Acta Phys. Hung. A 19/1 (2004) 000–000

HEAVY ION PHYSICS

Gamma-rays from muon capture in Al, Si, natural Ca, Fe, Ni, I, Au, and Bi

David F. Measday[1] and Trevor J. Stocki[1]

[1] Department of Physics and Astronomy, University of British Columbia
Vancouver, B.C. Canada V6T 1Z1

Received 1 January 2006

Abstract. A significant improvement has been made in the identification of gamma-rays from muon capture in Al, Si, natural Ca, I, Au, Bi, and to a lesser extent for Fe, and Ni. For calcium, capture was observed in ^{44}Ca and even ^{42}Ca, as well as the dominant ^{40}Ca. The (μ^-, ν) reaction was clearly observed in ^{27}Al, ^{28}Si, and ^{40}Ca, but, as in the past, no clear identification was made in heavier elements. The $(\mu^-, \nu n)$ reaction was clearly observed in all nuclei, and the intensity pattern of the gamma-rays corresponds better to the pattern observed in the $(\gamma$,p) reaction rather than to spectroscopic factors from the (d,^{3}He) or (t,α) reactions. Some $(\mu^-, \nu 2n)$ and other reactions have been observed at a lower yield.

Keywords: LaTeX NUCLEAR REACTIONS ^{A}Z(μ^-,$\nu\gamma$) ,^{A}Z(μ^-,νnγ), ^{A}Z(μ^-,ν2nγ) , ^{A}Z(μ^-,νpnγ) measured E$_\gamma$, I$_\gamma$; deduced yields and transitions to product nuclei.
PACS: 23.40.-s 36.10.Dr 27.40.+z 27.50.+e 21.10.Jx

1. Introduction

We shall summarize our results of an experiment which studied the gamma-rays emitted after muon capture. We used as targets a variety of nuclei ranging from Al to Bi, but we shall focus on the results for Ca, Fe and Ni for which the analysis is complete. The analysis of the other nuclei is progressing, and will be completed in the next few months.

Because the mass of the muon is about 106 MeV/c^2, there is plenty of energy available when the muon is absorbed on a proton in the nucleus, and, although the neutrino takes away most of the energy, the product nucleus can be excited to 10 or 20 MeV. Thus, for medium mass nuclides, about 20% of the time the (μ^-, ν)

1219-7580/04/ $ 20.00

reaction feeds bound states in the product having the same mass as the target nucleus, but about 50% of the time a single neutron is given off, 10% of the time two neutrons are emitted, and the rest of the time more complex reactions occur, emitting protons or alphas. Each one of these reactions can produce γ-rays, so quite a variety are produced. The present situation with regard to muon capture has recently been reviewed by Measday [1].

2. Experimental Method

The experimental technique is fairly straightfoward in comparison to many other experiments nowadays. These data were taken at the same time as our experiment on ^{14}N, and those data have recently been published [2], so the details of the equipment can be found in that publication. In brief, the experiment was performed on the superconducting muon channel at TRIUMF in Vancouver, Canada. Pions are produced by the 500 MeV proton beam, and then are allowed to decay to muons in a superconducting solenoid. A bending magnet selects the backward going muons, and removes any residual pions. The beam retains about 20% electrons, which are not a serious problem. The muons pass through some scintillators, and then stop in the target. At 90° to the beam there were two HPGe detectors, but we have used the data from one only, as it had three times the statistics of the other.

Now the muon capture occurs up to 1 μs after the muon stop, so the coincidence requirement is not very stringent in removing background from the experimental area, which is bathed in thermal neutrons, and 1 MeV neutrons are produced in the muon capture, and so add to the problems. Thus it is critical to measure the γ-ray energies with care and precision. A key advantage that we have with respect to earlier experiments is that the energies and branching ratios of γ-rays are much better known now (and much more easily accessible from the National Nuclear Data Center). Modern γ-ray detectors are somewhat better than they used to be, but more important is that they are larger and more efficient for γ-rays of a few MeV. Thus an experiment can now identify γ-rays of 2 to 6 MeV, even though the yield may be fairly low. In addition a modern accelerator like TRIUMF has a macroscopic duty-cycle of 100 %, so the data can be taken at a higher rate. The efficiency of the HPGe detector varies by over a factor of ten in the energy range of interest; it was obtained using a ^{152}Eu source which covers 122 to 1408 keV. Lower energies were obtained from a ^{133}Ba source, and higher energies from the muonic x-rays. These x-rays are an excellent normalization as about 80 % of the stops produce a 2p-1s x-ray in the target nucleus. In addition there have been many careful studies of muonic x-rays, so the energies are well known, and we can use them for a confirmation of our energy scale.

The runs on Si, Al, Ca, I, Au and Bi lasted several hours each, and the data are dependable and rare transitions were observed. The iron and nickel results were obtained as a check on backgrounds, and so were not so extensive, but turned out to be much better than existing data, so we analyzed those results too.

3. Results for Calcium

There have been two previous experiments on calcium, both over 30 years ago. The first one by Pratt [3] at Carnegie Mellon was rather sketchy, and soon after there was a more detailed study at the CERN SC by Igo-Kemenes et al. [4]. We first present our data for the muonic Lyman series in natural calcium in Table 1. We used the (2p-1s) muonic x-ray as the local energy calibration [5, 6]. In the table, we compare the other energies and the x-ray intensities with previous data [7, 8]. This shows that our energy scales are dependable, and illustrates that our overall normalization method is consistent with previous experiments.

Table 1. The muonic Lyman series for natural calcium. The intensity of the (2p-1s) transitions is used as an overall normalization for the muon capture data.

Muonic x-ray	**Energy(a) (keV)**	**Energy [5–7](keV) (keV)**	**Intensity(a) (%)**	**Intensity [7, 8] (%)**
2p-1s	783.659(25)(b)	782.68(2) 784.15(3)	83.8(10)	82.6(7)
3p-1s	940.63(10)	940.70(17)	6.2(2)	6.5(3)
4p-1s	995.48(10)	995.40(25)	2.0(1)	2.1(2)
5p-1s	1020.8(10)	1020.7(3)	2.0(1)	2.1(2)
6p-1s	1034.62(10)	1034.4(3)	1.8(1)	1.9(2)
7p-1s	1042.71(20)	1043.15(30)	1.4(1)	1.2(2)
(8-∞)p-1s	1046 - 1063(c)		2.8(4)	3.60(55)

(a) This experiment
(b) Value used as a calibration, and taken from Ref. [6]
(c) These energies correspond to the bump formed by the series end

Our results for the reaction ^{40}Ca(μ^-,ν)^{40}K are presented in Table 2; these results are the levels fed in the capture reaction. They are obtained by summing any transitions from a particular level, and removing any cascading into that level. We can then compare to the earlier results of Igo-Kemenes et al. [4]. Also a comparison is made to the reaction ^{40}Ca(p,n)^{40}Sc from Chittrakarn et al. [9] at about 10° in the lab. The agreement with Igo-Kemenes is quite satisfactory, although we have observed many more transitions. The comparison with the (p,n) reaction is not as simple as one might have thought. We observe several transitions not seen strongly in the (p,n) reaction, and conversely, it is hard to identify the levels at 2700 keV and at 3900 keV seen strongly excited in the (p,n) reaction.

One minor disagreement with the earlier results of Igo-Kemenes et al. [4] is that we do not observe the reaction ^{40}Ca(μ^-, ν2p)^{38}Cl. They claimed a yield of 1.24(20)% for the 1309 keV level in ^{38}Cl. This is actually an unexpectedly rather

Table 2. Yields for the muon capture reaction ^{40}Ca(μ^-,ν)^{40}K to specific levels in ^{40}K with the cascading effects removed, compared to the earlier results of Igo-Kemenes et al. [4]. Also a comparison is made to the reaction ^{40}Ca(p,n)^{40}Sc from Chittrakarn et al. [9] at about 10° in the lab.

Level in ^{40}K (keV)	**Yield per capture(a) (%)**	**Yield per capture [4] (%)**	**Yield in the reaction ^{40}Ca(p,n)^{40}Sc [9]**	**Level in ^{40}Sc (keV)**
0			~ 0	0
29.83			~ 0	34
800.14	5.1(5)	4.23(1.18)	1.3	772
891.40	0.2(1)			
1643.65	0.5(4)			
1959.08	1.2(2)	0.5(2)	0.25	1799
2047.35	0.9(3)	0.53(18)		
2069.81	0.7(3)			
2103.67	1.1(2)			
2260.40	<0.25			
2289.88	0.5(2)			
2290.50	<0.12			
2397.17	<0.3			
2419.18	0.4(3)	1.53(24)		
2730.38	<0.24		0.35	~ 2700
2807.88	0.34(21)			
3228.68	<0.8			
3868.67 3887.93 3923.8	<0.9 <0.6 <1.0		0.15	~ 3900
4537	0.85(42)		0.4	~ 4300

(a) This experiment

high yield, so we searched for the three transitions from this level and found none. We illustrate this in Fig. 1 for the region around the 638 keV transition, which has a branching ratio of 76%. The gamma-ray would be expected in channel 479. The peak at channel 485 is the 646 keV transition in ^{40}K, which has a yield of about 0.4%. Thus we can place a limit of about <0.33% for excitation of the 1309 keV level.

4. Results for Nickel

To illustrate another interesting effect, we present in Table 3 our yields for the reaction ^{58}Ni(μ^-, νn)^{57}Co, taken for natural nickel, but corrected for the abundance of ^{58}Ni, so the yields are those for a pure isotopic target. We also compare to the spectroscopic factors from the reaction ^{58}Ni(d,^{3}He)^{57}Co [10] and to the yields in the reaction ^{58}Ni(γ,pγ')^{57}Co [11]. We see that the 1378 and 2133 keV levels are strongly excited in the (μ^-, νn) and (γ,pγ') reactions, but not in the (d,^{3}He) reaction. This is also true for the 1920 keV level if we assume that the lack of data in the (d,^{3}He) reaction is due to the low excitation of this level. For the 1758 and 1897 keV levels, they are excited by all the reactions. This comparison has been made before in other elements, with the same conclusion that the (μ^-, νn) reaction can be thought of as a two-stage reaction which excites 1^- levels, actually spin-isospin levels mainly, and these correspond most closely to the levels excited by gamma rays, so they decay by similar nucleon branching ratios.

Table 3. Direct production of levels in ^{57}Co from the reaction ^{58}Ni(μ^-, νn)^{57}Co, given as % yields for a pure isotopic target, and compared to the spectroscopic factors from the reaction ^{58}Ni(d,^{3}He)^{57}Co [10] and to the yields in the reaction ^{58}Ni(γ,pγ')^{57}Co [11].

Level energy (keV)	**Level yield in $(\mu^-, \nu n)$ (a) (%)**	**Spectroscopic factor [10]**	**Level yield in $(\gamma, p\gamma')$ (MeV.mb) [11]**
0	nd	4.27	31(8)
1223.98	5(1)	0.06	nd
1377.66	8(1)	0.06	30(8)
1757.61	5.9(22)	0.11	10(3)
1897.40	5.7(19)	0.92	7.7(20)
1919.50	3.4(12)	nd	11(3)
2133.06	4.1(16)	0.04	12(3)

nd = no datum
(a) This experiment

5. Summary Tables

In this short account, we cannot present our other results in detail, but we can summarize the types of reactions that occur. In Tables 4 and 5 we present the overall results for ^{40}Ca and ^{56}Fe. We first give the sum of the observed transitions. Then, from a comparison with similar reactions, we can estimate the yield for the ground state transition, which, of course, is not observed in a γ-ray experiment.

Then working back from the observed neutron multiplicities of Macdonald et al. [12] we can estimate the missing strength. Now obviously these tables are just estimates, with unknown uncertainties, but the exercise is educational.

Table 4. Overall estimates of the (%) yields for muon capture in ^{40}Ca, using as a guide the neutron multiplicities of Macdonald et al. [12], see Table 4.7 in Ref. [1].

Reaction	**Observed**	**Ground state**	**Missing**	**Total**
^{40}Ca(μ^-,ν)^{40}K	12	-	15	27
^{40}Ca(μ^-,νn)^{39}K	20	8	15	43
^{40}Ca(μ^-,ν2n)^{38}K	0.7	0.3	2	3
^{40}Ca(μ^-,νp)^{39}Ar	6	4	-	10
^{40}Ca(μ^-,νpn)^{38}Ar	7	4	-	11
^{40}Ca(μ^-,νp2n)^{37}Ar	1	2	-	3
^{40}Ca(μ^-,$\nu\alpha$xn)Cl	2	1	-	3
Total	**49**	**19**	**32**	**100**

Table 5. Overall estimates for the (%) yields for muon capture in ^{56}Fe, using as a guide the neutron multiplicities of Macdonald et al. [12], see Table 4.7 in Ref. [1].

Reaction	**Observed**	**Ground state**	**Missing**	**Total**
^{56}Fe(μ^-,ν)^{56}Mn	-	-	17	17
^{56}Fe(μ^-,νn)^{55}Mn	36	12	9	57
^{56}Fe(μ^-,ν2n)^{54}Mn	8	3	-	11
^{56}Fe(μ^-,ν3n)^{53}Mn	2.2	1.6	5	9
^{56}Fe(μ^-,νpxn)Cr	2	1	1	4
^{56}Fe(μ^-,$\nu\alpha$xn)V	-	1	1	2
Total	**48**	**19**	**33**	**100**

6. Conclusions

We can conclude this summary by noting that the detailed results for Ca, Fe, and Ni will be published soon, and greatly expand our knowledge of muon capture in those nuclides. The results for I, Au, and Bi are nearly complete. Again no (μ^-,ν) reactions are observed, but the (μ^-,νn) reaction is observed very clearly, and, as for earlier results in heavy elements, reactions are observed with several neutrons being emitted. For Al and Si, more is known [13, 14], but again we can contribute more detail. In these elements the (μ,νn) reaction is observed very clearly, and many others as well. An interesting example of the (μ^-,ν) reaction is that we observe a very strong transition in ^{28}Si at 4813 keV, which we attribute to the reaction ^{28}Si(μ^-,ν)^{28}Al, even though there is some disagreement in the literature where this level should be.

Our main conclusion is a strong confirmation of what Igo-Kemenes et al. [4] and Miller et al. [13] suggested 30 years ago, viz. that the (μ^-,νn) reaction feeds the same levels as the (γ,p) reaction for γ-rays of about 30 MeV, but the spectroscopic factors from reactions such as (d,^{3}He) are not as good predictors of the (μ^-,νn) reaction nor the (γ,p) reaction.

Acknowledgements

We wish to thank the many people who contributed to the successful completion of this experiment. E. Gete, T.P. Gorringe, J. Lange, B.A. Moftah and M.A. Saliba who helped set up the original experiment on nitrogen, and took some shifts too. J. Chuma wrote the program "Physica" which was used for the data analysis, and he also wrote some of the macros specifically for this analysis. Of course, in a major laboratory like TRIUMF, many people help by keeping the cyclotron operating and preparing the experimental area for each experiment; the financial contribution for this essential activity is provided by the National Research Council of Canada. Finally we thank the Natural Sciences and Engineering Research Council, Canada, for providing the grants that made the experiment possible.

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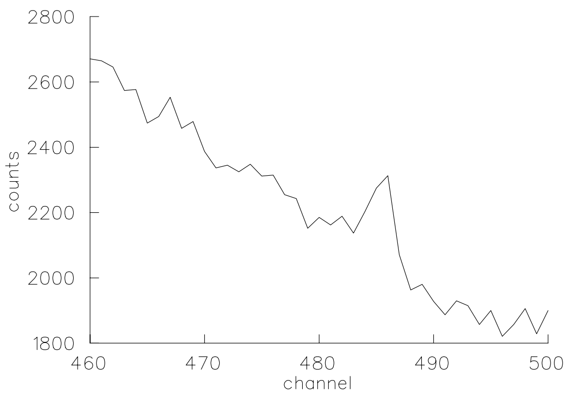

Fig. 1. A gamma-ray spectrum from muon capture in natural calcium, indicating that we do not observe the 638 keV transition in ^{38}Cl, which would be at channel 479. For orientation, the peak at channel 485 is the 646 keV transition in ^{40}K, which has a yield of about 0.4%.