Energy Levels in ^{89}Y†

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Bound levels in ^{89}Y have been studied up to 4.2-MeV excitation using a broad-range magnetic spectrograph. Examination of inelastic proton spectra at $E_p=9.06$ and 9.98 MeV and with 15-keV resolution revealed several new levels, including closely spaced multiplets not previously detected. Of special interest are a doublet at 2879, 2890 keV and a triplet of levels at 3075, 3114, and 3146 keV, each of which had been considered as a single level in prior experiments. Thus an explanation for many of the conflicting reports concerning these levels is now provided.

INTRODUCTION

The ^{89}Y nucleus has been the subject of considerable study over the last few years.[1–10] However, no high-resolution study of the $^{89}Y(p,p')$ reaction, except that of Fox *et al.*[11] for the first four levels, has been reported. Thus it was felt worthwhile to perform such a study, a preliminary report of which has been given.[12]

EXPERIMENTAL METHOD

A 65-cm broad-range magnetic spectrograph at the University of Pennsylvania tandem accelerator was used to analyze the inelastically scattered protons from the $^{89}Y(p,p')$ reaction. They were detected using 50-μ Ilford emulsions located on the focal surface of the spectrograph.

A. Targets and Resolution

The first set of measurements was made at $E_p=9.06$ MeV and at scattering angles of $\Theta_p=50°$ and 90°. A self-supporting target of ^{89}Y, nominally 400 μg/cm^2 thick, was placed at 45° to the beam direction for these measurements. The spectrum obtained at 90° is shown in Fig. 1. The low yield combined with the high background from slit scattering made this data somewhat unreliable for excitation energies above 3.3 MeV. A second set of data was therefore taken at $E_p=9.98$ MeV with $\Theta_p=50°$, 90°, and 120°. A slit target was used for these measurements in order to reduce the background from slit scattering. This target was made by evaporating ^{89}Y onto a 50-μg/cm^2 carbon foil through a mask such that a 150-μg/cm^2 layer was deposited onto an area of 0.5 mm by 3.0 mm. This technique[13] reduced the background but had the disadvantage of making impurity groups from the carbon foil and release agents much stronger relative to the $^{89}Y(p,p')$ groups. The chief impurities were ^{12}C, ^{13}C, ^{14}N, ^{16}O, ^{18}O, and ^{19}F, with traces of Na, Si, S, and Cl also present.

The energy resolution achieved was between 18 and 25 keV full width at half-maximum (FWHM) and was considerably worse than that attained with other targets.[13,14] The proton groups were asymmetrical, with a pronounced low-energy tail which made analysis of closely spaced doublets difficult. Contrary to expectation, the proton groups from some impurities and the carbon backing were considerably narrower than those from the target. Presumably, therefore, the poor resolution was due to coagulation of the target material producing target nonuniformities. Similar difficulties have been experienced by other workers using yttrium targets.[15]

B. Determination of Level Energies

The energies of the ^{89}Y levels were obtained from the positions of the proton groups as determined from the one-third height point on the high-energy edge of the

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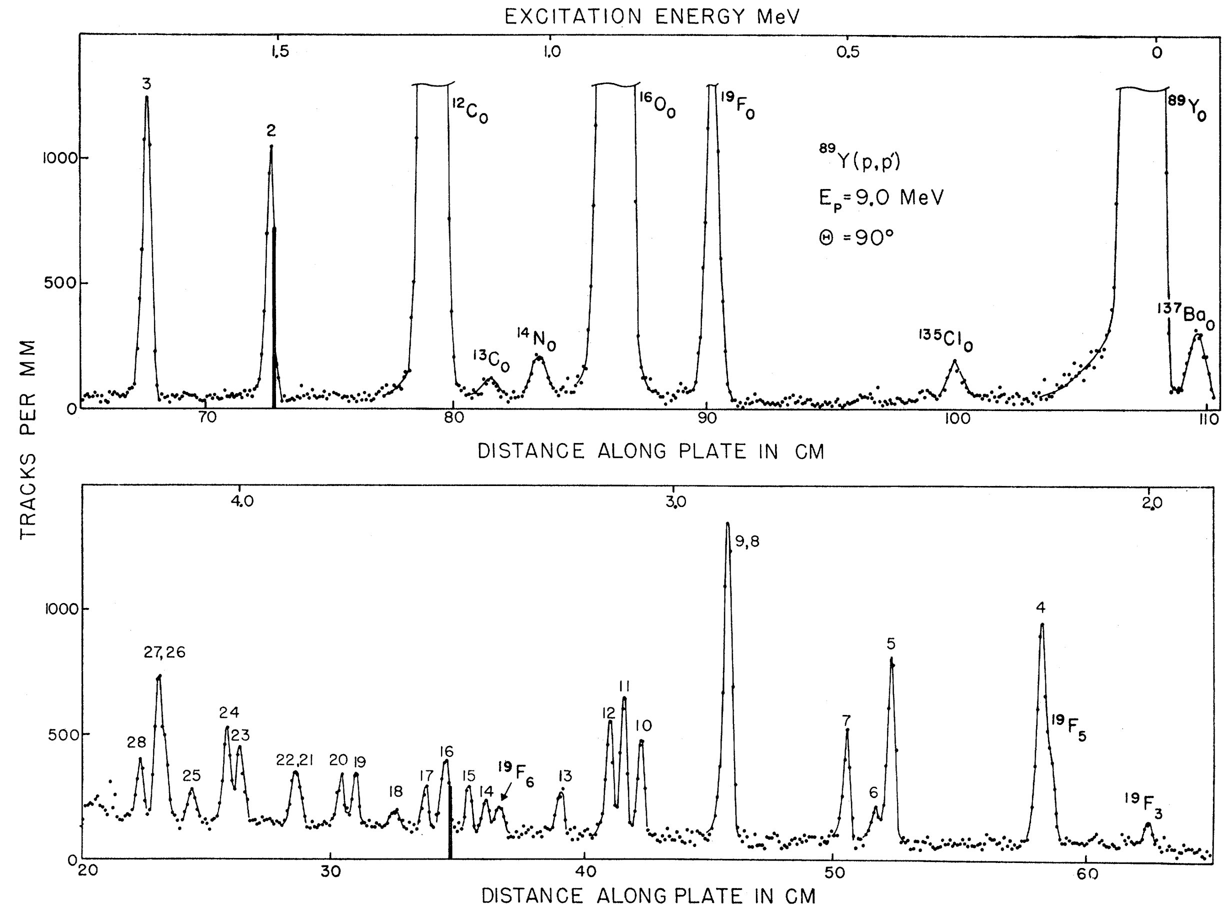

FIG. 1. Spectrum of protons scattered from a self-supporting ^{89}Y target at $\Theta_p=90°$ for an incident proton energy of 9.06 MeV.

group. Any groups that showed significant broadening were decomposed into component groups using line shapes derived from neighboring single groups. Because of a suspected misalignment of the photographic plates in the spectrograph for the first exposures, these data were not used when deriving the excitation energies; however, the existence of some of the weaker groups was confirmed by this data.

The spectrograph has been previously calibrated[16] assuming a value of $B\rho=33.1772\pm0.001$ kG cm for the magnetic rigidity of the ^{210}Po α particles.[17] The spectrograph field was measured with an NMR probe and a value of $\gamma/2\pi=4.25770\times10^7$ Hz m^2/Wb assumed for the gyromagnetic ratio of the proton. A computer program, which converted $B\rho$ to particle energy using an expansion in even powers of $(B\rho)$ up to the eighth, was used to calculate the reaction Q values. The $B\rho$ to energy conversion agreed with the tables of Enge[18] to within 1 keV.

Because of uncertainties in the accelerator calibration the incident energy was adjusted to fit the elastic groups from the impurities, and led to values of E_p that differed by less than 14 keV for the three exposures. The effect of such deviations on the calculated excitation energies is less than 0.6 keV for $E_x\leq4$ MeV. The ^{89}Y elastic groups were too intense to scan on the long exposures, and therefore short exposures were made prior to and subsequent to each long exposure. Errors in the position of the ^{89}Y elastic group are reflected in all the excitation energies, and an estimate of this source of error was made. The average deviation of E_x from the mean for all three exposures was calculated for each exposure, and led to deviations of -1.8 keV, $+1.1$ keV, and $+0.9$ keV, while the standard deviation from the mean for a single excitation energy was ±1.2 keV. To check the spectrograph calibration an exposure was made under identical conditions with a ^{72}Ge target and $\Theta_p=60°$. The excitation energies derived from some of the prominent ^{72}Ge groups are compared with the values obtained by Camp[19] in Table I. There is some indication of a systematic error, but this would

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TABLE I. Energies of prominent groups in $^{72}Ge(p,p')$ in keV.

Level No.	Spectrograph results[a]	Ge(Li) results[b]
3	1465	1463.9
4	1728	1728.2
6	2401	2402.2
8	2517	2514.7
9	2948	2943.3
10	3040	3035.6
11	3330	3325.0
Error	±3	±0.1

[a] Present data.
[b] Reference 19.

be less than 6 keV at 3.0-MeV excitation. An over-all error of between ±3 and ±6 keV is therefore assigned for the strong groups.

RESULTS AND DISCUSSION

The energies of 28 levels in ^{89}Y have been determined and are compared with the results from other reaction and β-decay studies of the ^{89}Y levels in Table II. Preliminary level energies from a separate study of the 78-h decay of ^{89}Zr with a Ge(Li) detector[20] are also listed. The present measurements reveal a number of

TABLE II. Energies of levels in ^{89}Y.[a]

Method	(p,p')						(d,d')	(α,α')		(e,e')		(n,n')	(n,n'γ)		β decay
Ref.	b	c		d		e	f	g		h		i	j		k
E_{in} MeV	9, 10	19.5		14.71		6–8		42		65–70		3.78	3–4.5		
ΔE keV	15	80		35		5		130		200					5
Level No.			J^π, l		l				J^π, l		J^π			J^π	
1	0.908 2	0.91	$\frac{9}{2}^+$	0.894	(5)	0.897	0.915	0.906	$\frac{9}{2}^+$			0.908	0.908	$\frac{9}{2}^+$	0.9091 1
2	1.507 3	1.49	$\frac{3}{2}^-$	1.502	2	1.499	1.510	1.51	$\frac{3}{2}^-$	1.50	$\frac{3}{2}^-$	1.51	1.51	$(\frac{3}{2}^-)$	
3	1.745 3	1.74	$\frac{5}{2}^-$	1.730	2	1.736	1.742	1.75	$\frac{5}{2}^-$	1.73	$\frac{5}{2}^-$	1.75	1.75	$\frac{5}{2}^-$	1.7444 7
4	2.222 4	2.22	$\frac{5}{2}^+$	2.207	3	2.219	2.227	2.22	$(\frac{5}{2})^+$	2.21	$\frac{5}{2}^+$	2.22	2.22	$(\frac{7}{2}^+,\frac{5}{2}^+)$	
5	2.532 4	2.52	$\frac{7}{2}^+$	2.518	3		2.533	2.53	$(\frac{7}{2})^+$	2.52	$\frac{7}{2}^+$	2.53	2.53	$(\frac{9}{2}^+,\frac{7}{2}^+)$	2.5297 8
6	2.572 6														2.5660 8
7	2.627 4			2.605	(5)			2.63	$(\frac{9}{2}^+)$				2.61		2.6211 8
8	2.879 4 }[l]	2.87	3	2.862	3		2.886	2.84	(3)	2.86	$\frac{7}{2}^+$	} 2.84	} 2.86	$(\frac{3}{2}^-)$	
9	2.890 6 }														
10	3.075 4														
11	3.114 5	3.12	2	3.115	2		} 3.135[l]	} 3.1	(2,4)	3.1		} 3.05[l]	} 3.09	$(\frac{3}{2}^-)$	
12	3.146 5														
13	3.254 5														
14	3.420 5														
15	3.459 5												3.49	$(\frac{5}{2}^-)$	
16	3.519 6[l]														
17	3.565 5														
18	3.634 6	3.62		3.622	0										
19	3.724 5			3.719	3		3.74	3.70	(3)	3.72					
20	3.756 5	3.75	$\frac{5}{2}^+$												
21	3.859 5 }[l]												} 3.85		
22	3.872 6 }														
23	3.998 5	3.99	2	3.992	2		4.02	3.98	(2)	4.0					
24	4.030 6														
25	4.112 6														
26	4.178 6 }[l]	4.18	2	4.163	2		4.20	4.17	(2)	4.16					
27	4.194 6 }														
28	4.238 6			(4.22)									(4.21)		

[a] In columns 4, 6, 11, 13, and 16 noninteger values refer to $J\pi$ assignments while integer values refer to orbital angular momentum transfer. The energy resolution ΔE is listed for some of the investigations. Errors for level energy determinations are given for the two most recent investigations (present work and Ref. 20).
[b] Present data.
[c] Reference 4.
[d] Reference 5.
[e] Reference 11.
[f] Reference 21.
[g] Reference 3.
[h] Reference 7.
[i] Reference 22.
[j] Reference 6.
[k] Reference 20.
[l] Unresolved multiplets.

[20] P. F. Hinrichsen (to be published).

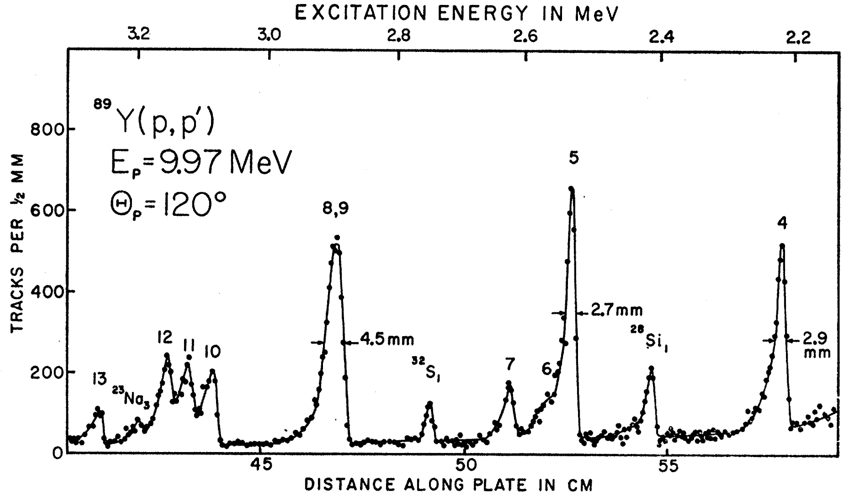

FIG. 2. Partial spectrum of protons inelastically scattered from a slit target of ^{89}Y at $\theta_p=120°$ and $E_p=9.97$ MeV. Of special interest are the shoulder labeled 6, which is due to a new level at 2572 keV, the strong group labeled 8, 9 due to a doublet at 2879 and 2890 keV, and the triplet of levels 10, 11, and 12 at 3075, 3114, and 3146 keV.

closely spaced multiplets which have previously been considered as single levels, notably the doublets at 2532 and 2572 keV, 2879 and 2890 keV, and the three levels at 3075, 3114, and 3146 keV. Above 2.4 MeV the levels become sufficiently closely spaced that good energy resolution is required to study the properties of single levels. The spin and parity assignments based on low-resolution data should therefore be treated with caution unless there is evidence that only one level was excited.

A. 2532-, 2572-keV Doublet

The first group that shows structure is that at 2.54 MeV, which is now seen to be due to two levels at 2532 and 2572 keV. The existence of the level at 2.57 MeV has been confirmed by the observation[20] of a weak transition from this level in the β decay of ^{89}Zr. Awaya[5] and Stautberg *et al.*[4] obtained good $l=3$ DWBA fits to the inelastic proton angular distributions of the 2.53-MeV group. The inelastic α scattering experiments of Alster *et al.*[3] also yielded an excellent fit for $l=3$ transfer for this group. The weak excitation of the 2.57-MeV level in the present work would suggest that the $l=3$ assignment for the 2.53-MeV level is probably correct.

B. 2879-, 2890-keV Doublet

The group at 2.88 MeV was consistently wider and approximately twice as intense as those from neighboring single levels, as indicated in Fig. 2. Unfortunately, the poor spectral line shape made analysis of this group rather difficult. The shape observed for this group can be accounted for if a 2879-, 2890-keV doublet is assumed; however the energy of the 2890-keV member is somewhat uncertain. The possibility of a doublet at this energy has been suggested on the basis of the $(n,n'\gamma)$ reaction data.[6] Both an $E3$ transition to the 0.91-MeV level and an $M1$-$E2$ transition to the ground state were assigned to a 2.86-MeV level. It is unlikely that both these transitions originate from the same level. Furthermore, the $(n,n'\gamma)$ angular distribution data[6] lead to a $\frac{3}{2}$ spin assignment, with negative parity being favored. On the other hand, the (p,p') experiments of Stautberg *et al.*[4] indicated a spin of $\frac{5}{2}^+$ or $\frac{7}{2}^+$, and this positive parity assignment is supported by the (α,α') experiments of Alster *et al.*[3] This assignment can now be understood, as the (α,α') reaction tends to excite collective states more strongly than single-particle or particle-hole states, and this level may be associated[4] with the collective 3^- state at 2.74 MeV in ^{88}Sr. The presence of this doublet could explain the poor $l=3$ DWBA fit obtained by Awaya[5] at $E_p=14.71$ MeV, while the good $l=3$ fit obtained by Stautberg *et al.*[4] at $E_p=19.5$ MeV is presumably due to the predominant excitation of the $(\frac{5}{2}^+,\frac{7}{2}^+)$ level. On the basis of the angular distribution[6] of the ground-state transition seen in the $(n,n'\gamma)$ reaction, the other member of the doublet has $J=\frac{3}{2}$. Thus the conflicting reports from these previous experiments can be accounted for by the present work, which has revealed at least two closely spaced levels near 2.88-MeV excitation in ^{89}Y.

C. 3075-, 3114-, 3146-keV Triplet

The existence of a possible doublet at 3.0 MeV has been suggested previously.[21,22] The present work clearly shows three levels at 3075, 3114, and 3146 keV, which are all excited to approximately the same degree (see Figs. 1 and 2). This observation provides an explanation for the conflicting spin and parity assignments of previous workers, i.e., $\frac{3}{2}^-$ from the $(n,n'\gamma)$ reaction[6] and an $l=2$ transfer in the (p,p') reaction.[5] An $(n,n'\gamma)$ or $(p,p'\gamma)$ angular distribution experiment with a Ge(Li) counter would help greatly to clarify the situation.

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D. Higher Levels

The groups at 3.87 and 4.18 MeV both showed appreciable broadening; however, the low yield and poor background made the analysis of these doublets difficult and the energies of the 3872- and 4194-keV levels are therefore less accurate than the other values. Owing to the poor statistics, background, and the increased level density, the data above 4.25-MeV excitation were not analyzed.

E. Level Density

The total number of levels $N(U)$ is plotted as a function of the excitation energy U in Fig. 3. Ericson[23] has defined a temperature τ by the equation

$$1/\tau = d\ln N(U)/dU,$$

and this is related to the nuclear temperature T by

$$\frac{1}{T}=\frac{1}{\tau}\left\{1-\frac{d\tau}{dU}\right\}.$$

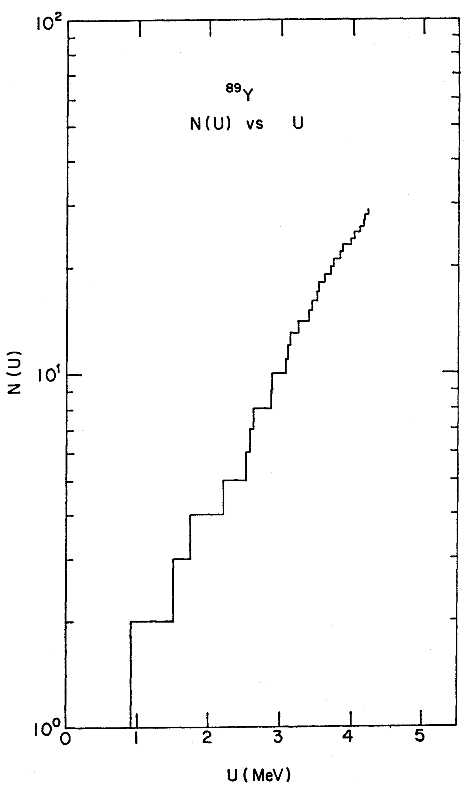

FIG. 3. The number of levels $N(U)$ versus excitation energy. The decrease in slope above 3.7 MeV is probably due to missed levels.

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It will be seen that for excitation energies below 3.7 MeV the slope is almost constant and leads to a value of τ approximately equal to 1.1 MeV. Between 3.7 and 4.2 MeV the slope appears to decrease somewhat and would lead to $\tau=1.5$ MeV; however, this decrease in slope is probably due to levels being missed on account of the background and poor resolution. Following the analysis of Katsanos,[24] the correction for missed levels has been calculated for an exponential distribution of energy-level spacings. Assuming that levels with a spacing $\Delta E_1 \geqq 24$ keV were definitely resolved and those with a spacing $\Delta E_2 \leq 10$ keV were unresolved, the number of missed levels between 3.7 and 4.2 MeV is estimated to be between 4 and 10, which would account for the change in slope. This correction does not take into account the levels missed due to low cross section. A corrected plot of $\rho(U)$ versus U gives a temperature $T=1.2$ MeV. This analysis should be treated as an approximate result since only 28 levels were observed and the correction for missed levels is large.

[*Note added in proof*. Two further measurements of the energy levels of ^{89}Y have recently been reported.[25,26] Van Bree[25] has measured (p,p') spectra with solid-state counters and reports values of 909, 1505, 1742, 2217, 2525, (2570), 2622, 2873, 3067, 3102, 3136, 3505, (3557), 3628, 3716, 3744, 3856, 3990, 4105, 4171, 4229, 4305, and 4462 keV with a quoted error of ± 10 keV. Buchanan *et al.*[26] have studied $(n,n'\gamma)$ spectra with a Ge(Li) spectrometer and report energy levels at 908, 1507, 1745, 2220, 2529, 2568, 2622, 2871, 2881, 3067, 3106, 3138, 3411, 3450, 3502, 3511, 3559, 3625, 3716, 3748, 3852, 3864, 3990, and 4020 keV. These two sets of data are consistent to within $\sigma_i = \pm 3$ keV and indicate a systematic error of $2.1\times 10^{-3}\ E_{ex}$ in the present data above about $E_{ex} \simeq 2.5$ MeV, which would be consistent with that deduced from the ^{72}Ge data. After the level energies listed in Table II are reduced by this amount, the errors stated should still apply. The level reported at 3502 keV in the $(n,n'\gamma)$ reaction was not resolved from the 3511-keV level in our data and this group fell at a plate edge, see group 16, Fig. 2. This group was, however, slightly wide in the 50° and 90° spectra, thus supporting the assignment of a doublet at this energy.]

ACKNOWLEDGMENTS

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