that the 6889-keV 4^+ level lies above the 6878 3^- level.[21,22] The doublet separation is found to be 10.9±0.5 keV. The weak decay of the 6878-keV state to the level at 4617 keV is definitely established by the presence of the 2261.2-keV γ ray in the spectrum shown in Fig. 1. The sum of the 2261.2- and 2838.2-keV γ rays is also 5099.4±0.5 keV.

TABLE V. Lifetimes of ^{28}Si levels excited in the ^{27}Al$(p,\gamma)^{28}$Si reaction.

Level (keV)	J^π	$F(\tau)$[a] ($Ep=1451$ keV)	$F(\tau)$[a] ($Ep=1589$ keV)	Lifetimes (psec) Present[b]	Other[c]
1779	2^+		0.16 ±0.02	$0.58_{-0.09}^{+0.10}$	0.63 ±0.03
4617	4^+	0.61 ±0.15	0.74 ±0.02	0.061±0.004	0.175±0.035
6276	3^+	0.066±0.009	0.070±0.030	$1.35_{-0.17}^{+0.22}$	1.0 ±0.1
6878	3^-		0.042±0.008	$2.3_{-0.4}^{+0.6}$	2.0 ±0.3
7380	1^+		0.95 ±0.01	0.013±0.003	<0.3
7416	2^+		0.84 ±0.01	0.040±0.003	<0.01
7798	3^+	0.25 ±0.02	0.16 ±0.06	0.31 ±0.03	0.30 ±0.09
8260	1^-		0.94 ±0.02	0.014±0.006	<0.01
8413	(3^+)		0.29 ±0.07	$0.28_{-0.06}^{+0.10}$	0.23 ±0.05
8588	3^+	0.89 ±0.01	0.91 ±0.02	0.025±0.002	<0.01
9163	(2^+)		0.84 ±0.02	0.039±0.005	...
9316	3^+	>0.95		<0.01	...
10 213			0.94 ±0.01	0.015±0.007	...

[a] Errors associated with $F(\tau)$ measurements are due to uncertainties in centroid determinations and the correction for gain and zero shifts.
[b] Errors associated with the lifetime results are based on an assumed 15% uncertainty in the nuclear specific-energy-loss curve as well as the uncertainty in $F(\tau)$.
[c] Reference 5.

The γ decay of most of the states of ^{28}Si below 9 MeV has been reasonably well established.[5] Our results essentially confirm the earlier work, with improved estimates and limits given in some cases. New decay modes are presented for states at 9163, 9316, 9415, 9482, and 10 213 keV.

An interesting feature of the decay scheme for the $Ep=1262$-keV resonance is the population of four $T=1$ states. The states at 9316 and 9382 keV have been established[19] as the analogs of the ground and first excited states of ^{28}Al. The low-energy 1725- and 1887-keV γ rays most likely constitute transitions to the $T=1$ states at 11 076 and 10 914 keV.[5] To confirm this, a careful search was made for 9297- and 9135-keV γ rays which correspond to transitions from the two $T=1$ excited states to the 1778.9-keV first excited state; both were found.

The γ decay of the level at 9163 keV leads with almost equal intensities to the 0^+ ground state, the 2^+ first excited state, and the 4^+ second excited state. The measured lifetime of 0.039 psec and observed relative transition intensities imply that the spin of the 9163-

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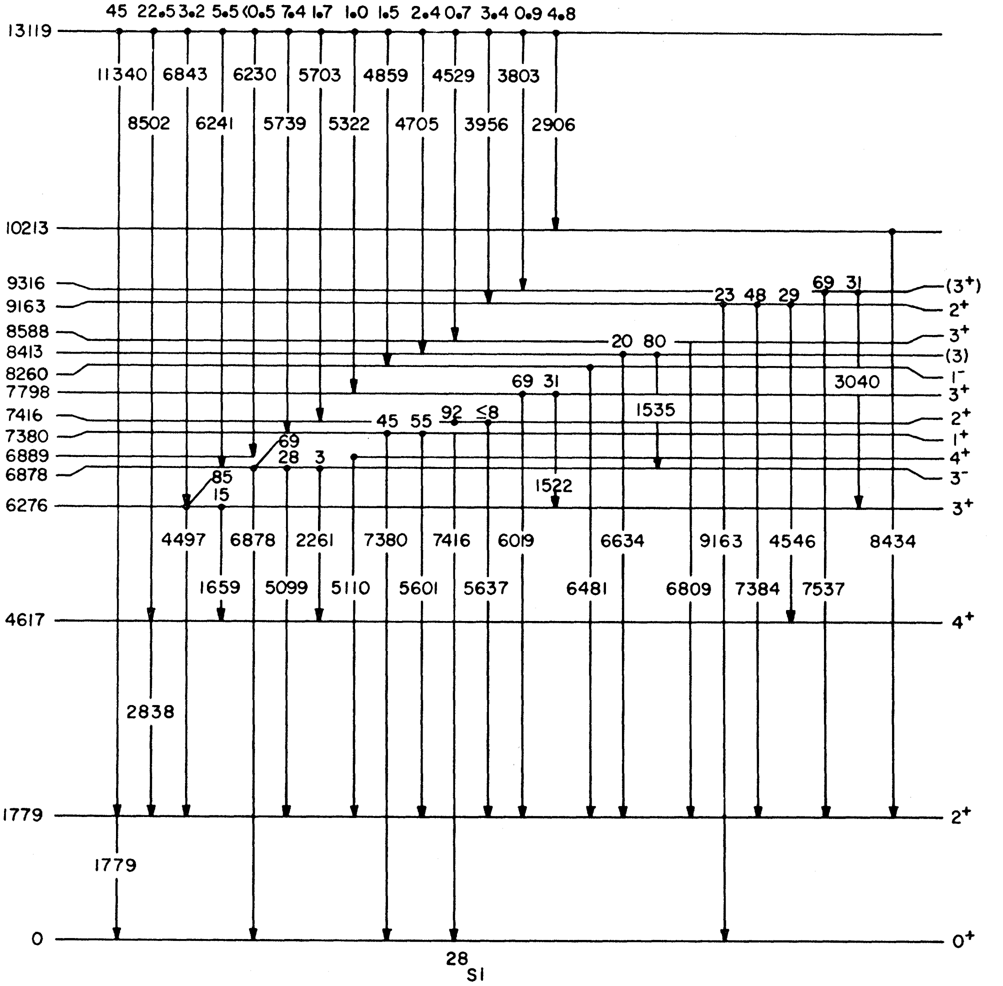

FIG. 4. Decay scheme for states excited in the ^{27}Al$(p,\gamma)^{28}$Si reaction at the $E_p=1589$-keV resonance. Indicated energies and branching ratios are best values obtained from studies at all resonances investigated. Lifetimes were measured for all but the 6889-keV level.

keV level must be 2: a higher spin would require an excessive strength for the transition to the ground state [40 Weisskopf units (WU) for $E3$ and 1.2×10^3 WU for $M3$], and a lower spin would require too great a strength for the transition to the 4^+ state (7×10^3 WU for $E3$ and 2.1×10^5 WU for $M3$). It appears likely that the parity of the 9163-keV level is even; in this case, the character of the transition to the 4617-keV 4^+ state is $E2$, with a strength of 0.61 WU (see Table VI), right in the average range of 0.1–1.0 WU for transitions in nuclei in the $A=20$–40 range[23]; an $M2$ transition would have to have a strength of ~18 WU, which is inconsistent with the average of about 0.1 WU.

Previous measurements have shown the parity of the 8413-keV level to be $(-)^{J+1}$,[5] where J is the level spin. The presence of transitions to the 1779-keV 2^+ first excited state and to the 6878-keV 3^- state indicates that 0^-, 1^+, 2^-, 3^+, 4^-, and 5^+ are possible J^π values. However, only $J^\pi=2^-$, 3^+, or 4^- are likely choices if transition strengths are considered. This is consistent with the tentative assignment of $J=3$ for this level from the ^{27}Al$(t,d)^{28}$Si reaction.[5]

The transitions from the first and second excited states of ^{28}Si are of considerable importance in testing the validity of various nuclear models. In Table VII, we summarize the theoretical results predicted by Hartree-Fock,[3] particle-hole,[1] and Davydov-Chaban[24] calculations. It is apparent that particle-hole calculations do not produce sufficient transition strength, as already noted by Farris and Eisenberg,[1] and a deformed Hartree-Fock potential is needed. The Davydov-Chaban model, included for comparison, yields ap-

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[24] A. S. Davydov and A. A. Chaban, Nucl. Phys. **20**, 449 (1960).

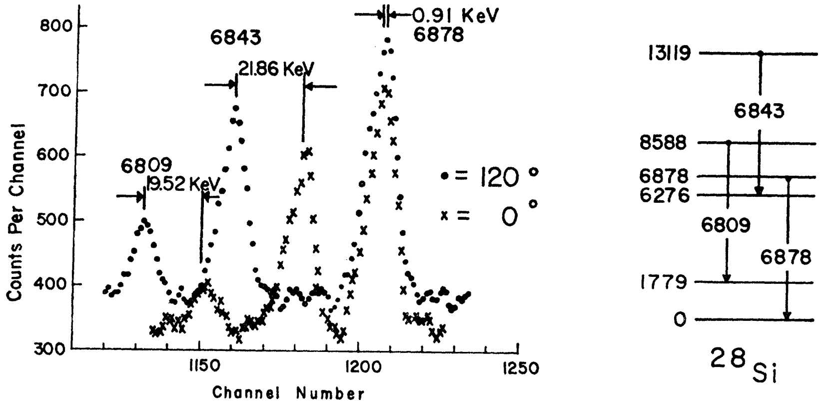

FIG. 5. Typical Doppler-shift data for the 6809-, 6843-, and 6878-keV γ rays. The Ge(Li) detector was located 2 in. from the target, at 0° and 120° relative to the incident-beam direction. The relevant portion of the decay scheme is indicated.

E_γ (keV)	Attenuated Doppler Shift (keV)	Full Doppler Shift (keV)	$f(\tau)$	Mean Lifetime (ps)
6811	19.52 ± .35	21.41	.91 ± .02	.023 ± .005
6843	21.86 ± .17	21.51	1.01 ± .01	
6878	0.91 ± .22	21.62	.042 ± .010	$20\ ^{+.6}_{-.3}$

TABLE VI. Transition strengths for ^{28}Si in Weisskopf units.

Level (MeV)	$(J^\pi)_i$	$(J^\pi)_f$	E_γ (MeV)	Lifetime (psec)	Transition strength $E1$	$E2$	$M1$	$M2$
1.779	2^+	0^+	1.779	0.58	⋯	15.3	⋯	⋯
4.617	4^+	2^+	2.838	0.061	⋯	14.1	⋯	⋯
6.276	3^+	2^+	4.497	1.35	⋯	0.05	2.2×10^{-4}	⋯
		4^+	1.659		⋯	1.4	7.6×10^{-4}	⋯
6.878	3^-	0^+	6.878	2.3	$E3=15.0$			⋯
		2^+	5.099		9.6×10^{-7}	⋯	⋯	0.17
		4^+	2.261		1.2×10^{-6}	⋯	⋯	1.0
7.380	1^+	0^+	7.380	0.013	⋯	⋯	2.7×10^{-3}	⋯
		2^+	5.601		⋯	1.2	7.5×10^{-3}	⋯
7.416	2^+	0^+	7.416	0.040	⋯	0.16	⋯	⋯
		2^+	5.637		⋯	0.05	3.3×10^{-4}	⋯
7.798	3^+	2^+	6.019	0.31	⋯	0.05	3.7×10^{-4}	⋯
		3^+	1.522		⋯	13	6.0×10^{-3}	⋯
8.260	1^-	2^+	6.481	0.014	2.8×10^{-4}	0.99	⋯	30
8.413	(3^+)	2^+	6.634	0.28	2.6×10^{-6}	8.8×10^{-3}	7.7×10^{-5}	0.26
		3^-	1.535		8.3×10^{-4}	53	2.5×10^{-2}	1600
8.588	3^+	2^+	6.809	0.025	⋯	0.43	4.0×10^{-3}	⋯
9.163	(2^+)	0^+	9.163	0.039	8.0×10^{-6}	0.014	2.4×10^{-4}	0.43
		2^+	7.384		3.2×10^{-5}	0.09	9.6×0^{-4}	2.7
		4^+	4.546		8.3×10^{-5}	0.61	2.5×10^{-3}	18
9.316	3^+	2^+	7.537	<0.01	⋯	>0.45	$>5.0\times10^{-3}$	⋯
		3^+	3.040		⋯	>19	$>3.5\times10^{-2}$	⋯
10.213	⋯	2^+	8.434	0.015	1.2×10^{-4}	0.25	3.5×10^{-3}	7.4

TABLE VII. Comparison of measured strengths of transitions from first two excited states of ^{28}Si with theoretical predictions.

Initial state Energy (MeV)	J^π	Final state Energy (MeV)	J^π	E (MeV)	$E2$ transition strength in Weisskopf units Farris and Eisenberg[a]	Davydov-Chaban[b]	Das Gupta and Harvey[c]	Experimental
1.779	2^+	0.0	0^+	1.779	1.64	15.8	9.9	15.3
4.617	4^+	1.779	2^+	2.838	0.24	8.6	14.1	14.1

[a] Reference 1.
[b] Parameters used were $\mu=0.54$, $\gamma=15.5°$. Theoretical lifetime was normalized to the experimental value for the 1779-keV transition.
[c] Based on solution b of Ref. 3 with $\mu=-0.2$, $C=3.2$, $b=1.83$.

proximately the proper strength for the 2838-keV transition, but only under the unrealistic assumption of axial symmetry characterized by $\gamma = 15.5°$.

Perhaps the type of calculation with the greatest chance for success in this region is typified by the work of Das Gupta and Harvey.[3] These authors have computed rotation bands based on the two Hartree-Fock minima and performed one-particle–one-hole calculations in the Tamm-Dancoff approximation on these. It is apparent from Table VII that the first two transition strengths are in quite satisfactory agreement with experiment. An important prediction of these calculations is that transitions from the 7416-keV 2^+ state, which is the 2^+ member of the $K=0$ band (prolate solution), to the members of the $K=0$ band (oblate solution) should be greatly inhibited. The small $E2$ transition strengths of 0.16 and 0.05 for the ground- and first-excited-state transitions, respectively, support the validity of this conclusion.

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Soft-Core Hamada-Johnston Nucleon-Nucleon Potential

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The phenomenological Hamada-Johnston nucleon-nucleon potential is modified by replacing the singular hard core with a soft core of the centrifugal type (r^{-2}). It is shown that the fits to experimentally determined elastic scattering phase shifts and deuteron data are little affected by such a modification.

In this paper we present a phenomenological soft-core potential which is fitted to the nucleon-nucleon phase shifts up to pion threshold and reproduces the deuteron data fairly well. Using the Hamada-Johnston[1] potential (HJP) we have replaced the hard core by a soft core. For convenience in the computation of scattering data a soft core of centrifugal type was chosen acting in each JLS state up to a separation radius d:

$$V_{\mathrm{sc}} = 6/mr^2. \tag{1}$$

$m = 938.2$ MeV is the nucleon mass. Similar work has been reported previously, especially by Bressel,[2] who used static square cores in the Hamada-Johnston potential. Kerman[3] and Levy have used a nonlocal separable core instead. The outer region ($r > d$) of our potential is represented by the unchanged HJ expression

$$V_{\mathrm{HJ}} = V_C + V_T S_{12} + V_{LS} LS + V_{LL} L_{12}, \tag{2}$$

where

$$\begin{aligned} V_C &= 0.08(\mu/3)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) Y[1 + a_c Y + b_c Y^2], \\ V_T &= 0.08(\mu/3)(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) Z[1 + a_T Y + b_T Y^2], \\ V_{LS} &= \mu G_{LS} Y^2[1 + b_{LS} Y], \\ V_{LL} &= \mu G_{LL} x^{-2} Z[1 + a_{LL} Y + b_{LL} Y^2], \end{aligned} \tag{3}$$

and $Y = e^{-x}/x$, $Z = (1 + 3/x + 3/x^2) Y$, with $x = \mu r$ ($\mu = 0.7067\ \mathrm{fm}^{-1}$). The operators $(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$, $(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$, S_{12}, and LS are defined in the usual way, while $L_{12} = \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \mathbf{L}^2 - [2(\mathbf{L} \cdot \mathbf{S})^2 + \mathbf{L} \cdot \mathbf{S} - \mathbf{L}^2]$. In Eqs. (3) the spin-parity–dependent coefficients a, b, and G given by HJ[1] have been applied without any alteration (Table I).

The only free parameter we have introduced is the state- and momentum-independent separation radius d defined in the following way:

$$\begin{aligned} V &= V_{\mathrm{sc}}, & r &\leqq d \\ &= V_{\mathrm{HJ}}, & r &> d, \end{aligned} \tag{4}$$

and determined by fitting the scattering and deuteron data:

$$d = 0.675\ \mathrm{fm}.$$

Note that this modification introduces a discontinu-

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