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Trans. Nonferrous Met. Soc. China 16(2006) 203-208

Transactions of Nonferrous Metals Society of China

www.csu.edu.cn/ysxb/

Thermodynamics and technology of extracting gold from low-grade gold ore in system of NH₄Cl-NH₃-H₂O

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Received 13 May 2005; accepted 29 August 2005

Abstract: According to the principles of simultaneous chemical equilibrium and electronic charge neutrality, the thermodynamics of Au-NH₄Cl-NH₃-H₂O system was studied by using the exponential computation method and through MATLAB programming, and the solid figure of potential- $c(NH_4Cl)$ - $c(NH_4OH)$ was drawn. The results show that when the sum concentration of Au⁺ and Au³⁺ is equal to 5×10^{-5} mol/L, $\varphi(Au^+/Au)$ is about -0.2 V; when the sum comes up to 0.5 mol/L, the value of $\varphi(Au^+/Au)$ increases to 0.2 V. In this case, $\varphi(O_2/OH^-)$ is as high as 0.7 V. This means that it is feasible to extract gold in this system. In addition, to predict the feasibility of reducing gold from the Au(I)-NH₄Cl-NH₃-H₂O system with copper or zinc powder, the solid figures of potential- $c(NH_4Cl)$ - $c(NH_4OH)$ for both systems of Cu-NH₄Cl-NH₃-H₂O and Zn-NH₄Cl-NH₃-H₂O were also drawn. The results indicate that both copper and zinc powders can reduce Au⁺ into metal gold, and zinc powder can also reduce H₂O into H₂, while copper powder can not. The leaching results of a cuprous gold ore show that the extraction of gold can reach 80% in this system. The preliminary results of reduction with copper and zinc powders show that with deoxygenizing, the reduction effects are relatively good.

Key words: gold; gold extraction; NH₄Cl-NH₃-H₂O; hydrometallurgy; thermodynamics; ammonium chloride

1 Introduction

Hydrometallurgy with ammoniacal ammonium chloride as extracting system is a new developing field with many merits. Above all, NH_3 and Cl^- ions existing in the system have relatively high complex ability with some heavy or noble metal ions. In addition, the pH value in this system varies from 5.0 to 12.0, so it has better selectivity than the sulfate acid system. Further more, the medium is free of toxicity.

In our previous work, the basic theory of extracting zinc in the system was studied. On this basis, we developed a new process for producing high purity zinc directly from complicated zinc oxide materials [1-4]. WANG[5, 6] also developed a new process of heap leaching and solvent extracting copper from copper oxide ore in NH₄Cl-NH₃-H₂O system.

At present time, the methods for treating gold ores are mainly cyanogens, thiourea, thiosulfate, and halogen approach, among which, the cyanogens approach has the advantages of low cost, high efficiency, and now is the main method for producing gold. However, the effect of leaching complicated ores with this method is very poor, due to its low leaching speed and easy effect by elements such as Cu, Fe, Pb, Zn, S and As. In addition, cyanogens is virulent, and because of the strict requirements of environmental protection by the governments around the world, its prospect is rather faint. For the thiourea approach, it has some advantages such as fast dissolving speed, low toxicity, good selectivity. But its drawbacks, i.e. low stability of thiourea, high cost infeasibility of treating the ores with relatively high alkalinity limit its uses. The thiosulfate approach has the advantages of fast dissolving speed, low toxicity, low sensibility with impurities and high extraction of gold. But due to its high consumption of thiosulfate, difficulty in reutilization, strict operating conditions, high leaching temperature, and pollution by high dosage ammonia, the approach is used seldom. The halogen approach is only used in treating complicated gold ores, which also has the drawbacks such as high cost, high toxicity and high pollution to environment [7-12].

In this paper, according to the principles of simultaneous chemical equilibrium and electronic charge neutrality, the thermodynamics of the system of $Au-NH_4Cl-NH_3-H_2O$ was studied by using exponential computation method proposed by TANG and through MATLAB programming, and the solid

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figure of potential- $c(NH_4Cl)$ - $c(NH_4OH)$ was drawn. In addition, to predict the feasibility of reducing gold from the system of Au(I)-NH₄Cl-NH₃-H₂O system with copper or zinc powders, the solid figures of potential- $c(NH_4Cl)$ - $c(NH_4OH)$ of both systems of Cu-NH₄Cl-NH₃-H₂O and Zn-NH₄Cl-NH₃-H₂O were drawn. Finally, a series of leaching and reducing experiments were conducted.

2 Thermodynamic analysis and model establishment

There are altogether 22 species in the system of Au-NH₃-NH₄Cl-H₂O such as Au(NH₃)⁺, Au(NH₃)², Au(NH₃)³⁺, Au(NH₃)³⁺, Au(NH₃)³⁺, Au(NH₃)³⁺, Au(NH₃)³⁺, AuCl(aq), AuCl²₂, AuCl²⁺, AuCl²₂, AuCl³⁺, AuCl₃(aq), AuCl³⁻₄, AuO³⁻₃, Au(OH)(s), Au(OH)₃(s), Au⁺, Au³⁺, Cl⁻, NH₃(aq), NH₄⁺, H⁺ and OH⁻.

Actually, the species such as Au(OH)(s) and Au(OH)₃(s) can only be produced when the pH value is very high. In this system, the pH value is kept in the range of 5.0-12.5. So these two species are ignored in this thermodynamic model. While for the species such as Au(NH₃), Au(NH₃)³⁺, Au(NH₃)²⁺, Au(NH₃)³⁺, AuCl(aq) and AuCl₃(aq), their stable constants are very small in the ammonia systems, so these species are also ignored in our thermodynamic model. In addition, due to the fact of being hard to exist solely in this system, Au⁺ and Au³⁺ are also ignored.

On the basis of the simultaneous equilibrium principle, every aurous complex is in equilibrium with elemental gold in the presence of metallic gold in the system.

$$Au + 2NH_3 = Au(NH_3)_2^+ + e^-$$
 (1)

$$Au + 4NH_3 = Au(NH_3)_4^{3+} + 3e^-$$
 (2)

$$Au + 2Cl^{-} = AuCl_{2}^{-} + e^{-}$$
(3)

$$Au + 4Cl^{-} = AuCl_{4}^{-} + 3e^{-}$$

$$\tag{4}$$

$$Au + 3OH^{-} = AuO_{3}^{3-} + 3H^{+} + 3e^{-}$$
 (5)

According to the exponential computation method proposed by TANG et al[13, 14] and supposition that the activity of each species is equal to its mole concentration, the concentration of these species can be expressed as

$$c(\mathbf{R}_{i}^{-J}) = \exp[AM_{\mathrm{E}} + BN_{\mathrm{p}} + C\ln c(\mathrm{Cl}^{-}) + D\ln c(\mathrm{NH}_{3}(\mathrm{aq})) + G]$$
(6)

where $c(\mathbf{R}_i^{-j})$ is the concentration of the ions to be calculated; $M_{\rm E} = FE/(RT)$; *E* is the value of potential; $N_{\rm p} = P \cdot \ln 10$; *P* is the value of pH; $c({\rm Cl}^-)$ is the

concentration of free Cl⁻ ligand in the solution, $c(NH_3(aq))$ is the concentration of free NH₃(aq) ligand in the solution; *A*, *B* are the numbers of electron and proton obtained or lost by a R_i^{-j} ; *C* is the number of Cl⁻ ligand; *D* is the number of NH₃(aq) ligand; $G = \alpha \cdot F \cdot E^0 / (298R)$.

The critical stability constants of aurous complexes, presented in Table 1, were chosen from Ref.[15].The thermodynamic data, presented in Table 2, were chosen from Ref.[16].

 Table 1
 Critical stability constants of main aurous coordination compounds at 298 K

Complex	$\lg \beta_i$	Complex	$\lg \beta_i$
$AuCl_2^-$	9.71	$Au(NH_3)_2^+$	26.50
$AuCl_4^-$	25.3	$\operatorname{Au}(\operatorname{NH}_3)_4^{3+}$	46.00

 Table 2
 Gibbs free energy of related species at 298 K

Species	$\Delta G^{\Theta}/(\mathbf{J} \cdot \mathbf{mol}^{-1})$	Species	$\Delta G^{\Theta}(\mathbf{J} \cdot \mathbf{mol}^{-1})$
NH ₃ (aq)	-75 322	Au	0
NH_4^+	-79 333	NH4OH	-26 712
H_2O	-237065	NH ₄ Cl(aq)	-210 522
H^+	0	OH^-	-157 899

By use of the data presented in Tables 1 and 2, the values of A, B, C, D, G in Eqn.(6) can be calculated as listed in Table 3.

Table 3 Constants in Eqn.(6) for calculating speciesconcentration in system of Au- NH_3 - NH_4Cl-H_2O

Species	A	В	С	D	G
$AuCl_2^-$	1	0	2	0	-45.279 3
$\operatorname{Au}(\operatorname{NH}_3)_2^+$	1	0	0	2	-4.684 1
$\operatorname{Au}(\operatorname{NH}_3)_4^{3+}$	3	0	0	4	-37.472 5
$AuCl_4^-$	3	6	0	0	-277.799 8
AuO_3^{3-}	3	6	0	0	-116.361 6
NH_4^+	0	1	0	1	21.427 0
H^+	0	1	0	0	0
OH^-	0	-1	0	0	-32.234 8

The sum concentration of aurous, ammonia and chloride can be expressed as Eqns.(7), (8) and (9), respectively.

$$c(Au)_{T} = c(Au(NH_{3})_{2}^{+}) + c(Au(NH_{3})_{4}^{3+}) + c(AuCl_{2}^{-}) + c(AuCl_{4}^{-}) + c(AuO_{3}^{3-})$$
(7)

$$c(\mathrm{NH}_{3}(\mathrm{aq}))_{\mathrm{T}} = c(\mathrm{NH}_{4}) + c(\mathrm{NH}_{3}(\mathrm{aq})) + 2c(\mathrm{Au}(\mathrm{NH}_{3})_{2}^{+}) + 4c(\mathrm{Au}(\mathrm{NH}_{3})_{4}^{3+})$$
(8)
$$c(\mathrm{Cl}^{-})_{\mathrm{T}} = c(\mathrm{Cl}^{-}) + 2c(\mathrm{Au}\mathrm{Cl}_{2}^{-}) + 4c(\mathrm{Au}\mathrm{Cl}_{4}^{-})$$
(9)

 (\mathbf{NIII}^+) .

(**NILL** (----))

According to the principle of electronic charge neutrality, the equation of electronic charge equilibrium can be expressed as

$$c(\operatorname{Au}(\operatorname{NH}_{3})_{2}^{+}) + 3c(\operatorname{Au}(\operatorname{NH}_{3})_{4}^{3+}) - c(\operatorname{Au}\operatorname{Cl}_{2}^{-}) - c(\operatorname{Au}\operatorname{Cl}_{2}^{-}) - c(\operatorname{Au}\operatorname{Cl}_{2}^{-}) - 3c(\operatorname{Au}\operatorname{O}_{3}^{3-}) + c(\operatorname{NH}_{4}^{+}) + c(\operatorname{H}^{+}) = c(\operatorname{Cl}^{-}) + c(\operatorname{OH}^{-})$$
(10)

Then the model of this system can be set up as a combination of Eqns.(7)-(10).

3 Model solution with MATLAB and discussion

The relation among the seven variables of E, $c(Au)_T$, $c(Cl^-)_T$, $c(NH_3(aq))_T$, $c(Cl^-)$, $c(NH_3(aq))$ and pH is confined by the above model. If three of them are given, the other four variables may be obtained from the above mentioned simultaneous equations by the computation program with MATLAB language compiled by ourselves.

During the actual calculating process, as the values of $c(Cl^{-})_{T}$ and $c(NH_{3}(aq))_{T}$ are determined by the concentration of the leaching reagent:

$$c(\mathrm{Cl}^{-})_{\mathrm{T}} = c(\mathrm{NH}_{4}\mathrm{Cl})$$
(11)
$$c(\mathrm{NH}_{3}(\mathrm{aq}))_{\mathrm{T}} = c(\mathrm{NH}_{4}\mathrm{Cl}) + c(\mathrm{NH}_{4}\mathrm{OH})$$
(12)

so it is preferable to specify these two values. In addition, if the value of $c(Au)_T$ is given, the value of potential which is needed to dissolve c(Au)T can be figured out.

According to the principle above, we worked out the values of potential, when the values of $c(Cl^{-})_{T}$ and $c(NH_{3}(aq))_{T}$ both vary from 0 to 5.0 mol/L, and the value of $c(Au)_{T}$ is 5.0×10^{-5} and 0.5 mol/L respectively. Then the solid figure of φ - $c(NH_{4}Cl)$ - $c(NH_{4}OH)$ is drawn as Figs.1 and 2.

In order to see the figure more clearly, Fig.1 is rotated as Fig.2.

It is shown in Figs.1 and 2 that, 1) without ammonium and chloride ions, the potential required for obtaining 5.0×10^{-5} mol/L aurous Au is very high, while there exist ammonium and chloride ions, the potential decreases to -0.2 V, and as the concentration of ammonia increases, the value declines slow- ly; 2) when the concentration of NH₄OH is lower than 0.6 mol/L, whatever high the concentration of potential is, the total concentration of aurous Au in the solution can not reach 0.5 mol/L; 3) when the concentration of NH₄OH is



Fig.1 Solid figure of φ - $c(NH_4Cl)$ - $c(NH_4OH)$ in system of Au-NH₃-NH₄Cl-H₂O: $\varphi(Au_{5e-5}^+/Au)$ is the value of potential needed for obtaining 5×10⁻⁵mol/L aurous Au; $\varphi(Au_{0.5}^+/Au)$ is the value of potential needed for obtaining 0.5×10⁻⁵mol/L aurous Au (Note: the first left curve of this figure is got when $c(NH_4OH)$ =0.05 mol • L⁻¹, and the same on the following figure.)



Fig.2 Rotated figure of φ -c(NH₄Cl)-c(NH₄OH) in system of Au-NH₃-NH₄Cl-H₂O

higher than or equal to 0.6 mol/L, to obtain 0.5 mol/L aurous Au in the solution, the potential is only 0-0.2 V; 4) $\varphi(O_2/OH^-)$ is as high as 0.7 V, which means that it is feasible to extract gold in this system.

4 Feasibility of reducing aurous with zinc powder or copper powder

4.1 Thermodynamic analysis of Zn-NH₄Cl-NH₃-H₂O system

There are altogether more than 20 species in the system of Zn-NH₄Cl-NH₃-H₂O. The four most important species, i.e. Zn^{2+} , ZnO_2^{2-} , $HZnO_2^{-}$ and $Zn(NH_3)_4^{2+}$ are taken into consideration, while the

other species are omitted. The thermodynamic data for calculation are found out and listed in Table 4.

Table 4 Critical stability constants of main Zn coordinationcompounds at 298 K and Gibbs free energy of related species at298 K

Species	$\Delta G^{\Theta}/(\mathbf{J} \cdot \mathbf{mol}^{-1})$	Complex	$\lg \beta_i$
ZnO_2^{2-}	-390 729	$Zn(NH_3)_4^{2+}$	9.65
$HZnO_2^-$	-465 780		

The data of other species needed such as $NH_3(aq)$, NH_4^+ , H_2O , OH^- and H^+ are shown in Table 2.

By using the data in Table 4, the values of A, B, C, D and G for this system in Eqn.(6) are calculated and listed in Table 5.

Table 5Constants in Eqn.(6) for calculating speciesconcentration in system of Zn-NH4Cl-NH3-H2O

Species	A	В	С	D	G
Zn^{2+}	2	0	0	0	58.342 6
$\operatorname{Zn}(\operatorname{NH}_3)_4^{2+}$	2	0	0	4	79.837 3
$HZnO_2^-$	2	3	0	0	-3.838 3
ZnO_2^{2-}	2	4	0	0	-33.777 3

The sum concentrations of zinc, ammonia and chloride can be expressed as

$$c(Zn^{2+})_{T} = c(Zn^{2+}) + c(Zn(NH_{3})_{4}^{2+}) + c(HZnO_{2}^{-}) + c(ZnO_{2}^{2-}) c(NH_{3}(aq))_{T} = c(NH_{4}^{+}) + c(NH_{3}(aq)) +$$
(11)

 $4c(Zn(NH_3)_4^{2^+})$ (12) $c(Cl^-)_T = c(Cl^-) + 4c(ZnCl_4^{2^-})$ (13)

According to the principle of electronic charge neutrality, the equation of electronic charge equilibrium can be expressed as

$$2c(\operatorname{Zn}^{2+})_{\mathrm{T}} + c(\operatorname{NH}_{4}^{+}) + c(\operatorname{H}^{+}) = c(\operatorname{Cl}^{-})_{\mathrm{T}} + c(\operatorname{OH}^{-}) \quad (14)$$

Then the model of this system can be set up as a combination of Eqns.(11)-(14).

4.2 Thermodynamic analysis of Cu-NH₄Cl-NH₃-H₂O system

There are altogether more than 26 species in the system of Cu-NH₄Cl-NH₃-H₂O. The five most important species, i.e. Cu^+ , Cu^{2+} , $CuCl_4^{3-}$, $Cu(NH_3)_2^+$ and $Cu(NH_3)_4^{2+}$ are take into

consideration, while other species are omitted. The thermodynamic data for calculation are found out and listed in Table 6.

The data of other species such as $NH_3(aq)$, NH_4^+ , H_2O , OH^- and H^+ are already listed in Table 2.

By using the data in Table 4, the values of A, B, C, D and G for this system in Eqn.(6) are calculated and listed in Table 7.

Table 6 Critical stability constants of main Cu coordinationcompounds at 298 K and Gibbs free energy of related species at298 K

Species	$\Delta G^{\Theta}/(\mathbf{J} \cdot \mathbf{mol}^{-1})$	Complex	$\lg \beta_i$
Cu^+	$-50\ 000$	$Cu(NH_3)_2^+$	10.58
Cu ²⁺	-65 490	$Cu(NH_3)_4^{2+}$	12.60
		CuCl ₄ ^{3–}	13.10

Table 7 Constants in Eqn.(6) for calculating speciesconcentration in system of $Cu-NH_4Cl-NH_4-H_2O$

Species	A	В	С	D	G
Cu^+	1	0	0	0	-20.297 6
Cu ²⁺	2	0	0	0	-26.465 0
$Cu(NH_3)_2^+$	1	0	0	2	4.293 7
$Cu(NH_3)_4^{2+}$	2	0	0	4	2.342 0
CuCl ₄ ^{3–}	1	0	4	0	9.992 7

The sum concentrations of copper, ammonia and chloride can be expressed as

$$c(Cu)_{T} = c(Cu^{+}) + c(Cu^{2+}) + c(Cu(NH_{3})_{2}^{+}) + c(Cu(NH_{3})_{4}^{2+}) + c(CuCl_{4}^{3-})$$
(15)

 $c(\mathrm{NH}_3(\mathrm{aq}))_{\mathrm{T}} = c(\mathrm{NH}_4^+) + c(\mathrm{NH}_3(\mathrm{aq})) +$

$$2c(Cu(NH_3)_2^+) + 4c(Cu(NH_3)_4^{2+})$$
(16)

$$c(Cl^{-})_{\rm T} = c(Cl^{-}) + 4c(CuCl_4^{3-})$$
 (17)

According to the principle of electronic charge neutrality, the equation of electronic charge equilibrium can be expressed as

$$2c(Cu(NH_{3})_{4}^{2+}) + 2c(Cu^{2+}) + c(Cu(NH_{3})_{2}^{+}) + c(Cu^{+}) - 3c(CuCl_{4}^{3-}) + c(NH_{4}^{+}) + c(H^{+}) = c(Cl^{-}) + c(OH^{-})$$
(18)

Then the model of this system can be set up as a combination of Eqns.(15)-(18).

4.3 Solution of two models with MATLAB and discussion

Supposing the values of $c(NH_4Cl)$ and $c(NH_4OH)$ both varying from 0 to 5.0 mol/L, and specifying $c(Cu)_T$ and $c(Zn^{2+})_T$ both equal to 0.01 mol/L, the potential of solution can be figured out with MATLAB programming. The results are shown in Figs.3 and 4.



Fig.3 φ -*c*(NH₄Cl)-*c*(NH₄OH) in system of Au-Cu-Zn-NH₃-NH₄Cl-H₂O

It is shown in Figs.3 and 4 that, in this system, $\varphi(Cu+/Cu)$ is about -0.5 V; $\varphi(Zn^{2+}/Zn)$ is about -1.0 V; $\varphi(O_2/OH^-)$ is about 0.7 V; $\varphi(H^+/H_2)$ is about -0.5 V. Thus, both copper and zinc powders can reduce Au+ into metal gold, and zinc powder can also reduce H₂O into H₂, while copper powder can not. In addition, because the potential of oxygen is much higher than those of Au⁺, Cu⁺, or H₂. This means that it is better to deoxygenize at the beginning of reduction.

5 Experiments

5.1 Result of leaching experiments



Fig.4 Rotated figure of φ -c(NH₄Cl)-c(NH₄OH) in system of Au-Cu-Zn-NH₃-NH₄Cl-H₂O

A low grade cupreous gold ore taken from Gansu Province was used in the following leaching experiments. Its chemical composition is shown in Table 8.

The phase composition analysis show that, the copper exists in a mixture of oxide and sulfide ore in the ore, and gold exists as tiny particles wrapping in gangues.

The leaching results are shown in Table 9.

5.2 Preliminary result of reduction experiments

Using the solution gained from the above experiments, whose composition is listed in Table 10, the reduction with copper powder and zinc powder were conducted and the results are shown in Table 11.

From Table 11, it is shown that the reduction of Au^+ is very low. This is mainly because that the oxygen dissolved in the solution is competitive with Au^+ in the reduction process. So, deoxygenizing is of great importance in this reduction process.

Table 8 Chemic	cal composition	n of low g	rade cupr	eous gold o	ore (mass	fraction, %	b)				
Au*	Ag*	Cu	Pb	Zn	Fe	SiO_2	Al_2O_3	CaO	MgCO ₃	S	Total
2.53	18.0	0.12	0.15	0.021	7.47	68.06	11.03	0.39	1.35	0.51	89.101

* indicates g • t⁻¹.

No.	Leach method and scale/	Ratio of liquid to solid/	Reagent co (mol	$\bullet L^{-1}$)	Oxidant and its dosage/	Size of ore particle/	Leaching time/	Gold extraction/
	kg	$(mL \cdot g^{-1})$	NH ₄ Cl	NH ₄ OH	g	mm	h	%
1	Trough, 1	8	4	0.5	No	<0.0510, 80%	12	19.5
2	Trough, 1	8	4	0.5	Ca(ClO) ₂ , 20	<0.0510, 80%	12	82.5
3	Column, 10	1	2	0.5	Ca(ClO) ₂ , 500	0.1-30	2 400	76.4
4	Column, 10	1	2	0.5	Air	0.1-30	2 400	80.1

Table 10 Ion concentration of solution used in reduction experiments $(mg \cdot L^{-1})$

2.04 2.30 5.26 0.0 1.77 5.00 100 120 51.0 8.91	Au	Ag	Fe	Mn	Co	Pb	Cu	Zn	NH ₄ Cl*	NH ₃ *
	2.04	2.30	5.26	0.0	1.77	5.00	100	120	51.0	8.91

* indicates g • L⁻¹.

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No.	Type of metal powder	Dosage	Reduction time/ min	Copper reduction/ %	Gold reduction/ %	Phenomena
1	Zinc	5 times of Au^+	13	_	25.98	_
2	Zinc	5 times of Cu^{2+}	13	90	30.39	Color thinning, bubbling
3	Zinc	20 times of Cu^{2+}	60	98	31.37	Colorless, bubbling
4	Copper	25 times of Au^+	60	_	22.06	_
5	Copper	5 times of Cu ²⁺	60	—	33.33	Color darken
6*	Zinc	5 times of Cu ²⁺	60	70	71.26	Little bubbling
7*	Copper	5 times of Cu^{2+}	60	_	60.35	_

 Table 11
 Preliminary results of reduction experiments

Note:* indicates after deoxygenizing

6 Conclusions

1) The thermodynamics study of the system Au-NH₃-NH₄Cl-H₂O shows that when the solution potential is higher than -0.2 V, the equilibrium concentration of Au in solution can reach 5×10^{-5} mol/L (about 10 mg/L); when the concentration of NH₄OH is larger than 0.6 mol/L, and the potential of solution is greater than 0.2 V, the equilibrium concentration of Au in solution can reach 0.5 mol/L; $\varphi(O_2/OH^{-1})$ in this system is about 0.7 V, which ensures that oxygen can easily oxidize element Au into solution. Therefore, a low cost and non cyanogens process for extracting gold from low grade ores is proposed.

2) The thermodynamic study of the system of Au-Zn-Cu-NH₃-NH₄Cl-H₂O shows that when $c(Cu)_T$ and $c(Zn^{2+})_T$ are both equal to 0.01 mol/L, $\varphi(Cu^+/Cu)$ is about -0.5 V; $\varphi(Zn^{2+}/Zn)$ is about -1.0 V; $\varphi(O_2/OH^-)$ is about 0.7 V; $\varphi(H^+/H_2)$ is about -0.5 V. Thus, both copper and zinc powders can reduce Au⁺ into metal gold, and zinc powder can also reduce H₂O into H₂, while copper powder can not.

3) The leaching results of a cuprous gold ore show that the extraction of gold can reach 80% in this system. The preliminary results of reduction with copper and zinc powders show that deoxygenizing is of great importance for the reduction process.

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(Edited by YUAN Sai-qian)