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^{58}Ni(α, α')^{58}Ni and the Nature of High-Lying States in ^{58}Ni

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(Received 19 May 1972)

We have studied levels in ^{58}Ni up to 10 MeV excitation energy through the (α,α') reaction at 30 MeV and found surprising overall agreement between the observed spectra and those from α-transfer reactions.

There has been considerable interest recently in higher excited states seen in the (^{16}O,^{12}C) reaction in f-p-shell target nuclei[1,2] and their interpretation in terms of quartet structure.[3] Although it is now reasonably well established that the (^{16}O,^{12}C) reaction is direct, the nature of such heavy-ion reactions makes it difficult to obtain spectroscopic information, or even to establish

TABLE I. Comparison of levels in ^{58}Ni above the first 3^- state at 4472 keV strongly excited in the (α,α') reaction and in the (^{16}O,^{12}C) and (^{7}Li,t) reactions.

E [a] (keV)	(α,α') J^π (This work)	(α,α') β_L (This work)	(^{16}O,^{12}C)[b] E (±0.05) (MeV)	(^{7}Li,t)[c] E (±0.03) (MeV)
4472	3^-	0.17	4.50	4.47
4750	4^+	0.076	...	...
5122	Multiplet (M)	...	5.22(?)	5.03(?)
5408	M	...	...	...
5582	2^+ [d]	0.067	5.59	(Impurity)
6024	3^-	0.059	6.03	5.98
6318	M	...	...	...
6463	M	...	6.45	6.42
6742	3^-	0.061	6.80	6.78
6847	3^-	0.073		
7056	M	...	...	7.03
7212	4^+	0.082	7.2 (±0.1)[e]	7.13
7521	3^-	0.063	7.56	7.53
7734	M	...	7.80	7.72
8108	M	...	8.06	
8493	$(3,1)^-$	0.052(3^-)		
8662	$(3,1)^-$	0.057(3^-)		
9290	M	...		

[a]The uncertainty, ΔE, is ±8 keV for the levels up to 6742 keV, increasing to, at most, ±15 keV for the higher levels.
[b]See Ref. 9.
[c]See Ref. 4.
[d]Given as 4^+ in Ref. 6; $4^+ + 5^-$ in Ref. 7.
[e]Taken from Ref. 1.

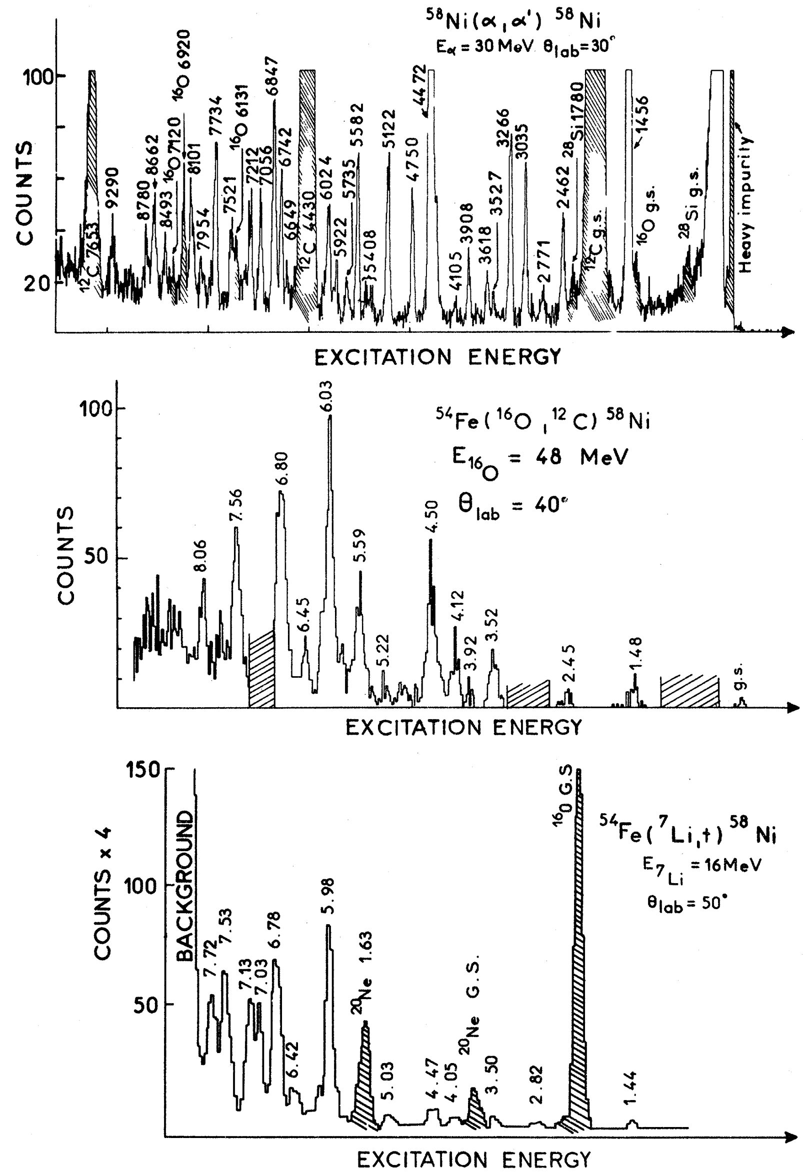

FIG. 1. ^{58}Ni$(\alpha,\alpha')^{58}$Ni spectra and, for comparison, ^{54}Fe$(^{16}$O, ^{12}C$)^{58}$Ni and ^{54}Fe$(^{7}$Li, $t)^{58}$Ni spectra from Refs. 9 and 4, respectively. The blocked areas in the $(^{16}$O, ^{12}C) spectrum correspond to the positions of impurity peaks.

the transferred l values. Recently, another four-nucleon transfer reaction $(^{7}$Li,$t)$ has been found to excite some of the same levels, although again l values are not determined.[4] Thus the main evidence for such quartet structures lies primarily in the existence of the discrete structure observed in a region of high-level density combined with the general predictions of quartet theory.[5] However, it should be noted that the (α,α') reaction in the f-p shell also populates relatively few states in the same region of excitation energy and that some states apparently correlate in energy with states observed in the four-nucleon transfer reaction. In an attempt to further examine the possible coincidence of levels, we have performed a high-resolution study of the reaction ^{58}Ni$(\alpha,\alpha')^{58}$Ni to compare with the reactions ^{54}Fe$(^{16}$O,^{12}C$)^{58}$Ni and ^{54}Fe$(^{7}$Li,$t)^{58}$Ni as well as previous inelastic-scattering measurements.[6-8]

The 30-MeV α-particle beam of the Saclay variable-energy cyclotron was used to bombard a self-supporting 600-μg/cm^2 ^{58}Ni target (98% enriched). Inelastically scattered α particles were detected in a (dE/dx)-E silicon detector telescope. A few spectra were also taken with a 150-μg/cm^2 target mounted on a ^{12}C backing with a single detector. Such a spectrum is shown in Fig. 1. No states in ^{58}Ni were seen beyond 9.8 MeV although background due to three-body final states could obscure weak states.

Angular distributions were obtained for most of the observed levels from 16° to 64° in the c.m. system. Comparison with macroscopic distorted-wave Born-approximation (DWBA) calculations then permitted values of J^{π} and of the β deformation parameter to be deduced for many of those levels. Figure 2 displays the angular distributions of the negative-parity levels identified in this experiment. Table I summarizes the results obtained for the strongest states above and including the first 3^- state at 4.472 MeV in ^{58}Ni. For most of the states below 6 MeV our results for J^{π} and β values were in excellent agreement with previous work, except for the level at 5582 keV, which we find to be a 2^+ state while previous studies have indicated it to be a 4^+ state[6] or $4^+ + 5^-$ states.[7] However, the data of Jarvis *et al.*[6] are consistent with a 2^+ assignment. It should be noted that most of the states seen below 6 MeV have positive parity, whereas most of the levels strongly excited above 6 MeV (Fig. 2) have negative parity and, in particular, appear to be 3^- states. Preliminary results on the (^{3}He, ^{3}He′) reaction show the same states being populated.

The relative energies and structure of the states excited by inelastic α scattering on ^{58}Ni may be understood in terms of the usual description of coherent mixtures of particle-hole excitations—in this instance comprising s-d, f-p and $g_{9/2}$ orbitals. Such a picture can provide positive-parity states between 0 and 5.5 MeV and at least eight 3^- states between 5.5 and 13 MeV in excitation. More complicated configurations certainly could contribute to these levels, but this simple picture appears to account for the gross structure of the observed spectrum. This description also predicts eight 1^- states in the same energy region, but they appear to be weakly excited and in no case unambiguously identified in the (α,α') reaction.

The strongly excited levels in the (α,α') reaction are compared with those observed in the (^{16}O,^{12}C)[9] and (^{7}Li,t)[4] reactions in Fig. 1 and Table I. The energy resolution and uncertainty in energy assignments are about 45 and ±15 keV for the (α,α') spectrum, 130 and ±50 keV for the (^{16}O,^{12}C) spectrum, and 120 and ±30 keV for the (^{7}Li,t) spectrum. In view of the underlying density of levels and with the available resolution (or lack of it), it is not possible to be sure that any one state corresponds exactly to any other in these spectra. Nevertheless, the overall correspondence of the strong states observed in all three reactions strongly suggests that the same set of levels is being populated. The agreement between the two α-transfer–reaction spectra, previously noted,[4] is not better than that of either with the inelastic-α-scattering spectrum.

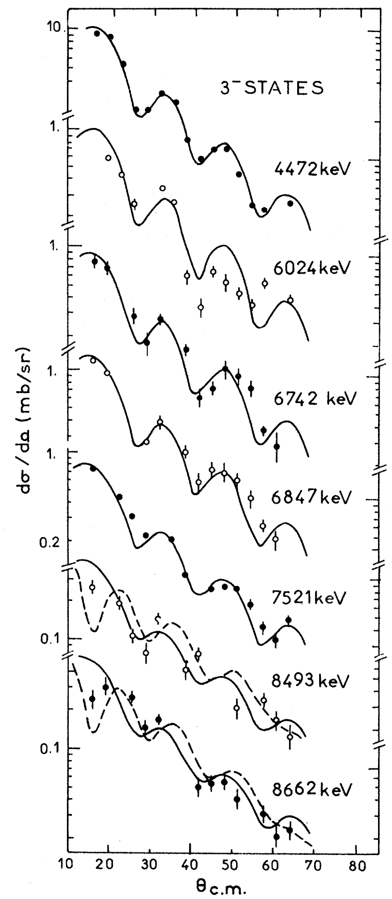

FIG. 2. Experimental angular distributions and macroscopic DWBA calculations for the negative-parity levels identified in the reaction ^{58}Ni$(\alpha,\alpha')^{58}$Ni at 30 MeV. Calculations for $l=3$ and 1 are represented by solid and dashed lines, respectively.

If indeed they are the same states, then one must reconcile this information with the fact that the (α,α') results appear capable of description by coherent single-particle excitations, whereas α-transfer reactions are usually thought to populate multi-particle-hole configurations. In addition, excitation of 3^- states in α transfer would appear inconsistent with the simple stretch scheme proposed for quartet states.[3] However, similar evidence exists in the $2s$-$1d$ shell for strong excitations of negative-parity states by α-

transfer reactions.[10] While further experimental studies are needed to confirm the correspondence of the states observed in ^{58}Ni in two such different reactions, perhaps a theoretical assessment of the structure of these states and the manner in which they might be populated is also required.

We are pleased to acknowledge helpful discussions with Dr. R. Schaeffer and Dr. A. Zuker. We wish to thank Dr. E. Cotton for providing the (^{16}O,^{12}C) spectrum prior to publication and S. Fortier for help during the experiment.

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Possible Evidence for a Contribution from Direct Collisions in K-Shell Internal Ionization Accompanying β Decay

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Using an improved one-step theory of electron shakeoff, we have performed rigorous calculations of the energy-dependent K-shell internal ionization probability. The measured probability for ^{147}Pm considerably exceeds the theoretical curve at low electron energies. This suggests that the direct collision process may play an important role when both a β particle and a K electron are emitted with low kinetic energies.

K-shell internal ionization during β decay, which causes simultaneous emission of a K-shell electron, a β particle, and a neutrino, is usually attributed to the sudden change of nuclear charge. This mechanism is often referred to as "electron shakeoff." The one-step theory of electron shakeoff was first proposed by Feinberg.[1] Using his formulation, Stephas and Crasemann[2] developed the theory, but there remained ambiguities as to the antisymmetrization of the two emitted electrons and the atomic matrix element. Recently, efforts to improve the theory have been made by Law and Campbell,[3] Mord,[4] and Shimizu.[5] Employing the improved theory, we have calculated the $E_\beta{}^0$-dependent K-shell internal ionization probability $P_K(E_\beta{}^0)$ to compare with the experimental $P_K(E_\beta{}^0)$ obtained by Isozumi and Shimizu.[6] Here, the parameter $E_\beta{}^0$ is defined as the sum of the energies of the β particle, E_β, and the emitted K electron, E_K, plus the K-shell binding energy of the daughter atom, B_K.

According to our theoretical treatment of electron shakeoff,[5,6] the $E_\beta{}^0$-dependent probability $P_K(E_\beta{}^0)$ is given by

$$P_K(E_\beta{}^0)=2\int_0^{E_\beta{}^0-B_K}\frac{S_K(E_\beta,E_0-E_\beta{}^0)}{S_\beta(E_\beta{}^0,E_0-E_\beta{}^0)}\,\frac{F(Z+1,E_\beta)}{F(Z+1,E_\beta{}^0)}\left(\frac{E_\beta(E_\beta+2)}{E_\beta{}^0(E_\beta{}^0+2)}\right)^{1/2}\frac{E_\beta+1}{E_\beta{}^0+1}\times|M_A(E_K)|^2\,\Xi(E_\beta,E_K)\,dE_K. \qquad (1)$$

In this expression, E_0 is the maximum kinetic energy of the continuous β-ray spectrum of ordinary β decay, $F(Z+1,E_\beta)$ is the Coulomb correction factor, and the factor of 2 accounts for the two K electrons. $S_K(E_\beta,E_0-E_\beta{}^0)$ and $S_\beta(E_\beta{}^0,E_0-E_\beta{}^0)$ are energy-dependent shape factors of K-electron shakeoff and ordinary β decay, respectively. For simplicity in calculating, both factors were assumed to be uni-