Levels in ^{78,80,82}As from the ^{78,80,82}Se(t, ^{3}He) reactions

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Levels of the neutron rich arsenic isotopes are studied by the Se(t,^{3}He)As reactions. In ^{78}As, 33 levels up to E_x = 2383 keV are identified. In ^{80,82}As where no levels have previously been assigned, 18 and 9 levels respectively were observed. A mass excess of -72182 ± 20 keV is obtained for ^{80}As which disagrees substantially with recent β-decay measurements. For ^{82}As the measured mass excess is -70067 ± 27 keV which differs by 300 keV from previous measurements.

[NUCLEAR REACTIONS ^{78}Se(t,^{3}He), ^{80}Se(t, ^{3}He), ^{82}Se(t,^{3}He), E=23.0 MeV; measured $\sigma(\theta)$. ^{78}As, ^{80}As, ^{82}As deduced levels. New masses of ^{80}As, ^{82}As.]

I. INTRODUCTION

The (t, ^{3}He) reaction has proved to be an extremely useful tool in the measurement of neutron rich nuclei in nuclei ranging from the s-d shell,[1] the $f_{7/2}$ shell[2] to the tin region.[3] Beta-decay measurements which have previously provided much of the known information about the residual nuclei reached in (t, ^{3}He) reactions can seldom lead to accurate energy measurements. Moreover, only a limited number of excited states can be populated in β decay because of the forbiddenness of reaction involving $\Delta J>1$. On the other hand, the (t, ^{3}He) reaction is known to be able to excite natural and unnatural parity states over a large range of angular momentum transfers. These features combined with the application of a magnetic spectrometer for measurement of the reaction ^{3}He ions permits a substantial increase in the accuracy of ground state mass measurements and excited state energies over β-decay techniques. The neutron rich arsenic nuclei are relatively uninvestigated with ^{78}As the heaviest isotope with known excited states.

^{78}As decays[4] by β^- emission with a half-life of 90.7 ± 0.2 min to a number of states[5,6] of ^{78}Se: The nature of the decay is such that $J^\pi=(2^-)$ is favored for the ground state of ^{78}As. This state, as well as states at 277.3 ± 0.3 and 293.9 keV are populated[6] in the β^- decay of ^{78}Ge. Recently Mordechai *et al.*[7] have studied the ^{80}Se(d, α) ^{78}As reaction, and have determined the mass of the ground state of ^{78}As and the location and characteristics of a number of states of ^{78}As with $E_x<1.3$ MeV.

^{80}As has a half-life[8] of 15.2 ± 0.2 s: It decays[9] by β^- emission to the ^{80}Se ground state (56%) and to the first excited state at 666 keV (32%). The character of the decay suggests[8,10] that the ground state of ^{80}As is $1^{(+)}$. $Q_{\beta^-}(\max)=5.37\pm0.12$ MeV (Ref. 9) which leads to an atomic mass excess of -72.39 ± 0.12 MeV for ^{80}As. Wapstra and Bos[11] list -72.06 ± 0.3 MeV which would correspond to $Q_{\beta^-}(\max)=5.7\pm0.3$ MeV. No levels of ^{80}As have been reported previously.

^{82}As has been populated in the ^{82}Se(n,p)^{82}As reaction, in the β^- decay of ^{82}Ge, and it has been isolated from fission products.[8,12,13] ^{82}As is then reported to β^- decay to states in ^{82}Se with $Q_{\beta^-}(\max)=7.2\pm0.2$ MeV.[12] Wapstra and Bos[11] suggest, on the basis of systematics, $Q_{\beta^-}(\max)=7.4$ MeV. Two states of ^{82}As are involved in the β^- decay which takes place[8] to states of ^{82}Se with two substantially different sets of J^π. One of these ^{82}As states, whose J^π is suggested to be (1^+), has a half-life of 19.1 ± 0.5 s (Ref. 8) and decays primarily to ^{82}Se$_{g.s.}$ with $J^\pi=0^+$; the other ^{82}As state, $J^\pi=(5^-)$, $\tau_{1/2}=13.0\pm0.6$ s,[12] does not decay to low spin states in ^{82}Se but instead to states with $J=(4,5)$: see Fig. 5 in Kratz *et al.*[8] for the proposed decay schemes of these two isomers. The isomeric transition between the (1^+) and (5^-) states in ^{82}As has not been observed,[8,12] and it is not known which of these two states is the ground state of ^{82}As. Aleklett *et al.*[14] have suggested 5^- for the ground state of ^{82}As. No excited states of ^{82}As, other than the isomeric state of unknown energy, have previously been reported.[15]

II. EXPERIMENTAL PROCEDURES AND RESULTS

The (t, ^{3}He) reactions on ^{78}Se, ^{80}Se, and ^{82}Se have been studied using a 23 MeV triton beam from the LASL three-stage Van de Graaff facility and a magnetic spectrometer of the quadrupole-dipole-dipole-dipole (Q3D) type. The ^{3}He ions were detected with a 1 m helical cathode focal plane detector having 0.8 mm spatial resolution.[16] The resolution [full width at half maximum (FWHM)] of typical single groups in this study was 25 keV, arising principally from the target thickness.

The selenium targets were placed at 20° to the incident beam. Each of the targets was a gold sandwich enclosing a layer of enriched selenium with an areal density of 160 to 180 μg/cm^2. The targets were able to withstand currents of ~200 nA for runs lasting over 15 h without apparent change in the thickness of the selenium. The enrichment[17] of the selenium targets was as follows: ^{78}Se 98.6% (also 1.0% ^{80}Se); ^{80}Se 99.5%; ^{82}Se 87.8% (also 3.8% ^{78}Se, 6.2% ^{80}Se). Data were taken at three angles, in the range 25° to 40°, for each of the three isotopes, with total integrated beam currents of 1.67 to 4.55 mC. Runs were also made with ^{28}Si and ^{24}Mg targets under identical conditions to the Se runs and preceding and following each of the runs to calibrate the channel number versus the energy of the outgoing ^{3}He ions.[18] The ^{28}Si(t, ^{3}He)^{28}Al reaction was used in conjunction with the ^{78}Se runs because of the similar Q value of the reactions: Q_m for ^{28}Si(t, ^{3}He) is −4624.4 ± 0.6 keV to the ground state ($J^\pi = 3^+$) and excited states are known[19] at 30.64 (2$^+$), 972.2 (0$^+$), 1014.0 (3$^+$), and 1372.8 (1$^+$) keV, in the region of interest. We note that at $E_t = 23$ MeV ($\theta_{1ab} = 30°$ and 35°) the excited state at 972 keV in ^{28}Al is not appreciably populated. In the case of the ^{80}Se and ^{82}Se runs the ^{24}Mg(t, ^{3}He)^{24}Na peaks[18] provided reliable calibration.

A. States of ^{78}As

Figure 1 shows the spectrum at $\theta_{1ab} = 30°$. The numbered groups correspond to states in ^{78}As: See Table I. Table I also displays the results obtained by Mordechai *et al.*[7] from a study of the ^{80}Se(d, α)^{78}As reaction. In the region of overlap the agreement between the present results and the (d, α) results is quite good. However, three groups attributed by Mordechai *et al.*[7] to single states of ^{78}As appear in our work to correspond to unresolved groupings of states casting doubt on the validity of one of their J^π assignments, although it is of course possible that more states are populated in the (t, ^{3}He) than in the (d, α) reaction. Further, this work extends the known excited states to $E_x = 2.38$ MeV. The possibility of spurious groups due to ^{80}Se(t, ^{3}He)^{80}As was considered; however, the 1% ^{80}Se present in the ^{78}Se target would at most contribute a total of 3 counts to groups 23–25.

The Q value of the ^{80}Se(d, α)^{78}As reaction,[7] 5755 ± 12 keV, leads to an atomic mass excess of −72805 ± 13 keV and to a mass of 79.921 841 (13) u for ^{78}As, assuming the masses of ^{80}Se, d, and α, and the mass-energy conversion of 931.5016 (26) MeV/amu used by Wapstra and Bos.[11]

B. States of ^{80}As

Figure 2 shows the spectra obtained at $\theta_{1ab} = 30°$ and 35°. The numbered groups correspond to states in ^{80}As: See Table II. The Q value for formation of the ground state of ^{80}As is measured to be −5560 ± 25 keV. This value leads to an atomic mass excess of −72182 ± 20 keV and to a mass of 79.922 509 (22) u, using the Wapstra-Bos[11] masses for ^{80}Se, t, and ^{3}He. Q_{β^-}(max) is then 5579 ± 20 keV, which can be compared with the Wapstra-Bos[11] value of 5.7 ± 0.3 MeV and the Q_{β^-}(max) measurement of Aleklett *et al.*[9] of 5.37 ± 0.12 MeV.

Assuming the half-life of 15.2 ± 0.2 s measured by Kratz *et al.*,[8] the branchings to the ground and 666 keV 0$^+$ and 2$^+$ states of ^{80}Se (56 and 32%, respectively) measured by Aleklett *et al.*,[9] a $J^\pi = 1^+$ assignment to ^{80}As$_{\rm g.s.}$ and the mass of ^{80}As determined in this work, we find that the allowed transitions to the ground and first excited states of ^{80}Se both have logft values[20] of 5.73.

C. States of ^{82}As

Figure 3 shows the spectrum obtained at $\theta_{1ab} = 25°$. The numbered groups correspond to states in ^{82}As: See Table III. The background over which the peaks are superimposed is due in part to the intense group of elastically scattered tritons which cannot be fully discriminated against at $\theta = 25°$, and to the 3.8% ^{78}Se and 6.2% ^{80}Se com-

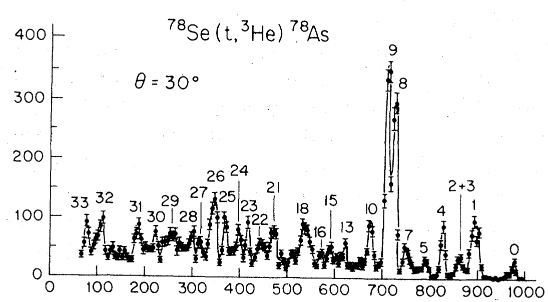

FIG. 1. Spectrum of the ^{3}He ions from the ^{78}Se(t, ^{3}He)^{78}As reaction at $E_t = 23.0$ MeV, $\Theta_{1ab} = 30°$, $B = 5.7003$ kG. The ordinate shows the total number of counts recorded in a 5-channel bin. The abscissa shows the channel number. The numbered groups are due to states in ^{78}As: See Table I.

position of the enriched target. We have studied groups 15 and 18 in Fig. 2 ($Q=-7051$ and -7355 keV) to see whether some of the high points in the background can be attributed to these groups. We find that group 18 would contribute a total of ~30 counts at about channel 710 and that group 15 could contribute a total of ~20 counts near channel 830.

The Q value for formation of the ground state of ^{82}As is found to be -7500 ± 25 keV. The atomic mass excess of ^{82}As is then -70067 ± 27 keV and its mass is 81.924 781 (29) u, based on the Wapstra-Bos[11] masses for ^{82}Se, t, and ^{3}He. Q_{β^-}(max)

TABLE I. States of ^{78}As.

Group No.[a]	Previous work[b] E_x (keV)	Previous work[b] J^π	This work E_x (keV)[c]	$d\sigma/d\Omega$[d] (μb/sr) (c.m.)
0	0[e]	(2^-)[g]	i	0.30
1	207 ±3		213 ±20[j]	1.8
2+3	277.3 ±0.3[f]	1^+	290 ±20[j]	
	294[f]			
4	376 ±6		374 ±15	0.92
5	459 ±4		463 ±15	
6	504 ±3	$(0,1,2)^-$	508 ±20[k]	
7	536 ±4	1^+[h]	562 ±20[j]	
8	617 ±5	$(0,1,2)^-$	624 ±15	3.1
9	664 ±6		≡664	4.1
10				
	752 ±6	$(0,1,2)^-$	752 ±15	0.92
11				
12	848 ±6	$((0,1,2)^-)$	850 ±20[k]	
13	891 ±7		888 ±15	
14	939 ±9		i	
15	967 ±14	1^+	970 ±20	
16	1007 ±7		1020 ±20	
17	1072 ±4	1^+	i	
18	1103 ±8		i	
19	1131 ±7		i	
20	1178 ±13		i	
21	1273 ±10		i,j	
22			1355 ±30[j]	
23			1428 ±20	
24			1480 ±20	
25			1558 ±20	0.84
26			1626 ±20[j]	
27			1710 ±25	
28			1757 ±30[j]	
29			1875 ±30[j]	
30			1973 ±20	
31			2068 ±20[j]	
32			2285 ±20[j]	
33			2383 ±30[k]	

[a] See Fig. 1 and Table I in Ref. 7 and Fig. 1 here.

[b] Mordechai *et al.* (Ref. 7): ^{80}Se(d,α) at $E_d=16$ MeV; errors shown are standard deviation from the mean excitation energy.

[c] E_x with respect to $E_x=664$ keV for group 9; errors shown are absolute errors including the uncertainty in E_x.

[d] $E_t=23$ MeV, $\theta_{\rm lab}=30°$ (±40%).

[e] $Q_0=5755\pm12$ keV for the ^{80}Se$(d,\alpha)^{78}$As reaction. This leads to $Q_0=-4208\pm12$ keV for the ^{78}Se$(t,{}^3$He$)^{78}$As reaction used in this work.

[f] Reference 6: from β^- decay of ^{72}Ge; Mordechai *et al.* (Ref. 7) observe a single group with $E_x=276\pm5$ keV which is too broad to be due to a single state. The J^π assignment, derived from a DWBA fit of $L=0+2$, presumably refers to the 277 keV state since it appears to be dominantly populated.

[g] See Ref. 4 and the Introduction.

[h] This J^π appears to us to be uncertain since the group appears due to unresolved states.

[i] Observed but Q and E_x not determined.

[j] This group, in the $(t,{}^3$He) work, is too broad to be due to a single state.

[k] Observed clearly at only one angle.

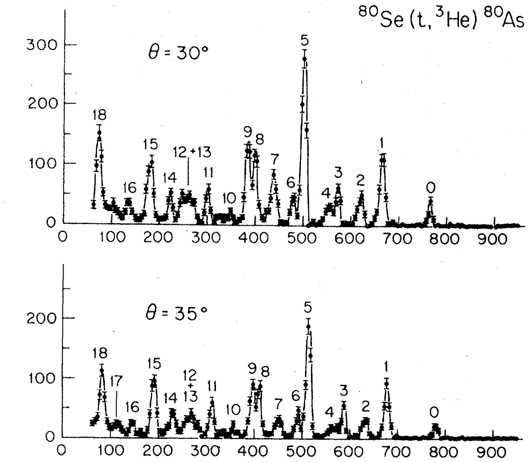

FIG. 2. Spectra of the ^{3}He ions from the ^{80}Se(t,^{3}He)^{80}As reaction at $E_t = 23.0$ MeV, $\theta_{lab} = 30°$ and 35°, $B = 5.5716$ and 5.5540 kG, respectively. The numbered groups are due to states in ^{80}As: See Table II. See also caption of Fig. 1.

$= 7.519 \pm 0.027$ MeV, as compared with 7.4 MeV from systematics[11] and 7.2 ± 0.2 MeV from the β-decay work of Van Klinken *et al.*[12] It is possible, of course, that the transition to the ground state is so weak that we have failed to observe it and that the group labeled 0 is due to an excited state. However, the beta-decay measurement is a difficult one and it would be useful to repeat it.

TABLE II. States of ^{80}As from ^{80}Se(t,^{3}He)^{80}As.

Group No.[a]	E_x in ^{80}As (keV)	$d\sigma/d\Omega$[b] (μb/sr) (c.m.)
0	0[c]	0.35
1	243 ±10	1.5
2	355 ±15[d]	0.60
3	470 ±15	0.62
4	517 ±15[d]	
5	649 ±15	3.0
6	706 ±20	0.4
7	805 ±20[d]	0.9
8	910 ±20	1.3
9	949 ±20	1.4
10	1045 ±20	
11	1170 ±20	0.61
12	1270 ±30[d,e]	
13	1310 ±30[e]	
14	1385 ±30	
15	1494 ±25[d]	1.4
16	1616 ±25	
17	1690 ±25[d]	
18	1790 ±25	

[a] See Fig. 2.
[b] $\theta_{lab} = 30°$; ±40%.
[c] Q_0 measured in this experiment is -5560 ± 25 keV.
[d] The group is too broad to be due to a single state.
[e] Not fully resolved.

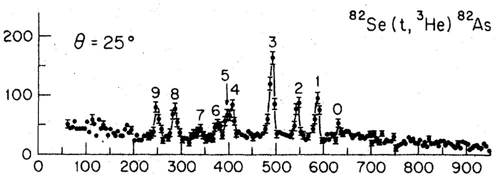

FIG. 3. Spectrum of the ^{3}He ions from the ^{82}Se(t,^{3}He)^{82}As reaction at $E_t = 23.0$ MeV, $\theta_{lab} = 25°$, $B = 5.3038$ kG. The numbered groups are due to states in ^{82}As: See Table III. See also caption of Fig. 1.

Let us assume then that the group labeled 0 is in fact the ground state of ^{82}As and that its J^π is 5^-. The strongest (49%) β decay[8] of that state is to a probable 4^- state in ^{82}Se at 2893 keV. Using the Gove-Martin Tables,[20] logft for that transition is then 5.34. While the excitation energy of the 1^+ isomeric state is not known, its strongest beta decay[8] is to the 0^+ ground state of ^{82}Se (78%). It is unlikely that group 0, because of its intensity and width, is due to both the 1^+ and 5^- states. If the 1^+ state is the 126 keV first excited state of ^{82}As (group 1) then logft for the transition to ^{82}Se$_{g.s.}$ is 6.30. An $M4$ γ transition between two states 126 keV apart does not compete[21] with the observed β-decay lifetime.

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TABLE III. States of ^{82}As from ^{82}Se(t,^{3}He)^{82}As.

Group No.[a]	E_x in ^{82}As (keV)	$d\sigma/d\Omega$[b] (μb/sr) (c.m.)
0	0[c]	~0.2
1	124 ±15	0.95
2	214 ±15	0.72
3	340 ±15	1.7
4	535 ±20	
5	559 ±20	
6	600 ±20	
7	(700 ±25)[d]	
8	818 ±20	0.72
9	912 ±25	0.66

[a] See Fig. 3.
[b] $E_t = 23$ MeV, $\theta_{lab} = 25°$; ±40% (except group 0).
[c] $Q_0 = -7500 \pm 25$ keV.
[d] Probably due to unresolved states.

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[1]E. R. Flynn and J. D. Garrett, Phys. Rev. C 9, 210 (1974); F. Ajzenberg-Selove, E. R. Flynn, S. Orbesen, and J. W. Sunier, *ibid.* 15, 1 (1977).
[2]E. R. Flynn, J. W. Sunier, and F. Ajzenberg-Selove, Phys. Rev. C 15, 879 (1977).
[3]F. Ajzenberg-Selove, E. R. Flynn, J. W. Sunier, and D. L. Hanson, Phys. Rev. C 17, 960 (1978).
[4]P. P. Urone and F. E. Bertrand, Nucl. Data Sheets 15, 107 (1975).
[5]D. K. McMillan and B. D. Pate, Nucl. Phys. A140, 529 (1970).
[6]P. Fettweis, P. del Marmol, and N. K. Aras, Radiochim. Acta 17, 55 (1972).
[7]S. Mordechai, M. E. Cobern, G. E. Moore, and H. T. Fortune, Nucl. Phys. A289, 36 (1977).
[8]J. V. Kratz, H. Franz, N. Kaffrell, and G. Hermann, Nucl. Phys. A250, 13 (1975).
[9]K. Aleklett, E. Lund, G. Nyman, and G. Rudstam, Nucl. Phys. A285, 1 (1977).
[10]L. R. Greenwood, Nucl. Data Sheets 15, 289 (1975).
[11]A. H. Wapstra and K. Bos, At. Nucl. Data Tables 19, 177 (1977).
[12]J. Van Klinken, L. M. Taff, H. T. Dijkstra, A. H. De Haan, H. Hanson, B. K. S. Koene, J. W. Maring, J. J. Schuurman, and F. B. Yano, Nucl. Phys. A157, 385 (1970).
[13]P. Del Marmol and P. Fettweis, Nucl. Phys. A194, 140 (1972).
[14]K. Aleklett, G. Nyman, and G. Rudstam, Nucl. Phys. A246, 425 (1975).
[15]J. F. Lemming and R. L. Auble, Nucl. Data Sheets 15, 315 (1975).
[16]E. R. Flynn, S. Orbesen, J. D. Sherman, J. W. Sunier, and R. Woods, Nucl. Instrum. Methods 128, 35 (1975); S. Orbesen, J. D. Sherman, and E. R. Flynn, LAMS report, 1976 (unpublished).
[17]The isotopes were prepared by the Stable Isotopes Division of ORNL.
[18]F. Ajzenberg-Selove, E. R. Flynn, S. Orbesen, and J. W. Sunier, Phys. Rev. C 15, 1 (1977).
[19]P. M. Endt and C. Van der Leun, Nucl. Phys. A310, 1 (1978).
[20]N. B. Gove and M. J. Martin, Nucl. Data Tables 10, 206 (1971).
[21]D. H. Wilkinson, in *Nuclear Spectroscopy—B*, edited by F. Ajzenberg-Selove (Academic, N.Y., 1960), p. 860.